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Volume II
Appendices

July 1991

Waste Isolation Pilot Plant

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LIST OF ACRONYMS

ANL	Argonne National Laboratory
ALARA	As Low As Reasonably Achievable
CAM	Continuous Air Monitor
C of C	Certificate of Compliance
CEDE	Cumulative Effective Dose Equipment
CFR	Code of Federal Regulations
CH	Contact-Handled
CH-TRU	Contact-Handled Transuranic
DOE	United States Department of Energy
DRZ	Disturbed Rock Zone
EAMP	Engineered Alternatives Multidisciplinary Panel
EATF	Engineered Alternative Task Force
EPA	United States Environmental Protection Agency
FEIS	Final Environmental Impact Statement
FSAR	Final Safety Analysis Report
FSEIS	Final Supplemental Environmental Impact Statement
G	G Value for Radiolysis
HAN	Hanford Reservation
HEPA	High Efficiency Particulate Air
HSWA	Hazardous and Solid Waste Amendments of 1984
IDLH	Immediate Danger to Life and Health
IMPES	Implicit Pressure Explicit Saturation
INEL	Idaho National Engineering Laboratories
IT Corp.	International Technology Corporation
ITEO	International Technology Engineering Operations
LANL	Los Alamos National Laboratories
LDMU	Law of Diminishing Marginal Utility
LLNL	Lawrence Livermore National Laboratory

LIST OF ACRONYMS
(CONTINUED)

LLW	Low-Level Waste
MAUT	Multi-Attribute Utility Theory
MB 139	Marker Bed 139
MRE	Measure of Relative Effectiveness
NDE	Number of Drum Equivalents
NMD	No-Migration Determination
NMED	New Mexico Environmental Department
NMVP	No-Migration Variance Petition
NRC	Nuclear Regulatory Commission
NTS	Nevada Test Site
OPC	Ordinary Portland Cement
ORNL	Oak Ridge National Laboratories
PA	Performance Assessment
PNL	Pacific Northwest Laboratories
PREPP	Process Experimental Pilot Plant
PRRC	Petroleum Research and Recovery Center
QA	Quality Assurance
RCRA	Resource Conservation and Recovery Act
rf	radius factor
RFP	Rocky Flats Plant
RH	Remote-Handled
SAR	Safety Analysis Report
SEIS	Supplemental Environmental Impact Statement
SF	Scale Factor
SNL	Sandia National Laboratories
SRS	Savannah River Site
SWB	Standard Waste Box
TF	Treatment Facilities
TLV	Threshold Limit Values
TRAMPAC	TRUPACT-II Authorized Methods for Payload Acceptance and Control
TRU	Transuranic

LIST OF ACRONYMS
(CONTINUED)

TRUPACT-II	Transuranic Package Transporter - II
TSD	Treatment, Storage, and Disposal
VR	Volume Reduction
WAC	Waste Acceptance Criteria
WACCC	Waste Acceptance Criteria Certification Committee
WERF	Waste Experimental Reduction Facility
WHB	Waste Handling Building
WIPP	Waste Isolation Pilot Plant
WPO	WIPP Project Office

APPENDIX A

REPORT OF THE WIPP ENGINEERED ALTERNATIVES MULTIDISCIPLINARY PANEL

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PREFACE

The WIPP Engineered Alternatives Multidisciplinary Panel, described in this report, was composed of individuals representing many disciplines and organizations. The primary Panel members included:

Member	Discipline	Organization*
Dr. Arun Agrawal	Metallurgy/Corrosion	Battelle Memorial Institute
Mr. Roger Hansen	Regulatory Compliance and Permitting	IT Corporation
Mr. Barry King	Microbiology	IT Corporation
Dr. Jon Myers	Geochemistry and Performance Assessment	IT Corporation
Mr. Milo Larsen	Waste Treatment	Haz Answers, Inc.
Mr. Mike McFadden	DOE/Institutional	U.S. Department of Energy WIPP Project Office
Mr. Vernon Daub	DOE/Institutional	U.S. Department of Energy WIPP Project Office
Mr. Jeff Paynter	Generator Waste Processing	EG&G Rocky Flats Incorporated
Mr. Kyle Peter	Generator Waste Processing	EG&G Rocky Flats Incorporated
Dr. Joe Tillerson	Rock Mechanics	Sandia National Laboratories
Mr. Bill White	Repository Operations	Westinghouse Electric Corporation Waste Isolation Division
Mr. Rod Palanca	Repository Operations	Westinghouse Electric Corporation Waste Isolation Division
Mr. Hans Kresny (Chairman)	Chairman and Facilitator	Solmont Corporation

*Current at the time the Panel convened in February, 1990.

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EXECUTIVE SUMMARY

The Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico, is an underground repository designed for the geologic disposal of radioactive wastes resulting from the defense activities and programs of the United States Department of Energy (DOE). The performance of nuclear waste repositories is governed by U.S. Environmental Protection Agency (EPA) Standard - 40 CFR Part 191 (EPA, 1985). The study conducted to demonstrate compliance with this regulation is called performance assessment. The performance assessment for the WIPP repository is being conducted by Sandia National Laboratories (SNL). The EPA standard requires that DOE provide a reasonable assurance, based on performance assessment, that cumulative releases of radioactivity to the accessible environment will not exceed the standard's criteria. Preliminary performance assessment performed by SNL (DOE, 1990a) has indicated that the current design of the WIPP repository, together with the waste forms at the DOE storage and generating sites, may not demonstrate compliance with the EPA Standard. In view of this concern, and prompted by recommendations from the National Academy of Sciences (NAS) (DOE, 1988c) and other external review groups, the DOE established the Engineered Alternatives Task Force (EATF) in September, 1989 (Hunt, 1990).

The objective of the EATF is to identify potential engineering modifications (referred to as engineered alternatives) to the existing WIPP design and/or to the transuranic (TRU) waste forms, and to evaluate their effectiveness and feasibility in facilitating compliance with the EPA Standard. These alternatives would be designed to completely eliminate or reduce any problems which might cause non-compliance with the EPA Standard. As an example, if excess gas generation from corrosion of steel containers is identified by performance assessment to be an impediment to demonstrating compliance with the EPA Standard, an engineered alternative consisting of a different waste container material which does not generate gas could be considered. Gas generation in WIPP and other potential problems are referred to as "performance parameters" and are being addressed by the performance assessment studies (DOE, 1990d).

The performance assessment studies to date have identified a number of important performance parameters that are listed in a later section. However, until the studies are completed, it will not be known which of these performance parameters are most important to demonstrating compliance with the EPA Standard. The EATF is dealing with this uncertainty by integrating its efforts with the performance assessment studies and addressing all performance parameters identified by the studies. Recommendations of the EATF will be forwarded by DOE to SNL for input into the performance assessment efforts, as needed.

The specific steps involved in accomplishing the goal of the EATF were to:

- Identify and screen potential engineered alternatives.
- Develop design analysis models for the evaluation of relative effectiveness of engineered alternatives in comparison to the existing WIPP design and TRU waste forms.
- Determine the mitigating effect of engineered alternatives for each performance parameter using a quantitative design analysis model.

- Determine potential locations for implementing recommended engineered alternatives.
- Provide estimated schedules and costs for implementation of engineered alternatives.
- Recommend selected alternatives to DOE.

The EATF convened an Engineered Alternatives Multidisciplinary Panel (EAMP) with the objective of accomplishing the first step; the initial qualitative screening and ranking of potential engineered alternatives. The EAMP comprised a group of experts from different disciplines to ensure that appropriate technical expertise was available to make the qualitative judgments regarding each potential alternative. The engineered alternatives screened by the EAMP would be subsequently used by the EATF for quantitative evaluation using design analysis models.

The following disciplines were represented on the EAMP:

- DOE/Institutional
- Generator TRU Waste Processing
- Geochemistry
- Metallurgy/Corrosion
- Microbiology
- Performance Assessment
- Regulatory Compliance and Permitting
- Repository Operations
- Rock Mechanics
- Waste Treatment.

The EAMP activities were carried out during November 1989 and February 1990. The EAMP members were briefed on WIPP, the EPA Standard 40 CFR Part 191 (EPA, 1985), the EPA land disposal restrictions in 40 CFR Part 268 (EPA, 1989), and the decision analysis methodology that was to be used. The EAMP also developed the criteria for screening and ranking the engineered alternatives. A total of 64 potential engineered alternatives suggested by the EATF and the EAMP were given preliminary scores by the EAMP for feasibility, and relative effectiveness in mitigating the effects of the performance parameters. These alternatives are listed in Table AES-1. Once the preliminary evaluations were completed, the EAMP took into consideration the heterogeneity of the TRU waste form and reevaluated the alternatives in terms of their ability to treat the different waste constituents (e.g., sludges, solid organics, etc.). The results of the EAMP formed the basis for recommendation of alternative waste forms for the WIPP Experimental Test Program (DOE, 1990b).

Methodology of Panel Evaluation

During the preliminary evaluations, ten performance parameters which might be important for demonstrating compliance with the EPA Standard were considered based on the performance assessment studies (Marietta et al., 1989). After further consultation with SNL's performance assessment group, the EAMP decided that the ten parameters could be condensed into a set

TABLE AES-1

POTENTIALLY USEFUL ENGINEERED ALTERNATIVES CONSIDERED BY THE ENGINEERED ALTERNATIVES MULTIDISCIPLINARY PANEL (EAMP)

WASTE FORM MODIFICATION ALTERNATIVES

Compact Waste
Incinerate and Cement
Incinerate and Vitrify
Wet Oxidation
Shred and Bituminize
Shred and Compact
Shred and Cement
Shred and Polymer Encapsulation
Shred, Add Salt, and Compact
Plasma Processing
Melt Metals
Add Salt Backfill
Add Other Sorbents
Add Gas Suppressants
Shred and Add Bentonite
Acid Digestion
Sterilize
Add Copper Sulfate
Add Gas Getters
Add Fillers
Segregate Waste Forms
Decontaminate Metals
Change Waste Generating Process
Add Anti-Bacterial Material
Accelerate Waste Digestion Process
Alter Corrosion Environment in WIPP
Alter Bacterial Environment in WIPP
Transmutation of Radionuclides
Vitrify Sludges

BACKFILL ALTERNATIVES

Salt Only
Salt Plus Gas Getters
Compact Backfill
Salt Plus Brine Sorbents
Preformed Compacted Backfill
Grout Backfill
Bitumen Backfill
Add Gas Suppressants

WASTE MANAGEMENT ALTERNATIVES

Minimize Space Around Waste Stack
Segregate Waste In WIPP
Decrease Amount of Waste Per Room
Emplace Waste and Backfill Simultaneously
Selective Vegetative Uptake

FACILITY DESIGN ALTERNATIVES

Brine Isolating Dikes
Raise Waste Above the Floor
Brine Sumps and Drains
Gas Expansion Volumes
Seal Disposal Room Walls
Vent Facility
Ventilate Facility
Add Floor of Brine Sorbents
Change Mined Extraction Ratio
Change Room Configuration
Seal Individual Rooms
Two Level Repository

PASSIVE MARKER ALTERNATIVES

Monument Forest Over Repository
Monument Covering the Entire Repository
Buried Steel Plate Over Repository
Artificial Surface Layer Over Repository
Add Marker Dye To Strata

MISCELLANEOUS ALTERNATIVES

Drain Castile Reservoir
Grout Culebra Formation
Increase Land Withdrawal Area
to Regulatory Boundary

WASTE CONTAINER ALTERNATIVES

Change Waste Container Shape
Change Waste Container Material

of five parameters, since some of the ten parameters are interdependent and not mutually exclusive of one another (Anderson, 1990).

The original parameters and the five performance parameters upon which the EAMP based its final results are:

Original Parameters	Condensed Set
Radiolytic Gas Generation	Radiolytic Gas Generation
Biological Gas Generation	Biological Gas Generation
Corrosion Gas Generation	Corrosion Gas Generation
Porosity of Waste	Permeability of the Waste Stack
Permeability of the Waste Stack	Radionuclide Solubility in Brine
Brine Inflow	
Leachability of Waste	
Shear Strength of Waste	
Radionuclide Solubility in Brine	
Human Intrusion	

The EAMP considered engineered alternatives in seven categories. These categories, along with examples of engineered alternatives evaluated, are presented below:

Category	Example
Waste Form Modification Alternatives	Vitrify sludges
Waste Management Alternatives	Segregate waste in WIPP
Backfill Alternatives	Grout backfill
Facility Design Alternatives	Change room configuration
Passive Marker Alternatives	Monument covering the entire repository
Miscellaneous Alternatives	Grout Culebra Formation
Waste Container Alternatives	Change waste container material

The EAMP's activities were conducted according to a management decision process that quantifies normally subjective information (Daugbjerg, 1980). The 64 potential engineered alternatives considered by the EAMP were first subjected to a "must" criteria test (i.e., criteria which each alternative must satisfy in order to be considered for further evaluation by the panel). The following "must" criteria were defined by the EAMP:

Regulatory Compliance and Permitting - The alternative must have a likelihood to demonstrate regulatory compliance.

Availability of Technology - Technology must have been demonstrated at a minimum of laboratory scale, and must have the potential for full-scale implementation.

Schedule of Implementation - The alternative must be implementable within eight years for newly generated waste, and within 15 years for retrievably stored waste.

Any alternative which failed to satisfy all three criteria was eliminated from further consideration. The remaining alternatives were then judged according to two criteria; their

effectiveness in mitigating the effects of each of the five performance parameters, and their feasibility in terms of the three "must" criteria listed above. The EAMP decided that for feasibility considerations, the order of importance of the three criteria was Regulatory Compliance and Permitting, followed by Availability of Technology, and Schedule of Implementation. This relative order of importance was reflected appropriately in the weights assigned to these criteria during the scoring process. The scoring process is described in detail below. The effectiveness criterion was not divided into any subcategories. However, the effectiveness of an alternative was evaluated separately for each of the performance parameters.

The overall scores for each alternative were calculated by taking both effectiveness and feasibility into account. The EAMP judged that effectiveness and feasibility were of almost equal importance, with effectiveness being marginally more important than feasibility. On a scale of 0 to 10 (a score of 10 being the most effective), effectiveness was assigned a weight of 5.1 and feasibility was assigned a weight of 4.9. Feasibility was further subdivided into the three criteria previously used as "must" criteria above. These criteria were now used as weighted components of the overall feasibility criterion and formed the basis for ranking the relative feasibility of the alternatives that were not previously eliminated.

Thus, the weights assigned to each criterion was as follows:

• Effectiveness	5.1
• Feasibility	
- Regulatory Compliance and Permitting	2.4
- Availability of Technology	1.5
- Schedule of Implementation	1.0
Total Weightage	10.0

The effectiveness of the alternatives was evaluated on a scale of 1 to 10 for each of the performance parameters. The feasibility of the alternatives was also evaluated on a scale of 10 for each one of the three feasibility criteria. Finally, the scores on the 10 point scale were multiplied by the appropriate weights as listed above to get effectiveness and feasibility scores, and then summed together to get a total score for each alternative for any particular performance parameter. The feasibility of each alternative was assumed to remain the same irrespective of the performance parameter being considered for effectiveness evaluation.

Thus, if an alternative received an effectiveness score of 9 for mitigating radiolytic gas generation, 5 for regulatory compliance and permitting, 6 for availability of technology, and 7 for schedule of implementation, its total weighted score would be as follows:

$$\underset{\text{Effectiveness}}{9 \times 5.1} + \underset{\text{Feasibility}}{(5 \times 2.4 + 6 \times 1.5 + 7 \times 1.0)} = \underset{\text{Total}}{73.9}$$

After the preliminary evaluations were completed, the heterogeneity of the TRU waste was addressed by evaluating the effectiveness of all applicable alternatives for the three types of waste forms that are expected to comprise the majority of the WIPP inventory. These waste forms are sludges, solid organics (combustibles), and solid inorganics (glass and metals). The

scoring methodology was similar, except that the effectiveness of the chosen alternatives was judged separately for each of the three major waste forms. In addition, only the condensed set of five performance parameters was considered instead of the original ten.

RESULTS OF PANEL EVALUATION

The results of the EAMP's screening of potential engineered alternatives indicate that numerous alternatives are available, if needed, to improve the performance of the WIPP repository. It should be emphasized that the screening process provides the basis for the quantitative design analyses of the engineered alternatives, and does not constitute an end result by itself. Therefore, the results must be considered preliminary to the follow-on design analyses and engineering studies to be conducted by the EATF.

In addition, it should be noted that a high scoring alternative is not necessarily an automatic choice over the others. In fact, the selection of an alternative is dependent on the extent of the problem (if any), as identified by the ongoing performance assessment studies. If the problem associated with a performance parameter is deemed to be minor by the performance assessment studies, even an alternative with low scores might be adequate to correct the problem.

The EAMP screening process eliminated all but 35 of the 64 engineered alternatives originally considered for evaluation. In addition, the EAMP added one alternative (cementation of the sludges) to the list, resulting in a total of 36 scored alternatives in six categories:

Waste Form Modification Alternatives	17
Waste Management Alternatives	2
Backfill Alternatives	6
Facility Design Alternatives	5
Passive Marker Alternatives	4
Waste Container Alternatives	2

The EATF has used the results of the EAMP and classified the waste form modification alternatives into seven generalized categories based on the similar final waste forms resulting from these treatments. These categories and the alternatives grouped into each category are:

- Vitrification of waste
  - Microwave melting (sludges only)
  - Plasma processing
  - Incinerate and vitrify (solid organics only)
  - Acid digest, calcine, and vitrify (solid organics only)

- Cementation of waste
  - Cementation of sludges into monoliths
  - Shred and cement (solid organics and inorganics)
  - Incinerate and cement (solid organics only)

- Compaction of waste (does not apply to sludges)
  - Compact
  - Shred and compact
  - Shred, add salt, then compact

- Encapsulation of waste (does not apply to sludges)
  - Shred and encapsulate with polymer
  - Shred and encapsulate with bitumen

- Preparation of ingots from melted metal waste (applicable only to solid inorganics)

- Shredding of waste followed by addition of bentonite

- pH buffering of waste
  - Buffering by lime
  - Buffering by cement
  - Buffering by alumina.

In addition, the EATF has included one more category in the above list which is not a waste form modification, but considered by the EATF to be an equally important group of alternatives. This new category is:

- Changing of waste container material.

In conjunction with the deliberations of the EAMP, the EATF has noted that there are some groups of alternatives which consistently received high scores for effectiveness, primarily because of their ability to eliminate the potential problem associated with a performance parameter. For example, all the different vitrification options (i.e., plasma processing, acid digestion, etc.) received consistently high effectiveness scores for the parameters associated with radiolytic gas generation, because they would (for all practical considerations) eliminate the potential associated with radiolytic gas generation. On the other hand, there are groups of alternatives which have been assigned low to moderate scores for effectiveness, because they can only slow down the rate processes associated with the parameter (instead of eliminating the potential). For example, any form of compaction of the waste was assigned low to moderate scores by the EAMP for corrosion gas generation, because these alternatives would only reduce the rate of corrosion gas generation but not eliminate it. Therefore, in order to develop a generalized set of recommendations for future design analysis, and for the WIPP Experimental Test Program, the EATF has divided the alternatives into two categories for each performance parameter:

- Alternatives which essentially eliminate the potential associated with a performance parameter

- Alternatives which only reduce or control the rate processes.

Alternatives belonging to both of the above categories were identified for the three gas generation parameters. The remaining parameters (permeability of waste stack and radionuclide solubility in brine) did not have any applicable alternatives belonging to the first category. In other words, the EAMP concluded that permeability and solubility can only be reduced or controlled but never completely eliminated.

Since the objectives of the WIPP Experimental Test Program and the design analysis modeling are primarily related to the effectiveness of an alternative, the EATF has summarized the panel

deliberations on the basis of effectiveness scores, and the two categories of alternatives mentioned above. It should be noted, however, that the feasibility of the alternatives is also being studied in detail as part of the overall EATF objectives.

Table AES-2 presents the set of alternatives which were consistently assigned high scores by the EAMP for their effectiveness for eliminating the potential associated with a performance parameter. Table AES-3 presents similar information for alternatives assigned low to moderate scores for effectiveness because they can only reduce the rate processes associated with a parameter, and cannot eliminate the potential. Since the extent to which the rate can be reduced or controlled is different for each alternative, the alternatives are listed in descending order of merit for each performance parameter.

It should be noted that since the properties of the final waste forms resulting from a lot of the alternatives are very similar, for the sake of brevity, alternatives in Tables AES-2 and have been grouped into one of the seven generalized categories described earlier. For example, all the different forms of compacting the waste have been grouped together as "compaction" in Table AES-3.

The EATF will perform design analyses of appropriate combinations of engineered alternatives from Tables AES-2 and AES-3 to quantify the improvement in repository performance using alternative waste forms. An example of such a combination for reducing the potential of radiolytic gas generation would be to cement the sludges, shredding and cementing the solid organics, and decontaminate the metals. Either grout or salt could be added in the repository as a backfill material. Similarly, decontamination of all corroding metals from the waste inventory, and changing the waste container material could be used to eliminate the potential of corrosion gas generation.

The EAMP considered ranking a set of combined alternatives based on their effectiveness and feasibility. However, it was decided that since the evaluation process was primarily qualitative, ranking the combinations merely on the basis of summation of their individual scores would not be meaningful, and therefore not advisable.

The results of the EAMP's evaluations will be used to:

1. Recommend waste form alternatives that should be included in the WIPP Experimental Test Program.

2. Provide a basis for identification of combinations of alternatives that should be quantitatively analyzed for relative effectiveness.

3. Provide a basis for evaluation of the relative cost and schedule ramifications for implementation of the most effective and feasible alternatives.

The final choice of alternative(s), and whether any alternatives are needed, will be decided in conjunction with the performance assessment studies when the extent of mitigation required is determined.

TABLE AES-2

WASTE FORM MODIFICATIONS FOR ELIMINATING POTENTIAL

	WASTE FORM		
PARAMETER	SLUDGES	SOLID ORGANICS	SOLID INORGANICS
Radiolytic Gas Generation	Vitrification	Plasma processing Incinerate and Vitrify Acid digest and Vitrify	Vitrification
Biological Gas Generation	Vitrification	Plasma processing Incinerate and Cement Incinerate and Vitrify Acid digest and Vitrify	Category does not pose biological gas generation problem
Corrosion Gas Generation	Vitrification	Category does not pose corrosion gas generation problem	Decontamination of corroding metals Change existing waste container material
Permeability of the Waste Stack	None	None	None
Radionuclide Solubility in Brine	None	None	None

TABLE AES-3

WASTE FORM MODIFICATIONS FOR REDUCING/CONTROLLING POTENTIAL

	WASTE FORM		
PARAMETER	SLUDGES	SOLID ORGANICS	SOLID INORGANICS
Radiolytic Gas Generation	Cementation* pH Buffers	Incinerate and Cement Compaction pH Buffers	Decontamination Melted metals pH Buffers
Biological Gas Generation	Cementation* pH Buffers	Shred and Cement Compaction pH Buffers Shred, add bentonite	Category does not pose biological gas generation problem
Corrosion Gas Generation	Cementation* pH Buffers	Category does not pose corrosion gas generation problem	Vitrification pH Buffers Encapsulation Melted metals Shred and cement Compaction Shred, add bentonite
Permeability of the Waste Stack	Vitrification Cementation* pH Buffers	Vitrification Encapsulation Cementation Shred, add bentonite Compaction pH Buffers	Vitrification Melted metals Shred, add bentonite Encapsulation Shred and Cement Decontaminate metals Compaction pH Buffers
Radionuclide Solubility in Brine	Cementation* pH Buffers	Cementation pH Buffers Vitrification	Decontaminate metals pH Buffers Shred and cement Melted metals

*Cementation into monoliths.

1.0 INTRODUCTION

1.1 BACKGROUND

The Waste Isolation Pilot Plant (WIPP), a Department of Energy (DOE) project near Carlsbad, New Mexico, is intended as a geologic repository designed for the safe disposal of transuranic (TRU) radioactive wastes that have been generated by the defense activities of the U.S. government. The performance of nuclear waste repositories (such as WIPP) is regulated by the U.S. Environmental Protection Agency (EPA) Standard - 40 CFR Part 191 (EPA, 1985) promulgated in 1985. The EPA Standard addresses the waste isolation capability of radioactive waste sites and includes specific requirements regarding containment of radioactivity, quality assurance, individual radiation protection for the public, and limits on groundwater radionuclide concentrations. The containment requirements mandate that radioactive waste disposal systems be designed to provide a "reasonable expectation" that cumulative releases of radionuclides over 10,000 years will not exceed specified levels, based on studies referred to as performance assessment. The assurance requirements were selected to provide confidence that containment requirements can be met and mandate active institutional controls (e.g., boundary markers, etc.) over disposal sites for as long a period of time as is "practicable" after disposal. However, for the purposes of assessing the performance of a geologic repository, these institutional controls are assumed not to contribute to waste isolation longer than 100 years following disposal.

Since TRU wastes to be emplaced in WIPP are also contaminated with hazardous chemical wastes, they are subject to regulations under the Resource Conservation and Recovery Act (RCRA). The land disposal of untreated hazardous wastes is prohibited by EPA Standard 40 CFR Part 268.6 (EPA, 1989), unless the DOE can obtain a variance for WIPP waste by demonstrating to the EPA that the wastes will not migrate from the disposal unit. A petition for a variance was submitted by the DOE to the EPA (DOE, 1990c), and the EPA granted a conditional No-Migration Determination in November, 1990 (EPA, 1990).

The performance assessment for WIPP is being conducted by Sandia National Laboratories (SNL) and is expected to be completed by 1994 (DOE, 1990d). However, preliminary performance assessment (DOE, 1990a) has indicated that the current design of the WIPP repository and the existing waste forms at the storage/generator sites may not be able to demonstrate compliance with the EPA Standard 40 CFR Part 191. In consideration of such an eventuality, the National Academy of Sciences (NAS) WIPP Panel recommended in March 1988, that DOE investigate the feasibility of possible technical "fixes" to the WIPP site and/or to the waste itself (DOE, 1988c). If the performance assessment studies cannot demonstrate compliance with the EPA Standard 40 CFR Part 191, then these "fixes" could be applied to successfully rectify any potential scenario of noncompliance.

The NAS provided examples of such "fixes" including:

- Getters to absorb gases
- Inhibitors to suppress bacterial activity
- Repository ventilation until closure
- Absorbers for brine reduction
- Waste processing into a dense, chemically stable form

- Brine drainage (sumps)
- Drum void space reduction.

Based on this recommendation by the NAS, and the recommendations of other external review groups, the DOE established the Engineered Alternatives Task Force (EATF) in September, 1989 (Hunt, 1990).

The objective of the EATF is to identify potential engineering modifications (referred to as "engineered alternatives") to the current design of WIPP and/or to the present waste forms in order to enhance repository performance. These alternatives would either eliminate or mitigate any problems associated with demonstrating compliance with the EPA Standard 40 CFR Part 191. As an example, if excess gas generation from corrosion of steel waste containers is identified by performance assessment as an impediment to demonstrating compliance with 40 CFR Part 191, an engineered alternative such as modifying the waste container material could be implemented. Potential problems such as gas generation are referred to as "performance parameters" and are being addressed by the performance assessment studies (DOE, 1990d).

The studies have identified a number of different performance parameters (Marietta et al., 1989). However, until the performance assessment studies are completed, it will not be known which specific performance parameters are most important to demonstrating compliance with the EPA Standard. The EATF is dealing with this uncertainty by integrating its efforts with the ongoing performance assessment studies at SNL and addressing all performance parameters identified in conjunction with these studies. While the studies are being conducted, the results of the EATF may provide one or more engineered alternatives to mitigate the effects of the identified parameter(s), if compliance with EPA Standard 40 CFR Part 191 cannot be demonstrated otherwise.

The various tasks of the EATF are to:

- Identify and screen potential engineered alternatives and evaluate their feasibility of implementation.
- Develop a deterministic design analysis model to evaluate the effectiveness of the engineered alternatives in comparison with the existing WIPP design and TRU waste forms.
- Evaluate the mitigating effect of potential engineered alternatives on waste forms and on repository performance for each performance parameter using the developed design analysis model.
- Provide estimated schedules and costs for implementation of engineered alternatives.
- Recommend potential locations for implementation of engineered alternatives.
- Recommend selected alternatives to the DOE.

The Engineered Alternatives Multidisciplinary Panel (EAMP) was formed to accomplish the first of the EATF Tasks; the qualitative initial screening and ranking of potential engineered alternatives. The composition of the EAMP is described in the following section.

1.2 COMPOSITION OF THE EAMP AND ITS OBJECTIVES

In view of the technical expertise needed in the areas associated with the engineered alternatives, and in consideration of other important regulatory and operational issues associated with the WIPP repository, the following disciplines were represented on the panel:

- DOE/Institutional
- Generator Waste Processing
- Geochemistry
- Metallurgy/Corrosion
- Microbiology
- Performance Assessment
- Regulatory Compliance and Permitting
- Repository Operations
- Rock Mechanics
- Waste Treatment.

A description of the EAMP requirements and qualifications of panel members is provided in Attachment A. The specific objectives of the EAMP were to:

- Identify potential alternatives, and establish screening criteria that any potential alternative must satisfy in order to be considered for further evaluation.

- Establish criteria for the qualitative evaluation of each alternative regarding its mitigating effects on each performance parameter.

- Rank the screened engineered alternatives for their mitigating effects using the established criteria and decision analysis techniques.

1.3 NONCOMPLIANCE SCENARIOS AND PERFORMANCE PARAMETERS

The scenarios that were considered to be bounding conditions for selecting performance parameters consisted of both natural (undisturbed performance) and human intrusion events. Seven hypothetical scenarios were developed by SNL (Marietta et al., 1989), a base case scenario and six additional scenarios which may be expected to occur during the regulatory periods described in EPA Standard 40 CFR Part 191 (EPA, 1985). The performance parameters are based on these seven scenarios. The seven scenarios shown in Figure A-1 include:

Base Case - This was defined as an undisturbed repository with gas generation, brine inflow from the Salado Formation, and normal creep closure of the salt.

Human Intrusion - Six cases were considered:

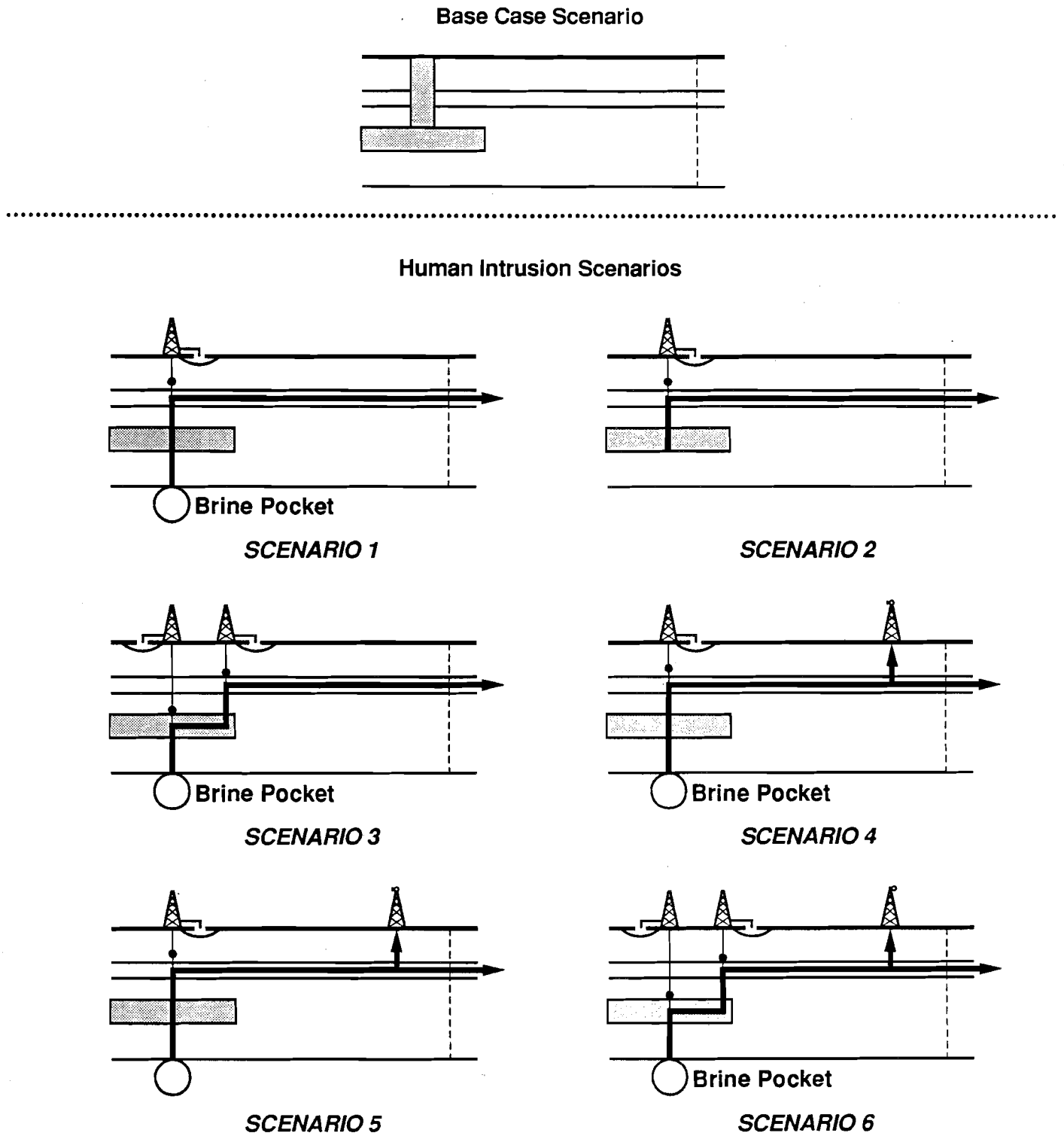

Figure A-1
Base Case and Intrusion Scenarios

1. A single borehole is drilled through the repository to a postulated pressurized brine pocket. Before the borehole is plugged, release occurs directly to the surface. After the borehole is plugged, release also occurs along a horizontal pathway above the repository to the regulatory boundary.

2. Same as Scenario 1, except that drilling stops in the repository horizon.

3. Two boreholes are drilled, consisting of Scenarios 1 and 2, with the commensurate releases.

4. Same as Scenario 1, except that extraction of water takes place within the regulated boundary.

5. Same as Scenario 2, except that extraction of water takes place within the regulated boundary.

6. Same as Scenario 3, except that extraction of water takes place within the regulated boundary.

Under the above scenarios, there are three basic elements that have the potential to create the conditions that could lead to non-compliance with the EPA Standards. These basic elements are:

- Mobility of the waste
- The release path to the regulated boundary
- The release mechanisms that move waste to the accessible environment, or beyond the unit boundary in the case of the RCRA requirements.

The ten performance parameters associated with the three elements that have been identified based on the performance assessment studies are (Marietta et al., 1989):

PERFORMANCE PARAMETER	SCENARIO(S)
Radiolytic Gas Generation	Base Case
Biological Gas Generation	Base Case
Corrosion Gas Generation	Base Case
Waste Permeability	Base Case & Human Intrusion
Waste Porosity	Base Case & Human Intrusion
Waste Strength	Human Intrusion
Radionuclide Leachability	Base Case & Human Intrusion
Radionuclide Solubility	Base Case & Human Intrusion
Brine Inflow	Base Case & Human Intrusion
Human Intrusion Probability	Human Intrusion

The subsequent sections of this report describe the methodology used by the EAMP to accomplish its objectives of screening and ranking engineered alternatives with reference to the parameters listed above, the results of the EAMP deliberations, and finally, the conclusions reached by the EAMP and the EATF regarding the effectiveness of engineered alternatives.

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2.0 METHODOLOGY USED TO EVALUATE ENGINEERED ALTERNATIVES

The EAMP activities were carried out during November 1989 and February 1990. The panel members were briefed on WIPP, the EPA Standard 40 CFR Part 191 (EPA, 1985), the EPA land disposal restrictions in 40 CFR Part 268 (EPA, 1989), the performance parameters, and the decision analysis methodology that was to be used. The EAMP, in conjunction with the EATF, prepared a list of potential engineered alternatives (described in Attachment B) in seven different categories. The 64 potential engineered alternatives are listed in Table A-1. The seven different categories are listed below with an example for each category:

Category	Example
Waste Form Modification Alternatives	Vitrify sludges
Waste Management Alternatives	Segregate waste in WIPP
Backfill Alternatives	Grout backfill
Facility Design Alternatives	Change room configuration
Passive Marker Alternatives	Monument covering the entire repository
Miscellaneous Alternatives	Grout Culebra Formation
Waste Container Alternatives	Change waste container material

After developing the criteria against which to screen and rank the engineered alternatives, each alternative was subjected to a preliminary evaluation which considered ten parameters for alternative effectiveness and three for alternative feasibility. A brief description of the preliminary evaluation and results is provided in Attachment C. Once the preliminary evaluations were completed, the EAMP incorporated the heterogeneity of TRU waste in the evaluation process by examining the applicability of each alternative for each one of the three major constituents of TRU waste. These three constituents of TRU waste are as follows:

- Sludges
- Solid Organics (Combustibles)
- Solid Inorganics (Glass and Metals).

This was necessary because not all alternatives apply to all types of waste. As an example, compaction does not apply to sludges. Also, based on an update from SNL (Anderson, 1990), only five performance parameters were considered instead of the original ten because some of the ten parameters are interdependent, and therefore could be combined into one parameter. The five parameters were:

- Radiolytic Gas Generation
- Biological Gas Generation
- Corrosion Gas Generation
- Permeability of the Waste Stack
- Radionuclide Solubility (in Brine).

The remaining parameters that were considered by the EAMP during the preliminary evaluations are inherent in the above parameters. For instance, leachability and solubility are

TABLE A-1

POTENTIALLY USEFUL ENGINEERED ALTERNATIVES CONSIDERED BY THE ENGINEERED ALTERNATIVES MULTIDISCIPLINARY PANEL (EAMP)

WASTE FORM MODIFICATION ALTERNATIVES

Compact Waste
Incinerate and Cement
Incinerate and Vitrify
Wet Oxidation
Shred and Bituminize
Shred and Compact
Shred and Cement
Shred and Polymer Encapsulation
Shred, Add Salt, and Compact
Plasma Processing
Melt Metals
Add Salt Backfill
Add Other Sorbents
Add Gas Suppressants
Shred and Add Bentonite
Acid Digestion
Sterilize
Add Copper Sulfate
Add Gas Getters
Add Fillers
Segregate Waste Forms
Decontaminate Metals
Change Waste Generating Process
Add Anti-Bacterial Material
Accelerate Waste Digestion Process
Alter Corrosion Environment in WIPP
Alter Bacterial Environment in WIPP
Transmutation of Radionuclides
Vitrify Sludges

BACKFILL ALTERNATIVES

Salt Only
Salt Plus Gas Getters
Compact Backfill
Salt Plus Brine Sorbents
Preformed Compacted Backfill
Grout Backfill
Bitumen Backfill
Add Gas Suppressants

WASTE MANAGEMENT ALTERNATIVES

Minimize Space Around Waste Stack
Segregate Waste In WIPP
Decrease Amount of Waste Per Room
Emplace Waste and Backfill Simultaneously
Selective Vegetative Uptake

FACILITY DESIGN ALTERNATIVES

Brine Isolating Dikes
Raise Waste Above The Floor
Brine Sumps and Drains
Gas Expansion Volumes
Seal Disposal Room Walls
Vent Facility
Ventilate Facility
Add Floor of Brine Sorbents
Change Mined Extraction Ratio
Change Room Configuration
Seal Individual Rooms
Two Level Repository

PASSIVE MARKER ALTERNATIVES

Monument Forest Over Repository
Monument Covering the Entire Repository
Buried Steel Plate Over Repository
Artificial Surface Layer Over Repository
Add Marker Dye To Strata

MISCELLANEOUS ALTERNATIVES

Drain Castile Reservoir
Grout Culebra Formation
Increase Land Withdrawal Area to Regulatory Boundary

WASTE CONTAINER ALTERNATIVES

Change Waste Container Shape
Change Waste Container Material

related, as are porosity and permeability. Brine inflow and waste strength are dependent, to a large extent, on permeability. The EAMP also re-evaluated the backfill alternatives in terms of their ability in mitigating the effect of the five performance parameters. The following subsections describe in detail the criteria established and the decision analysis technique used by the EAMP.

2.1 ESTABLISHMENT OF SCREENING CRITERIA

The evaluation criteria was based upon a management decision process that quantifies normally subjective information (Daugbjerg, 1980). The 64 potential engineered alternatives were first subjected to a "must" criteria test for initial screening (i.e., criteria which each alternative must satisfy in order to be considered for further evaluation). The following "must" criteria were defined by the EAMP:

- Regulatory Compliance and Permitting - The alternative must have the likelihood to demonstrate regulatory compliance including local, state, or federal permits to operate, based in part on past experience with other similar facilities/processes, including public opinion considerations.

- Availability of Technology - The alternative must have been demonstrated at a minimum of laboratory scale and must have the potential for full-scale implementation in the future.

- Schedule of Implementation - The EAMP assumed that waste disposal at WIPP should begin no later than 8 years from 1989 for newly-generated waste and 15 years for retrievably stored waste. Based on this assumption, it was decided that any alternative must be implementable within 8 years for newly-generated waste and 15 for retrievably stored waste.

Alternatives which failed to satisfy all the three "must" criteria were eliminated from further consideration. In addition, some of the alternatives which were deemed to be similar in nature were combined to eliminate redundancies. A list of the alternatives which were eliminated from further consideration and the reasons for their elimination are presented in Table A-2. The process of elimination resulted in 35 remaining alternatives which were considered for further evaluation. Also, the EAMP added an alternative (cementation of sludges) to increase the total to 36 evaluated alternatives. These alternatives are listed in Table A-3.

2.2 ESTABLISHMENT OF EVALUATION CRITERIA

The process of evaluation of the 36 alternatives was based on two basic criteria; effectiveness of the alternative in mitigating the effects of each performance parameter, and its feasibility.

2.2.1 Evaluation of Effectiveness

The effectiveness of each alternative in mitigating the effect of each of the ten original performance parameters was evaluated on a scale of 1 to 10 (a score of 10 being the most effective) in the preliminary evaluation. In cases where an alternative was judged to have no effect on a parameter (positive or negative), it was not given a score (represented by a "-" in the scoring column). On the other hand, if an alternative was judged to have an adverse

TABLE A-2

ALTERNATIVES DELETED FROM FURTHER CONSIDERATION AND THE REASONS FOR THEIR DELETION

ALTERNATIVES	REASONS FOR DELETION
Wet Oxidation	Technology Not Demonstrated For Solid Waste
Sterilization of Waste Package	Not Feasible To Maintain Long Term Effectiveness
Add Copper Sulfate	Potential for Hydrogen Generation by Galvanic Coupling of Deposited Copper
Add Anti-Bacterial Material	Unable To Identify A Long Term Anti-Bacterial Material
Accelerate Waste Digestion	Technology For Fast Waste Digestion Not Demonstrated
Transmutation of Radionuclides	Technology Not Demonstrated for Large Waste Amounts
Change Generating Process	Scope Is Too Broad To Be Evaluated
Selective Vegetative Uptake	Not Been Laboratory Demonstrated For TRU Waste
Brine Sumps and Drains	Brine Flow Will Stop After Reconsolidation of Salt
Seal Disposal Room Walls	Technology Has Not Been Demonstrated
Vent Facility	Not Regulatory Feasible After Institutional Control
Artificial Surface Layer	Not Possible To Identify A Feasible Concept
Drain Castile Reservoir	Technologically Not Feasible
Grout Culebra Formation	Technologically Not Feasible
Increase Land Withdrawal Area	This Is Not An Engineered Alternative
Add Salt Backfill	Considered Under Backfill Alternatives
Add Brine Sorbents	Considered Under Backfill Alternatives
Add Gas Suppressants	Considered Under 'Add Gas Getters'
Add Fillers	Considered Under Backfill Alternatives
Alter Bacterial Environment	Considered In Evaluation of Other Alternatives
Decrease Waste Per Room	Considered Under Backfill Alternatives
Simultaneous Emplacement of Waste/Backfill	Considered Under Compact Backfill
Gas Suppressants as Backfill	Considered Under Salt Plus Alkali In Backfills
Preformed Compacted Backfill	Considered Under Compact Backfill
Brine Isolating Dikes	Considered Under Sealing Individual Rooms
Raise Waste Above Floor	Considered Under Add Sorbents To Backfill
Gas Expansion Volume	Indeterminate Unless Total Volume of Gas Is Known
Add Floor Of Brine Sorbent	Considered Under Backfill Alternatives
Segregate Waste Forms	Alternative Is Not A Stand-Alone Process

TABLE A-3

ALTERNATIVES CONSIDERED FOR FURTHER EVALUATION BY THE ENGINEERED ALTERNATIVES MULTIDISCIPLINARY PANEL (EAMP)

WASTE FORM MODIFICATION ALTERNATIVES

Compact Waste
Incinerate and Cement
Incinerate and Vitrify
Shred and Bituminize
Shred and Compact
Shred and Cement
Shred and Polymer Encapsulation
Shred, Add Salt, and Compact
Plasma Processing
Melt Metals
Shred and Add Bentonite
Acid Digestion
Add Gas Getters
Decontaminate Metals
Alter Corrosion Environment in WIPP
Vitrify Sludges
Cementation of Sludges

BACKFILL ALTERNATIVES

Salt Only
Salt Plus Gas Getters
Compact Backfill
Salt Plus Brine Sorbents
Grout Backfill
Bitumen Backfill

WASTE MANAGEMENT ALTERNATIVES

Minimize Space Around Waste Stack
Segregate Waste In WIPP

FACILITY DESIGN ALTERNATIVES

Ventilate Facility
Change Mined Extraction Ratio
Change Room Configuration
Seal Individual Rooms
Two Level Repository

PASSIVE MARKER ALTERNATIVES

Monument Forest Over Repository
Monument Covering the Entire Repository
Buried Steel Plate Over Repository
Add Marker Dye To Strata

WASTE CONTAINER ALTERNATIVES

Change Waste Container Shape
Change Waste Container Material

effect on a parameter (i.e., it worsened the situation instead of mitigating it), then the alternative was given a score of zero and eliminated from further consideration for that particular parameter. The difference between the "adverse effect" case and the "no effect" case is explained later in Section 2.2.3.

2.2.2 Evaluation of Feasibility

The feasibility was evaluated in terms of the three criteria originally defined as "must" criteria, and mentioned earlier in Section 2.1. These criteria were now used as weighted components of the overall feasibility criterion and formed the basis for ranking the relative feasibility of the alternatives that were still under consideration. The alternatives were scored on a scale of 1 to 10 based on their relative ease or difficulty in satisfying these criteria as judged by the EAMP. It should be noted that unlike the evaluation of effectiveness, the term "adverse effect" does not apply in this case because the feasibility of an alternative was assumed to be independent of the parameter being considered.

2.2.3 Overall Scoring Process for Alternatives

The overall scores for an alternative for mitigating the effects of a parameter were calculated by combining its effectiveness and feasibility scores using a weighted summation approach. The EAMP judged that effectiveness and feasibility were of almost equal importance with effectiveness being marginally more important than feasibility. Therefore on a weighing scale of 10, effectiveness was assigned a weight of 5.1 and feasibility was assigned a weight of 4.9. However, since the feasibility was evaluated in terms of the three criteria originally used as "must" criteria, the weight of 4.9 was further subdivided among the three criteria depending on their relative importance. It was decided that for feasibility considerations, the most important of these three criteria was Regulatory Compliance and Permitting, followed by Availability of Technology, and then Schedule of Implementation. This relative order of importance for the feasibility criteria was appropriately reflected in the weights assigned to these criteria. The relative weights assigned to the different evaluation criteria were as follows:

• Effectiveness	5.1
• Feasibility	
- Regulatory Compliance and Permitting	2.4
- Availability of Technology	1.5
- Schedule of Implementation	1.0
	10.0

The effectiveness and feasibility scores developed by the EAMP in each of the three subcategories (all on a scale of 1 to 10) were multiplied by the appropriate weights listed above and then added together to get the overall score for each alternative for a given performance parameter. The feasibility of an alternative was assumed to be independent of the performance parameter, and therefore remained the same irrespective of the parameter being considered. Figures A-2 and A-3 depict this evaluation process.

As an example, if an alternative received an effectiveness score of 9 for mitigating radiolytic gas generation, 5 for regulatory compliance and permitting, 6 for availability of technology, and 7 for schedule of implementation, then its overall score would be calculated as follows:

9x5.1	+	(5x2.4 + 6x1.5 + 7x1.0)	=	73.9
Effectiveness		Feasibility		Total

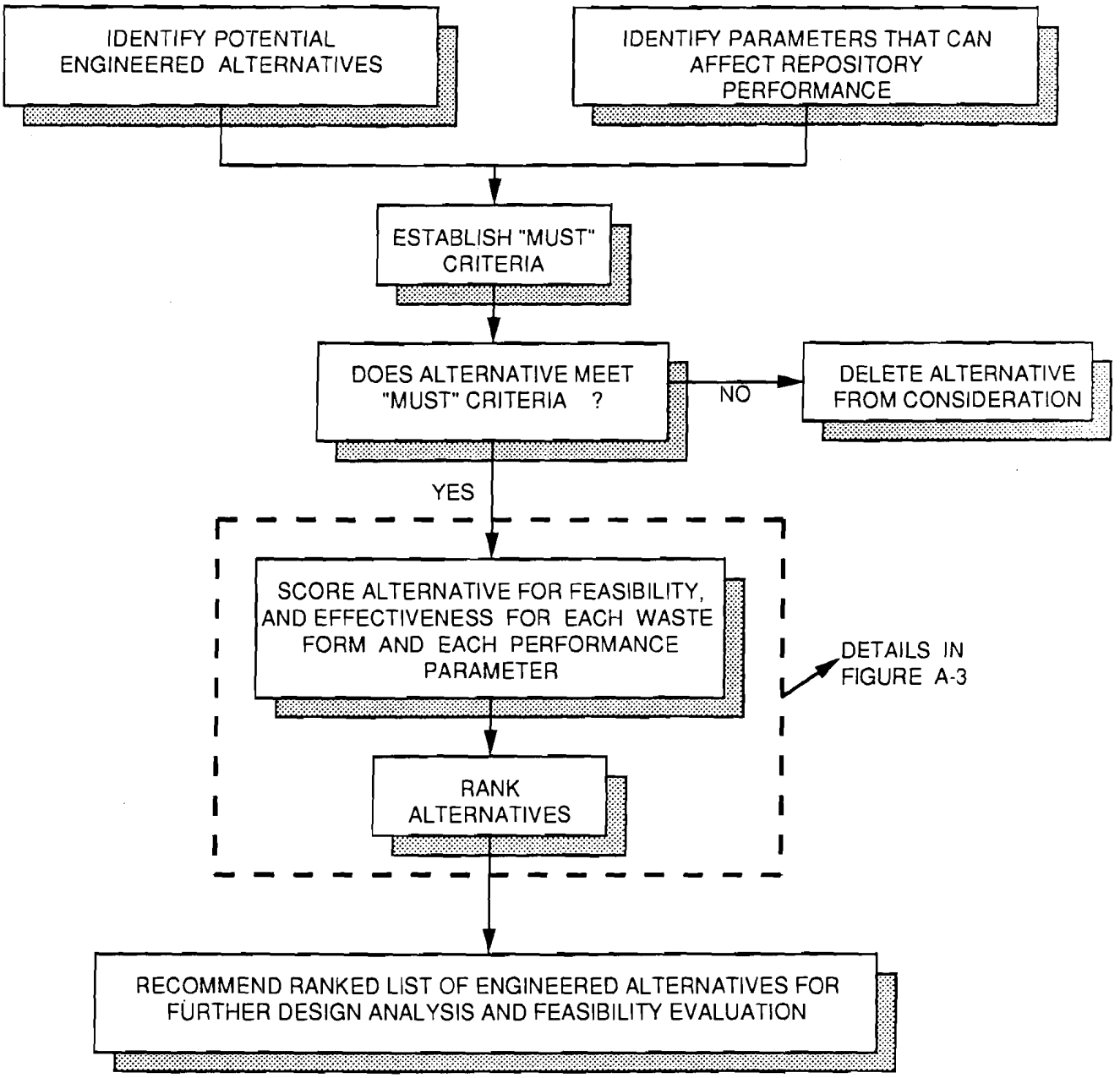

Figure A-2 . Identification and Ranking of Potentially Feasible Engineering Alternatives

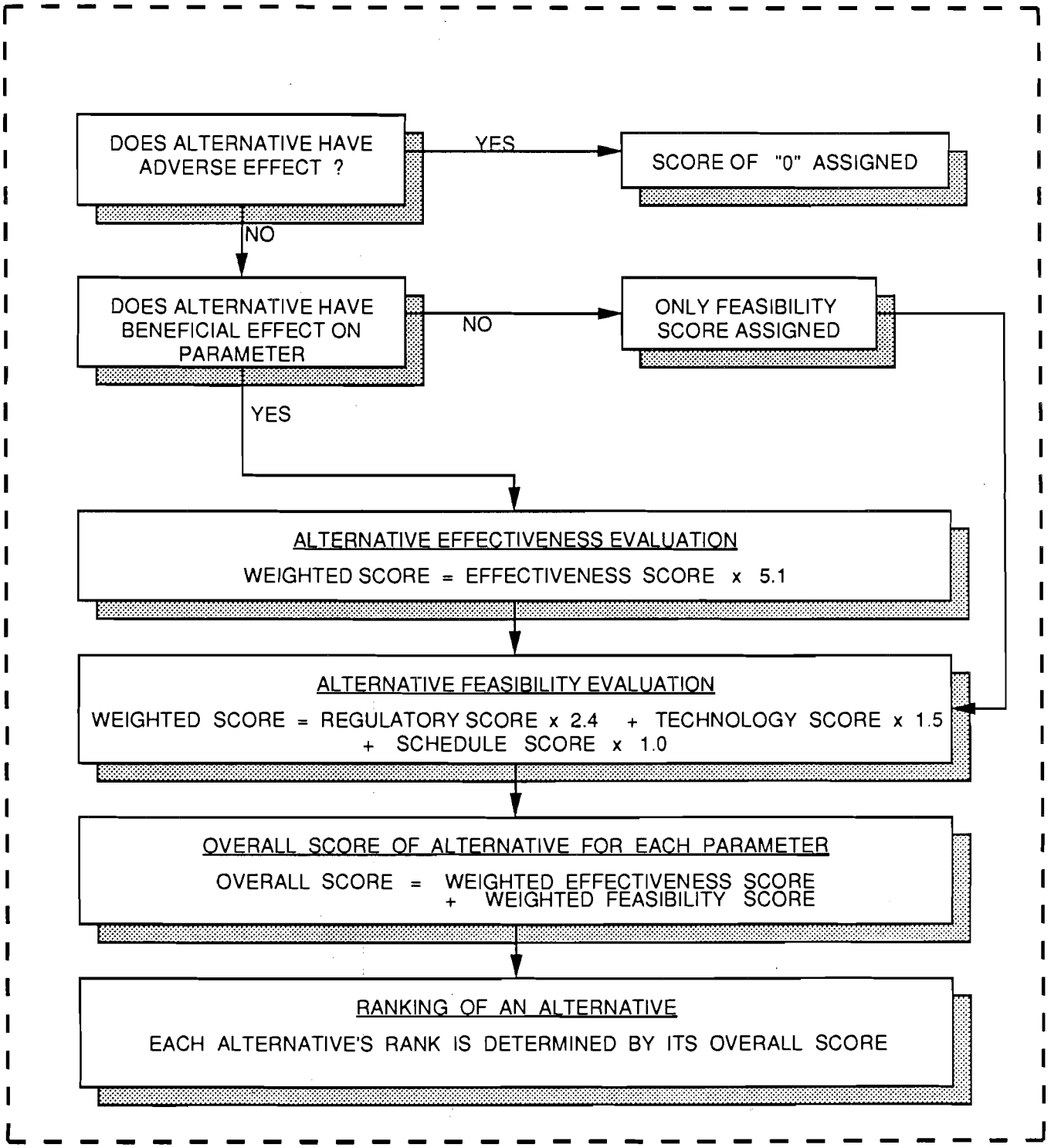

Figure A-3. Ranking of Alternatives for each Parameter

There were two exceptions to the weighted summation approach for calculating overall scores. If an alternative was judged to have an adverse effect on a performance parameter, (i.e., it was assigned a score of zero), then its overall score was also a zero irrespective of its feasibility score. On the other hand, if an alternative was judged to have no effect at all (positive or negative), then its overall score was simply equal to its feasibility score.

2.3 EVALUATION INCORPORATING HETEROGENEITY OF TRU WASTE

After the preliminary evaluations were completed, the EAMP addressed the heterogeneity of the TRU waste recognizing that each major waste form may require different treatment. The composition of TRU waste comprising the potential WIPP inventory was provided to the EAMP by the EATF and is presented in Table A-4.

The EAMP addressed those waste forms that represent the largest quantities. These waste forms are:

- Sludges
- Solid Organics (combustibles)
- Solid Inorganics (glass and metals).

From Table A-4, these three waste forms comprise 89 percent of the total inventory volume and 83 percent of the total inventory weight. The EAMP believed that the remaining waste forms could be treated using the alternatives identified for the majority of the waste. Since all waste form modification alternatives are not applicable to all the major waste forms (e.g., compaction does not apply to sludges), the EAMP first identified those alternatives that could be applied to each of the three major waste forms (Table A-5).

The scoring methodology used was similar to the one described in Sections 2.2.1 - 2.2.3 with a few minor exceptions:

- Since the feasibility of an alternative is independent of the type of waste form being treated, the feasibilities were assumed to remain the same and were therefore not recorded.

- Only five performance parameters were considered instead of ten (as explained in Section 2.0).

TABLE A-4

COMPOSITION OF TRANSURANIC (TRU) WASTE*

WASTE FORMS	VOLUME %	WEIGHT %
Sludges	15.3	37
Solid Organics (combustibles)	39.8	14
Filters	4.5	2
Asphalt/Dirt	2.1	5
Solid Inorganics (glass and metals)	34.3	32
Others (Salts, etc.)	4.0	10

* Calculated from DOE, 1988b.

TABLE A-5

WASTE FORM MODIFICATIONS APPLICABLE TO THE THREE MAJOR WASTE FORMS

SLUDGES	SOLID ORGANICS	SOLID INORGANICS
Alter Environment	Alter Environment	Alter Environment
Cementation	Add Gas Getters	Add Gas Getters
Plasma Processing	Plasma Processing	Plasma Processing
Vitrification	Compact	Compact
	Shred, Add Bentonite	Shred, Add Bentonite
	Shred and Bituminize	Shred and Bituminize
	Shred and Cement	Shred and Cement
	Shred and Compact	Shred and Compact
	Shred and Encapsulate	Shred and Encapsulate
	Acid Digestion	Melt Metals
	Incinerate and Cement	Decontaminate Metals
	Incinerate and Vitrify	Shred, Add Salt, and Compact
	Shred, Add Salt, and Compact	

3.0 RESULTS OF THE EAMP DELIBERATIONS

The results of the EAMP deliberations represent the relative effectiveness and feasibility of the listed alternatives and should not be considered in absolute terms. When specific problems associated with regulatory compliance have been identified, the results of the EAMP, supplemented by the results of design analysis studies, will determine which alternatives should be recommended to DOE for inclusion in WIPP performance assessment. At that time, alternatives that were not ranked highest for effectiveness and/or feasibility may, nevertheless, be found to be adequate to resolve the problem(s), if any, associated with regulatory compliance.

3.1 EFFECTIVENESS OF ALTERNATIVES

The results of the preliminary evaluation are provided in Attachment C. The EAMP deliberations resulted in the scoring of alternatives for waste form modification, waste management, backfills, facility design, passive markers, waste container, and miscellaneous concepts for each of the ten parameters. The overall scores, combining effectiveness and feasibility, are also provided in Attachment C.

The final results of the scoring process for the alternatives which were evaluated on the basis of the heterogeneity of the TRU waste are shown in Table A-6. As mentioned in Section 2.3, the feasibility scores developed during the preliminary evaluations were not changed, and are reflected in Table A-6. The columns grouped under "Alternative Overall Score" show the total scores (effectiveness plus feasibility) for each parameter calculated according to the methodology described earlier in Section 2.0. These scores form the basis for ranking the relative merit of each engineered alternative in mitigating the effects of each performance parameter.

3.1.1 Waste Form Modification Alternatives

The rationale behind the effectiveness scores assigned to various alternatives listed in Table A-6 for each one of the five major parameters is discussed in this section.

The alternatives "adding gas getters", "altering the (corrosion) environment", and "cementation", were also considered effective pH buffers. Therefore the term "pH-buffers" has often been used in the subsequent sections to refer to these three alternatives as well.

3.1.1.1 Radiolytic Gas Generation

Sludges

Since the EAMP considered only the inorganic sludges which are a vast majority, the alternatives were rated primarily on their ability to remove the water present in the sludges, and to lower brine access to the waste (e.g., by lowering permeability). Plasma processing of the sludges was considered the best treatment for this waste form because it can remove all the water present as well as eliminating the most porosity. In comparison, vitrification, by more conventional means, was considered nearly as effective as plasma processing, but it may not remove as much residual porosity. The two other alternatives, cementation and altering

TABLE A-6

SUMMARY OF OVERALL SCORES FOR ENGINEERED ALTERNATIVES

ALTERNATIVE	EFFECTIVENESS (Wt.=5.1) SCORE						FEASIBILITY (Wt=4.9) SCORE			SUM	ALTERNATIVE OVERALL SCORE EFFECTIVENESS + FEASIBILITY					
	RAD GAS	BIO GAS	CORR GAS	PERM	SOLUB	HUMAN INTRUS	REG (2.4)	TECH (1.5)	SCH (1.0)	REG + TECH SCH	RAD GAS	BIO GAS	CORR GAS	PERM	SOLUB	HUMAN INTRUS
WASTE FORM MODIFICATION ALTERNATIVES																
SLUDGES																
Vitrification	9.0	8.0	9.0	9.0	0.0	-	4.0	7.0	6.0	26.1	72.0	66.9	72.0	72.0	26.1	26.1
Plasma Processing	10.0	10.0	10.0	10.0	0.0	-	3.0	4.0	1.0	14.2	65.2	65.2	65.2	65.2	14.2	14.2
Cementation	4.0	1.0	7.0	3.0	10.0	-	9.0	10.0	9.0	45.6	66.0	50.7	81.3	60.9	96.6	45.6
Alter Environment	4.0	2.0	7.0	2.0	10.0	-	6.0	7.0	6.0	30.9	51.3	41.1	66.6	41.1	81.9	30.9
SOLID ORGANICS																
Compact Waste	1.0	2.0	3.0	3.0	-	-	9.0	10.0	7.0	43.6	48.7	53.8	58.9	58.9	43.6	43.6
Shred and Compact Waste	1.0	3.0	4.0	3.0	-	-	9.0	10.0	7.0	43.6	48.7	58.9	64.0	58.9	43.6	43.6
Shred & Cement Waste	0.0	4.0	6.0	6.0	8.0	-	9.0	10.0	9.0	45.6	0.0	66.0	76.2	76.2	86.4	45.6
Shred & Polymer Encapsulate	0.0	0.0	5.0	8.0	0.0	-	9.0	5.0	6.0	35.1	0.0	0.0	60.6	75.9	35.1	35.1
Shred, Add Salt, Compact	1.0	3.0	5.0	7.0	-	-	9.0	10.0	7.0	43.6	48.7	58.9	69.1	79.3	43.6	43.6
Shred & Bituminize	0.0	0.0	5.0	8.0	0.0	-	3.0	10.0	5.0	27.2	0.0	0.0	52.7	68.0	27.2	27.2
Plasma Processing	10.0	10.0	10.0	10.0	6.0	-	3.0	4.0	1.0	14.2	65.2	65.2	65.2	65.2	44.8	14.2
Shred & Add Bentonite	0.0	1.0	6.0	6.0	-	-	9.0	10.0	9.0	45.6	0.0	50.7	76.2	76.2	45.6	45.6
Acid Digestion	9.0	9.0	10.0	9.0	6.0	-	3.0	4.0	2.0	15.2	61.1	61.1	66.2	61.1	45.8	15.2
Add Gas Getters	1.0	2.0	-	2.0	8.0	-	5.0	9.0	5.0	30.5	35.6	40.7	30.5	40.7	71.3	30.5
Incinerate & Cement	5.0	9.0	8.0	6.0	10.0	-	2.0	7.0	2.0	17.3	42.8	63.2	58.1	47.9	68.3	17.3
Incinerate & Vitrify	9.0	9.0	10.0	9.0	6.0	-	2.0	7.0	2.0	17.3	63.2	63.2	68.3	63.2	47.9	17.3
Alter Environment	1.0	2.0	7.0	2.0	8.0	-	6.0	7.0	6.0	30.9	36.0	41.1	66.6	41.1	71.7	30.9
SOLID INORGANICS																
Compact Waste	0.0	-	2.0	1.0	-	-	9.0	10.0	7.0	43.6	0.0	43.6	53.8	48.7	43.6	43.6
Shred & Compact Waste	0.0	2.0	2.0	3.0	-	-	9.0	10.0	7.0	43.6	0.0	53.8	53.8	58.9	43.6	43.6
Shred & Cement Waste	0.0	3.0	3.0	6.0	10.0	-	9.0	10.0	9.0	45.6	0.0	60.9	60.9	76.2	96.6	45.6
Shred & Polymer Encapsulate	0.0	0.0	3.0	7.0	0.0	-	9.0	5.0	6.0	35.1	0.0	0.0	50.4	70.8	35.1	35.1
Shred, Add Salt, Compact	-	2.0	-	5.0	-	-	9.0	10.0	7.0	43.6	43.6	53.8	43.6	69.1	43.6	43.6
Shred & Bituminize	0.0	0.0	5.0	7.0	0.0	-	3.0	10.0	5.0	27.2	0.0	0.0	52.7	62.9	27.2	27.2
Plasma Processing	10.0	10.0	8.0	10.0	8.0	-	3.0	4.0	1.0	14.2	65.2	65.2	55.0	65.2	55.0	14.2
Melt Metals	4.0	4.0	5.0	8.0	10.0	-	3.0	7.0	3.0	20.7	41.1	41.1	46.2	61.5	71.7	20.7
Shred & Add Bentonite	0.0	1.0	1.0	7.0	-	-	9.0	10.0	9.0	45.6	0.0	50.7	50.7	81.3	45.6	45.6
Decontaminate Metals	6.0	6.0	10.0	6.0	10.0	-	7.0	9.0	7.0	37.3	67.9	67.9	88.3	67.9	88.3	37.3
Add Gas Getters	1.0	2.0	NA	2.0	10.0	-	5.0	9.0	5.0	30.5	35.6	40.7	NA	40.7	81.5	30.5
Alter Environment	1.0	2.0	7.0	2.0	10.0	-	6.0	7.0	6.0	30.9	36.0	41.1	66.6	41.1	81.9	30.9

RAD = Radiolytical; BIO = Biological; CORR = Corrosion; PERM = Permeability of the Waste Stack; NA = Not Applicable
SOLUB = Radionuclide Solubility in Brine; REG = Regulatory; TECH = Technological; SCH = Schedule; HUMAN INTRUS = Human Intrusion

TABLE A-6
(contd.)
SUMMARY OF OVERALL SCORES FOR ENGINEERED ALTERNATIVES

ALTERNATIVE	EFFECTIVENESS (Wt.=5.1) SCORE: RAD GAS	BIO GAS	CORR GAS	PERM	SOLUB	HUMAN INTRUS	FEASIBILITY (Wt=4.9) SCORE: REG (2.4)	TECH (1.5)	SCH (1.0)	SUM REG + TECH SCH	ALTERNATIVE OVERALL SCORE EFFECTIVENESS + FEASIBILITY: RAD GAS	BIO GAS	CORR GAS	PERM	SOLUB	HUMAN INTRUS
WASTE CONTAINER ALTERNATIVES																
Change Waste Cont. Shape	1.0	1.0	1.0	1.0	-	-	9.0	10.0	9.0	45.6	50.7	50.7	50.7	50.7	45.6	45.6
Change Waste Cont. Material	-	-	2.0	-	-	-	8.0	8.0	9.0	40.2	40.2	40.2	50.4	40.2	40.2	40.2
WASTE MANAGEMENT ALTERNATIVES																
Min. Space Around Waste Stack	1.0	2.0	1.0	1.0	-	-	10.0	10.0	10.0	49.0	54.1	59.2	54.1	54.1	49.0	49.0
Segregate Waste In WIPP	-	5.0	0.0	-	-	-	8.0	10.0	8.0	42.2	42.2	67.7	0.0	42.2	42.2	42.2
BACKFILL ALTERNATIVES																
Salt Only	4.0	2.0	2.0	2.0	-	-	8.0	7.0	9.0	38.7	59.1	48.9	48.9	48.9	38.7	38.7
Salt + Alkali	5.0	8.0	9.0	2.0	10.0	-	8.0	7.0	9.0	38.7	64.2	79.5	84.6	48.9	89.7	38.7
Compact Backfill	6.0	3.0	3.0	2.0	-	-	4.0	3.0	6.0	20.1	50.7	35.4	35.4	30.3	20.1	20.1
Salt + Brine Sorbents	8.0	5.0	5.0	2.0	-	-	8.0	7.0	7.0	36.7	77.5	62.2	62.2	46.9	36.7	36.7
Grout Backfill	10.0	10.0	10.0	7.0	10.0	-	8.0	8.0	9.0	40.2	91.2	91.2	91.2	75.9	91.2	40.2
Bitumin Backfill	0.0	0.0	5.0	10.0	0.0	-	3.0	5.0	5.0	19.7	0.0	0.0	45.2	70.7	0.0	19.7
FACILITY DESIGN ALTERNATIVES																
Ventilate Facility	4.0	5.0	4.0	-	-	-	4.0	4.0	4.0	19.6	40.0	45.1	40.0	19.6	19.6	19.6
Change Extraction Ratio	1.0	2.0	1.0	1.0	-	-	8.0	7.0	9.0	38.7	43.8	48.9	43.8	43.8	38.7	38.7
Change Room Configuration	-	-	-	-	-	3.0	7.0	10.0	7.0	38.8	38.8	38.8	38.8	38.8	38.8	54.1
Seal Individual Rooms	-	-	-	8.0	-	-	9.0	8.0	9.0	42.6	42.6	42.6	42.6	83.4	42.6	42.6
Two Level Repository	-	-	-	-	-	5.0	1.0	8.0	1.0	15.4	15.4	15.4	15.4	15.4	15.4	40.9
PASSIVE MARKER ALTERNATIVES																
Monument "Forest"	-	-	-	-	-	6.0	9.0	10.0	10.0	46.6	46.6	46.6	46.6	46.6	46.6	77.2
Monument Covering Repository	-	-	-	-	-	10.0	8.0	10.0	10.0	44.2	44.2	44.2	44.2	44.2	44.2	95.2
Buried Steel Plate Over Rep.	-	-	-	-	-	5.0	7.0	10.0	10.0	41.8	41.8	41.8	41.8	41.8	41.8	67.3
Add Marker Due To Strata	-	-	-	-	-	1.0	4.0	1.0	10.0	21.1	21.1	21.1	21.1	21.1	21.1	26.2

OVERALL SCORE CALCULATION

OVERALL SCORE = 5.1 X EFFECTIVENESS SCORE + 2.4 X (REGULATORY FEASIBILITY SCORE)
+ 1.5 X (TECHNOLOGICAL FEASIBILITY SCORE) + 1.0 X (SCHEDULING FEASIBILITY SCORE)

RAD = Radiolytical; BIO = Biological; CORR = Corrosion; PERM = Permeability of the Waste Stack; NA = Not Applicable
SOLUB = Radionuclide Solubility in Brine; REG = Regulatory; TECH = Technological; SCH = Schedule; HUMAN INTRUS = Human Intrusion

the environment were judged less effective. These alternatives eliminate free water but would only reduce the radiolytic gas generation rates instead of eliminating the potential.

Solid Organics

The primary contributors to radiolytic gas generation in this waste form are the organic materials such as cellulosics. Therefore, the scores were based primarily on the ability of the alternative to destroy organics.

Plasma processing was judged to be the most effective alternative because it is able to break down all the bonds in plastics and thus destroy the organics. Assuming that plasma would operate at much higher temperatures than normal incineration temperatures, incineration followed by vitrification was considered almost as effective as plasma processing for destroying organics. Acid digestion which was defined by the EAMP as acid digestion followed by calcination and vitrification, was considered as effective as incineration plus vitrification. However, some porosity may remain by using this process. Incineration and cementation was scored considerably lower. Although solid organics are incinerated, cementation leads to addition of water which increases the potential for radiolytic gas generation. Compaction will not have any positive effect on radiolytic gas generation except for reducing the permeability which in turn will lower the access to brine. The same is also true for the other forms of compaction like shredding followed by compaction, and shredding followed by addition of salt and compaction. Therefore, these three alternatives were given a lower score. Since the majority of the radiolytic gas generated is hydrogen, and there are no known effective, long-term gas getters for hydrogen, the gas getter alternative was given a low score. Altering the environment (e.g., adding large amounts of pH buffers) will not have much of an effect in mitigating radiolytic gas generation, except that it could reduce some brine inflow if large enough quantities of the buffer substantially reduced void volumes. All the other alternatives shredding and bituminizing, shredding and encapsulating, shredding and adding bentonite, and shredding with the addition of cement were considered adverse alternatives since they do not eliminate organics and in some cases would aggravate the problem of radiolytic gas generation by either increasing organics or increasing water content.

Solid Inorganics

Although glass and metals themselves will not contribute substantially to radiolytic gas generation, the main concern of the EAMP was the plastic liners and plastic bags in the drums.

If the need for an alternative that destroys these plastics is identified, the EAMP assumed that the old waste has liners but the newly generated waste would not be stored in liners. Under these assumptions, it was hypothesized that for the old waste, plasma would destroy all the liner material and therefore is the best alternative. Decontaminating metals or melting metals would separate the liners from the metals and make the liners a part of the combustible waste. This would be a case of an alternative having no effect because the problem of gas generation from the liners is neither eliminated nor reduced but instead transferred to another waste form category. Assuming that the newly generated waste contains no liner, plasma and melting metals would get the same ranking because in both cases permeability, and therefore brine transport, would be reduced substantially. However, decontaminating metals will rank higher in comparison to both plasma and melting metals because only the residue would remain, which could be in a vitrified form.

Gas getters and altering the environment were both assigned a low score for the same reasons explained earlier under the combustibles category. Two of the three methods of compaction were assigned an adverse score because of the potential for increasing the radionuclide concentration by compaction, thereby potentially increasing radiolytic gas generation. The panel reasoned that this adverse effect outweighs the benefits of reducing the permeability through compaction since compacted metals are still quite permeable. Adding salt before compaction was considered to have no net effect because the potential for increased concentration of radionuclides would be offset by the increase in total volume due to the added salt. The other alternatives, shredding and cementing, shredding and bituminizing, and shredding and adding bentonite, were all assigned adverse scores for the same reasons explained earlier under the combustibles category.

3.1.1.2 Biological Gas Generation

Sludges

The primary basis for scoring these waste form modification alternatives was the ability of the alternative to eliminate the nitrates present in sludges. Plasma processing will destroy the nitrates by decomposition into nitrogen oxides. Although there is a possibility of nitrogen combining with some of the metal to form metal nitrides, plasma processing still appeared to be the best alternative relative to other alternatives. Vitrification by microwave melting would not reach as high a temperature as plasma, and therefore was given a lower score because it may not destroy all the nitrates. Cementation would add sulfates which might be detrimental. However, it would increase strength, decrease particulates, and help reduce permeability, thereby partially isolating the nitrates from the rest of the waste. Therefore, the panel agreed that cementation might have a small positive effect. Altering the environment, which refers to raising the pH, was considered somewhat better than cement because $Ca(OH)_2$ will absorb some carbon dioxide, and unlike cementation, no sulfates are added.

Solid Organics

Plasma processing was considered the best alternative because the processed product would have the lowest carbon content among the alternatives. Incineration plus vitrification or cementation, and acid digestion were not considered quite as effective as plasma processing for destroying organics and were scored slightly lower.

Some of the remaining alternatives would have an indirect positive effect by reducing generation rates, reducing permeability, or reducing the access to brine. Shredding and cementing would raise the pH and thereby decrease gas generation rates, but it would add some sulfates. The only benefits provided by any form of compaction would be to reduce permeability and limit brine access. Shredding will improve compaction, so this alternative was considered slightly better than compaction alone. Addition of salt is marginally beneficial for reducing voids in compacted combustibles and therefore shredding, adding salt and then compacting was given the same score as shredding and compaction. Shredding with the addition of bentonite may reduce free brine, but still provides moisture for gas generation when the bentonite absorbs brine. Both gas getters and altering the environment would be effective in absorbing some of the carbon dioxide generated. Shredding with the subsequent addition

of bitumen or polymer encapsulation were both expected to have adverse effects by adding food sources for the bacteria.

Solid Inorganics

The main concern in this category is the plastic liner and bags in the drums. Therefore, the alternatives were ranked for their effectiveness in treating these plastics. The scoring for plasma processing, decontaminating metals, and melting metals was the same as for the radiolytic gas generation parameter. Since metals cannot be compacted to the degree needed to effectively reduce permeability, compaction was not considered an effective alternative. Shredding and cementing as well as shredding and compacting would not be quite as effective for glass and metals as they would be for combustibles, and were therefore scored lower than combustibles. The alternatives involving bitumen and polymer encapsulation were considered adverse alternatives for the same reasons mentioned for combustible waste. Shredding and adding bentonite would only reduce brine access somewhat, and was given a low score. The benefits of shredding, adding salt and then compacting are the same as for combustibles. However, for glass and metals the product will have more porosity and hence this alternative received a slightly lower score than it received for treating combustibles. Gas getters and altering the environment are beneficial in the near term. However, there is some doubt about their long term effectiveness, since bacteria may be able to adapt to this environment.

3.1.1.3 Corrosion Gas Generation

Sludges

The scoring of alternatives was based on their ability to reduce permeability and moisture, with the additional objectives of reducing brine inflow and/or raising the pH of the waste disposal areas.

Plasma processing was given the highest score for its ability to reduce porosity, resulting in maximum void volume reduction. Since vitrification may not eliminate quite as much porosity as plasma processing, it was given a somewhat lower score. Cementation would tend to raise pH and reduce free water thus lowering gas generation rates. However, it has some potential for long-term release of water. Altering the environment will reduce moisture and increase pH, but is not expected to reduce voids completely.

Solid Organics

The panel considered any alternative favorably which could substantially reduce void volume and thereby reduce brine inflow. Therefore, plasma processing, incineration and vitrification, and acid digestion were given high scores because these waste treatments reduce void volume better than other alternatives. Incineration plus cementation will result in higher porosity than the aforementioned alternatives. Shredding with the addition of bentonite may produce void reduction properties similar to those of shredding and cementation. Altering the environment will help absorb some brine, raise the pH, and fill void volumes if large enough quantities of material are added. Shredding and adding bitumen produces a low permeability with small porosity and results in a plastic medium. Polymer encapsulation will have properties similar to bitumen. Compaction by itself is considered a marginal alternative. However, it has the positive effect of reducing permeability and consequently limiting brine inflow. Shredding before compaction enhances the reduction of voids, and was therefore scored

slightly higher than compaction alone. Adding salt to the shredded waste before compaction, is somewhat better than shredding and compacting alone for reducing permeability. Gas getters were judged to have no effect since the EAMP could not identify any effective long term getters for hydrogen gas.

Solid Inorganics

This is the most important category for corrosion gas generation due to the large weight percent of corrodible metal in the waste inventory. For the undisturbed scenario, the panel assumed that the limited amount of brine inflow is insufficient to corrode the entire metal inventory. The EAMP also assumed that engineered alternatives to reduce permeability of the waste would be implemented if corrosion gas is recognized as a major problem. Reducing the permeability would limit the total corrosion gas potential from metal corrosion, if human intrusion causes large quantities of brine to enter the repository.

Based on the above assumptions, decontaminating metals received the highest score because metals would not be brought to WIPP for disposal. Plasma processing was given a somewhat lower score because, even though metal corrosion would be limited by reduced surface area and physical passivation, metal would still be brought to WIPP for disposal. Melting metals and plasma processing could result in preferential migration of the actinides into the resulting slag, thereby having a similar effect as decontamination of metals. However, the panel decided that there is not enough evidence available to justify scoring the alternatives on that basis. Therefore, melting metals was given a lower score than decontamination of metals. Altering the environment has the same effectiveness as explained in the previous section under combustibles. Gas getters were not given a score because they are not applicable in this case. Compaction would not decrease metal surface area sufficiently, though it will reduce overall volume, and room re-pressurization will occur more quickly. Shredding before compaction was not expected to enhance the end results appreciably. Shredding followed by polymer encapsulation, and shredding followed by cementation were considered good near-term waste treatments and will limit the rate of corrosion. However, both materials (polymer and cement) may crack providing brine access to the metals. By comparison, shredding and then adding bitumen was considered more effective because, unlike the preceding alternatives, bitumen would not be expected to crack, thus preventing the brine from reaching the metal. Shredding and subsequently adding bentonite puts the absorbed brine in close contact with the metal. However, it does prevent contact with free brine.

3.1.1.4 Permeability of the Waste Stack

The permeability parameter refers to the permeability of the waste stack itself. The panel decided that backfill permeability would be considered separately. Since the EAMP could not, during the time available, determine the long term effectiveness of waste form treatments for reduction of permeability, it was decided to evaluate the alternatives based on their initial permeability to brine.

Sludges

Plasma processing was considered most effective because it would almost completely eliminate interconnected porosity and thus reduce permeability to the greatest extent. Vitrification is

expected to leave slightly more porosity compared to plasma and so was scored somewhat lower.

Cement was considered a good alternative for lowering permeability in the near term. However, because of the presence of nitrates in the sludges, its longevity is questionable. The addition of calcium oxide or activated alumina will have a small effect on permeability by filling some voids.

Solid Organics

Plasma processing was judged to produce the lowest waste permeability. Both incineration followed by vitrification, and acid digestion were considered to be of equal merit but not quite as good in densifying the waste as plasma. Compaction will reduce voids, but interconnections between pores will remain. Shredding before compaction will result in further reduction of volume. Cementation preceded by either shredding or incineration were considered reasonably effective because both alternatives will reduce voids and decrease interconnected pores. The two types of encapsulation, with either a polymer or bitumen, were both considered very effective because they will result in a low initial permeability, but may not decrease voids to the extent achieved by plasma or vitrification. Shredding followed by the addition of bentonite was considered virtually as effective as cemented waste forms, based on the assumption that bentonite will swell upon contact with the high magnesium brine encountered at WIPP. The addition of gas getters or altering the environment was not considered effective except for increasing the pH and filling some voids. Adding salt after shredding and then compacting would be an improvement for reducing voids, compared to shredding with the addition of bentonite, but it would not be as effective as encapsulation.

Solid Inorganics

Plasma processing will result in the maximum reduction of permeability and so was given the highest score. Melting metals was scored somewhat lower because the residue from this process has a somewhat higher porosity than that resulting from plasma processing, and depends on the process used to solidify the residue. The panel came to the conclusion that the relative scores of many of the remaining alternatives would not change from those presented for combustibles. However, since metals cannot be volumetrically reduced as much as solid organics, some of the scores for glass and metals were slightly lower than for solid organics. Decontaminating metals does not result in permeability reduction per se, but does eliminate a highly permeable waste form. The EAMP assumed that the residue after decontamination would be cemented or vitrified. Compaction of glass and metals to a low permeability is difficult and therefore received a low score. Shredding before compaction was considered to be helpful in reducing the permeability to a level lower than by compaction only. Adding salt before compaction improves upon the preceding option. The addition of gas getters or altering the environment provide a marginal reduction of voids.

3.1.1.5 Radionuclide Solubility in Brine

The term solubility refers to the solubility of radionuclides or hazardous chemical wastes in brine and is defined as the maximum amount of the solute that can dissolve in brine under given conditions of brine composition, pH and temperature. Since the temperature under repository conditions is not expected to vary substantially, solubility can be controlled by adjusting pH. In contrast, leachability deals with a rate process and is defined as the rate at

which a solute dissolves in a solvent to attain the maximum concentration possible under the given conditions. Whereas solubility can be reduced by increasing the pH and reducing the amount of organics present, leachability can be controlled by adjusting a number of factors. The desirable factors for having a low leaching rate are high pH, low surface area, low permeability, low level of organics, dense forms, and reduction of brine volumes. A reduction in solubility will also decrease the concentration gradient for mass transfer and thus decrease leachability.

Sludges

Cementation or altering the environment were considered the best alternatives because they increase the pH through the addition of cement and lime respectively, leading to low solubilities and providing a stable environment for the precipitated hydroxide form of the nuclides.

The prime concern about plasma processing or vitrification was that these high temperature treatments will destroy the hydroxide form and the pH will be dominated by the pH of brine, which is around 5 to 6. At this low pH, oxides are more soluble, which would have an adverse effect if these alternatives are used. Although this problem can be eliminated if either lime or cement are added after high temperature processing to provide a pH buffer, these alternatives were scored as having adverse effects.

Solid Organics

The effect of combustibles on the solubility parameter results mainly from the presence of organics which potentially provide complexing agents. Therefore, the panel decided that any alternative is attractive if it destroys organics. If an alternative could not destroy organics but did increase the pH sufficiently through the addition of cement, lime, or similar alkaline material, this could be even more beneficial than destroying organics. Finally, if an alternative could accomplish both the destruction of organics and provide the pH buffer, it would be considered the most effective alternative.

Based on the above considerations, incineration followed by cementation was the only alternative that both destroyed organics and provided a pH buffer. Cementation with prior shredding, altering the environment, and gas getters all satisfied the pH buffering criterion. Plasma processing, acid digestion, and incineration followed by vitrification would all destroy organics, but fail to satisfy the pH consideration. However, these waste treatments are expected to produce waste forms with lower leachability. The two forms of encapsulation, either with polymers or bitumen, were considered adverse alternatives because they add organics which would have an adverse effect on solubility. The different forms of compaction would have no effect on solubility because they do not change the status of organics or modify the pH. Shredding with the addition of bentonite was also judged to have no net effect, based on the assumption that nuclide adsorption on bentonite in a high-magnesium saturated brine is low, leaving the nuclides available for dissolution.

Solid Inorganics

For glass and metals, the destruction of organics is of second order importance. Therefore, alternatives that provide sufficient pH buffer were considered the most effective for treating the glass and metal waste form.

Based on this consideration, altering the environment, gas getters, and cementation with prior shredding were all given top scores. Decontaminating metals and melting metals were also scored high based on the assumption that the residue, in both cases, could be cemented. Plasma processing would destroy organics, but it does not provide a pH buffer. Both forms of encapsulation were considered adverse alternatives because they would add organics. The remaining alternatives, which included the three forms of compaction and shredding with the addition of bentonite, were all judged to have little or no effect for the same reasons given during discussion of combustible wastes.

Leachability Considerations

After evaluating the alternatives on the basis of solubility, the panel considered the effects on leachability to check if any of the scores might change. It was found that some of the alternatives would indeed rank higher if leachability was considered.

All the alternatives resulting in permeability reduction (e.g., plasma processing, vitrification, acid digestion, and encapsulation) would result in a lower effective leachability, since less brine will come in contact with the waste. Therefore, the panel noted that the rankings for these alternatives could be higher if leachability, rather than solubility as the bounding characteristic, is considered the controlling parameter.

3.1.2 Waste Management Alternatives

The EAMP considered two of the five potential waste management alternatives - Minimize Space Around the Waste Stack, and Segregate Waste in WIPP. The remainder were considered in conjunction with other alternatives or were not feasible.

Minimize Space Around the Waste Stack

It was assumed that implementation of this alternative would eliminate the need for backfill, and that space around the waste stack is needed only as long as waste operations are taking place in the storage panel to prevent the walls and back (ceiling) from contacting the waste. This alternative would actually take the place of backfill, but interstitial voids between waste containers and between the waste and waste disposal room walls would still exist, unless the waste container shape is modified. Therefore this alternative was scored lower than most of the backfill alternatives.

Segregate Waste in WIPP

This concept attempts to segregate the potential challenges associated with the different waste forms coming to WIPP. It was assumed that waste would be segregated by waste disposal panel, and operations in more than one panel at a time would be necessary. On the basis of these assumptions the EAMP recognized that the WIPP ventilation system would probably have to be redesigned to allow operations in more than one panel at a time. Since each operational panel would have to remain open longer than currently planned, premature creep closure was a concern. If all the sludges were stored together, a relatively high corrosion gas inventory could build up in those waste disposal rooms. The most promising result of waste segregation would be separation of nutrients (NO_3) from biological substrate (cellulosics), and

potentially lower biological gas generation. The EAMP concluded that this was the only potential benefit of this alternative.

3.1.3 Backfill Alternatives

The backfill alternatives were considered during the preliminary evaluation of the alternatives. The EAMP decided to re-evaluate the backfill alternatives based on the five remaining performance parameters, and certain associated assumptions. For the sake of brevity the alternatives "Compact Backfill" and "Preformed Compacted Backfill," were combined into a single alternative, designated "Compacted Backfill." Thus, the following six backfill alternatives were reevaluated with respect to their mitigating effect on the five parameters:

- Salt Only
- Salt and pH Buffers
- Compacted Backfill
- Salt and Brine Sorbents
- Grout
- Bitumen.

The evaluation of backfills for the five parameters was based on the following assumptions:

- All organics are potential candidates for biodegradation.
- Bentonite and salt will reduce the voids to approximately the same extent, but salt will reconsolidate.
- Positive effects of backfill are reduction of initial void volume, minimization of brine flow through waste, and an increase in the pH to minimize corrosion and biological gas generation, and solubility of radionuclides.
- Backfilling takes place in a 13' x 33' x 300' room.
- Retrievability, after a disposal decision has been made, is not a consideration.
- All waste forms have been treated to minimize permeability.
- The backfill material needs to be reasonably free-flowing to effectively backfill between drums, or some engineering or operational changes may be necessary.
- Backfill around waste stack is independent of waste form.
- Backfills are not considered highly effective for mitigating the effects of gas generation parameters, compared to waste form alternatives, although backfills can absorb brine, raise pH, absorb carbon dioxide, and facilitate closure. Backfills affect gas generation rates rather than total gas potential.
- If solubility is found to be the only problem, then the backfill that adequately raises the pH may be the only solution needed.

3.1.3.1 Radiolytic Gas Generation

Grout was given the highest score because it was considered the best backfill to reduce brine inflow and thereby mitigate radiolytic gas generation from that source. The positive effects identified were the filling of most voids, quicker room reconsolidation, keeping brine out, and having reasonable structural integrity. Salt with brine sorbents would not be as effective as grout in filling voids. It was assumed that absorption of brine will cause bentonite to swell against lithostatic pressure and moisture would not be squeezed out. Compacted salt backfill will not easily fill the interstitial voids between drums, which will maintain a higher permeability than could be achieved if these voids were filled. As a backfill, salt by itself does not have any notable chemical effects that would reduce or aggravate radiolytic gas generation. However, it is expected to reconsolidate quickly, achieving a relatively low permeability to brine in its reconsolidated state. The addition of pH buffers to crushed salt will enhance moisture absorbing capability compared to salt alone. Bitumen would keep moisture out, but would have the adverse effect of adding organics.

3.1.3.2 Biological Gas Generation

The most effective alternative was judged to be grout because, in addition to keeping brine out, it would also increase the pH, both of which will decrease biological gas generation rates. Salt with the addition of pH buffers was also considered effective because it would have a pH buffering effect to partially compensate for the additional brine inflow. The addition of salt alone does not have a chemical effect on biological gas generation. However, since the transport of nutrients occurs in liquid media, the addition of salt will reduce the pathways for nutrient transport. Compacted backfills would be slightly better than salt alone because there are less initial voids. Salt with brine sorbents will be a better deterrent than salt alone to initially reduce brine inflow. Since bitumen adds organics, it was considered an adverse alternative. The safety concerns associated with emplacing hot bitumen underground was also considered by the EAMP.

3.1.3.3 Corrosion Gas Generation

Grout was judged to be the most effective alternative because of its pH buffering capability. Salt plus pH buffers would keep brine out as well as raise pH but its initial permeability would not be as low as grout. Salt plus sorbents would absorb moisture and slow the gas generation rates. Bitumen does not provide pH control, but would restrict brine inflow. However, the emplacement challenges discussed earlier need to be considered. Salt alone and compacted salt backfill will reduce voids and thus reduce brine inflow, thereby possibly reducing the rate of corrosion gas generation.

3.1.3.4 Permeability of the Waste Stack

Since this parameter is not concerned with pH control or the presence of organics, bitumen would be the best backfill if emplacement challenges could be overcome. Compared to bitumen, grout would have a higher porosity. The remaining backfill alternatives were judged approximately equivalent because none of them would be able to easily fill the interstitial voids between drums, since they are not as free flowing as bitumen or grout.

3.1.3.5 Radionuclide Solubility in Brine

For this parameter, the backfills were scored on the basis of their pH buffering capacity and the addition of organics. Grout and salt with pH buffers were judged to be the most effective in their ability to raise pH. Bitumen was considered an adverse alternative because the addition of organics has the adverse effect of increasing radionuclide solubility. The remaining alternatives would have no effect on pH, and therefore were judged to have no effect on solubility.

3.1.4 Facility Design Alternatives

The EAMP evaluated 12 facility design alternatives and concluded that six were considered in conjunction with other alternatives or were not feasible.

Gas Expansion Volume

The intent of this concept was to prevent overpressurization by waste generated gases, if this poses a potential but inconclusive threat to facility integrity. The alternative was to be considered only if gas generation is a marginal problem, requiring a relatively small expansion volume. The EAMP decided that the effectiveness of this alternative could not be determined. The addition of free volume could increase the time required for reconsolidation of the waste disposal rooms, thereby actually increasing the potential for brine inflow and gas generation. The added volume would probably not be able to accommodate the additional gas generated.

Ventilate Facility

The EPA Standards permit active institutional control by the implementing agency (DOE) for up to 100 years. This alternative would take advantage of this time period by continuing active ventilation of the waste disposal rooms, thereby evaporating inflowing brine until rooms had achieved closure. After that time, the reconsolidated room would resist the inflow of brine. The EAMP was concerned about this alternative due to several factors. There is no assurance that the ventilation spaces will remain uniformly open. The partial or total cessation of ventilation would allow brine to accumulate. There was also concern about safety problems associated with potentially breached waste containers, and sealing the waste disposal panels under these circumstances. Nevertheless, this alternative was given mid-range scores for mitigating the effects of brine inflow since there is no need to develop basic technologies, and engineering solutions may be available to overcome the alternative's shortcomings.

Change Extraction Ratio

The mined extraction ratio at WIPP is very small compared to what conventional mining techniques would suggest. If the ratio of mined volume to unmined pillar volume were increased, the waste disposal room creep closure would be expected to accelerate, thereby achieving room reconsolidation faster. This in turn would reduce the total brine inflow from the Salado Formation. This alternative was not given a high score because of the concern that the disturbed zone volume surrounding the waste disposal rooms and panels would increase, allowing a greater accumulation of brine during the pre-closure period.

Change Room Configuration

This alternative, as described in Attachment B, has several options. The EAMP considered only the option of a taller room to reduce the overall footprint of the repository. The remaining options were considered part of other alternative evaluations. This alternative was considered potentially effective for mitigating the human intrusion probability parameter only. A low score was assigned because of the need for roof bolting throughout the mined areas, the question whether such a design could be validated, and in a broader context of human intrusion, the potentially higher consequences resulting from penetration of more waste containers during the intrusion event.

Seal Individual Rooms

This alternative was considered for mitigating the effects of the two-borehole scenario, and to a limited extent, the single borehole drilled into the Castile brine. The EAMP modified this alternative by suggesting that floor to ceiling salt seals could be installed at each end of the waste disposal rooms, as well as at appropriate locations within the rooms. This would decrease the effective permeability of each waste disposal panel, and prevent hydraulic communication between the two boreholes. If this alternative is implemented, it would appear to effectively eliminate the effects of the two-borehole scenario. The score reflects the limited application of this alternative, and questions remained regarding how ventilation would be affected during installation of the seals.

Two-Level Repository

The concept of a two level repository would effectively halve the footprint of the repository and reduce the probability of human intrusion by a like amount. However, in a broader context, the probability of penetrating twice the number of waste containers is a distinct possibility. Therefore, this alternative was not given a high score.

3.1.5 Passive Marker Alternatives

These alternatives apply only to the human intrusion probability parameter. Therefore they were evaluated relative to each other within this narrow context, and their scores should not be compared to the scores of alternatives outside the passive marker category. Four of the five potential alternatives were evaluated. The fifth alternative, "Artificial Surface Layer," was eliminated because a feasible concept could not be identified.

Monument "Forest" over Repository

This concept received the second highest score among the passive marker alternatives. Although the individual markers, or pylons, would be deeply anchored, their longevity was somewhat questionable because they could be removed more easily than a single large monument.

Monument Covering the Entire Repository

This alternative, possibly in the form of a truncated pyramid, would cover the entire footprint of the underground waste disposal area. Although this concept entails a very large

construction effort, it received the highest passive marker score because of its anticipated longevity and visibility.

Buried Steel Plate Over Repository

Although the concept of a steel plate buried some distance below the surface, above the entire repository footprint, received a mid-range score for effectiveness, the EAMP recognized that many questions remain unanswered regarding the plate's longevity.

Add Marker Dye to Waste or Strata Above the Repository

The EAMP could not identify any long lasting marker dyes during its deliberations. It is also conceivable that the dye would be indistinguishable in drilling mud. Nevertheless, since the concept had some small merit, it was given the lowest score possible.

3.1.6 Miscellaneous Alternatives

Three potential alternatives were initially identified - Draining the Castile (Brine) Reservoir which may be located below the repository, Grouting Culebra Formation Above Repository, and Increasing Land Withdrawal Area to Regulatory Boundary. The latter was not considered to be an engineered alternative, and the remainder were considered not technically feasible.

3.1.7 Waste Container Alternatives

The TRU waste is currently stored in steel containers which will generate corrosion gas after disposal in the repository. The EAMP therefore considered modifying the existing polyethylene liner so that it could be used in place of a metal drum, or the use of concrete containers. The alternative did not receive a high score because, by itself, it is only marginally effective. Total metal corrosion is a function of the amount of brine in the waste storage rooms. It is anticipated that there will not be enough brine to corrode either all the steel waste containers or all the metal waste. Since the total corrosion gas is limited by brine availability, elimination of the steel waste containers does not change the total amount of gas that can be generated. If metal wastes are processed or eliminated, together with the elimination of steel waste containers, then this combined alternative would score very high.

The EATF has convened a panel of knowledgeable persons (the Waste Container Materials Panel) in the areas of metals, ceramics, concrete, fabrication, etc., to evaluate alternative waste container materials that would not generate gas in the WIPP environment.

The EAMP also discussed the role that the waste container shape can play for reducing waste stack permeability. If the shape can be modified so that the interstitial voids between the existing drums can be minimized, then the effective waste stack permeability would be reduced. By itself, this alternative was considered only marginally effective.

3.2 FEASIBILITY OF ALTERNATIVES

Of the 64 alternatives evaluated by the EAMP, 14 were considered not feasible. This section provides a brief discussion concerning the overall feasibility scores assigned to each alternative. The relative feasibilities of the alternatives were considered in a broad sense,

assigning the best alternative the highest score, while other alternatives received scores relative to this "best" alternative. As discussed in Section 2.2.3, the feasibility of each alternative was determined by considerations of regulatory requirements and concerns, state of technology, and schedular factors.

3.2.1 Waste Form Modification Alternatives

Compact Waste

This alternative represents an existing full-scale technology for processing radioactive wastes, and implementation is not expected to pose any major regulatory concerns. However, compactors would require preparation of National Environmental Policy Act (NEPA) documentation. It was given the highest score for the state of technology, but a somewhat lower score for regulatory requirements and schedular considerations.

Incinerate and Cement

The technologies of incineration, and cementation, are well established. However, the EAMP recognized that some existing incinerator systems for nuclear waste treatment are not operating because of current regulatory challenges. Therefore, the feasibility score for this alternative is low because of the current regulatory climate and public opinion, and the effect this has on schedule.

Incinerate and Vitrify

The feasibility of this alternative is similar to "Incinerate and Cement", for the same reasons given above.

Wet Oxidation

The EAMP concluded that this technology has not been adequately demonstrated for other than liquid wastes. Therefore it was deleted from further consideration.

Shred and Bituminize

Shredding is a well established technology. Bituminization is being used abroad but has not been applied to long-term waste disposal in the United States. The EAMP was concerned that the application of hot bitumen in an alpha waste facility could give rise to regulatory and safety challenges since flammable, volatile organic compounds are involved. A bitumen plant would need to be permitted and require the preparation of NEPA documentation. Based on experience abroad, the alternative was scored higher than incineration alternatives.

Shred and Compact

Shredding and compacting are well established technologies and are not expected to present any major regulatory problems. However, NEPA documentation would be required. This alternative was scored the same as the compaction alternative.

Shred and Cement

This alternative received essentially the same score as "Shred and Compact", except that the possibility of starting waste treatment at the Process Experimental Pilot Plant (PREPP) gave this alternative a slightly higher score for the schedule criterion. An on-surface cementing plant would need to be permitted and require preparation of NEPA documentation.

Shred and Polymer Encapsulate

The EAMP could not identify any major regulatory concerns for implementing this alternative, except for NEPA documentation. This technology was developed for the commercial nuclear power industry, but was not used. Since this technology is not as well developed for application to TRU waste disposal and the disposal environment, the technology criterion and consequently the schedule criterion received lower scores than some of the more conventional alternatives.

Shred, Add Salt, and Compact

This alternative did not appear to present any major technological or regulatory difficulties and therefore received the same scores as those for the compaction alternative. Preparation of NEPA documentation would be required.

Plasma Processing

This alternative is in the demonstration phase and has not yet been applied to radioactive materials. The regulatory concerns may be similar to those involving incineration. Therefore, this alternative received the lowest overall feasibility score.

Melt Metals

The technology for melting metals under adverse circumstances is reasonably well established. However, because this is a thermal process, it may encounter regulatory difficulties, possibly similar to those of "Plasma Processing" and was therefore given a relatively low overall feasibility score.

Add Salt Backfill

This alternative is inherent in other alternatives considered by the EAMP, and therefore was not subjected to separate evaluation.

Add Other Sorbents

This alternative is inherent in other alternatives considered by the EAMP, and therefore was not subjected to separate evaluation.

Add Gas Suppressants

This alternative is inherent in other alternatives considered by the EAMP and therefore was not subjected to separate evaluation.

Shred and Add Bentonite

This alternative received the same score as "Shred and Cement" because the process is relatively simple, basic technology development is not required, there should be few if any regulatory difficulties, and the process can be implemented in a relatively short time. The process will, however, require NEPA documentation.

Acid Digestion

The EAMP believed that regulatory concerns regarding this alternative would be similar to those encountered for thermal processes. The technology was only developed to the pilot stage, and the implementation schedule was considered marginal for newly generated waste.

Sterilize

The EAMP did not believe that the waste, and waste disposal rooms at WIPP, could be effectively sterilized in a manner that would permanently eliminate microbes and the consequent biological gas generation. Therefore, this alternative was deleted from further consideration.

Add Copper Sulfate

This alternative was deleted because of the possibility that deposited copper may act as a galvanic couple, thereby increasing gas production rates to undesirable levels.

Add Gas Getters

The regulatory process for this alternative is not expected to be complex. However, the possibility of additional worker exposure, while adding gas getters to existing waste containers, may complicate the process. This concern is reflected in the regulatory score. Preparation of additional NEPA documentation may be required. There is no basic technology development required, and the implementation schedule is expected to comply with the newly generated waste processing requirements.

Add Fillers

This alternative is inherent in other alternatives considered by the EAMP, and therefore was not subject to separate evaluation.

Segregate Waste Forms

This alternative is inherent in, or can be combined with, virtually any other alternative. Therefore, the EAMP did not evaluate this concept as a stand-alone alternative.

Decontaminate Metals

Various technologies currently exist for decontaminating metals, such as those currently used in the commercial nuclear industry. While decontamination of hazardous constituents could be advantageous from a RCRA standpoint, this alternative would probably require a new

facility, preceded by NEPA documentation, permitting, and other regulatory considerations. To maximize the effectiveness of the alternative, the waste container material would have to be changed from steel to a non-corroding material. This may also entail additional regulatory activities. On this basis, technology was given a high score, while the regulatory and schedule scores were reduced to reflect the uncertainties.

Change Waste Generating Process

The EAMP considered this to be a worthwhile alternative for future study. However, the subject is too broad to be evaluated qualitatively and therefore did not receive further consideration.

Add Anti-Bacterial Matrix

It was concluded that this technology has not been demonstrated for use in a repository environment and therefore this alternative was deleted from consideration.

Accelerate the Waste Digestion Process

It was concluded that this technology has not been demonstrated for this application and therefore the alternative was deleted from further consideration.

Alter Corrosion Environment in WIPP

The EAMP considered such options as activated alumina, lime, and cement as means for altering the corrosion environment in WIPP. Although no major regulatory or technological challenges were identified concerning this alternative, uncertainties about selection of material(s) and processes lowered the scores for this alternative.

Alter Bacterial Environment in WIPP

This alternative was considered during evaluation of the alternative "Add Anti-Bacterial Matrix" and was not considered feasible because the technology has not been demonstrated in a repository environment.

Transmutation of Radionuclides

This technology has not been demonstrated to the degree needed to process large quantities of waste containing low concentrations of TRU isotopes. The EAMP felt that this alternative could not be implemented in a timely fashion.

Vitrify Sludges

The vitrification of sludges by microwave or Joule melting is in the demonstration phase. The regulatory difficulties of this alternative were considered to be somewhat less than for incineration (of combustibles), so the score given this alternative is somewhat higher than for incineration. Since the process still needs to be fully demonstrated, the scores for technology and schedule were lower than those for more fully developed systems.

3.2.2 Waste Management Alternatives

Minimize Space Around Waste Stack

The EAMP did not identify any regulatory, technological or schedular challenges for this alternative that would hinder its implementation, so the highest scores were assigned for these criteria.

Segregate Waste in WIPP

The EAMP did not identify any technological challenges that would hinder the implementation of this alternative. Some administrative control of transportation and waste emplacement management will be required, potentially having a small effect on the regulatory requirements.

Decrease the Amount of Waste Per Room

This alternative was considered together with some of the backfill alternatives, and hence not evaluated separately.

Emplace Waste and Backfill Simultaneously

This alternative was considered together with the "Preformed Compacted Backfill" alternative, and therefore not evaluated separately.

Selective Vegetative Uptake

This alternative has not been demonstrated for TRU waste. Therefore, the alternative was deleted from further consideration.

3.2.3 Backfill Alternatives

Salt Only

Crushed salt resulting from mining of the underground storage facility is the basic backfill material currently being considered to reduce void volume and hasten room closure. The EAMP did not identify any major impediments to using this material for backfill. There was some question whether the backfill emplacement methods are sufficiently developed to effectively fill the void spaces between waste containers. Therefore, the technology score was reduced somewhat to reflect this uncertainty.

Salt Plus Gas Getters

The EAMP considered only the addition of dry cement or lime as a getter for carbon dioxide, and judged the feasibility of this alternative the same as for the "Salt Only" alternative. No effective getters could be identified for hydrogen, nitrogen, or methane.

Compact Backfill

Compacting salt backfill in place has not been specifically demonstrated, but the EAMP felt that such a process could be developed and does not present extraordinary challenges.

However, there were concerns about the additional worker exposure and also the potential for additional regulatory concerns that might accrue from this process. Therefore, all scores were significantly lower than for the "Salt Only" alternative.

Salt Plus Sorbents

This alternative's regulatory and technological feasibility was judged to be about the same as salt backfill only. However, since the effectiveness of specific sorbents may need to be confirmed, schedular feasibility was downgraded somewhat to allow time for experimentation.

Preformed Compacted Backfill

The EAMP considered only salt as a preformed compacted backfill. The feasibility of this alternative was judged somewhat higher than compacting backfill in place, but additional worker exposure during emplacement was still a concern.

Grout Backfill

The preparation and emplacement of grout in various industrial circumstances is a well established practice. Tailored, free-flowing grouts have been designed for numerous applications. Therefore, this backfill alternative was judged to have the highest feasibility since it can be efficiently emplaced, is expected to flow between waste packages, and worker exposure should be no more than encountered during emplacement of salt only backfill. The technology score is higher than for the "Salt Only" alternative to reflect the possibility of more easily filling the voids between the waste containers.

Bitumen Backfill

The use of bitumen as a backfill was judged to have the lowest feasibility because of potential fire hazards, worker exposure to volatile organic compounds, the difficulty of emplacement, and the required NEPA documentation. Although this alternative was considered to be feasible, recommendations for not using the alternative were voiced during the EAMP meetings.

Gas Suppressants

This alternative was considered together with the "Salt Plus Gas Getters" alternative, and therefore was not subject to separate evaluation.

3.2.4 Facility Design Alternatives

Brine Isolating Dikes

This alternative was considered to be similar to the "Seal Individual Rooms" alternative, and therefore was not subjected to separate evaluation.

Raise Waste Above Floor

This alternative was considered to be part of the "Salt Plus Sorbents" backfill alternative, and therefore did not undergo separate evaluation.

Brine Sumps and Drains

This alternative was deleted because the EAMP believed that the flow paths leading to the sumps would not remain open long enough to allow substantial amounts of brine to be isolated from the waste.

Gas Expansion Volume

The technology of mining and preparing these expansion volumes contiguous with the WIPP waste storage areas is currently available. Therefore, the alternative received the highest score for technology. Some concern was voiced by a few EAMP members about the accumulation of potentially hazardous gases in such unrestricted volumes, which prompted lower scores for the regulatory and schedular criteria.

Seal Disposal Room Walls

This alternative was deleted because sealing technology for this application has not been demonstrated. The EAMP judged that such technology could not be developed in a timely fashion.

Vent Facility

This alternative was deleted. Venting the facility after active institutional control has been relinquished would not meet regulatory requirements.

Ventilate the Facility

The EAMP voiced several concerns about ventilating the facility for up to 100 years (the active institutional control period). These included regulatory concerns about maintaining active facility control for such a long period, the difficulty of assuring continuous ventilation in all spaces, and the potential for rupturing waste containers during the ventilation period. The difficulty of safely sealing the rooms and panels of the facility, after so many years of creep closure has taken place, was also considered. Also, ventilation might violate the RCRA "no migration" variance proposed for WIPP. Based on these considerations, low feasibility scores were assigned to this alternative.

Add Floor of Brine Sorbent Material

This alternative was considered together with the "Salt Plus Sorbents" backfill alternative, and therefore not evaluated separately.

Change Mine Extraction Ratio

The ratio of mined to unmined volumes in the WIPP underground is considerably lower than normally found in extractive mining industry practice. This large safety factor makes it feasible to increase the ratio so that closure and reconsolidation take place faster. On this basis, the alternative was assigned reasonably high scores.

Change Room Configuration

The EAMP limited this alternative to increasing the height of the waste disposal rooms. Such a design change could affect regulatory documentation and agreements with the State of New Mexico. Although some potential complications of intersecting additional clay seams or marker beds were recognized, the EAMP considered the technology well established. Therefore, the alternative received the highest score for technology and reduced scores for the regulatory and schedular criteria.

Seal Individual Rooms

The concept of sealing individual rooms or portions of rooms, using thick salt "dikes" which isolate smaller volumes of waste from each other, was considered the most feasible facility design alternative. While judging the feasibility of this alternative, the EAMP considered the potential for increased waste emplacement durations and a small increase in worker radiation exposure.

Two-Level Repository

Existing technology can be used to construct a two-level repository, and so this alternative received a relatively high technology score. However, the EAMP recognized that a previous two level design for WIPP was intended to accommodate both transuranic waste and spent fuel. If a proposal was made to change the WIPP design to a two-level format, considerable public debate could take place, creating a difficult regulatory challenge and causing schedular delays. Preparation of NEPA documentation would be required for the revised facility design. The very low regulatory and schedule scores reflect these concerns.

3.2.5 Passive Marker Alternatives

The schedular feasibility criterion, as established by the EAMP, irrelevant for the construction of passive surface markers since they can be constructed during the waste emplacement period, or even after closure of WIPP but before active institutional control ends. Therefore these alternatives were given the highest schedule feasibility scores available.

Monument "Forest" Over Repository

The EAMP could not identify any major impediments to implementation of this alternative. Preparation of NEPA documentation would be required. The possibility that regulatory concerns might be voiced, since the surface would not be returned entirely to its original condition, was reflected in the scores. However, the EATF has later realized that returning the surface to its original condition will not be a regulatory issue (DOE, 1980). Therefore, if this was incorporated in the EAMP deliberations, then this alternative would have scored higher.

Monument Covering the Entire Repository

The feasibility of this alternative is similar to the previous alternative except that potential regulatory concerns may be somewhat greater. Preparation of NEPA documentation would be required. By covering the entire surface footprint of the repository with a single (or multiple

contiguous) monument, that portion of the land surface cannot be returned to its original condition, and the regulatory score reflects this concern. This alternative would also have scored higher for the same reasons mentioned above.

Buried Steel Plate Over Repository

While the technology for implementing this alternative exists, the need for corrosion control of the plate may raise regulatory challenges. Since NEPA documentation would probably be required, this alternative was scored somewhat lower for regulatory feasibility.

Artificial Surface Layer Over Repository

No feasible concept could be identified, and therefore this alternative was deleted.

Add Marker Dye to Waste or Strata Above Repository

The EAMP considered marker dye only in the strata above the repository. The technology required to implement this alternative is not well developed, so a very low score was assigned to the technology criterion. The EAMP was not in a position to identify specific dyes that would be effective over a long period. Additionally, regulatory problems may make this alternative unfeasible if only toxic dyes are available for effective use as markers, which is reflected in the regulatory score.

3.2.6 Miscellaneous Alternatives

Drain Castile Reservoir

This alternative was not considered to be feasible because of the relatively sparse information about the nature of the Castile reservoir and concern over potential subsidence of the repository itself if the reservoir is drained. Such questions as the amount of fluid in the reservoir, potential for recharge, and the time needed to pump the reservoir made the feasibility of this alternative indeterminate.

Grout Culebra Formation Above Repository

The EAMP questioned the ability to effectively grout the Culebra Formation, considering the extent of the formation and the longevity requirements. It was concluded that this alternative was not feasible.

Increase Land Withdrawal Area to the Regulatory Boundary

The EAMP did not consider this to be an engineered alternative, and therefore it was not evaluated further.

3.2.7 Waste Container Alternatives

Change Waste Container Shape

The EAMP could not identify any major regulatory or technological challenges associated with this alternative. Some DOE sites are already using boxes (instead of drums) for storage and

disposal of their wastes. However, if implementation of this alternative introduces the need to redesign the Transuranic Package Transporter-II (TRUPACT-II), then additional regulatory activities may need to be considered.

Change Waste Container Material

No major regulatory or technological challenges were identified concerning this alternative. The EAMP considered only existing technology, which can be implemented quickly if needed, and so the alternative received a high score for schedule considerations. However, since the existing (stored) waste would have to be repackaged, the scores for technology and regulatory considerations were somewhat lower. Newly generated waste could be packaged directly into the new waste containers. Discussion of alternate waste container materials is provided in Appendix H, Report of the Waste Container Materials Panel.

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4.0 CONCLUSIONS

The EAMP concluded that numerous potential engineered alternatives are available, if needed, to demonstrate compliance with the EPA Standard 40 CFR Part 191 (EPA, 1985). However, the qualitative evaluation process which ranked the relative effectiveness and feasibility of the alternatives precluded the recommendation of any particular alternative or a group of alternatives. The evaluations provide a basis for quantitative analysis of selected alternatives using design analysis models. If the performance assessment studies identify one or more parameters that impede the demonstration of compliance with EPA Standard 40 CFR Part 191, then the results from design analysis will provide one or more engineered alternative(s) to mitigate the problem.

The EAMP screening process eliminated all but 35 of the original 64 potential engineered alternatives originally suggested by the EATF. The EAMP added one alternative during the deliberations (cementation of sludges) making a total of 36 feasible alternatives belonging to the following categories:

Waste Form Modification Alternatives	17
Backfill Alternatives	6
Waste Management Alternatives	2
Facility Design Alternatives	5
Passive Marker Alternatives	4
Waste Container Alternatives	2

The EATF has used the results of the EAMP, and classified the waste form modification alternatives into seven generalized categories based on the similar final waste forms resulting from these treatments. These categories and the alternatives grouped into each category are:

- Vitrification of waste
  - Microwave melting (sludges only)
  - Plasma processing
  - Incinerate and vitrify (solid organics only)
  - Acid digest, calcine, and vitrify (solid organics only)

- Cementation of waste
  - Cementation of sludges into monoliths
  - Shred and cement (solid organics and inorganics)
  - Incinerate and cement (solid organics only)

- Compaction of waste (does not apply to sludges)
  - Compact
  - Shred and compact
  - Shred, add salt, then compact

- Encapsulation of waste (does not apply to sludges)
  - Shred and encapsulate with polymer
  - Shred and encapsulate with bitumen

- Preparation of ingots from melted metal waste (applicable only to solid inorganics)
- Shredding of waste followed by addition of bentonite
- pH buffering of waste
  - Buffering by lime
  - Buffering by cement
  - Buffering by alumina

In addition, the EATF has included one more category in the above list which is not a waste form modification, but considered by the EATF to be an equally important group of alternatives. This new category is:

- Changing of waste container material.

Based on Table A-6, and in conjunction with the deliberations of the EAMP, the EATF has noted that in Table A-6 there are some groups of alternatives which consistently received high scores for effectiveness, primarily because of their ability to eliminate the potential problem associated with a performance parameter. For example, all the different vitrification options (i.e., plasma processing, acid digestion, etc.) received consistently high effectiveness scores for the parameters associated with radiolytic gas generation, because they would (for all practical considerations) eliminate the potential associated with radiolytic gas generation. On the other hand, there are groups of alternatives in Table A-6 which have been assigned low to moderate scores for effectiveness because they can only slow down the rate processes associated with the parameter (instead of eliminating the potential). For example, any form of compaction of the waste was assigned low to moderate scores by the EAMP for corrosion gas generation, because these alternatives would only reduce the rate of corrosion gas generation but not eliminate it. Therefore, in order to develop a generalized set of recommendations for future design analysis, and for the WIPP Experimental Test Program, the EATF has divided the alternatives into two categories for each performance parameter:

- Alternatives which essentially eliminate the potential associated with a performance parameter.
- Alternatives which only reduce or control the rate processes.

Alternatives belonging to both of the above categories were identified for the three gas generation parameters. The remaining parameters (permeability of waste stack and radionuclide solubility in brine) did not have any applicable alternatives belonging to the first category. In other words, the EAMP concluded that permeability and solubility can only be reduced or controlled but never completely eliminated.

Since the objectives of the WIPP Experimental Test Program and the design analysis modeling are primarily related to the effectiveness of an alternative, the EATF has summarized the panel deliberations on the basis of the effectiveness scores in Table A-6 and the two categories of alternatives mentioned above. It should be noted, however, that the feasibility of the alternatives is also being studied in detail as part of the overall EATF objectives.

Table A-7 presents the set of alternatives which were consistently assigned high scores by the EAMP in Table A-6 for their effectiveness for eliminating the potential associated with a

performance parameter. Table A-8 presents similar information extracted from Table A-6 for alternatives which were assigned low to moderate scores for effectiveness because they can only reduce the rate process associated with a parameter, and cannot eliminate the potential.

Since the extent to which the rate can be reduced or controlled is different for each alternative, the alternatives are listed in descending order of merit for each performance parameter.

It should be noted that since the properties of the final waste forms resulting from a lot of the alternatives in Table A-6 are very similar, for the sake of brevity, alternatives in Tables A-7 and A-8 have been grouped into one of the seven generalized categories described earlier. For example, all the different forms of compacting the waste have been grouped together as "compaction" in Table A-8.

The EATF will perform design analyses of appropriate combinations of engineered alternatives from Tables A-7 and A-8 to quantify the improvements in repository performance using alternative waste forms. An example of such a combination for reducing the potential of radiolytic gas generation would be to cement the sludges, shredding and cementing the solid organics, and decontaminate the metals. Either grout or salt could be added in the repository as a backfill material. Similarly, decontamination of all corroding metals from the waste inventory, and changing the waste container material could be used to eliminate the potential of corrosion generation.

The EAMP considered ranking a set of combined alternatives based on their effectiveness and feasibility. However, it was decided that since the evaluation process was primarily qualitative, ranking the combinations merely on the basis of summation of their individual scores would not be meaningful and therefore not advisable.

The results of the EAMP's evaluations will be used to:

1. Recommend waste form alternatives that should be included in the WIPP Experimental Test Program.

2. Provide a basis for identification of combinations of alternatives that should be quantitatively analyzed for relative effectiveness.

3. Provide a basis for evaluation of the relative cost and schedule ramifications for implementing the most effective and feasible alternatives.

The final choice of alternative(s), and whether any alternatives are needed, will be decided in conjunction with the performance assessment studies when the extent of mitigation required is finally determined after these studies are completed.

TABLE A-7

WASTE FORM MODIFICATIONS FOR ELIMINATING POTENTIAL

	WASTE FORM		
PARAMETER	SLUDGES	SOLID ORGANICS	SOLID INORGANICS
Radiolytic Gas Generation	Vitrification	Plasma processing Incinerate and Vitrify Acid digest and Vitrify	Vitrification
Biological Gas Generation	Vitrification	Plasma processing Incinerate and Cement Incinerate and Vitrify Acid digest and Vitrify	Category does not pose biological gas generation problem
Corrosion Gas Generation	Vitrification	Category does not pose corrosion gas generation problem	Decontamination of corroding metals Changing existing waste container materials
Permeability of the Waste Stack	None	None	None
Radionuclide Solubility in Brine	None	None	None

TABLE A-8

WASTE FORM MODIFICATIONS FOR REDUCING/CONTROLLING POTENTIAL

	WASTE FORM		
PARAMETER	SLUDGES	SOLID ORGANICS	SOLID INORGANICS
Radiolytic Gas Generation	Cementation* pH Buffers	Incinerate and cement Compaction pH Buffers	Decontamination Melted metals pH Buffers
Biological Gas Generation	Cementation* pH Buffers	Shred and cement Compaction pH Buffers Shred, add bentonite	Category does not pose biological generation problem
Corrosion Gas Generation	Cementation* pH Buffers	Category does not pose corrosion gas generation problem	Vitrification pH Buffers Encapsulation Melted metals Shred and cement Compaction
Permeability of the Waste Stack	Vitrification Cementation pH Buffers	Vitrification Encapsulation Cementation Shred, add bentonite Compaction pH Buffers	Vitrification Melted metals Shred, add bentonite Encapsulation Shred and cement Decontaminate metals Compaction pH Buffers
Radionuclide Solubility In Brine	Cementation pH Buffers	Cementation pH Buffers Vitrification	Decontaminate metals pH Buffers Shred and cement Melted metals

*Cementation into monoliths.

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ATTACHMENT A

EAMP REQUIREMENTS AND QUALIFICATIONS OF MEMBERS

REQUIREMENTS

The Engineered Alternatives Task Force identified the disciplines needed for the Panel and established the requirements for Panel members based on its knowledge of the WIPP project and the challenge of demonstrating compliance with the EPA Standards.

CHAIRMAN - Broad understanding of the nuclear industry and the defense transuranic waste program, including the WIPP project, and a general knowledge of the disciplines denoted below. Undergraduate degree with 20 or more years of experience.

DOE/INSTITUTIONAL - Familiar with DOE programmatic sensitivities and requirements. Knowledgeable about institutional issues and the ability to project past challenges to future conditions. Ability to understand complex technical issues and to recognize potential solutions. Undergraduate degree with ten or more years of experience.

GENERATOR WASTE PROCESSING - Broad understanding of transuranic waste generation and waste processing at DOE facilities. Experience should provide the ability to form judgments regarding the impact of various waste form alternatives on the basic waste generation processes. Undergraduate degree with five or more years experience at DOE weapons production facilities.

GEOCHEMISTRY - Geology or geochemistry background, preferably in the hazardous or radioactive waste disposal areas. Capable of making judgments regarding processes occurring in the WIPP repository if engineered alternatives are applied. Familiarity with WIPP geology and/or geochemistry of the region. Graduate degree with ten or more years experience.

METALLURGY/CORROSION - Extensive experience solving corrosion problems and an in-depth understanding of corrosion mechanisms and products of corrosion. Understanding of corrosion inhibition and the effects of near saturated brines on corrosion of metals. Graduate degree with ten or more years experience.

MICROBIOLOGY - Experienced microbiologist with considerable background in bacterial degradation of hazardous, mixed waste, and nuclear waste forms. Understanding of bacterial energetics and reactions of halotolerant and halophilic organisms and the effect of salt environments on bacterial communities. Graduate degree with ten or more years experience.

PERFORMANCE ASSESSMENT - Familiarity with the EPA Standards 40 CFR Part 191 and the requirements to conduct performance assessment of deep geologic repositories. Generally knowledgeable about current performance assessment activities and challenges. Undergraduate degree with five or more years of experience.

REGULATORY - Background involving regulatory compliance activities, familiarity with 40 CFR Part 191, RCRA and states' permitting requirements. Sufficient experience in regulatory matters to understand the probability of permitting of new technologies by state and federal

agencies. Technical or legal background preferred. Graduate degree with five or more years experience.

REPOSITORY OPERATIONS - Operation and/or engineering experience on the WIPP project, including familiarity with mining, surface and underground facility design, and waste handling. Undergraduate degree (or equivalent) with five or more years of experience.

ROCK MECHANICS - Experience with mechanical deformation of rock, understanding of repository sealing technology and requirements and underground design experience. Overall familiarity with deep geologic repository underground design. Graduate degree with ten or more years of experience.

WASTE TREATMENT - Broad experience in nuclear and hazardous waste treatment technologies. Background should include development, design, and operation of waste treatment systems and facilities. Undergraduate degree with ten or more years of experience.

QUALIFICATIONS OF PANEL MEMBERS

CHAIRMAN

Mr. Hans Kresny (Chairman and Facilitator)

Mr. Kresny is the President of Solmont Corporation, and a consultant to IT Corporation, with over 33 years of multidisciplined technical and managerial experience in the nuclear industry. His background includes engineering and project management involving major nuclear facilities and programs, institutional issues resolution between the WIPP project and 23 States, shielding and radiation analysis, and nuclear space systems and power plant design. Education: Bachelor of Marine Engineering.

PRIMARY PANEL MEMBERS

Mr. Mike McFadden (DOE/Institutional)

Mr. McFadden has 14 years of experience, the major portion of which includes management positions with the Department of Energy. His background includes engineering and management of such projects as geothermal and laser facilities, management of the DOE Transuranic Waste Program, the WIPP transportation system, transporter development programs, and integration of WIPP and transuranic waste generator activities. Education: B.S., Civil Engineering.

Mr. Vernon Daub (DOE/Institutional)

Mr. Daub has 15 years of management and engineering experience. He has held the positions of mechanical engineer, test engineer, Chief of Test Engineering within the Department of Defense, and Research and Development Engineer, and Transportation Manager within the Department of Energy. He has extensive experience and has had significant responsibilities in a wide range of areas on the WIPP Project. Education: B.S., Mechanical Engineering; M.S., Industrial Engineering.

Mr. Jeff Paynter (Generator Waste Processing)

Mr. Paynter has six years of experience at the DOE Rocky Flats Plant, including criticality safety engineering; waste processing; operations; and package design, analysis, and testing. Education: B.S., General Engineering, Nuclear Option.

Mr. Kyle Peter (Generator Waste Processing)

Mr. Peter has nine years experience at the DOE Rocky Flats Plant, including responsibility for design, start-up, operation, and maintenance of waste processing treatment facilities. He is familiar with RCRA permitting, treatment, and storage regulations. Education: B.S., Chemical Engineering; M.S., Business Administration.

Dr. Jonathan Myers (Geochemistry and Performance Assessment)

Dr. Myers is a Technical Associate at IT Corporation with over ten years of geologic and geochemical experience solving technical problems in the field of hazardous and nuclear waste management. He has been actively involved in the WIPP and Yucca Mountain nuclear waste disposal projects, as well as the Swedish and Canadian waste disposal programs. He has also been an active participant in the WIPP Performance Assessment program. Education: B.S. and M.S., Geology; Ph.D., Geochemistry.

Dr. Arun Agrawal (Metallurgy/Corrosion)

Dr. Agrawal is a Senior Research Scientist at Battelle Memorial Institute and has been active in the corrosion and electrochemical fields for more than 15 years. He has extensive experience conducting research in these fields for various nuclear and nonnuclear organizations including the Electric Power Research Institute, Gas Research Institute, Department of Energy, Nuclear Regulatory Commission, and the National Science Foundation. Education: B.Sc. and M.S., Chemical Engineering; Ph.D., Chemical Engineering.

Mr. Barry King (Microbiology)

Mr. King is a Technical Associate and environmental biologist at IT Corporation with more that 23 years of experience including projects related to biodegradation of mixed hazardous wastes; long-term effects of geologic disposal; and various aspects of biological treatment, bioremediation, and technology development. Education: B.S., Microbiology; M.S., Environmental Biology.

Mr. Roger Hansen (Regulatory Compliance and Permitting)

Mr. Hansen is an environmental attorney and project director at IT Corporation with 27 years of legal experience. He has a multidisciplinary background in environmental law, land use and environmental planning, and communications. He is currently responsible for environmental regulatory analysis, permitting, documentation preparation, and providing technical and legal support for permitting and operation of hazardous, radioactive, and mixed waste management facilities. He is a registered Colorado attorney and a member of the American Bar Association. Education: B.S., Journalism; J.D.

Mr. Bill White (Repository Operations)

Mr. White has over 14 years of experience involved with operation of nuclear submarine and land-based nuclear power plants. He has held positions as Waste Handling Operations Manager and Start-up Engineer at the WIPP, was a Chief Operator at the Fast Flux Test Facility, and was a leading Petty Officer and Staff Instructor for nuclear plant operations in the U.S. Navy. Education: University of Texas at El Paso, plus various Navy nuclear power and engineering schools.

Mr. Rodney Palanca (Repository Operations)

Mr. Palanca has 27 years of experience with operation of nuclear submarine and land based nuclear plants. He attained the rank of Lieutenant Commander in the U.S. Navy and has supervisory and technical experience in nuclear reactor operation and testing, nuclear instrumentation and controls, nuclear chemistry and radiological controls, training curriculum planning and scheduling. He is currently an operations engineer in the WIPP Operations Support Group. Education: B.S., Chemical Engineering, plus numerous Navy nuclear training programs.

Dr. Joe Tillerson (Rock Mechanics)

Dr. Tillerson is Supervisor of the WIPP Sealing and Rock Mechanics Programs at Sandia National Laboratory. He has 15 years of experience including underground design, rock mechanics analysis, sealing programs, site characterization, rock mechanics measurement, code development and modeling of salt creep, and geotechnical analysis of oil storage caverns in salt. Education: B.S. and M.S., Aero Engineering; Ph.D., Aero Engineering.

Mr. Milo Larsen (Waste Treatment)

Mr. Larsen is President and General Manager of Haz Answers, Inc. He has over 20 years of experience in the nuclear industry including reactor operations, waste engineering development, waste treatment process development, and waste reduction operations. Mr. Larsen has extensive knowledge of the status of nuclear waste treatment technologies. Education: B.S., Physics.

ALTERNATE PANEL MEMBERS

Alternate Panel members were occasionally required to substitute for the primary members due to schedular conflicts.

Dr. Murthy Devarakonda (Geochemistry)

Dr. Devarakonda is a project engineer at IT Corporation with six years of experience in solvent recovery, waste water treatment, interactions among waste components in WIPP and the fate of mixed hazardous waste in WIPP over prolonged periods of time. Education: Bachelor of Technology, Chemical Engineering; Ph.D., Environmental Engineering.

Dr. Paul Drez (Geochemistry)

Dr. Drez is a Senior Technical Associate at IT Corporation with 20 years of experience. He is currently the Technical Director for the Engineered Alternatives Task Force effort. He has a broad background as a research geochemist for geologic exploration programs, and has been a key participant for evaluating the characteristics of TRU wastes destined for disposal at WIPP. He has also been actively involved in the WIPP performance assessment process, Supplemental Environmental Impact Statement, No-Migration Variance Petition, R&D Test Plan, and licensing of the TRUPACT-II and RH transportation systems. Education: B.S., Chemistry; Ph.D., Geochemistry.

Ms. Barbara Deshler (Performance Assessment)

Ms. Deshler is a geologist at IT Corporation with four years of experience including co-authorship of the WIPP No-Migration Variance Petition. As a result of her key involvement in preparing the WIPP Plan for Performance Assessment and Operations Demonstration, she has become very familiar with the performance assessment process. Her experience also includes the acquisition and start-up of a gas chromatograph/mass spectrometer laboratory at the WIPP site, environmental monitoring instrumentation, and technical input to environmental regulatory permit applications. Education: B.S., Geology; M.S., Geology (in progress).

Ms. Karen Knudtsen (Regulatory)

Ms. Knudtsen is a Project Scientist at Benchmark Environmental, Inc. with ten years experience in solid and hazardous waste management and environmental assessment. Her experience includes evaluation of hazardous and radioactive mixed waste characteristics and mechanisms of contaminant transport in the environment, preparation of regulatory summaries, development of technical positions regarding RCRA and CERCLA regulatory compliance, and permitting assistance for hazardous waste facilities. Education: B.S., Soil Science; M.S., Soil Chemistry.

Mr. Clinton Kelley (Repository Operations)

Mr. Kelley is a Senior Engineer for Westinghouse on the WIPP project with 15 years of experience in the nuclear industry. His principal duties currently involve planning, implementation and supervision of waste handling operations at the WIPP facility. His experience includes reactor operations for advance reactor systems, operations training, supervision of waste handling technicians, and preparation of operations procedures. Education: Science and math courses at several universities as well as numerous in-house technical and management courses.

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ATTACHMENT B

DESCRIPTION OF ENGINEERED ALTERNATIVES

Engineered alternatives being considered for reducing the consequences of potential WIPP waste release scenarios are described in this Attachment as they were presented to the Panel for consideration. Assumptions made by the Panel which supplement the description of some of the alternatives are also included.

WASTE FORM MODIFICATION ALTERNATIVES

COMPACT WASTE

Stored and newly generated waste is loosely packed in steel drums and boxes. Compacting the waste to much lower porosity and permeability, using state-of-the-art compactors, can reduce the ability of brine to either permeate the waste or flow through the waste matrix, thereby carrying some of the waste to the accessible environment or beyond the unit boundary.

Panel Assumption: It was assumed that compaction applies to all waste form categories except sludges. The Panel recognized but did not take into account the possibility of increased gas generation due to compaction, as discussed in Kroth and Lammertz (1988). The Panel also recognized that compacting the waste reduces initial void volume allows repressurization of waste rooms to occur sooner.

INCINERATE AND CEMENT

Incineration of combustible waste and cementation of the ash into an ash/cement matrix reduces the void volume and permeability of the waste. This alternative destroys essentially all organics and therefore is expected to eliminate microbial gas generation.

Panel Assumptions: Cemented form can be maintained until salt creep effectively encapsulates the waste. The Process Experimental Pilot Plant (PREPP) technology (rotary kiln incinerator) was assumed. Although there were plans for implementation of the PREPP process at the time the EAMP convened, the reader should note that the project has since been discontinued and not expected to be operational. The Panel also recognized that incineration may have the advantage of meeting the treatment standard for some types of organics restricted from land disposal under 40 CFR Part 268.

INCINERATE AND VITRIFY

This alternative is similar to "Incinerate and Cement" except that the residue is fused into a glass rather than a cement matrix and is likely to have a lower permeability and remain stable for a longer period of time.

WET OXIDATION

Wet oxidation involves the accelerated oxidation of waste in the presence of heated water vapor or steam, with the intent to chemical degradation of the waste prior to emplacement in WIPP. This technique has not been demonstrated for application to solid wastes.

SHRED AND BITUMINIZE

This alternative involves filling the voids of shredded waste with a bituminous compound. This has the effect of reducing waste permeability but may enhance microbial and radiolytic gas generation. All waste forms except sludges can be bituminized.

SHRED AND COMPACT

Compaction alone is limited by the available compaction forces (i.e., state-of-the-art equipment) and the stress strain characteristics of the waste form. Some advantage may be gained by first shredding the waste thereby compacting the waste to a more impermeable form. All waste forms except sludges can be compacted.

SHRED AND CEMENT

This alternative involves shredding the waste prior to cementation and repackaging. The intent is to reduce the permeability of the waste form. This alternative does not apply to the sludges.

Panel Assumption: The Panel assumed that the Process Experimental Pilot Plant (PREPP) shredding technology will be used.

SHRED AND POLYMER ENCAPSULATION

This alternative is similar to the shred and cement alternative except that the shredded waste would be encapsulated in a polymer. The use of polymers may increase microbial and radiolytic gas generation potential. All waste forms except the sludges can be encapsulated.

SHRED, ADD SALT, AND COMPACT

The purpose of this alternative is to reduce the permeability and initial void volume of shredded and compacted waste by mixing crushed salt into the shredded waste before compacting. The intent is to fill the voids that normally remain after compaction with crushed salt. The alternative can be applied to glass, metals, and combustibles. Corrosion and gas generation may be accelerated unless this alternative effectively excludes brine.

PLASMA PROCESSING

This alternative uses a high temperature plasma furnace to essentially eliminate organics and melt metals and sludges into a solid form. The products of this process are a vitrified glass form and solid metal.

Panel Assumptions: This alternative is in the demonstration phase. Therefore regulatory challenges may be similar to those concerning incineration.

MELT METALS

Since compacting metal wastes to a low permeability even after shredding may be difficult, an alternative is to melt the metals into ingots of a weight that is transportable. Some metals may require size reduction depending on furnace size. By definition, this alternative does not apply to sludges or combustibles.

Panel Assumptions: Depending on the process, the slag resulting from melting may contain most of the transuranic elements, substantially reducing metal waste volume while the ingots may qualify as low level waste. The slag resulting from melting may need to be solidified in cement or another medium.

ADD SALT BACKFILL

Adding crushed or pulverized salt into the larger void spaces around the waste in each waste container has the advantage of reducing the permeability of the waste but may induce accelerated corrosion and gas evolution.

ADD OTHER SORBENTS

Evaluation of sorbents in addition to or other than bentonite may lead to improved waste characteristics of permeability and porosity. These sorbents are intended to sorb brine and radionuclides.

ADD GAS SUPPRESSANTS

Adding materials to the waste that could reduce gas generation rates, such as materials that raise the pH of brine that comes in contact with the waste, could prove beneficial in reducing gas pressure buildup in the waste disposal rooms.

SHRED AND ADD BENTONITE

This alternative considers the addition of bentonite, a swelling, absorptive and colloidal clay, to shredded waste to reduce waste permeability, absorb brine that might otherwise come in contact with the waste, and sorb radionuclides to reduce their mobility. This alternative does not apply to sludges.

Panel Assumptions: Bentonite will absorb both brine and residual liquids in the waste.

ACID DIGESTION

This alternative would dissolve the waste in a strongly acidic solution that is subsequently neutralized and precipitated, resulting in a reduced volume sludge waste form, which is then solidified. In particular, the ability of organics and metals to generate gases is eliminated, and since the residue can be solidified, waste permeability and mobility are reduced.

Panel Assumptions: Waste may have to be segregated and shredded, with different process lines for metals and organics. The process may not be able to digest all plastics and may increase the nitrate inventory of the waste. The residue from this alternative will have to be combined with a solidification process such as calcining, cementation or vitrification. This alternative applies only to combustibles.

STERILIZE

Prior to emplacement of the waste in WIPP, sterilize the contents of each waste package to eliminate or reduce microbial gas generation. To be sufficiently effective, this alternative would probably have to be used in conjunction with sterilization of the entire underground waste disposal area, which is not considered a credible alternative at this time.

ADD COPPER SULFATE

The addition of copper sulfate to the waste is expected to reduce the generation of gases resulting from anoxic corrosion of iron based metals. The copper sulfate reacts with iron, forming ferrous sulfate and preventing the production of free hydrogen gas.

ADD GAS GETTERS

Several gases will constitute the major volumes generated over time in the waste disposal area of WIPP. If generation of gases cannot be prevented, gas getters added to the waste may eliminate significant gas volumes and prove to be a solution to the potentially negative effect that large gas volumes may have on repository performance. Carbon dioxide may be removed by the addition of gas getters that will react with the gas to produce a solid phase.

Panel Assumptions: The getters assumed were either lime or hydrated lime added to waste to reduce the carbon dioxide gas inventory. These were the only getters considered and assumes that enough getter material can be added to the waste to be effective.

ADD FILLERS

Adding filler materials to the waste in order to reduce initial void volume will reduce the waste's permeability and can reduce brine inflow during room reconsolidation.

SEGREGATE WASTE FORMS

This alternative refers to isolating each major waste form (i.e., sludges, combustibles, etc.) from one another. By segregating the various waste forms that are now intermingled within waste packages, several engineered alternatives could be applied to smaller waste quantities, thereby possibly reducing costs and overall schedule.

Panel Assumptions: It was assumed that this alternative would require that new waste be segregated as it is generated while stored waste would have to be sorted.

DECONTAMINATE METALS

The disposal of metals in WIPP is expected to generate hydrogen from anoxic corrosion. These metals may also be difficult to compact to a sufficiently low permeability. An alternative solution may be to decontaminate the metals and dispose of them as low-level or nonradioactive wastes. The residue from this process would be handled in a manner similar to that resulting from the "Acid Digestion" alternative. This alternative is not applicable for sludges or combustibles.

Panel Assumptions: To be completely effective, this alternative would have to be combined with "Change Waste Container Material", since a large part of the metal inventory consists of steel drums and boxes. The residue resulting from the decontamination process will have to be solidified by vitrification, cementation, or other means.

CHANGE WASTE GENERATING PROCESS

Since two-thirds of the waste that will ultimately be emplaced in WIPP has not yet been generated, an opportunity exists to change the processes that generate the remaining waste to minimize waste porosity, permeability, and gas generation. Some progress

has already been made in reducing waste generation volumes, and compaction of waste at generator sites is an example of a process that reduces porosity and permeability.

CHANGE WASTE CONTAINER SHAPE

A major goal of the Engineered Alternatives program is to evaluate reduction of void volumes in waste packages and in the repository in general. A square cornered or hexagonal waste package configuration could essentially eliminate void volumes between emplaced waste packages in the disposal areas. Other configurations may also provide similar results, such as interlocking waste packages that fit together tightly when emplaced in WIPP. This alternative will only reduce the interstitial spaces between waste packages disposed of in WIPP. Stored waste needs to be repackaged. Space around the waste stack is not affected.

CHANGE WASTE CONTAINER MATERIAL

The corrosion of steel drums or boxes that are currently used to package waste may add considerably to the gas generated by anoxic corrosion after waste emplacement. The use of alternate materials may reduce the amount of gas generated from this process. For instance, copper or ceramic materials may be candidates that could reduce or eliminate metal corrosion induced gas generation.

Panel Assumptions: The Panel assumed that the polyethylene drum and box liners could be made sufficiently strong to act as waste containers.

ADD ANTIBACTERIAL MATERIAL

The addition of an antibacterial material to the waste could alleviate some gas production if such a material does not pose a greater challenge than the gas itself. The material must have an estimated effective lifetime sufficient to prevent those microbes already present in the repository from eventually overtaking its effectiveness.

ACCELERATE THE WASTE DIGESTION PROCESS

This alternative suggests that the gas generation process might be accelerated so that gas generation is minimized after decommissioning of the repository. This requires the addition of appropriate bacterial agents to hasten waste digestion, which would have to be essentially complete before decommissioning.

ALTER CORROSION ENVIRONMENT IN WIPP

The use of copper sulfate has already been identified as an engineered alternative that might modify the corrosion process to generate less gas. Other alternatives may alter the chemical environment of the waste storage rooms, such as assuring dryness or maintaining a pH buffer, so that corrosion is minimized.

Panel Assumptions: Copper sulfate was not considered for reasons given under that alternative's description. The addition of activated alumina, calcium oxide or cement was considered. These additives may increase the total number of waste packages required but result in a drier environment.

ALTER BACTERIAL ENVIRONMENT IN WIPP

This alternative is analogous to "Alter Corrosion Environment in WIPP." By changing the chemistry of the waste, microbial gas generation rates may be reduced to acceptable levels.

TRANSMUTATION

This alternative considers transmutation of long-lived radionuclides to short-lived nuclides, eliminating the need for long-term disposal.

VITRIFY SLUDGES

Sludges have a high moisture content compared to other waste forms. Vitrifying the sludges using microwave or Joule melters will reduce waste volume, remove excess moisture, and possibly remove nitrates.

BACKFILL ALTERNATIVES

SALT ONLY

This is the basic backfill material being considered to reduce void volume around the waste and to hasten room closure. The material results from mining the disposal rooms and drifts and can be processed by crushing or pulverizing to enhance backfilling operations. Unless this salt is preformed into compact shape(s), it has significant initial porosity and permeability, but will rapidly reconsolidate as a result of creep closure.

Panel Assumptions: Backfilling the void spaces around the waste will probably reduce the amount of brine entering the waste rooms. However, the void volume and permeability of the waste itself remains substantial and moisture in the waste (e.g., sludges) is not effected by this alternative.

SALT PLUS GAS GETTERS/ALKALI/pH BUFFERS

The addition of gas getters with the salt backfill may be advantageous for preventing buildup of unacceptable gas volumes. A potential disadvantage of applying getters in this manner is that salt reconsolidation takes place fairly quickly. If reconsolidation prevents interaction of gases with the getters in the salt matrix, it could prove ineffective. An added advantage of certain gas getters (e.g., CaO) is they will act as pH buffers thereby minimizing corrosion and radionuclide solubility in brine.

COMPACT BACKFILL

Compacting backfill in place could reduce its permeability sufficiently to prevent significant brine mobility. Such a procedure would probably require more storage space than currently planned to permit equipment access between and around the waste packages.

SALT PLUS BRINE SORBENTS

The presence of brine in the waste rooms is considered the primary medium for waste mobility to the accessible environment for certain scenarios. The brine source may be from a hypothesized brine reservoir or from migration of Salado brine from the surrounding salt into the waste disposal rooms. The expected volume of brine from the surrounding salt appears to be lower than previously anticipated. Therefore, sorbents such as bentonite added to the backfill may effectively preclude free brine in the

repository from this source. Sorbents may also be effective for reducing the mobility of radionuclides.

Panel Assumptions: The sorbents considered were bentonite, diatomaceous earth, and vermiculite. Approximately 30 percent sorbent in the backfill was considered enough to be effective. The effectiveness of backfill plus sorbents might be enhanced if installed below the waste as well.

PREFORMED COMPACTED BACKFILL

Preforming backfill into dense compacted modules, such as bricks or blocks, or shapes that can be inserted between waste packages, may reduce the overall permeability of the waste disposal rooms, thereby reducing the potential for brine contact with the waste. Compacted backfill reduces the time required for room closure and the amount of brine that can migrate into the room from the surrounding salt.

Panel Assumptions: Only salt was considered as a compacted backfill, and the precompacted material was assumed to be nearly formfitting around waste packages.

GROUT BACKFILL

The use of a grout as backfill instead of salt has the operational advantage of handling a semi-liquid material that can flow relatively easily. However, the emplacement of grout between waste containers may still be a challenge. The relative impermeability of grout is an advantage, whereas its poor stability characteristics in a salt/brine environment are potentially disadvantageous unless room closure acts to mechanically stabilize the entire waste/grout monolith.

Panel Assumptions: Grout was assumed between waste packages, with concrete around the waste stack.

BITUMEN BACKFILL

Bitumen has been considered as a backfill medium, but the operational challenges of handling large quantities of hot bitumen underground, and the potential for this backfill acting as an additional source for microbial gas generation, probably precludes the material from consideration.

ADD GAS SUPPRESSANTS

This alternative is analogous to that described for the waste form (same name) but the suppressing material would be mixed with the backfill.

WASTE MANAGEMENT ALTERNATIVES

MINIMIZE SPACE AROUND WASTE STACK

The waste disposal room dimensions were chosen so that retrieval after a five-year demonstration period would not be precluded by premature room closure. Therefore, space is available between the waste stack and the walls and ceiling which also acts as a ventilation flow path. Reduction or elimination of this space would result in the need for less backfill, quicker room closure, and less Salado brine migration into the room.

Panel Assumptions: Rooms will have to be mined to minimize space around the waste stack, consistent with remote-handled waste emplacement requirements. It was assumed that no backfill is required for this alternative.

SEGREGATE WASTE IN WIPP

The segregation of different waste forms in or among waste disposal rooms could prove beneficial. For instance, the segregation of permeable metal wastes in small amounts within more easily compacted or previously compacted waste could "encapsulate" the metals with other waste that is less permeable. The segregation of high gas-generation waste from more benign waste would focus the solution on a smaller area of WIPP. There may also be an advantage in segregating sludges that contain nitrates, from combustible wastes to prevent nitrate reducing bacteria from generating nitrogen gas.

Panel Assumptions: Administrative control of waste shipments is required. Segregation is by waste disposal panel. WIPP ventilation system redesign may be needed.

DECREASE AMOUNT OF WASTE PER ROOM

By leaving the room size the same as currently designed, but emplacing less waste volume per room, sufficient space may be gained around the waste stack to isolate the stack from the surrounding host salt. This would be accomplished by creating a waste stack that is as compact as practicable, surrounded by relatively "plastic" backfill containing sorbents and gas getters that would act as a secondary encapsulation medium. The host salt would, of course, remain the primary barrier.

EMPLACE WASTE AND BACKFILL SIMULTANEOUSLY

The intent of this alternative is to emplace backfill more efficiently so that its effect is maximized. This alternative would be used in conjunction with compacting in place or using precompacted (and preformed if necessary) backfill.

SELECTIVE VEGETATIVE UPTAKE

Using the vegetative uptake of certain plants to concentrate radionuclides has been proposed. Some work has been done demonstrating the vegetative concentration of heavy metals.

FACILITY DESIGN ALTERNATIVES

BRINE-ISOLATING DIKES

Brine dikes can consist of partial or full-height walls of material that separate waste quantities to reduce the amount of waste accessed by inflowing brine or a driller's circulating mud.

RAISE WASTE ABOVE FLOOR

If it can be postulated that Salado brine will collect on the waste disposal room floor, then isolating the waste from the floor may be beneficial. If it can be further postulated that humidity generated by brine can be isolated from the waste, then this alternative may reduce the amount of corrosion-induced gas generation.

Panel Assumptions: The Panel assumed that crushed salt, bentonite or other absorbent material would be placed between the waste disposal room floor and the waste. On that basis, the Panel considered this alternative part of the "Add Floor of Brine Sorbent Material" alternative as defined by the Panel's assumptions for that alternative.

BRINE SUMPS AND DRAINS

By properly sloping the floor of waste disposal rooms toward collection sumps, it may be possible to isolate inflowing brine from the waste. Isolating the brine during room closure and designing the sumps so that they become "encapsulated" after closure, may result in reduced corrosion-induced gas generation.

GAS EXPANSION VOLUMES

This alternative refers to the mining of recesses within the repository to allow free expansion of the gases generated and thus reduce gas pressure.

Panel Assumptions: It was assumed that brine would not fill the void volumes. This alternative was considered only if gas generation is a marginal problem, requiring only small expansion volumes to prevent overpressurization.

SEAL DISPOSAL ROOM WALLS

This alternative refers to a flexible, impermeable seal applied to the walls of each room such that closure does not break the seal. The intent is to prevent contact between the waste stack and interstitial brine.

VENT FACILITY

If gas generation results in the potential for overpressurizing waste disposal rooms, providing a small engineered vent could alleviate this condition.

VENTILATE THE FACILITY

Continuous ventilation of the waste disposal rooms until complete closure has taken place would eliminate concern about brine from the surrounding Salado Formation collecting in the repository.

Panel Assumptions: Permanent panel seals and backfill would not be installed during the institutional control period.

ADD FLOOR OF BRINE SORBENT MATERIAL

The intent of this alternative is to prevent free brine from contacting the waste stack, thereby reducing the potential for corrosion induced gas generation.

Panel Assumptions: See "Raise Waste Above Floor."

CHANGE MINED EXTRACTION RATIO

By changing the mined extraction ratio (i.e., leaving less supporting salt around the mined waste disposal rooms), room closure can be affected more quickly, reducing brine inflow from surrounding Salado salt.

Panel Assumptions: An increase in the creep rate will result in faster closure, but the possibility of a larger disturbed zone may add to the brine inflow rate.

CHANGE ROOM CONFIGURATION

This alternative involves several possibilities. Stacking the waste tightly against the walls would eliminate initial void volume and enhance closure time. Another option involves increasing room size, which would also increase the extraction ratio, making room for a buffer of sorbents and getters completely surrounding the waste stack. A third option involves increasing room height and stacking the waste higher to reduce the overall footprint of the repository.

Panel Assumptions: Since several of the stated options were considered under other alternatives, this alternative was considered only from the standpoint of stacking the waste higher than currently designed and reducing the overall footprint of the repository. Although the probability of a human intrusion event penetrating the waste stack is reduced, the consequences may be higher than for the current design.

SEAL INDIVIDUAL ROOMS

If human intrusion were to take place, sealing off each room instead of sealing the panels may preclude brine from "sweeping" past enough waste to cause out-of-compliance releases of radionuclides. The effectiveness of this alternative depends on the mobility of the waste form, such as solubility of radionuclides in brine.

Panel Assumptions: The Panel considered this alternative for mitigating the effects of the single and two borehole scenarios only. The Panel assumed that there is a low probability of two boreholes penetrating the same waste storage room. Although waste permeability is unchanged, the individual room seals would decrease the overall effective "permeability" of the underground disposal area.

TWO-LEVEL REPOSITORY

A two-level repository refers to decreasing the facility's surface footprint by placing half the waste disposal area above the other, creating a two-level facility. Although reduction of the facility footprint will reduce the probability of human intrusion into the underground disposal area, the consequences could double if the intrusion event penetrates both levels of the repository.

PASSIVE MARKER ALTERNATIVES

MONUMENT "FOREST" OVER REPOSITORY

The use of closely spaced surface markers, consisting of long-lasting materials, can be used to alert potential intruders about the existence of the repository. These monuments could be mass produced and include pictorial and other designations describing the location and content of the disposal area. Each marker would be deeply anchored in bedrock.

Panel Assumptions: It was assumed that this alternative is applicable only for the reduction of human intrusion probability.

MONUMENT COVERING THE ENTIRE REPOSITORY

The waste disposal area of WIPP consists of approximately 100 acres. A monument 2,100 feet on a side, consisting of natural and/or man-made materials, could provide

adequate warning to potential intruders as well as adding to the difficulty of drilling into the repository. The alternative could consist of a single "pyramid" or multiple contiguous monuments.

Panel Assumptions: It was assumed that this alternative is applicable only for the reduction of human intrusion probability.

BURIED STEEL PLATE OVER REPOSITORY

The action of a drill bit makes it difficult to penetrate non-friable materials. Burying a relatively thick steel or other metal plate at some distance below the surface over the repository could alert an intruder that this is an unusual site. The plate would probably have to be sandwiched between corrosion inhibitors to assure longevity. Additionally, site exploration and evaluation prior to drilling would alert geologists that further exploration is needed.

Panel Assumptions: It was assumed that this alternative is applicable only for the reduction of human intrusion probability.

ARTIFICIAL SURFACE LAYER OVER REPOSITORY

Replacing the natural surface materials over the repository with a layer of artificial or sterile material to a reasonable depth is another way of alerting potential intruders to explore further before taking any action.

Panel Assumptions: It was assumed that this alternative is applicable only for the reduction of human intrusion probability.

ADD MARKER DYE TO WASTE OR STRATA ABOVE REPOSITORY

The use of a marker dye that is sufficiently strong to discolor the drillers mud pond may alert the intruder that some further evaluation is necessary.

Panel Assumptions: It was assumed that this alternative is applicable only for the reduction of human intrusion probability.

MISCELLANEOUS ALTERNATIVES

DRAIN CASTILE RESERVOIR (Brine Pocket)

This alternative refers to the draining of the Castile brine reservoir, and thus reducing the effect of human intrusion through the repository.

GROUT CULEBRA FORMATION ABOVE REPOSITORY

The Culebra is a potential conduit for releasing radionuclides to the accessible environment. Grouting the Culebra above the repository may reduce this pathway.

INCREASE LAND WITHDRAWAL AREA TO THE REGULATORY BOUNDARY

Currently planned land withdrawal boundaries do not extend to the regulatory boundaries of 40 CFR Part 191. Extending the land withdrawal boundaries to coincide with the permitted regulatory boundaries would provide longer nuclide transit times before reaching the boundaries used to calculate repository performance.

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ATTACHMENT C

PRELIMINARY EVALUATION OF ENGINEERED ALTERNATIVES

The results of the preliminary evaluation process are depicted in Attachment C. The alternatives shown comprise the total list of the 64 potential engineered alternatives considered by the EAMP. After eliminating the alternatives that did not satisfy the "must" criteria, the EAMP assigned each remaining alternative a preliminary score based on its effectiveness for mitigating each of the ten original performance parameters, and its feasibility of implementation. The scores were based on a scale of zero to ten, with ten being the highest score and zero denoting an "adverse effect." Some alternatives were judged to have "no effect" on a performance parameter, in which case no score was assigned (represented by a "-" in the scoring column).

The EAMP assumed all of the ten performance parameters to be mutually exclusive of one another, because it is not yet evident which parameter(s) will control the demonstration of compliance with EPA Standard 40 CFR Part 191. However, the feasibility of an alternative was assumed to remain the same irrespective of the performance parameter being considered for evaluation of effectiveness.

The overall scores for an alternative for mitigating the effects of a performance parameter were calculated by combining its effectiveness and feasibility scores using a weighted summation approach. This approach is described in Section 2.2.3.

The following equation represents this scoring process:

$$\begin{aligned}\text{Total score} = {} & 5.1 \times (\text{Effectiveness score}) \\ & + 2.4 \times (\text{Regulatory score}) \\ & + 1.5 \times (\text{Technology score}) \\ & + 1.0 \times (\text{Schedule score})\end{aligned}$$

There were two exceptions to the above equation. If an alternative was assigned an effectiveness score of zero for "adverse effect," then its total score would also be equal to zero. On the other hand, if an alternative was assigned a "-" for "no effect," then its total score was represented as follows:

$$\begin{aligned}\text{Total score} = {} & 2.4 \times (\text{Regulatory score}) \\ & + 1.5 \times (\text{Technology score}) \\ & + 1.0 \times (\text{Schedule score}).\end{aligned}$$

ATTACHMENT C

PRELIMINARY EVALUATION OF ENGINEERED ALTERNATIVES

ALTERNATIVE	EFFECTIVENESS SCORE										FEASIBILITY SCORE			WEIGHTED FEASIBILITY SCORE	TOTAL SCORE OF AN ALTERNATIVE									
	RAD GAS	BIO GAS	CORR GAS	PERM	POR	STREN	LEACH	SOLUB	BRINE	HUMAN INTRU	(2.4) REG	(1.5) TECH	(1.0) SCH	WT. = 4.9	RAD GAS	BIO GAS	CORR GAS	PERM	POR	STREN	LEACH	SOLUB	BRINE	HUMAN INTRU
WASTE FORM MODIFICATION ALTERNATIVES																								
COMPACT WASTE	-	2.0	2.0	4.0	4.0	8.0	6.0	1.0	5.0	-	9.0	10.0	7.0	43.6	43.6	53.8	53.8	64.0	64.0	84.4	74.2	48.7	69.1	43.6
INCINERATE & CEMENT	5.0	8.0	3.0	1.0	1.0	3.0	5.0	3.0	2.0	-	2.0	7.0	2.0	17.3	42.8	58.1	32.6	22.4	22.4	32.6	42.8	32.6	27.5	17.3
INCINERATE & VITRIFY	6.0	8.0	3.0	2.0	2.0	4.0	6.0	2.0	2.0	-	2.0	7.0	2.0	17.3	47.9	58.1	32.6	27.5	27.5	37.7	47.9	27.5	27.5	17.3
WET OXIDATION	DELETED-TECHNOLOGY NOT DEMONSTRATED																							
SHRED & BITUMINIZE	-	0.0	2.0	5.0	5.0	3.0	6.0	-	5.0	-	3.0	10.0	5.0	27.2	27.2	0.0	37.4	52.7	52.7	42.5	57.8	27.2	52.7	27.2
SHRED & COMPACT	-	2.0	2.0	5.0	5.0	8.0	4.0	1.0	6.0	-	9.0	10.0	7.0	43.6	43.6	53.8	53.8	69.1	69.1	84.4	64.0	48.7	74.2	43.6
SHRED & CEMENT	2.0	4.0	3.0	4.0	4.0	5.0	5.0	3.0	4.0	-	9.0	10.0	9.0	45.6	55.8	66.0	60.9	66.0	66.0	71.1	71.1	60.9	66.0	45.6
SHRED & POLYMER ENCAP	0.0	2.0	3.0	5.0	5.0	5.0	5.0	3.0	5.0	-	9.0	5.0	6.0	35.1	0.0	45.3	50.4	60.6	60.6	60.6	60.6	50.4	60.6	35.1
SHRED,ADD SALT,COMPACT	-	2.0	-	7.0	7.0	8.0	5.0	1.0	7.0	-	9.0	10.0	7.0	43.6	43.6	53.8	43.6	79.3	79.3	84.4	69.1	48.7	79.3	43.6
PLASMA PROCESSING	10.0	10.0	8.0	10.0	10.0	10.0	10.0	9.0	10.0	-	3.0	4.0	1.0	14.2	65.2	65.2	55.0	65.2	65.2	65.2	65.2	60.1	65.2	14.2
MELT METALS	1.0	1.0	4.0	3.0	3.0	3.0	3.0	2.0	1.0	-	3.0	7.0	3.0	20.7	25.8	25.8	41.1	36.0	36.0	36.0	36.0	30.9	25.8	20.7
ADD SALT BACKFILL	CONSIDERED UNDER OTHER TYPE OF ALTERNATIVES																							
ADD OTHER SORBENTS	CONSIDERED UNDER OTHER TYPE OF ALTERNATIVES																							
ADD GAS SUPPRESSANTS	CONSIDERED UNDER 'ADD GAS GETTERS'																							
SHRED & ADD BENTONITE	2.0	1.0	1.0	3.0	3.0	-	0.0	-	3.0	-	9.0	10.0	9.0	45.6	55.8	50.7	50.7	60.9	60.9	45.6	0.0	45.6	60.9	45.6
ACID DIGESTION	5.0	6.0	2.0	4.0	4.0	5.0	6.0	3.0	5.0	-	3.0	4.0	2.0	15.2	40.7	45.8	25.4	35.6	35.6	40.7	45.8	30.5	40.7	15.2
STERILIZE	DELETED-TECHNOLOGY NOT DEMONSTRATED																							
ADD COPPER SULFATE	POTENTIAL FOR H2 GENERATION IF DEPOSITED COPPER FORMS GALVANIC COUPLE																							
ADD GAS GETTERS	1.0	2.0	3.0	1.0	-	-	-	3.0	1.0	-	5.0	9.0	5.0	30.5	35.6	40.7	45.8	35.6	30.5	30.5	30.5	45.8	35.6	30.5
ADD FILLERS	CONSIDERED UNDER OTHER TYPE OF ALTERNATIVES																							
SEGREGATE WASTE FORMS	ALTERNATIVE IS NOT A STAND ALONE PROCESS																							
DECONTAMINANT METALS	1.0	2.0	1.0	1.0	1.0	-	4.0	1.0	1.0	-	7.0	9.0	7.0	37.3	42.4	47.5	42.4	42.4	42.4	37.3	57.7	42.4	42.4	37.3
CHANGE WASTE GEN. PROC.	TOO BROAD TO EVALUATE																							
ADD ANTI-BACTERIAL MATRIX	DELETED-TECHNOLOGY NOT DEMONSTRATED																							
ACCEL WASTE DIGESTION	DELETED-INEFFECTIVE ALTERNATIVE																							
ALTER CORROSION ENV. WIPP	5.0	7.0	8.0	2.0	2.0	-	-	-	8.0	-	6.0	7.0	6.0	30.9	56.4	66.6	71.7	41.1	41.1	30.9	30.9	30.9	71.7	30.9
ALTER BACTERIAL ENV. WIPP	CONSIDERED IN EVALUATION OF OTHER ALTERNATIVES																							
TRANSMUTATION	TECHNOLOGY NOT DEMONSTRATED FOR SUCH LARGE AMOUNTS OF WASTE																							
VITRIFY SLUDGES	3.0	3.0	2.0	2.0	2.0	3.0	3.0	2.0	2.0	-	4.0	7.0	6.0	26.1	41.4	41.4	36.3	36.3	36.3	41.4	41.4	36.3	36.3	26.1
BACKFILL ALTERNATIVES																								
SALT ONLY	-	1.0	-	1.0	1.0	-	-	-	1.0	-	8.0	7.0	9.0	38.7	38.7	43.8	38.7	43.8	43.8	38.7	38.7	38.7	43.8	38.7
SALT + GAS GETTER	-	2.0	-	1.0	1.0	-	-	5.0	4.0	-	8.0	7.0	9.0	38.7	38.7	48.9	38.7	43.8	43.8	38.7	38.7	64.2	59.1	38.7
COMPACT BACKFILL	-	1.0	-	1.0	1.0	-	-	-	2.0	-	4.0	3.0	6.0	20.1	20.1	25.2	20.1	25.2	25.2	20.1	20.1	20.1	30.3	20.1
SALT + SORBENTS	3.0	3.0	4.0	1.0	1.0	-	-	2.0	6.0	-	8.0	7.0	7.0	36.7	52.0	52.0	57.1	41.8	41.8	36.7	36.7	46.9	67.3	36.7
PREFORMED COMPACTED BACKFILL	1.0	2.0	1.0	1.0	1.0	-	-	-	2.0	-	6.0	5.0	7.0	28.9	34.0	39.1	34.0	34.0	34.0	28.9	28.9	28.9	39.1	28.9
GROUT BACKFILL	1.0	2.0	3.0	1.0	1.0	-	-	3.0	2.0	-	8.0	8.0	9.0	40.2	45.3	50.4	55.5	45.3	45.3	40.2	40.2	55.5	50.4	40.2
BITUMEN BACKFILL	1.0	0.0	5.0	1.0	1.0	-	-	-	4.0	1.0	3.0	5.0	5.0	19.7	24.8	0.0	45.2	24.8	24.8	19.7	19.7	19.7	40.1	24.8
GAS SUPPRESANTS	CONSIDERED UNDER GAS GETTERS IN BACKFILL																							

ATTACHMENT C
(contd.)
PRELIMINARY EVALUATION OF ENGINEERED ALTERNATIVES

ALTERNATIVE	EFFECTIVENESS SCORE: RAD GAS	BIO GAS	CORR GAS	PERM	POR	STREN	LEACH	SOLUB	BRINE	HUMAN INTRU	FEASIBILITY SCORE: (2.4) REG	(1.5) TECH	(1.0) SCH	WEIGHTED FEASIBILITY SCORE WT. = 4.9	TOTAL SCORE OF AN ALTERNATIVE: RAD GAS	BIO GAS	CORR GAS	PERM	POR	STREN	LEACH	SOLUB	BRINE	HUMAN INTRU
FACILITY DESIGN ALTERNATIVES																								
BRINE ISOLATING DIKES	CONSIDERED UNDER 'SEAL INDIVIDUAL ROOMS																							
RAISE WASTE ABOVE FLOOR	NEEDS TO BE COMBINED WITH ADD SORBENTS TO BACKFILL																							
BRINE SUMPS AND DRAINS	DELETED-BRINE CAN'T FLOW DUE TO SALT RECONSOLIDATION																							
GAS EXPANSION VOLUME	10.0	10.0	10.0	-	-	-	-	-	-	-	7.0	10.0	7.0	38.8	89.8	89.8	89.8	38.8	38.8	38.8	38.8	38.8	38.8	38.8
SEAL DISPOSAL ROOM WALLS	TECHNOLOGY HAS NOT BEEN LABORATORY DEMONSTRATED																							
VENT FACILITY	NOT REGULATORY FEASIBLE																							
VENTILATE FACILITY	4.0	5.0	4.0	-	-	-	-	-	9.0	-	4.0	4.0	4.0	19.6	40.0	45.1	40.0	19.6	19.6	19.6	19.6	19.6	65.5	19.6
ADD FLOOR OF BRINE SORBENT	CONSIDERED UNDER BACKFILL + SORBENTS																							
CHANGE EXTRACTION RATIO	1.0	2.0	1.0	1.0	1.0	-	-	-	2.0	-	8.0	7.0	9.0	38.7	43.8	48.9	43.8	43.8	43.8	38.7	38.7	38.7	48.9	38.7
CHANGE ROOM CONFIGURATION	-	-	-	-	-	-	-	-	-	3.0	7.0	10.0	7.0	38.8	38.8	38.8	38.8	38.8	38.8	38.8	38.8	38.8	38.8	54.1
SEAL INDIVIDUAL ROOMS	-	-	-	8.0	-	-	-	-	-	-	9.0	8.0	9.0	42.6	42.6	42.6	42.6	83.4	42.6	42.6	42.6	42.6	42.6	42.6
TWO LEVEL REPOSITORY	-	-	-	-	-	-	-	-	-	5.0	1.0	8.0	1.0	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	40.9
WASTE MANAGEMENT ALTERNATIVES																								
MIN SPACE AROUND WASTE STACK	1.0	2.0	1.0	1.0	1.0	-	-	-	2.0	-	10.0	10.0	10.0	49.0	54.1	59.2	54.1	54.1	54.1	49.0	49.0	49.0	59.2	49.0
SEGREGATE WASTE IN WIPP	-	5.0	0.0	-	-	-	-	-	-	-	8.0	10.0	8.0	42.2	42.2	67.7	0.0	42.2	42.2	42.2	42.2	42.2	42.2	42.2
DECREASE AMT OF WASTE/ROOM	CONSIDERED UNDER ADD SORBENTS/GAS GETTERS TO BACKFILL																							
EMPLACE WASTE/BACKFILL SIMUL	CONSIDERED UNDER PREFORMED COMPACTED BACKFILL																							
SELECTIVE VEGETATIVE UPTAKE	NOT LAB DEMONSTRATED FOR TRU WASTE																							
WASTE CONTAINER ALTERNATIVES																								
CHANGE WASTE CONT. SHAPE	1.0	1.0	1.0	1.0	1.0	-	-	-	1.0	-	9.0	10.0	9.0	45.6	50.7	50.7	50.7	50.7	50.7	45.6	45.6	45.6	50.7	45.6
CHANGE WASTE CONT. MATERIAL	-	-	2.0	-	-	-	-	-	-	-	8.0	8.0	9.0	40.2	40.2	40.2	50.4	40.2	40.2	40.2	40.2	40.2	40.2	40.2
PASSIVE MARKER ALTERNATIVES																								
MONUMENT "FOREST"	-	-	-	-	-	-	-	-	-	6.0	9.0	10.0	10.0	46.6	46.6	46.6	46.6	46.6	46.6	46.6	46.6	46.6	46.6	77.2
MONUMENT COVERING REPOSITORY	-	-	-	-	-	-	-	-	-	10.0	8.0	10.0	10.0	44.2	44.2	44.2	44.2	44.2	44.2	44.2	44.2	44.2	44.2	95.2
BURIED STEEL PLATE OVER REP.	-	-	-	-	-	-	-	-	-	5.0	7.0	10.0	10.0	41.8	41.8	41.8	41.8	41.8	41.8	41.8	41.8	41.8	41.8	67.3
ARTIFICIAL SURFACE LAYER	DELETED-UNABLE TO IDENTIFY A FEASIBLE CONCEPT																							
ADD MARKER DYE TO STRATA	-	-	-	-	-	-	-	-	-	1.0	4.0	1.0	10.0	21.1	21.1	21.1	21.1	21.1	21.1	21.1	21.1	21.1	21.1	26.2
MISCELLANEOUS ALTERNATIVES																								
DRAIN CASTILE RESEVOIR	DELETED-NOT CONSIDERED FEASIBLE																							
GROUT CULEBRA	DELETED-NOT CONSIDERED FEASIBLE																							
INCR. LAND WITHDRAWAL AREA	NOT AN ENGINEERED ALTERNATIVE																							

TOTAL SCORE CALCULATIONS:

EFFECTIVENESS WEIGHTED SCORE = EFFECTIVENESS SCORE X (5.1)
FEASIBILITY WEIGHTED SCORE = REGULATORY SCORE X 2.4 + TECHNOLOGY SCORE X 1.5 + SCHEDULE SCORE X 1.0

TOTAL SCORE OF AN ALTERNATIVE = EFFECTIVENESS WEIGHTED SCORE + FEASIBILITY WEIGHTED SCORE

ABBREVIATIONS

RAD GAS = Radiolytic Gas Generation
BIO GAS = Biological Gas Generation
CORR GAS = Corrosion Gas Generation
PERM = Permeability of the Waste Stack
POR = Porosity of the Waste
STREN = Shear Strength of the Waste
LEACH = Leachability of the Waste
SOLUB = Radionuclide Solubility in Brine
BRINE = Brine Inflow
HUMAN INTRU = Human Intrusion
REG = Regulatory Score
TECH = Technology Score
SCH = Schedule Score

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APPENDIX B

DEVELOPMENT OF THE ROOM-SCALE COMPONENT OF THE DESIGN ANALYSIS MODEL

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1.0 DESIGN ANALYSIS MODEL PROGRAM LOGIC

1.1 PROGRAM LOGIC FOR GAS GENERATION

The ROOM-SCALE component of the Design Analysis Model is outlined in the flow diagram in Figures B-1 to B-3. The other component, the SHAFT-SEAL program is outlined in Appendix C. The Design Analysis Model instructions are written in a modular format such that the main program (ROOM-SCALE) is a driver routine which coordinates the functions performed by subroutines (Appendix B) used in modeling the processes considered (Section 2.0 in Volume I). Permeabilities of the shaft and panel seals are obtained by using the SHAFT-SEAL program (Appendix C) prior to use of the ROOM-SCALE program. This analysis provides data necessary in generating equations describing shaft-seal conductance over time. Calculations performed in the Design Analysis Model are dependent on data obtained from input files. Parameters which vary from one run to the next, such as brine inflow rate, creep closure rate, and waste form and backfill properties, are entered into the input file. The initial procedure of the program is to read this data file by calling a subroutine entitled READAT (Circle 1 in Figure B-1). After acquiring the variables from the data file, the program calls the next subroutine entitled INITIALIZE (Circle 2 in Figure B-1). The purpose of this subroutine is to perform the remaining calculations necessary to initialize the variables required by the model. These calculations provide information (which is evaluated using data from the input file) such as the initial void volume in a panel and the initial moles of each gas present in the panel. Following initialization, the actual simulation process begins. Time is set to start at zero and the entire set of calculations is performed and repeated as the time variable is incremented (for instance, by one year) until the termination conditions are satisfied.

After the initial void volume and ambient pressure in the panel are defined, the subroutine BRINFLOW (Circle 3 in Figure B-1) calculates the cumulative inflow of brine during the current time increment and determines the moles of H_2O contained in the brine. BRINFLOW (Circle 4 in Figure B-1) calculates the cumulative inflow of brine during the current time increment and determines the moles of H_2O available in the panel. COMPACTION (Circle 4 in Figure B-1) then computes the compaction stress due to the mechanical resistance to closure provided by the waste/backfill composite. The density of the solids within the panel is calculated based upon the current panel volume and the initial mass of the waste/backfill composite. The subroutine CREEP (Circle 5 in Figure B-1) calculates the extent of salt creep during the time increment and the height and width of a room-equivalent at the end of the time increment.

The program then calls the subroutine MASSGAS (Circle 6 in Figure B-1) to estimate the molar rates of gas generation due to the combination of radiolysis and microbial activity, and due to anoxic corrosion. MASSGAS also accounts for gas consumption and transport due to various mechanisms.

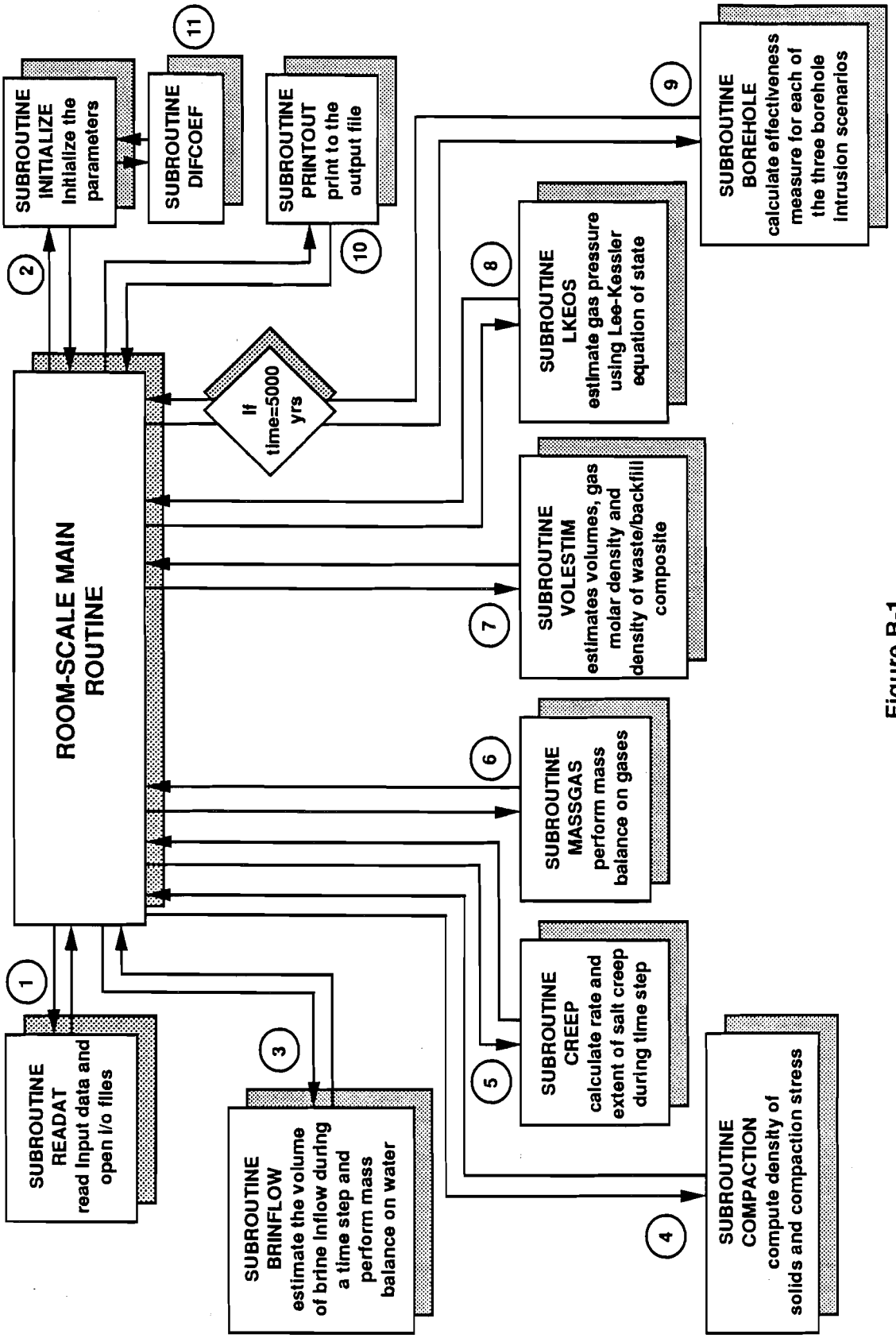

Figure B-1
ROOM-SCALE Flow Diagram

During the mass balance calculations, MASSGAS uses a number of subroutines in the following order:

- GASOLUB (Circle 11 in Figure B-2) estimates the solubilities and Henry's Law Constants (in brine) of the various gases present in the panel.

- ADVECTION (Circle 1 in Figure B-2) estimates the rate of advection of gases into Marker Bed 139 and across the repository seals (Section 2.0 in Volume I). ADVECTION uses the following subroutines in evaluating the total molar advection rate at each point in time:

  - VISCORR (Circle 7 in Figure B-2) estimates the gas mixture viscosity using a correlation that is applicable to both low and high pressure conditions.

  - MBFLOW (Circle 8 in Figure B-2) estimates the void volume available for gas storage in the disturbed anhydrite beds at each point in time as brine is driven from the disturbed to the intact portions of the anhydrites.

  - SHFTCOND (Circle 9 in Figure B-2) evaluates the total conductance of the four shaft seals as a function of time.

- DIFFUSION (Circle 2 in Figure B-2) calls DIFCOEF (Circle 10 in Figure B-2) to determine the applicable diffusion coefficients and then calculates the molar rates of diffusion of gases out of the panel into the brine saturated host rock formation.

- VAPLIQEQ (Circle 4 in Figure B-2) evaluates the number of moles of each gas that will dissolve into the volume of brine available in the panel (Section 2.0). Subroutine GASOLUB is called to evaluate the Henry's Law Constants of the gases in brine.

- BRINTERACT (Circle 5 in Figure B-2) determines the amount of CO_2 that can react with portlandite at the current panel pressure, the moles of portlandite consumed, and the water generated by the reaction. The moles of each gas in the panel are then updated in the MASSGAS to reflect the CO_2 consumption.

The changes occurring in the MASSGAS subroutine are reflected in the number of moles of gases and liquids present in the panel.

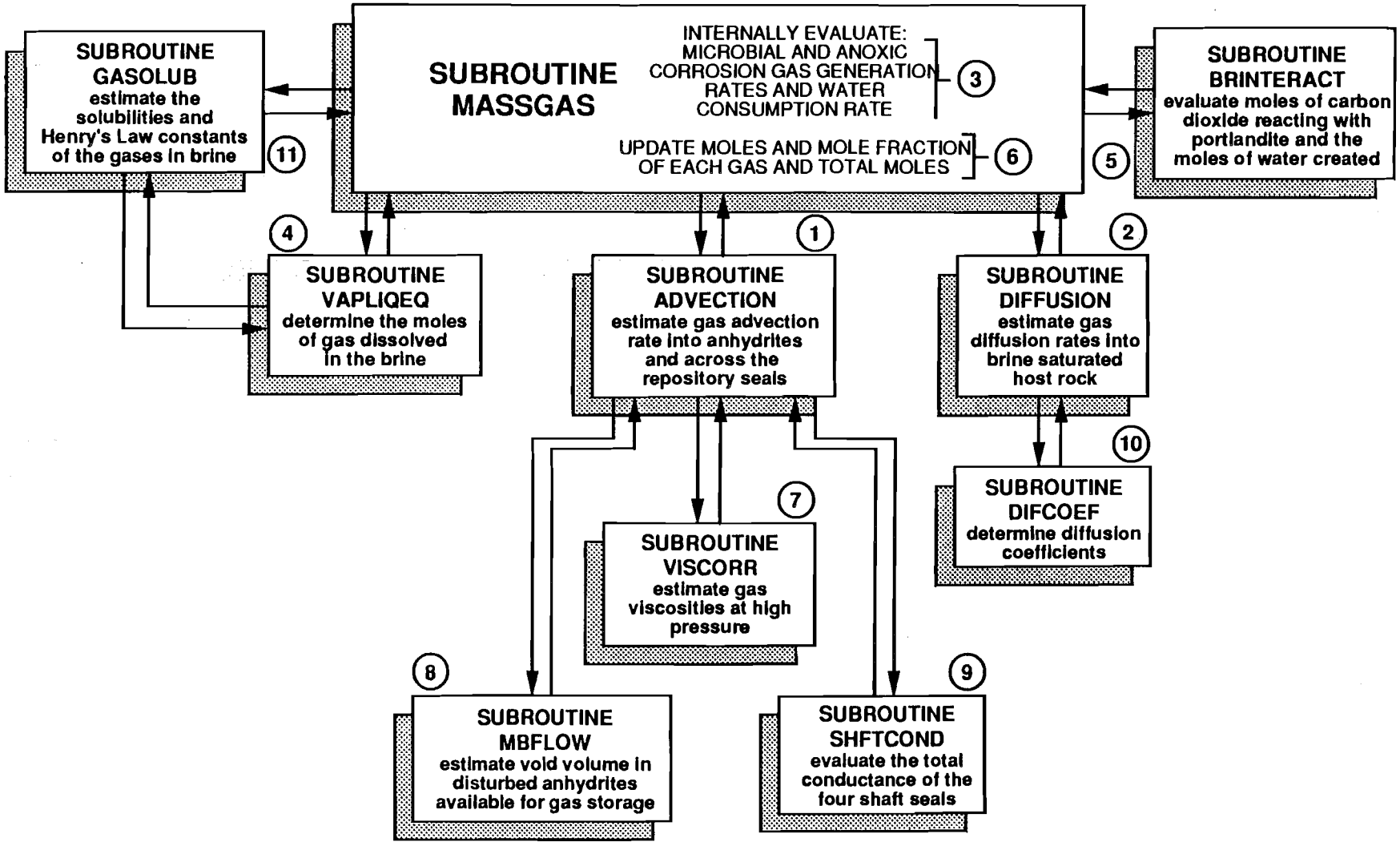

Figure B-2
MASSGAS Flow Diagram

VOLESTIM (Circle 7 in Figure B-1) calculates the volume of the panel, and the volume of the air gap above waste/backfill composite (if no contact with the waste stack and the ceiling of the panel has occurred). These volumes are then used to calculate the void volume of the entire panel. In addition, the molar volume, molar density, and the density of the waste/backfill composite are evaluated. Prior to incrementing the time step, the subroutine LKEOS (Circle 8 in Figure B-1) evaluates the panel fluid pressure. This subroutine uses the Lee-Kessler Equation of State (Reid et al., 1987) taking into account the compressibility of the gases.

Consideration of the complex interactions that occur between the above processes enables the Design Analysis Model to predict the changes in fluid pressure, porosity, permeability and effective stress as a function of time for a typical storage room filled with waste and backfill.

1.2 PROGRAM LOGIC FOR HUMAN INTRUSION

The effects of human intrusion events may also be evaluated at any time. For consistency in the evaluation of alternatives, the intrusion is assumed to occur 5,000 years after decommissioning. At time equal to 5,000 years, the subroutine BOREHOLE (Circle 9 in Figure B-1) simulates the release of radionuclides resulting from three borehole intrusion scenarios (Section 2.0 in Volume I). All program values reflecting the conditions existing in the panel at the time of intrusion are sent to the BOREHOLE subroutine. The subroutine evaluates the permeability of the waste/backfill composite and the solubility of each radionuclide in brine. In addition, the volume of the cuttings removed from the repository by a drill bit and deposited on the surface is assessed for radionuclide content. For each of the three intrusion scenarios considered (Subroutines ISE1, ISE2, ISE1E2 in Figure B-3), the flow path through the panel contents is different (Marietta et al., 1989). The BOREHOLE subroutine makes use of the following subroutines:

- ESTHCKSS (Circle 1 of Figure B-3) estimates the hydraulic conductivity and the specific storage (volume of fluid released by a unit volume of aquifer under unit decline in hydraulic head) of the waste/backfill composite at the time of intrusion.

- RADACTIM (Circle 2 of Figure B-3) predicts the mass and activity of each radionuclide at the time of intrusion (5,000 years).

- CUTTINGS (Circle 3 of Figure B-3) estimates the release of radionuclides to the aboveground surface due to drill bit penetration of the repository. The erosion of the waste material immediately surrounding the bit is included and depends on the anticipated strength of the waste/backfill composite in the panel. In addition, the mass and activity of each radionuclide are evaluated on a panel basis.

- RADSOLUB (Circle 4 of Figure B-3) evaluates the solubility of each radionuclide in brine.

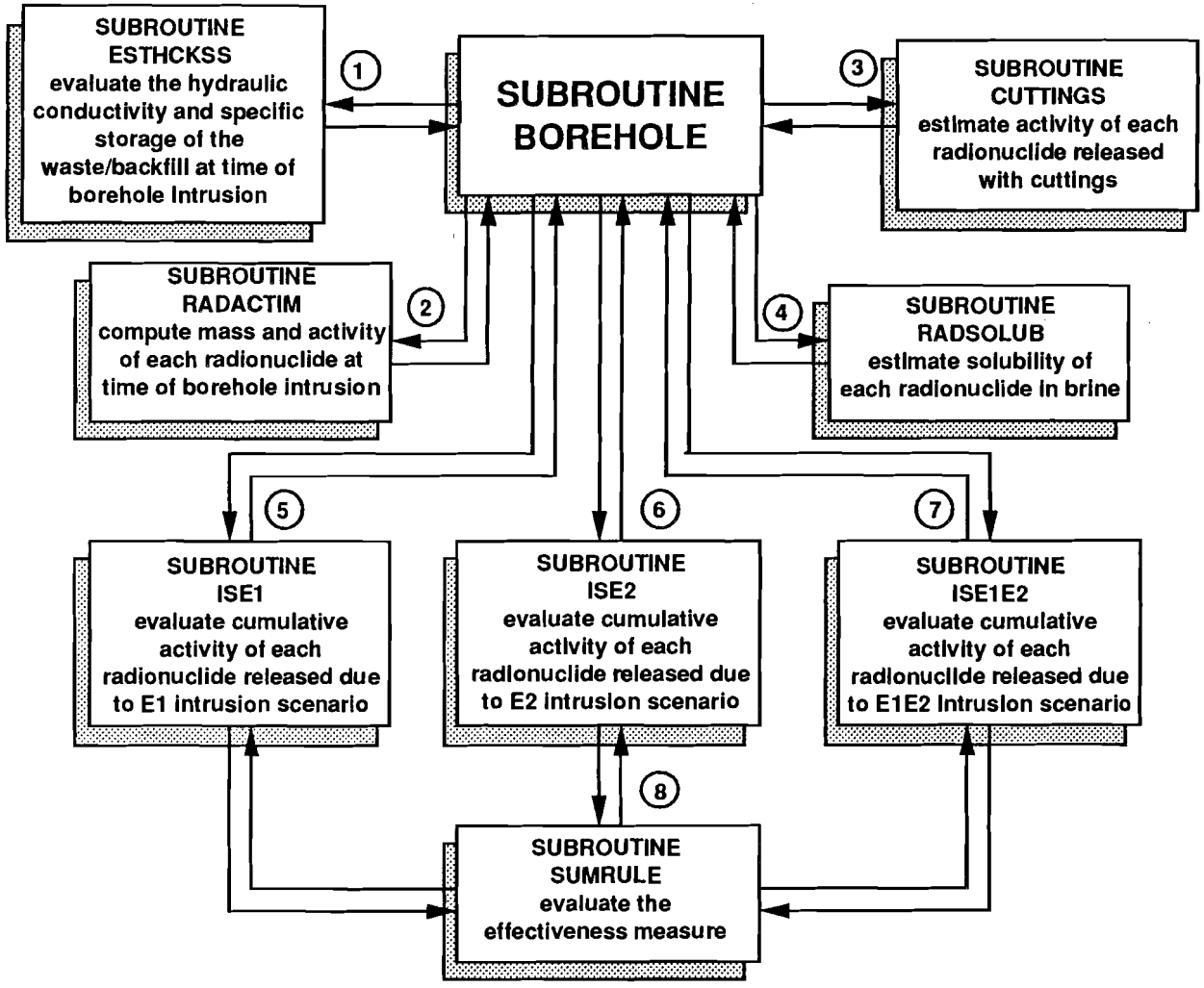

Figure B-3.
BOREHOLE Flow Diagram

- Subroutines ISE1, ISE2, and ISE1E2 (Circles 5, 6, and 7 in Figure B-3) are used to estimate the resulting radionuclide releases during each of the three intrusion events simulated (Marietta et al., 1989). Separate evaluation schemes are necessary as the three scenarios vary significantly in flow path configuration (Section 2.0 in Volume I).

- SUMRULE (Circle 8 in Figure B-3) is used to calculate the Measure of Effectiveness of an engineered alternative for each one of the three intrusion scenarios (Section 2.0 in Volume I).

Following the BOREHOLE calculations, the program prints the resulting values to the output file and terminates. If intrusion is not being considered during the current run, the program continues to calculate the conditions existing in the panel until preset termination conditions are satisfied.

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2.0 PROCESSES AND EQUATIONS CONSIDERED IN THE DESIGN ANALYSIS MODEL

2.1 INPUT DATA AND PROGRAM INITIALIZATION (READAT AND INITIALIZE)

The input required by the Design Analysis Model for evaluating the effectiveness of each engineered alternative is obtained from the input data file in subroutine READAT. The data in the input file are specific to the alternative being evaluated (see Section 3.0 in Volume I for data development methodology). The parameters in the input file include:

- Initial room dimensions (height, width) and initial panel volume
- Time step size
- Stress exponent in the creep equations
- Print counters
- Horizontal and vertical creep rate constants for the creep equations
- Number of gas components
- Lithostatic pressure
- Brine inflow rate assuming one atmosphere pressure is maintained in the panel
- Initial porosity of the waste/backfill composite
- Width of the air gap clearance above the waste/backfill composite
- Temperature in the panel
- Microbial and radiolytic gas generation rates
- Maximum potential hydrogen gas generation from anoxic corrosion of iron (steel)
- Duration of microbial activity
- Initial density of the waste/backfill composite
- Stress-density and hydraulic conductivity-stress coefficients
- Void ratio-stress coefficients
- Element solubilities in brine
- Volume of waste/backfill versus stress coefficients for use in estimating the activity of radionuclides released to the surface with the cuttings of intrusion boreholes
- Radius factor (number of borehole radii removed with cuttings)
- Number of drum equivalents per panel
- Time of human intrusion
- Distance between boreholes in human intrusion scenario E1E2

- Brine pore pressure in intact anhydrite beds
- Permeability of the anhydrite beds.

The use of these parameters in the Design Analysis Model will be discussed in subsequent sections of this Appendix.

The subroutine INITIALIZE is called to initialize the variables which are used in the Design Analysis Model. The initial void volume in a panel is among the basic parameters required by the model. This requires that the volume of the air gap above the waste/backfill stack be evaluated as follows. Refering to Figure 2-1 (Vol. I), there are 7 storage rooms in a panel. Separating the rooms are 100 ft. (30.48 m) wide salt pillars. In the drift area along the ends of the salt pillars, there are a total of 12 sections, each with height and width equivalent to that of a room (as specified in the input file), and each 100 ft. (30.48 m) long. As seen in Figure 2-1, there are 14 intersectional areas between rooms and access drifts which are square and have lateral dimensions equivalent to the width of a room. Thus, the volume of the air gap clearance is:

$$V_{clmc} = 7h_{clmc}w_{room}l_{room} + 12h_{clmc}w_{room}\ w_{pillar} + 14h_{clmc}\ w_{room}^2 \qquad (2.1\text{-}1)$$

where,

V_{clmc} = *volume of air gap clearance* (m^3)
h_{clmc} = *thickness of air gap clearance* (m)
w_{room} = *width of the room* (m)
l_{room} = *length of the room* (91.44m)
w_{pillar} = *width of the salt pillars between rooms* (30.48m).

The following variables are then initialized:

- The initial gas pressure in the panel, P_o is set to 0.101325 MPa (1 atm)
- The gas constant is initialized as 8.314 Nm/mol °K
- The moles of portlandite, $Ca(OH)_2$, in a panel is estimated as the product of 13.03 mol/drum and the number of unprocessed drum equivalents per panel.
- The brine density is initialized to 1220 kg/m^3.
- The molecular weight of the WIPP brine is set to 20.49 g/mol.

- The molar density of the gas mixture in the panel (RHOM) is then evaluated as:

$$RHOM = \frac{P_0}{RT} \tag{2.1-2}$$

where,

P_0 = *initial fluid pressure in the panel (Pa)*
R = *gas constant* (8.314 *Nm/mol °K*)
T = *absolute temperature* (300 *°K*)

- The initial void volume in a panel is then calculated as:

$$V_{void} = V_{clmc} + (V_{pnl} - V_{clmc})\ n_{WB} \tag{2.1-3}$$

where,

V_{void} = *initial void volume in the panel* (m^3)
V_{clmc} = *volume of the air gap clearance* (m^3)
V_{pnl} = *initial panel volume* (m^3)
which is specified in the data input file
n_{WB} = *initial waste-backfill porosity*

- The total moles of gas present in the panel (N_{total}) initially is estimated as:

$$N_{total} = RHOM\ V_{void} \tag{2.1-4}$$

- Air is assumed to be the only gas present in the panel initially. Thus the mole fractions of nitrogen and oxygen are initialized to 0.79 and 0.21 respectively.

- The initial moles of nitrogen and oxygen are evaluated by multiplying the initial total moles of gas (N_{total}) by the mole fraction of each gas (i.e., 0.79 for N_2 and 0.21 for O_2).

- It is assumed that no brine is present in the panel initially

- The gases are initially assumed to behave as ideal gases; thus, the compressibility factor is assigned as 1.0

- The porosity of the intact Salado Formation is initialized as 0.001 (Marietta et al., 1989)

- The area available for diffusion of gases is assigned a value of 31756 m^2 based upon the areas of the floors, ceilings, and walls in the rooms and access drifts

- The molar rate of oxygen consumption is calculated by dividing the initial moles of oxygen present in a panel by 100 years, such that all the oxygen is consumed in the first 100 years

- The volume occupied by the waste and backfill less pores (V_{WB}) is estimated as:

$$V_{WB} = (V_{pnl} - V_{clmc})\ (1 - n_{WB}) \tag{2.1-5}$$

- The initial mass of the solids in the panel (m_{solids}) is then calculated as:

$$m_{solids} = \rho_{initial}\ (V_{pnl} - V_{clmc}) \tag{2.1-6}$$

where,

$\rho_{initial}$ = *initial density of the waste/backfill which is specified in the data input file*

The final executable statement in the subroutine INITIALIZE is a call to the subroutine DIFCOEF. The DIFCOEF subroutine evaluates the diffusion coefficients of the various gases in brine, as described in the next section.

2.2 ESTIMATION OF GAS-BRINE DIFFUSION COEFFICIENTS (DIFCOEF)

The diffusion coefficient of a solute "A" (gas), in solvent "B" (brine), is estimated in subroutine DIFCOEF using the Wilke-Chang correlation (Reid et al., 1987) for each gas present in the panel.

The correlation takes the form:

$$D_{AB} = \frac{7.4 \times 10^{-12} (\phi M_B)^{0.5} T}{\mu_B V_A^{0.6}} \qquad (2.2\text{-}1)$$

where,

D_{AB} = *mutual diffusion coefficient of solute A in brine B* (m^2/s)
M_B = *molecular weight of brine* (20.49 *g/mol*)
T = *absolute temperature* (300°*K*)
μ_B = *viscosity of brine* (1.60 *centipoise*)
V_A = *molar volume of solute at its normal boiling temperature* (cm^3/mol)
the molar volumes of the various solutes are tabulated below:

$V_{Hydrogen}$ = 17.7 cm^3/mol
V_{Oxygen} = 25.7 cm^3/mol
$V_{Carbon\ dioxide}$ = 33.3 cm^3/mol

ϕ = *association factor of solvent*
(*the value for brine is assumed to be the same as for water, i.e.,* 2.6)

2.3 ESTIMATION OF VOLUME OF BRINE AND WATER INFLOW (BRINFLOW)

The volumetric rate of brine inflow is assumed to be directly proportional to the difference between lithostatic pressure and the current fluid pressure in a panel. It is assumed that if the panel gas pressure equals or exceeds lithostatic pressure, brine inflow will cease. The volume of brine inflow during a time step is evaluated in the subroutine BRINFLOW as:

$$DELVB = Q_{Brine} P_B \qquad (2.3\text{-}1)$$

where,

$DELVB$ = *volumetric brine inflow rate into a panel during the time interval (t to t+dt) (m^3/yr)*

Q_{Brine} = *brine inflow rate assuming the pressure in a panel is maintained at 1 atm*

P_B = *dimensionless pressure term defined as*

$$= \frac{(P_F - P)}{(P_F - P_0)}$$

where,

P_F = *lithostatic or farfield pressure, 14.8 MPa (146.1 atm)*

P = *fluid pressure in panel at time, t = 0 (1 atm)*

P_B is 1.0 if gas pressure in the panel remains at 1.0 atm;

P_B is 0.0 if the gas pressure equals or exceeds lithostatic pressure, P_F.

The cumulative volume of brine, VBCUM, which has flowed into the panel during time, t, is:

$$VBCUM = \int_0^t DELVB\ dt \qquad (2.3\text{-}2)$$

which may be expressed numerically as

$$VBCUM(t+dt) = VBCUM(t) + DELVB\ dt \qquad (2.3\text{-}3)$$

where,

dt = time step size (yr).

The actual volume of brine remaining in the panel, VB, (i.e., brine which has not yet been consumed by anoxic corrosion) is also incremented by the same quantity, thus:

$$VB(t+dt) = VB(t) + DELVB\ dt \qquad (2.3\text{-}4)$$

2.4 ESTIMATION OF ROOM CREEP CLOSURE (CREEP)

Chabannes (1982) has shown that the closure rate in a circular opening in a viscoplastic media at plane strain conditions with Norton's Law, is a power function of the difference between the far-field (lithostatic) and internal stresses. DOE (1988a) proposed an empirical equation for the creep closure in the rectangular rooms at WIPP. This empirical equation was based on the regression analyses of existing closure measurements at various locations at WIPP. Based on the above

two creep equations, and as first-order approximation, the creep equations for horizontal and vertical closure rate in the Design Analysis model then take the form:

$$\frac{dw}{dt} = -\,\varepsilon_w \left[\frac{(\sigma_\infty - \sigma)}{\sigma_c}\right]^\nu h^{1.065}\, w^{0.63}\, t^{-0.32} \text{ (horizontal)} \qquad (2.4\text{-}1)$$

$$\frac{dh}{dt} = -\,\varepsilon_h \left[\frac{(\sigma_\infty - \sigma)}{\sigma_c}\right]^\nu h^{1.18}\, w^{1.039}\, t^{-0.24} \text{ (vertical)} \qquad (2.4\text{-}2)$$

where,

w = *width of panel (ft)*
h = *height of panel (ft)*
dw/dt = *horizontal creep rate (in/yr)*
dh/dt = *vertical creep rate (in/yr)*
σ_c = *constant* (6.8975×10^{-3} *MPa*)
ε_w = *horizontal creep constant* (5.523×10^{-19})
ε_h = *vertical creep constant* (1.464×10^{-19})
σ_∞ = *lithostatic stress* (14.8 *MPa*)
σ = *internal stress in the panel which is the sum of the effective stress of the waste backfill composite (see Section 2.15) and the panel fluid pressure (MPa)*
ν = *stress exponent* (4.95)

The height and width of a panel room are evaluated at each time step by numerically integrating equations (2.4-1) and (2.4-2). This numerical integration is performed in the subroutine CREEP as:

$$h\,(t+dt) = h\,(t) + \frac{dh}{dt}\,dt \qquad (2.4\text{-}3)$$

and

$$w\,(t+dt) = w\,(t) + \frac{dw}{dt}\,dt \qquad (2.4\text{-}4)$$

where,

dt = *time step size (yr)*
t = *time at previous time step (yr)*
$t+dt$ = *current time (yr)*

The derivatives dh/dt and dw/dt are evaluated using the values of internal stress in the panel from the previous time step.

The creep constants were evaluated using equations (2.4-1) and (2.4-2) assuming an internal stress level in the panel equal to 0.101325 MPa (1 atm). The resulting values of the creep constants, ε_w and ε_h, respectively, calculated in this manner are 5.523×10^{-19} /yr and 1.464×10^{-19} /yr.

If the internal stress equals or exceeds lithostatic stress, creep is assumed to cease. In the vertical direction, only gas pressure is assumed to impede creep if a clearance exists above the waste stack. Once the clearance is eliminated by closure, both the panel gas pressure and the effective stress of waste compaction will retard the rate of creep closure. This neglects any effects of changing pore pressure on the creep constants.

2.5 MASS BALANCES ON GASES IN THE PANEL (MASSGAS)

In the routine MASSGAS a mass balance on water and on each gas is performed considering the following processes:

- Advection into the intact host rock
- Advection up the four shaft seals
- Diffusion into brine saturated host rock
- Dissolution of gases in brine which is present in the panel
- Generation of gases by microbial and radiolytic mechanisms
- Hydrogen generation by anoxic corrosion of metals
- Consumption of water (brine) by anoxic corrosion of metals
- Removal of carbon dioxide by reaction with cement present in the waste.

The rates of gas advection into the intact host rock and up the shaft seals are evaluated in the subroutine ADVECTION (Sections 2.6 and 2.7).

Gases are assumed to diffuse into a fully brine saturated host rock. The rates of this mechanism of transport are evaluated in the subroutine DIFFUSION (Section 2.11).

The amount of each gas which can dissolve in the brine present in the panel is evaluated in the subroutine VAPLIQEQ (Section 2.9). Evaluation is based upon solubilities and Henry's Law constants computed in the subroutine GASOLUB (Section 2.10).

The consumption and generation of gases by microbial/radiolytic processes is modeled in the subroutine MASSGAS using assumptions described in Section 2.12.

Anoxic corrosion of metals present in the waste can potentially generate 1.7 moles of hydrogen per year for each drum present in a room (see Section 2.13). This rate will require $5x10^{-5}$ cubic meters of water per year, per unprocessed waste drum. If the water (in brine) availability is less than the required amount to sustain the maximum generation rate, the hydrogen generation rate is scaled down appropriately.

2.6 ADVECTION OF GASES INTO UNDISTURBED ANHYDRITE BEDS (ADVECTION AND MBFLOW)

The advection of gases from the panel into the surrounding host rock is a potential mechanism by which generated gases may be dissipated. Several assumptions were made to simulate this process in the Design Analysis Model. The pores in the surrounding intact formation (outside the DRZ) are assumed to be saturated with brine. For gases to advect into the host rock, the pressure of the fluid in the panel must exceed the sum of the pressure in the brine plus the threshold pressure. The threshold pressure is defined as the capillary pressure corresponding to full saturation under draining conditions. This pressure (also referred to as the bubbling or breakthrough pressure) is the pressure required to overcome capillary forces at the gas-brine interface and create an incipient, interconnected, gas-filled pore network. A table of predicted threshold pressures (as a function of intrinsic permeability) was developed by Davies (1989). The permeability of the intact Salado Formation is approximately 10^{-21} m^2 (Lappin et al., 1989, Table 3-1) which corresponds to a threshold pressure of 10 MPa. Therefore, the fluid pressure in the panel would have to exceed 24.8 MPa [10 MPa (threshold pressure) + 14.8 MPa (lithostatic pressure)] for advection of gases into the Salado to occur.

The mechanism of advection into the surrounding Salado Formation is thus not considered due to the extreme panel pressures required to advect gases into the intact halite (10 MPa greater than lithostatic). However, the intact Marker Bed 139 (MB 139) is made up of anhydrite, and may have a permeability as much as three orders of magnitude higher than that of the intact halite (Rechard et al., 1990, p. 171). Pressure tests of MB 139 indicate that the pore pressure is sub-lithostatic, resulting in a lower panel pressure being required to advect gases into the anhydrite beds. In modeling the advection of gases into the anhydrite beds, the anhydrites layers "a" and "b" overlying the repository are treated as a single bed and Market Bed 139 underlying the repository is treated as another bed.

The baseline case analysis assumes that the anhydrite bed pore pressure is 70% of lithostatic (10.36 MPa), and the permeability is 10^{-18} m^2, with a corresponding 0.94 MPa threshold pressure (Davies, 1989). Thus advection into the undisturbed anhydrite bed may occur when the panel fluid pressure exceeds 11.3 MPa [10.36 MPa (pore pressure) + 0.94 MPa (threshold pressure)]. The model assumes that the anhydrites above and below the repository are disturbed (fractured due to the mine operations) and are represented by two disks of 400 m radius and thickness of 1 m for MB 139, and 0.27 m for the anhydrite "a" and "b" composite layer. These disturbed

anhydrite beds are assumed to be directly connected to the panels through fractures. Draining of the disturbed anhydrites above the repository due to gravity, has not been considered for this analysis. As a result, the anhydrites are assumed to be initially fully saturated with brine. Actual measurements have found both saturated and partially saturated conditions in these anhydrites.

A two-phase flow computer code was used to calculate quasi-steady state advection rates of gases across the intact-disturbed anhydrite interface as a function of:

- Panel fluid pressure
- MB 139 brine pore pressure
- MB 139 intrinsic permeability.

A description of this two-phase flow code comprises Appendix D. A parametric equation was developed using multi-parameter least squares regression (Box et al., 1978) from data obtained from a number of sensitivity runs varying panel fluid pressure and MB 139 brine pore pressure. The baseline case analysis assumed an anhydrite permeability of 10^{-18} m^2 and a brine pore pressure of 10.36 MPa which is 70% of lithostatic. The parametric equation is used in subroutine ADVECTION, and takes the following form:

$$\begin{aligned}\dot{m}_{ANH} = (1.27 - b_{ab} - b_{MB})\{&-1.06966x10^{-5} \\ &- 8.99901x10^{-7}P_{ANH}^{2} \\ &+ 8.39754x10^{-7}P^{2} \\ &- 1.04066x10^{-6}(P - P_{ANH}) \\ &+ 8.68640x10^{-7}(P - P_{ANH})^{2}\}\end{aligned} \qquad (2.6\text{-}1)$$

where,

$\dot{m}_{ANH}$	=	molar advection rate of gases into intact anhydrite beds (mol/yr)
P_{ANH}	=	brine pore pressure in MB 139 (MPa)
P	=	panel fluid pressure
b_{MB}	=	height of brine in the disturbed marker bed 139 (m)
b_{ab}	=	height of brine in the disturbed anhydrite "a" and "b" composite layer (m).

The height of brine in the two anhydrite beds vary with time in the Design Analysis Model and are evaluated at each time step in the subroutine MBFLOW. The fluid pressure in the panel must exceed the brine pore pressure in the anhydrite before brine flows from the disturbed anhydrite into the intact anhydrite. If the fluid pressure in the panel exceeds the assumed brine pore pressure in the Salado (14.8 MPa), additional brine will flow from the disturbed anhydrite into the Salado above the anhydrite "a" and "b" composite layer and into the Salado below MB 139. A Salado permeability of 3 x 10^{-21} m^2 (Lappin et al., 1989) is used in the calculations. The volume of brine which flows out translates into an additional storage volume for panel gases. The flow into the intact marker bed is assumed to be one-dimensional. The intact marker bed is assumed to be saturated with brine at a pore pressure of P_{ANH} and is infinite in extent, with a permeability of 10^{-18} m^2. The transient one dimensional flow equation:

$$D \frac{\partial^2 h}{\partial x^2} = \frac{\partial h}{\partial t}$$

was solved subject to initial and boundary conditions:

- The hydraulic heads in the intact anhydrite and the intact Salado layers are initially h_{ANH} and h_{SAL}, respectively.
- At a distance far enough from the intact-disturbed interfaces, the hydraulic heads are h_{ANH} in the anhydrite and h_{SAL} in the Salado formation.
- The hydraulic head at the intact-disturbed marker bed interface, h_p, is equal to the pressure head in the panel.

Thus the solution is (Crank, 1975):

$$h(x,t) = h_i + (h_p - h_i)\, erfc \frac{x}{2(D_i\, t_{R_i})^{0.5}} \qquad (2.6\text{-}2)$$

where,

D = *hydraulic diffusivity* (m^2/yr)
t_R = *time since the panel fluid pressure exceeded the marker bed brine pore pressure,* P_{MB} (yr)
h_p = $P/\rho g$ = *hydraulic head at the disturbed-intact marker bed interface* (m)
P = *fluid pressure in panel* (Pa)
ρ = *brine density* (1220 kg/m^3)
g = *gravitational acceleration* (9.80665 m/s^2)

•Subscript "i" refers to either anhydrite MB 139 (MB) or anhydrite "a" and "b" composite layer (ab), or Salado (SAL).

The volumetric flow rate of brine into the intact layer (Q_i) is evaluated from Darcy's Law as:

$$Q_i = -K_i A_i \frac{\partial h}{\partial x}\Big|_{x=0} \qquad (2.6\text{-}3)$$

where,

Q_i = *volumetric flow rate of brine from the disturbed anhydrite into the intact layer "i"* (m^3/yr)

K_i = *hydraulic conductivity of the intact layer "i" relative to brine* (m/yr)

A_i = *cross-sectional area over which flow is occurring* (m^2)

$\frac{\partial h}{\partial x}|_{x=0}$ = *partial derivative of hydraulic head with respect to distance from the intact-disturbed anhydrite interface.*

Thus differentiating Equation (2.6-2) and evaluating the gradient at the interface (x = 0):

$$Q_i = K_i A_i \frac{(h_p - h_i)}{(\pi D_i t_{R_i})^{0.5}} \tag{2.6-4}$$

The above solution has only been used for the flow during at time step such that time is not cumulative, and the pressure is updated at each time step.

For the anhydrite beds, a hydraulic conductivity of 2.36 x 10^{-4} m/yr was calculated and used in the model based on a brine density of 1220 kg/m^3, and a viscosity of 0.0016 Pa·s (Lappen et al., 1989). The specific storage 1.21x10^{-5} m^{-1} was evaluated based on a marker bed compressibility of 10^{-9} Pa^{-1} (Freeze and Cherry, 1979), a brine compressibility of 4.4x10^{-10} Pa^{-1} (Freeze and Cherry, 1979), and an assumed porosity, n, of 0.025. The hydraulic diffusivity was then calculated as the ratio of the hydraulic conductivity to that of the specific storage (Freeze and Cherry, 1979) and is equal to 19.5 m^2/yr. A hydraulic diffusivity of 10.4 m^2/yr was used for the Salado assuming a permeability of 3 x 10^{-21} m^2 (Lappin et al., 1989). The cross-sectional area over which flow is occurring is calculated as:

$$A_{MB} = 2\pi r_{dist}\, b_{MB} \tag{2.6-5a}$$

$$A_{ab} = 2\pi r_{dist}^2\, b_{ab} \tag{2.6-5b}$$

$$A_{SAL} = \pi r_{dist}^2 = 502{,}655\ m^2 \tag{2.6-5c}$$

where,

r_{dist} = *radius of disturbed anhydrite beds* (400 *m*).

To retain a balance of volume within the disturbed anhydrite beds, any volume of brine which flows out of the disturbed anhydrite is assumed to be replaced by gas from the room. This is realized as the gas occupying the top of the disturbed anhydrites provides some area for gas advection. This area is then subtracted from that available for brine to flow into the intact anhydrites.

Therefore, the cross-sectional areas vary with time, since b_{MB} and b_{ab} change with time, and are evaluated at each time step as:

$$b_{MB}(t+dt) = b_{MB}(t) - (Q_{SAL} + Q_{MB})\ dt/(\pi r_{dist}^2\ n) \tag{2.6-6a}$$

$$b_{ab}(t+dt) = b_{ab}(t) - (Q_{SAL} + Q_{ab})\ dt/(\pi r_{dist}^2\ n) \tag{2.6-6b}$$

The total cumulative void volume that is available for gas storage in the disturbed marker bed, V_{tot}, is evaluated as:

$$V_{tot}(t+dt) = V_{MB}(t) + V_{ab}(t) + 0.109\ (Q_{MB} + Q_{ab} + 2Q_{SAL})\ dt \tag{2.6-7}$$

If the height of the brine for the next time step, in either the marker bed (b_{MB}) or the anhydrite composite (b_{ab}), evaluated through Equation (2.6-6) is negative, the height is set to zero and the cumulative void volume for the bed is then given by:

$$V_{MB} = 0.109\pi r_{dist}^2 b_{MB}(0)\, n \tag{2.6-8a}$$

$$V_{ab} = 0.109\pi r_{dist}^2 b_{ab}(0)\, n \tag{2.6-8b}$$

where,

$b_{MB}(0)$ = *initial height of brine in the disturbed marker bed* (1.0*m*)
$b_{ab}(0)$ = *initial height of brine in the disturbed "a" and "b" composite layer* (0.27*m*).

At each time step, an increase in available void volume is calculated on a per-panel basis, based upon the desaturation of the disturbed anhydrites. In order to obtain the cumulative void volume per panel, the factor 0.109 is used. This factor is the ratio of the panel floor area to that of the total storage floor area (8 panels and 2 equivalent panels) as listed in Table 4.7 of Lappin et al. (1989). This void volume is then added to the total voids available for pressurization by gases. The panel fluid pressure is then evaluated (see Section 2.16) using the total void volume.

2.7 ADVECTION OF GASES UP THE SHAFT SEALS (ADVECTION AND SHFTCOND)

The rock below the repository is assumed to be fractured such that all regions with void volumes are interconnected. However, the lateral fractures in the halite between the panels are not considered to be continuous, so that it is unlikely that there will be any actual flow between the rooms. Thus, the anhydrites are considered to have interconnected lateral porosity so that there might be equilibration of pressure, but no actual connection for gas flow between the panels and the shafts will occur until it is first established within the anhydrites. Therefore, the panel fluid pressure is the same as the pressure at the base of the shaft. Since the disturbed marker bed is assumed to be saturated with brine, advection up the shafts cannot occur until the panel fluid pressure exceeds the marker bed brine pore pressure (to open a pathway). The four shafts which are to be sealed in the current repository design are (DOE, 1990c):

- The Waste Shaft (diameter = 6.096 m)
- The Construction and Salt Handling (C&SH) Shaft (diameter = 3.607 m)
- The Air Intake Shaft (diameter = 6.172 m)
- The Exhaust Shaft (diameter = 4.572 m).

A pseudo steady-state approach was taken in modeling advection up the shafts. The steady state gas continuity equation was combined with Darcy's flow equation through porous media. According to an equation of state, the density of the gas is directly proportional to the fluid pressure. This is based on isothermal conditions, due to low decay heats.

The resulting differential equation which describes the steady state fluid pressure distribution as a function of distance is:

$$\frac{d^2P^2}{dz^2} = 0 \qquad (2.7\text{-}1)$$

where,

P = *fluid pressure in shaft (MPa)*
z = *vertical distance through the shaft to the ground surface (m)*

The applicable boundary conditions are:

$$P(z = 0, \text{ i.e., at the base of a shaft}) = P_p \qquad (2.7\text{-}2a)$$
$$P(z = L, \text{ i.e., at the ground surface}) = P_{atm} \qquad (2.7\text{-}2b)$$

where,

P_p = *panel fluid pressure (evaluated at each time step)*
P_{atm} = *atmospheric pressure of* 0.101325 *MPa.*

The solution to equation (2.7-1) with the above boundary conditions is:

$$P = \{(P_{atm}^2 - P_p^2)\frac{Z}{L} + P_p^2\}^{0.5} \tag{2.7-3}$$

The volumetric advection rate at the base of the shaft is evaluated as:

$$Q_{advection} = -\frac{kA}{\mu}\frac{dP}{dz}\Big|_{z=0} 31.5576x10^6 \ s/yr \tag{2.7-4}$$

Differentiation of (2.7-3) provides:

$$Q_{advection} = -\frac{A\,k\,(P_{atm}^2 - P_p^2)}{\mu\,2\,L\,P_p} 31.5576x10^6 \ s/yr \tag{2.7-5}$$

where,

$Q_{advection}$ = *volumetric advection rate up the shaft* (m^3/yr)
A = *area of shaft* (m^2)
k = *permeability of shaft* (m^2)
μ = *viscosity of gas mixture in panel* (*MPa·s*).

The molar advection rate may be evaluated using an equation of state in the form:

$$\dot{m}_{shaft} = \frac{Q_{advection}P_p}{ZRT} \tag{2.7-6}$$

where,

$\dot{m}_{shaft}$ = *molar advection rate up the shaft at the shaft base* (*mol/yr*)
R = *gas constant* (8.314*Nm/mol °K*)
Z = *compressibility factor of the panel gas mixture*
T = *absolute temperature* (300 *°K*).

Combining equations (2.7-5) and (2.7-6) and defining $Ak/L = C_{TOT}$ gives

$$\dot{m}_{shaft} = \frac{C_{TOT}\,(P_p^{\,2} - P_{atm}^{\,2})}{2\,\mu\,Z\,R\,T} \qquad (2.7\text{-}7)$$

where,

C_{TOT} = *total conductance of the four shaft seals.*

The permeability and the length of each shaft is assumed to be the same, although the diameters are different. The conductance of the waste shaft seal was obtained as a function of time by using the shaft-seal component of the Design Analysis Model (Appendix C). The total conductance of the four shaft seals was evaluated by scaling the cross-sectional areas of the other shafts relative to the cross-sectional area of the waste shaft. It is assumed that the radius of the disturbed rock zone (DRZ) surrounding the shafts is 5 times the radius of the shaft itself. The equations which describe the variation of the total conductance, C_{TOT} in (mDarcy m), of the four shaft seals with time, t, are listed below and are coded in subroutine SHFTCOND as:

For $0 < t \leq 35$ years

$$C_{TOT} = \exp(-6.306 - 4.7843 \times 10^{-2} t) \qquad (2.7\text{-}8)$$

For 35 years $< t \leq 95$ years

$$C_{TOT} = \exp(-6.7619 - 2.706\times10^{-3} t + 5.4411\times10^{-5} t^2 - 3.714\times10^{-7}\, t^3) \qquad (2.7\text{-}9)$$

For 95 years $< t \leq 125$ years

$$C_{TOT} = \exp(-1.429 - 5.5256\times10^{-2}\, t) \qquad (2.7\text{-}10)$$

For 125 years $< t \leq 775$ years

$$C_{TOT} = \exp(-8.1159 - 1.7525\times10^{-3}\, t) \qquad (2.7\text{-}11)$$

For $t > 775$ years

$$C_{TOT} = \exp(-9.3899 - 3.5659 \times10^{-4}\, t) \qquad (2.7\text{-}12)$$

2.8 ESTIMATION OF VISCOSITY OF GAS MIXTURE (VISCORR)

The viscosity of the gas mixture in a panel is evaluated in the subroutine VISCORR. The viscosity is used in equation (2.7-7) for estimating the gas advection rates through the shaft seals.

The Chung mixing rules (Reid et al., 1987, pp 413-414) are used to estimate the pseudocritical temperature, T_{cm}, and the pseudocritical volume, V_{cm}, of the mixture.

The critical mixture compressibility factor, Z_{cm} is evaluated using Kay's rule (Reid et al., 1987, pp 76-77) as:

$$Z_{cm} = \Sigma\, y_i\, Z_{ci} \tag{2.8-1}$$

where,

y_i = *mole fraction component, "i"*
Z_{ci} = *critical compressibility factor of component, "i".*

The critical mixture pressure, P_{cm} is evaluated using the Prausnitz and Gunn combination (Reid et al., 1987, p 77) as:

$$P_{cm} = R\, Z_{cm} \frac{T_{cm}}{V_{cm}} \tag{2.8-2}$$

where,

R = *gas constant* (8.314 *Nm/mol °K*).

The Reichenberg method (Reid et al., 1987, pp 420-421) is used to estimate the viscosity of the gas mixture at high pressure. This method requires knowledge of the viscosity of the gas mixture at low (atmospheric) pressure. The low (atmospheric) pressure gas mixture viscosity is evaluated using the Wilke correlation (Reid et al., 1987, p 407). The viscosity of a gas mixture according to Wilke is:

$$\mu_o = \sum_{i=1}^{NC} \left[\frac{y_i\, \mu_i}{\sum_{j=1}^{NC} y_j\, \phi_{ij}} \right] \tag{2.8-3}$$

where,

$$\phi_{ij} = \frac{[1 + (\mu_i/\mu_j)^{1/2}(M_j/M_i)^{1/4}]^2}{[8(1 + M_i/M_j)]^{1/2}} \tag{2.8-4}$$

and,

μ_0 = *viscosity of the gas mixture at low (atmospheric) pressure*
μ_i = *viscosity of pure component, "i"*
M_i = *molecular weight of pure component, "i" (g/mol)*
NC = *number of components.*

The viscosity ratio according to the Reichenberg method is given as (Perry et al., 1984):

$$\frac{\mu}{\mu_0} = 1 + \frac{Q\ A\ P_r^{3/2}}{B\ P_r + (1 + C\ P_r^D)^{-1}} \tag{2.8-5}$$

where,

μ = *gas mixture viscosity at high pressure*

$$A = \left(\frac{1.9824 \times 10^{-3}}{T_r}\right) \exp(5.2683\ T_r^{-0.576}) \tag{2.8-6}$$

$$B = A(1.6552\ T_r - 1.2760) \tag{2.8-7}$$

$$C = \left(\frac{0.1319}{T_r}\right) \exp(3.7035\ T_r^{-79.8678}) \tag{2.8-8}$$

$$D = \left(\frac{2.9496}{T_r}\right) \exp(2.9190\ T_r^{-16.6169}) \tag{2.8-9}$$

$$T_r = \frac{T}{T_{cm}} \tag{2.8-10}$$

$$P_r = \frac{P}{P_{cm}} \tag{2.8-11}$$

$$Q = (1 - 5.655 DM_r) \tag{2.8-12}$$

$$DM_r = 52.46\ DM_m^2\ \frac{P_{cm}}{T_{cm}^2} \tag{2.8-13}$$

T = absolute temperature (°K)
P = pressure (MPa)

and the gas mixture dipole moment, (DM_m), is evaluated as:

$$DM_m = [\sigma_m^3 \sum_{j=1}^{NCNC} \sum_{i=1} (\frac{y_i\ y_j\ DM_i^2\ DM_j^2}{\sigma_{ij}^3})]^{1/4} \tag{2.8-14}$$

$$\sigma_i = 0.809\ V_i^{1/3} \tag{2.8-15}$$

V_{ci} = *critical volume of pure component "i"*

$$\sigma_{ij} = (\sigma_i\ \sigma_j)^{1/2} \tag{2.8-16}$$

$$\sigma_m^3 = \sum_{i=1}^{NC} \sum_{j=1}^{NC} y_i y_j \sigma_{ij}^3 \tag{2.8-17}$$

DM_i = *dipole moment of component "i" (debye)*

2.9 DISSOLUTION OF GASES IN BRINE (VAPLIQEQ)

The brine is assumed to contain considerable quantities of nitrogen and methane (DOE, 1983). Therefore, the dissolution and exsolution of these two gases is not considered in the Design Analysis Model. The amounts of other gases dissolved in the liquid phase at each time step are evaluated in the subroutine VAPLIQEQ. The final equation used in the subroutine was derived as follows.

A mass balance on gas "*i*" during a time step may be stated as:

moles of gas "i" which have dissolved in brine during the time step (l_i^{dt})	=	moles of gas "i" in gas phase at time, t (g_i^t)	-	moles of gas "i" in gas phase at time, t+dt (g_i^{t+dt})

or,

$$l_i^{dt} = g_i^t - g_i^{t+dt} \tag{2.9-1}$$

Assuming changes in both the compressibility factor, Z, and gas pressure, P, are negligible during a time step, then from the equation of state:

$$g_i^{t+dt} = \frac{y_i^{t+dt} PV}{ZRT} \tag{2.9-2}$$

where,

y_i = *mole fraction gas "i" in the gas phase*
P = *fluid panel pressure*
V = *void volume in panel* (m^3)
Z = *gas mixture compressibility factor*
R = *gas constant* (8.314*Nm/mol °K*)
T = *absolute temperature* (300 *°K*)

Assuming the moles of gas dissolved in the liquid phase during a time step are negligible relative to the moles of liquid phase present at time, t, then:

$$x_i^{t+dt} = \frac{l_i^{dt} + l_i^t}{L^t} \tag{2.9-3}$$

where,

x_i^{t+dt} = *mole fraction gas solute "i" in liquid phase at time, t+dt*
l_i^{dt} = *moles of gas dissolved in liquid phase during a time step*
l_i^t = *moles of gas solute "i" in liquid phase at the start of the time step, i.e., at time, t*
L^t = *total moles of liquid phase at time, t.*

Substitution of equation (2.9-2) into equation (2.9-1) gives an equation with two unknowns, y_i^{t+dt} and l_i^{dt}.

A second equation relating y_i^{t+dt} and l_i^{dt} may be derived using Henry's Law (Reid et al., 1987) and equation (2.9-3).

Henry's Law states that:

$$y_i^{t+dt} P = x_i^{t+dt} H_{i,brine} \tag{2.9-4}$$

where,

$H_{i,brine}$ = *Henry's Law constant for component "i" in brine (MPa) which is evaluated in routine GASOLUB.*

Combining equations (2.9-3) and (2.9-4) yields:

$$y_i^{t+dt} P = (l_i^{t+dt} + l_i^t) \frac{H_{i,brine}}{L^t} \tag{2.9-5}$$

Substituting equation (2.9-5) into (2.9-2) and the resulting equation into equation (2.9-1) yields:

$$g_i^t = \left\{\frac{(l_i^{dt} + l_i^t)\ H_{i,brine}}{L^t}\right\} \frac{V}{ZRT} + l_i^{dt} \tag{2.9-6}$$

Solving for the moles of gas "i" dissolved in the liquid phase during a time step, l_i^{dt}, in equation (2.9-6) provides the final equation which is coded in subroutine VAPLIQEQ.

$$l_i^{dt} = \frac{g_i^t - \dfrac{l_i^t H_{i,brine} V}{L^t Z R T}}{1 + \dfrac{H_{i,brine} V}{L^t Z R T}} \tag{2.9-7}$$

Once the values of l_i^{dt} have been evaluated for each gas using equation (2.9-7), the values of g_i, l_i, and L^{t+dt} are updated for the next time step as:

$$g_i^{t+dt} = g_i^t - l_i^{dt} \tag{2.9-8}$$

$$l_i^{t+dt} = l_i^t + l_i^{dt} \tag{2.9-9}$$

where,

$$NC \equiv \textit{number of components}$$

2.10 SOLUBILITIES AND HENRY'S LAW CONSTANTS OF GASES IN BRINE (GASOLUB)

The solubility of each gas in brine for use in diffusion calculations (see next section), and the Henry's Law constants for use in subroutine VAPLIQEQ (Section 2.9), are evaluated in subroutine GASOLUB at each time step. The brine is assumed to contain considerable quantities of nitrogen and methane so that neither dissolution nor diffusion of these gases into brine takes place (DOE, 1983).

For dilute solutions, Henry's law provides a good estimate of solubilities (Reid et al., 1987). Solubilities of various gases in water will be evaluated first and then corrected for dissolution in brine.

At equilibrium the following relations hold (Reid et al., 1987, pp 332 - 339):

$$f_i^L = f_i^V \tag{2.10-1}$$

$$H_{i,water}\, x_i = \phi_i\, y_i\, P \tag{2.10-2}$$

where,

f_i^L = *fugacity of gas "i" in water (MPa)*
f_i^V = *fugacity of gas "i" in gas phase (MPa)*
$H_{i,water}$ = *Henry's Law constant for gas "i" in water (MPa)*
x_i = *mole fraction gas "i" in water*
ϕ_i = *vapor phase fugacity coefficient of gas "i"*
y_i = *mole fraction gas "i" in gas phase*
P = *fluid pressure (MPa).*

The vapor phase fugacity coefficient of component "i", ϕ_i will be assumed to be 1, as it is for ideal gases.

The Henry's Law constant is corrected for pressure using (equation 8-11.3 of Reid et al., 1987, p 335) as:

$$\ln\left(\frac{y_i P}{x_i}\right) = \ln H_{i,water}^{P} = \ln H_{i,water}^{VP} + \frac{V_i^{\infty}(P - VP)}{(RT)} \qquad (2.10\text{-}3)$$

where,

$H_{i,water}^{VP}$ = *Henry's Law constant for solute gas "i" in the solvent (water) at the vapor pressure of the solvent (MPa)*
$H_{i,water}^{P}$ = *Henry's Law constant for solute gas "i" in the solvent (water) at the gas pressure in the panel (MPa)*
V_i^{∞} = *partial molar volume of solute gas "i" at infinite dilution in water (cm^3/mol) The volumes of the various gases are tabulated below and are extracted from (Reid et al., 1987, p. 336)*
VP = *vapor pressure of solvent (water) at 300°K (0.03 atm)*
R = *gas law constant (8.314 Nm/mol °K)*
T = *absolute temperature (300°K).*

Henry's Law constants for the gases in water are listed in Table B-1 (Atkins, 1982, p. 226).

TABLE B-1

MOLAR VOLUMES AND HENRY'S LAW CONSTANTS FOR GASES IN WATER

GAS	V_i^{∞} (cm^3/mol)	$H_{i,water}^{vp}$ (MPa)
Hydrogen	26	7,119
Oxygen	31	4,400
Carbon Dioxide	33	167

The Henry's Law constant for a gas "i" in brine will be estimated using the relation (Cramer, ND)

$$\log\left(\frac{H^P_{i,brine}}{H^P_{i,water}}\right) = k_s\, m_s \qquad (2.10\text{-}4)$$

where,

$H^P_{i,brine}$ = *Henry's Law constant for gas "i" in brine at pressure P*
k_s = *salting-out coefficient (kg/mol)*
M_s = *molality of dissolved salts in the WIPP brine* (8.80 *mol/kg*).

The salting-out coefficients for methane, carbon dioxide and oxygen are listed in Table 13 of (Cramer, ND) at several temperatures. The salting-out coefficients at 27 °C (300 °K) were estimated by linear interpolation of the values for 20 °C and 40 °C. The coefficient for hydrogen was not available and was assumed to be equal to the average of the values for methane, carbon dioxide and oxygen. The salting-out coefficients are tabulated in Table B-2.

The mole fraction gas "i" in brine, x_i, may then be evaluated by rearranging equation (2.10-2), with $\phi_i = 1$ as:

$$x_i = y_i \frac{P}{H^P_{i,brine}} \qquad (2.10\text{-}5)$$

Once the mole fraction in brine has been evaluated, the solubility concentration may be estimated using the following conversions:

$$C_{si} = x_i \rho_{brine} \frac{(10^6 cm^3/m^3)}{M_{brine}} \qquad (2.10\text{-}6)$$

where,

C_{si} = *solubility of gas "i" in brine* (mol/m^3)
M_{brine} = *molecular weight of WIPP brine* (20.49 *g/mol*)
ρ_{brine} = *density of WIPP brine* (1.22 g/cm^3).

TABLE B-2

SALTING-OUT COEFFICIENTS FOR EXPECTED GASES

GAS	SALTING-OUT COEFFICIENT k_s (kg/mol)
Hydrogen	0.125*
Oxygen	0.135
Carbon Dioxide	0.104
Methane	0.136

* The value of the salting-out coefficient for hydrogen was not available and is assumed to be the average of the values for oxygen, carbon dioxide and methane.

2.11 DIFFUSION OF GASES INTO BRINE SATURATED HOST ROCK (DIFFUSION)

The host rock is assumed to be an infinite medium whose pores are saturated with brine. A potential exists for gases to dissolve and then diffuse into the brine due to concentration gradients. The gas diffusion rates are estimated within the subroutine DIFFUSION. The solubility of gases in brine at the gas-brine interface will be continuously increasing as a function of time according to Henry's Law due to increasing partial pressure of the gases. The functional form for the increase is not known in advance due to the complex coupling of processes within the panel. For a constant concentration at the gas-brine interface, the concentration profile for one dimensional diffusion into an infinite medium may be described by the following relation (Crank, 1975, p. 122):

$$C_A/C_{S,A} = erfc \left\{ \frac{x}{2(D_{AB}t)^{0.5}} \right\} \qquad (2.11\text{-}1)$$

where,

D_{AB} = *diffusion coefficient of gas "A" in brine "B"* (m^2/yr)
The diffusion coefficients of gases are evaluated in the subroutine DIFCOEF of the Design Analysis Module (see Section 2.2)

$C_{s,A}$ = *solubility of gas "A" in brine "B" and is equal to the* (mol/m^3) *concentration of "A" at the gas-brine saturated host rock interface. These concentrations are evaluated in routine VAPLIQEQ of the Design Analysis Module (see Section 2.9)*

C_A = *concentration of gas "A" at a distance x from the gas-brine saturated host rock interface* (mol/m^3)

t = *time since repository decommissioning* (yr).

Fick's Law of Diffusion (Crank, 1975, p 2) is then used to evaluate the molar flowrate of gas "A" into brine at each time step, based upon an initial condition of zero within the brine, as:

$$\dot{m}_A = \varepsilon\ A\ D_{AB}\ \frac{\partial C_A}{\partial x}\Big|_{x=0} \qquad (2.11\text{-}2)$$

where,

$\dot{m}_a$ = *molar rate of diffusion of gas "A" into brine (mol/yr)*
ε = *porosity of the brine filled host rock*
A = *area available for diffusion* (31756 m^2).

Differentiating equation 2.11-1 with respect to distance, x and evaluating the derivative at the gas-brine saturated host rock interface yields:

$$m_A = \frac{\varepsilon\ A\ D_{AB}\ C_{s,A}}{(\pi\ D_{AB}\ t)^{0.5}} \qquad (2.11\text{-}3)$$

2.12 MICROBIAL AND RADIOLYTIC GENERATION OF GASES (MASSGAS)

The rate and total potential amount of gas generated microbially and radiolytically are assumed to agree with Lappin et al. (1989). Since radiolysis and microbial activity utilize the same substrates (organics), the rate of 0.85 mole/drum/yr is assumed to represent both radiolysis and microbial activity. For gas generation due to anoxic corrosion, only brine (specifically the water in the brine) has been assumed to be the source of moisture. Water which is available from the waste is assumed to be consumed in microbial activities. Clarifying, the two competing reactions for water (corrosion and microbial activity) are assumed to partition the sources of water (water in brine and water in the waste). While this partitioning is artificial, it assures that the same component is not used in two different reactions. Estimates were made to determine if excess water available from the waste will exist to support the microbial activity.

An initial estimate of the amount of cellulose in the WIPP inventory is 6.07 x 10^6 lb (Lappin et al., 1989). Assuming a yield (mass of biomass produced per mass of substrate consumed) of 0.1 (typical yields are in the range of 0.3 to 0.8), degradation of the waste would result in the generation of 2.76 x 10^8 g of biomass. Assuming a water content of 80% for the biomass, the water requirement for microbial activity is 2.2 x 10^8 g, or 220000 liters. Assuming a total of 4 x 10^5 drums stored in the WIPP, the required free water requirement per drum is 0.55 liters.

In summary, the water required for anoxic corrosion is provided by, and is limited by the availability of brine. The water required for microbial gas generation is provided by the water in the waste, and is not considered to be limiting. These assumptions may be modified and updated when better estimates of the rates become available.

The ratio being used for gases expected to be generated in the WIPP repository is arbitrary and is based on the following assumptions:

- The gases being generated in any significant amounts due to microbial activity are N_2, CO_2, and CH_4

- Although anaerobic conditions are assumed for the repository, methane is not the predominant gas generated. Under ideal conditions in a digester, methane and CO_2 are generated in the ratio 7:3 (Atlas, 1984). The methane generation is easily upset under non-ideal conditions. In the repository, the pH, carbon-to-phosphorus-to-nitrogen ratio, oxygen depletion, etc., are far from being ideal for methane generation. Radiolysis may generate pockets of oxygen (still under oxygen limiting conditions) which will favor CO_2 generation. Hence CO_2 has been assumed to be generated in larger quantities than methane.

Based on the previous discussion, these are the microbial gas generation parameters used in the modeling:

- During the first 100 years, oxygen is completely consumed with an equivalent molar rate of carbon dioxide production taking place. Accelerated microbial activity is assumed to set in only after this period. This is a reasonable assumption, since microbial activity at optimum rates requires availability of substrate, nutrients and water. This may be possible only after intimate mixing of the waste in the panel.

- Accelerated microbial activity is assumed to ensue after 100 years at the rate of 0.85 moles/drum/year with a gas production potential of 606 moles/drum (Lappin et al., 1989, p. 4-7).

- Therefore, the duration of microbial generation is 713 years, beginning 100 years after the start of the simulation. The gases which would be generated are methane, carbon dioxide, and nitrogen in the molar ratio 15:20:12.

2.13 HYDROGEN GENERATION BY ANOXIC CORROSION OF METALS (MASSGAS)

Anoxic corrosion of the metal drums is assumed to start at time = 0 and proceed until the gas production potential (894 moles of hydrogen/drum) has been generated (Lappin et al., 1989, p. 4-10). The maximum hydrogen generation rate is 1.70 moles/drum/year if 5×10^{-5} m^3 of water are available, per year, per unprocessed waste drum. This is based on the assumption that amakanite is produced requiring 2 moles of water per mole of iron. If brine/water availability is less than the amount required for maximum hydrogen generation, the hydrogen generation rate

is scaled down based on the amount of available water contained in the brine present in the panel.

2.14 REACTIONS OF CARBON DIOXIDE WITH BRINE AND CEMENT (BRINTERACT)

It was estimated that there are approximately 13.03 moles of portlandite [$Ca(OH)_2$] per equivalent drum in a panel of 75,240 drums. Carbon dioxide, which may potentially be generated, will dissolve in brine and react with the portlandite to yield calcite and water by the following reaction (see Appendix E):

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O \qquad (2.14\text{-}1)$$

The geochemical modeling codes EQ3NR and EQ6 (Wolery, 1983; Wolery, 1984) were used to determine the fugacity of carbon dioxide in the brine, at equilibrium. This fugacity was calculated to be 0.08 atm. At equilibrium, the fugacity of a component in the liquid phase is the same as the fugacity in the gas phase. The fugacity of carbon dioxide in the gas phase is assumed to be equal to the partial pressure of the gas (true for ideal gases). The moles of carbon dioxide which are available for precipitation in brine are evaluated as:

$$\text{mole of } CO_2 \text{ available} = \text{mole of } CO_2 \text{ in gas phase} - \frac{0.08 \text{ atm} \times V_v}{ZRT} \qquad (2.14\text{-}2)$$

where,

V_v = *void volume in panel* (m^3)
Z = *compressibility factor of panel gases*
R = *gas law constant* (8.206×10^{-5} *atm* $\cdot m^3/mol°K$)
T = *absolute temperature* (300°K).

The number of moles of CO_2 available is scaled down by a factor which relates the amount of CO_2 which can react to form calcite to the amount of brine present in a panel. It is assumed that the reaction cannot proceed in the absence of brine.

This scale factor is evaluated through the following relation:

$$SCALFACT = 1 - \left[\frac{V_v}{(V_v + V_B)}\right] \qquad (2.14\text{-}3)$$

where,

V_B = *volume of brine in panel* (m^3).

The actual moles of carbon dioxide which are removed from the gas phase is then:

$$\underset{removed}{mole\ CO_2} = \underset{available}{mole\ CO_2} \times SCALFACT \tag{2.14-4}$$

The moles of portlandite consumed is then equal to the moles of carbonate minerals precipitated. If there are less moles of portlandite present in the room than what can potentially be consumed, then the maximum consumed is equal to the moles present. The moles of calcite and water formed is equal to the moles of portlandite consumed. The moles of water and the moles comprising the liquid phase are updated based on the quantity of water generated. The total mass of the solids in the panel is also updated based upon the mass of calcite created and the mass of portlandite consumed.

2.15 ESTIMATION OF EFFECTIVE STRESS OF WASTE/BACKFILL COMPOSITE (COMPACTION)

As discussed in Section 2.4, the difference between the lithostatic stress and the sum of the gas pressure and the effective stress of the waste/backfill composite defines the rate at which rock creep (closure) occurs. Densities of the waste/backfill composite, as a function of applied stress level, have been evaluated for each engineered alternative (Section 3.0 in Volume I). The effective stress is the stress that is transferred between the solid particles of the waste/backfill composite. Regression equations relating effective stress as a function of density have been derived from the density-stress data. Coefficients of the regression polynomials are included in the input data file created for each alternative. The density of the waste/backfill composite is evaluated at each time step by dividing the mass of the solids by the difference of the panel volume and the volume of the air gap clearance in subroutine VOLESTIM (Section 2.17). The effective stress of the waste/backfill composite is then evaluated at each time step using the effective stress versus density regression equations in subroutine COMPACTION.

2.16 PRESSURE ESTIMATION USING THE LEE-KESSLER EQUATION OF STATE (LKEOS)

The pressure of the gas mixture in the panel is evaluated using the Lee-Kessler equation of state. This equation is a modification of the Benedict-Webb-Rubin equation of state (Reid et al., 1987). The Lee-Kessler equation is recommended by Reid et al. (1987), for generalized use in the computation of fluid pressure at expanded ranges of temperature and pressure. The equation is capable of accurately representing the liquid phase. In comparing the predicted compressibilities with experimental data, average errors were less than two percent for both the

vapor and liquid phases. A complete description of the equation is provided in Reid et al. (1987), pp. 47-49 and pp. 84-87.

The following is a summary of the methodology.

The pseudocritical properties of the gas mixture are computed as follows:

$$T_{cij} = (T_{ci}\ T_{cj})^{1/2}\ k_{ij} \tag{2.16-1}$$

$$V_{cij} = \frac{(V_{ci}^{1/3} + V_{cj}^{1/3})^3}{8} \tag{2.16-2}$$

$$T_{cm} = \frac{(\sum_{j=1}^{NCNC}\sum_{i=1} y_i\ y_j\ V_{cij}^{1/4}\ T_{cij})}{V_{cm}^{1/4}} \tag{2.16-5}$$

$$P_{cm} = \frac{(0.2905-0.085\Omega_m)R\ T_{cm}}{V_{cm}} \tag{2.16-6}$$

where,

T_{ci} = *critical temperature of component "i" (°K)*
T_{cm} = *pseudocritical mixture temperature (°K)*
k_{ij} = *binary interaction coefficient*
V_{ci} = *critical volume of component "i" (cm^3/mol)*
V_{cm} = *pseudocritical mixture volume (cm^3/mol)*
y_i = *mole fraction component "i"*
Ω_m = *Pitzer acentric factor of mixture*
R = *gas constant (82.057 atm cm^3/mol °K)*
P_{cm} = *pseudocritical mixture pressure (atm)*
NC = *number of components.*

In practice, the compressibility factor of an actual fluid is evaluated from the properties of a "simple fluid" (one for which Pitzer's acentric factor is zero) and those of n-octane, which is the reference fluid for this method (Reid et al., 1987). Once the mixture pseudocritical properties are computed, the simple fluid compressibility factor, $Z^{(0)}$ is evaluated as:

$$Z^{(0)} = \frac{1 + \frac{B}{V_r} + \frac{C}{V_r^2} + \frac{D}{V_r^3} + c_4 \left[\beta + \frac{\tau}{V_r^2}\right] exp\left(\frac{-\tau}{V_r^2}\right)}{T_r^3 \; V_r^2} \tag{2.16-7}$$

where,

$$T_r = \frac{T}{T_{cm}} \tag{2.16-8}$$

$$V_r = \frac{P_{cm} \; V}{R \; T_{cm}} \tag{2.16-9}$$

$$B = b_1 - b_2/T_r - b_3/T_r^2 - b_4/T_r^3 \tag{2.16-10}$$

$$C = c_1 - c_2/T_r + c_3/T_r^3 \tag{2.16.11}$$

$$D = d_1 + d_2/T_r \tag{2.16-12}$$

where the constants b_1, b_2, b_3, b_4, c_1, c_2, c_3, c_4, d_1, d_2, β and τ are given in Table B-3 under the "Simple fluid" heading. Next, the compressibility factor for the reference fluid, $Z^{(R)}$ is computed using equations (2.16-7) through (2.16-12), but using the constants b_1, b_2, b_3, b_4, c_1, c_2, c_3, c_4, d_1, d_2, β and τ of the reference fluid from Table B-3.

The compressibility factor, Z, for the gas mixture is then calculated as:

$$Z = Z^{(0)} + \frac{\Omega_m}{0.3978}(Z^{(R)} - Z^{(0)}) \tag{2.16-13}$$

The pressure of the gas mixture is then:

$$P = \frac{Z \; R \; T}{V} \tag{2.16-14}$$

where,

V = molar volume of gas mixture (cm^3/mol).

TABLE B-3

LEE-KESSLER EQUATION OF STATE CONSTANTS

CONSTANT	SIMPLE FLUID	REFERENCE FLUID
b_1	0.1181193	0.2026579
b_2	0.265728	0.331511
b_3	0.154790	0.027655
b_4	0.030323	0.203488
c_1	0.0236744	0.0313385
c_2	0.0186984	0.0503618
c_3	0.0	0.016901
c_4	0.042724	0.041577
$d_1 \times 10^4$	0.155488	0.48736
$d_2 \times 10^4$	0.623689	0.0740336
β	0.65392	1.226
τ	0.060167	0.03754

Reid et al., 1987, p. 48

2.17 ESTIMATION OF VOLUMES IN PANEL (VOLESTIM)

Several volume related parameters are calculated in subroutine VOLESTIM and are described here.

Once the height, h, and width, w, of an equivalent room are evaluated in subroutine CREEP (Section 2.4) the volume of the panel (V_{pnl}), at the end of a time step is evaluated as:

$$V_{pnl} = 7hwl_{room} + 12hww_{pillar} + 14hw^2 \qquad (2.17\text{-}1)$$

where,

l_{room} = *length of the room* (91.44*m*)
w_{pillar} = *width of a salt pillar between rooms* (30.48*m*)

The volume of the air gap clearance above the waste/backfill composite stack, V_{clmc} is then evaluated based on the discussion in (Section 2.1).

$$V_{clmc} = 7(h - h_{stack})wl_{room} + 12(h - h_{stack})ww_{pillar} + 14(h - h_{stack})w^2 \qquad (2.17\text{-}2)$$

where,

h_{stack} = *height of the waste/backfill composite stack* (3.3528*m*)

The creep of the surrounding halite creates an additional void volume within a zone of enhanced porosity which the panel gases will occupy. The rate and extent of creep closure will govern the magnitude of this void volume. This void volume is calculated at each time step as the product of the porosity of the intact Salado Formation (0.001) (Marietta et al., 1989, Table 3-9) and the difference between the initial panel volume and the panel volume at the current time step. It is assumed that the zone of enhanced porosity does not contain brine and that all pores are interconnected.

The void volume in the panel, V_v, is then evaluated as:

$$V_v = V_{pnl} - V_{WB} - V_B + (V_{pnl}(0) - V_{pnl})n + V_{MB} \qquad (2.17\text{-}3)$$

where,

V_{WB} = *volume of the waste/backfill composite less pores* (m^3)
V_B = *volume of brine in the panel* (m^3)
$V_{pnl}(0)$ = *initial panel volume* (m^3)
V_{pnl} = *panel volume at current time step*(m^3)
n = *porosity of the intact Salado Formation* (0.001) (*Marietta et al.*, 1989)
V_{MB} = *cumulative void volume that is available for gas storage in the disturbed marker Bed* 139 *underlying the repository* (m^3) (*Section* 2.6).

The molar volume [for use in pressure estimation (Section 2.18)] is calculated by dividing the void volume in the panel by the total number of moles of gas present in the panel.

Finally, the density of the solids in the panel is calculated as:

$$\rho_{solid} = \frac{m_{solid}}{V_{pnl} - V_{clmc}} \tag{2.17-4}$$

where,

ρ_{solid} = *density of the waste/backfill composite* (kg/m^3)
m_{solid} = *mass of solids in the panel* (kg).

2.18 SIMULATION OF BOREHOLE INTRUSION CONSEQUENCES (BOREHOLE)

The consequences of three borehole intrusion scenarios designated as E1, E2 and E1E2 (Marietta et al., 1989) were evaluated as part of the EATF modeling effort. The effectiveness and relative effectiveness measures of engineered alternatives are defined in Section 2.25. For consistency in evaluating the relative effectiveness measures of engineered alternatives, the intrusion is assumed to occur 5000 years into the simulation, for all cases. This results in a 5000 year time span for the release of contaminated brine, which is herein defined as the "release time."

The driver subroutine in the Design Analysis Model which coordinates the intrusion scenario simulations is called BOREHOLE. This subroutine calls other subroutines to calculate the effectiveness measure for the three scenarios, for each alternative studied. The sequence of calls to various subroutines is indicated by the order of the descriptions below. A detailed description of each subroutine follows in the subsections of this chapter.

Subroutine ESTHCKSS is called to evaluate the hydraulic conductivity and specific storage of the waste/backfill composite at the time of borehole intrusion.

Subroutine RADACTIM evaluates the mass and activity of each radionuclide in the total inventory at the time of borehole intrusion.

Subroutine CUTTINGS is called to evaluate the activity of each radionuclide released to the surface with the cuttings and eroded material resulting from the drilling extraction process. In addition the mass and activity of each radionuclide is also evaluated in this subroutine, on a panel basis.

Subroutine RADSOLUB evaluates the solubility of each radionuclide in brine.

Subroutine ISE1 evaluates the volume of contaminated brine reaching the Culebra as a result of intrusion scenario E1 (Marietta et al., 1989).

Subroutine SUMRULE is called to evaluate the effectiveness measure of an engineered alternative as a result of intrusion scenario E1.

Subroutine ISE2 evaluates the volume of contaminated brine released to the Culebra as a result of intrusion scenario E2 (Marietta et al., 1989).

Subroutine SUMRULE is called to evaluate the effectiveness measure of an engineered alternative as a result of intrusion scenario E2.

Subroutine ISE1E2 evaluates the volume of contaminated brine released to the Culebra as a result of intrusion scenario E1E2 (Marietta et al., 1989).

Subroutine SUMRULE is called to evaluate the effectiveness measure of an engineered alternative as a result of intrusion scenario E1E2.

2.19 ESTIMATION OF WASTE/BACKFILL COMPOSITE HYDRAULIC CONDUCTIVITY AND SPECIFIC STORAGE (ESTHCKSS)

During the development of physical and chemical properties resulting from the use of engineered alternatives, a table of hydraulic conductivity versus stress level was generated for each alternative. The methodology for hydraulic conductivity development is described in Section 3.0 in Volume I. The natural logarithm of the hydraulic conductivity is expressed as a ninth order polynomial function of the effective stress level of waste compaction. Therefore, from knowledge of the effective stress level of waste compaction at the time of borehole intrusion, the hydraulic conductivity is obtained from a regression equation.

The specific storage of a porous media such as the waste/backfill composite can be evaluated from the following equation (Freeze and Cherry, 1979, p. 59):

$$S_s = \rho g(\alpha + n\beta) \qquad (2.19\text{-}1)$$

where,

S_s = *specific storage* (1/*m*)
ρ = *density of brine* (1220*kg/m*^{3})
α = *compressibility of the waste/backfill composite*
n = *porosity of the waste/backfill composite*
β = *compressibility of brine* ($4.4 x 10^{-10} Pa^{-1}$) (*Freeze and Cherry*, 1979).

The compressibility of the waste-backfill matrix can be evaluated through the following relation (Freeze and Cherry, 1979, p. 338):

$$\alpha = \frac{-1}{(1+e_0)} \frac{de}{d\sigma} \qquad (2.19\text{-}2)$$

where,

e = *void ratio of the waste/backfill composite*
e_o = *void ratio of the waste/backfill composite at zero stress level*
σ = *effective stress level of waste compaction* (*MPa*).

For each engineered alternative, a table of porosity at various stress levels was developed (Section 3.0 in Volume I). The void ratio corresponding to a porosity value, n, is calculated through the relation:

$$e = \frac{n}{(1 - n)} \qquad (2.19\text{-}3)$$

For each effective stress level of waste compaction, a corresponding void ratio is computed. A ninth order polynomial provides an adequate expression for the void ratio as a function of stress level. The derivative of the void ratio with respect to stress level (de/dσ) is then obtained by differentiating the ninth order polynomial with respect to stress level:

$$\frac{de}{d\sigma} = c_2 + 2c_3\sigma + 3c_4\sigma^2 + 4c_5\sigma^3 + 5c_6\sigma^4 + 6c_7\sigma^5 + 7c_8\sigma^6 + 8c_9\sigma^7 + 9c_{10}\sigma^8 \qquad (2.19\text{-}4)$$

where,

$c_2 ... c_{10}$ = *void ratio vs. stress level regression coefficients*

and evaluating this derivative at the effective stress level corresponding to the time of borehole intrusion. The coefficients of this regression equation are included in the input data file created for each engineered alternative.

2.20 ESTIMATION OF THE INVENTORY RADIONUCLIDE ACTIVITIES (RADACTIM)

To evaluate the effectiveness measure of an engineered alternative, it is necessary to compute the activity and mass of each radionuclide in the inventory, as a function of time. The activity of each radionuclide can then be estimated for any assumed time of intrusion. The modified inventory and simplified radionuclide chains (Lappin et al., 1989, p. 4-25) were used in the calculations.

The simplified radionuclide chains are:

$$^{240}Pu \rightarrow {}^{236}U$$

$$^{241}Am \rightarrow {}^{237}Np \rightarrow {}^{233}U \rightarrow {}^{229}Th$$

$$^{238}Pu \rightarrow {}^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{210}Pb$$

$$^{239}Pu \rightarrow$$

The following table (Table B-4) contains the differential equations describing the variation of the quantity of each radionuclide with time, the decay constants and the initial activity of each radionuclide.

where,

n_i = *atoms of radionuclide "i"*
α = *decay constant of radionuclide "i"*
The decay constants were computed from the half-lives listed on pp. 4-25 of (Lappin et al., 1989) using the relation $\alpha = \ln 2/\textit{half-life}$.

The differential equations listed in Table B-4 were solved analytically. The activity of each radionuclide at the time of intrusion was calculated as the product of the atoms of each nuclide and the decay constant of the nuclide. The evaluation of radionuclide activities and masses is performed in the subroutine RADACTIM of the Design Analysis Program.

2.21 ESTIMATION OF ELEMENT SOLUBILITIES (RADSOLUB)

The solubilities specified in the input data file of the Design Analysis Model are given by individual element and are not isotope (radionuclide) specific. To provide estimates of specific radionuclide

TABLE B-4

ACTIVITY DIFFERENTIAL EQUATIONS, INITIAL ACTIVITIES AND DECAY CONSTANTS OF RADIONUCLIDES

Radionuclide Constant	ID index "i"	Activity Differential Equation	Initial Activity (curies)	Decay (α) (yr^{-1})
^{240}Pu	1	$dn_1/dt = -\alpha_1 n_1$	1.05×10^5	1.060×10^{-4}
^{236}U	2	$dn_2/dt = \alpha_1 n_1 - \alpha_2 n_2$	0	2.962×10^{-8}
^{241}Am	3	$dn_3/dt = -\alpha_3 n_3$	7.75×10^5	1.604×10^{-3}
^{237}Np	4	$dn_4/dt = \alpha_3 n_3 - \alpha_4 n_4$	8.02	3.239×10^{-7}
^{233}U	5	$dn_5/dt = \alpha_4 n_4 - \alpha_5 n_5$	7.72×10^3	4.395×10^{-6}
^{229}Th	6	$dn_6/dt = \alpha_5 n_5 - \alpha_6 n_6$	0	9.329×10^{-5}
^{238}Pu	7	$dn_7/dt = -\alpha_7 n_7$	3.90×10^6	7.904×10^{-3}
^{234}U	8	$dn_6/dt = \alpha_7 n_7 - \alpha_6 n_8$	0	2.841×10^{-6}
^{230}Th	9	$dn_9/dt = \alpha_8 n_8 - \alpha_9 n_9$	0	9.002×10^{-6}
^{226}Ra	10	$dn_{10}/dt = \alpha_9 n_9 - \alpha_{10} n_{10}$	0	4.332×10^{-4}
^{210}Pb	11	$dn_{11}/dt = \alpha_{10} n_{10} - \alpha_{11} n_{11}$	0	3.108×10^{-2}
^{239}Pu	12	$dn_{12}/dt = -\alpha_{12} n_{12}$	4.25×10^5	2.876×10^{-5}

[Lappin et al., 1989]

solubilities, the following dimensional analysis relation is assumed valid:

$$S_i = M_e \, AW_i \, mf_i \, 1000 \; l/m^3 \tag{2.21-1}$$

where,

S_i = *solubility of radionuclide "i" in brine (g "i"/m³)*
M_e = *solubility of element "e" in brine (mol "e"/ l brine)*
AW_i = *atomic weight of radionuclide "i" (g "i"/mol i)*
mf_i = *mass fraction of radionuclide "i"*
= *mass of radionuclide "i" in waste divided by the sum of masses of all isotopes (radionuclides in the waste of the element which includes isotope "i").*

The mass fraction of ^{210}Pb is evaluated by dividing the mass of ^{210}Pb in the inventory at the time of intrusion by the total lead in the inventory. The mass of stable lead in the inventory used in the calculation was 513,000 kg (Drez and James-Lipponer, 1989).

The specific radionuclide solubilities are evaluated in the subroutine RADSOLUB of the Design Analysis Model program.

2.22 ESTIMATION OF RADIONUCLIDE RELEASES WITH CUTTINGS (CUTTINGS)

The activity of each radionuclide released to the surface (with the cuttings and eroded waste/backfill material) during the drilling process is evaluated in the subroutine CUTTINGS.

The radionuclides are assumed to be evenly distributed in the waste and in the backfill existing between the waste containers and on top of the waste [i.e., it is assumed no radionuclides exist in the backfill on the sides of the waste stack to be conservative since this maximizes the activity density (Section 3.0 in Volume I)]. For each alternative, this effective waste volume (denoted by the variable VOLWST) is expressed by a ninth order polynomial equation. This equation was obtained by regressing the effective waste volume versus the effective stress-level of waste compaction data. The regression coefficients from this analysis are included in the input data file created for each individual engineered alternative.

At the time of borehole intrusion, the effective waste volume is estimated using this regression equation (from knowledge of the effective stress-level of waste compaction). The most recent estimate of the number of drum equivalents in the repository is 5.56×10^5 (Lappin et al., 1989, p. 5-9). The activity of each radionuclide in the total repository at the time of borehole intrusion is evaluated in subroutine RADACTIM (Section 2.19). The activity of each radionuclide for each drum equivalent is then established. The number of drum equivalents per panel is specified in the input data file. The activity of a radionuclide per panel is then evaluated as the product of the

activity of that radionuclide per equivalent drum and the number of equivalent drums per panel. The activity density (curies of a radionuclide per cubic meter of waste and backfill on top) is then the ratio of the activity of that radionuclide per panel to the value of VOLWST.

The activity of each radionuclide released to the surface with the cuttings and eroded material resulting from the drilling of a single borehole (assumed to have a cylindrical shape) is evaluated in the subroutine CUTTINGS as:

$$A_{cut,i} = \frac{\pi\ (rf\ r_{bor})^2\ h_{room}\ A_{rep,i}}{5.56\ x\ 10^5\ drum\ equivalents/repository}\ x\ \frac{NDE}{VOLWST} \qquad (2.22\text{-}1)$$

where,

$A_{cut,i}$ = *activity of radionuclide "i" released to the surface with the cuttings and eroded material from a single borehole (curie)*
rf = *radius factor (see below for description)*
r_{bor} = *radius of the intrusion borehole (m)*
h_{room} = *height of room (m)*
$A_{rep,i}$ = *activity of radionuclide "i" in the entire repository (curie)*
$VOLWST$ = *effective waste volume (m^3)*
NDE = *number of drum equivalents per panel.*

The radius factor will vary with the waste form to reflect the anticipated amount of erosion. For waste forms which are cemented and vitrified, one borehole radius was assumed (i.e., rf = 1). For all other waste forms a radius factor (rf) of 2 was assumed, except for supercompacted waste forms for which a radius factor of 1.5 was assumed.

The mass and activity of each radionuclide are then evaluated as:

$$M_{panel,i} = \frac{M_{rep,i}\ NDE}{5.56\ x\ 10^5\ drum\ equivalents/repository} - \frac{A_{cut,i}}{SA_i} \qquad (2.22\text{-}2)$$

and

$$A_{panel,i} = \frac{A_{rep,i}\ NDE}{5.56\ x\ 10^5\ drum\ equivalents/repository} - A_{cut,i} \qquad (2.22\text{-}3)$$

where,

$A_{panel,i}$ = *activity of radionuclide "i" in a panel after removal of activity with cuttings (curie)*
$M_{panel,i}$ = *mass of radionuclide "i" in panel at the time of borehole intrusion (g)*
$M_{rep,i}$ = *mass of radionuclide "i" in entire repository at the time of borehole intrusion (g)*
SA_i = *specific activity of radionuclide i (curie/g).*

2.23 CONTAMINATED BRINE VOLUME RELEASED DUE TO E1 INTRUSION SCENARIO (ISE1)

Intrusion scenario E1 is modeled as a single borehole penetrating a waste-filled area located at the intersection of a room and drift (Marietta et al., 1989). The borehole passes through the repository and continues penetrating until a pressurized brine pocket in the Castile Formation is struck. This scenario was modeled as a two-dimensional problem using the SWIFT-III flow code. The hydraulic conductivity of the waste/backfill is assumed to be homogeneous and isotropic, with impermeable boundaries at the room edges. The borehole is also assumed to be homogeneous and isotropic, with a conductivity of 1×10^{-3} m/s. In addition, the borehole is assumed to have fixed pressures at the top and bottom of the repository. These pressures were evaluated by hydrostatic interpolation assuming 0.92×10^{6} Pa in the Culebra (located 440 m above repository) and 16.0×10^{6} Pa in the Castile formation (located 270 m below repository) (Marietta et al., 1989). Preliminary sensitivity runs indicated that steady state conditions are attained in a short time span relative to the release time.

Multi-parameter least-squares regression (Box et al., 1978) was used to derive parametric equations for the steady state flowrate (Q_w) of Castile brine through the waste/backfill composite. These equations were based on data obtained from a series of SWIFT-III runs varying the hydraulic conductivity (K) of the composite and the intrusion borehole radius (r). The developed equations are given below:

For $K < 1 \times 10^{-8}$ m/s

$$Q_w \times 10^5 = 0.2752 - 0.4831r + 92.675r^2 - 0.0276(-\log K) \qquad (2.23\text{-}1)$$

For 1×10^{-8} m/s $\leq K \leq 1 \times 10^{-6}$ m/s

$$Q_w \times 10^5 = 131.4734 + 6.5171r + 81.2264r^2 - 34.78(-\log K) - 2.2282(-\log K)^2 \qquad (2.23\text{-}2)$$

For K > 1 x 10^{-6} m/s

$$Q_w \times 10^4 = 1608.0937 + 25.7528r - 847.4249(-\log K) + 149.0608(-\log K)^2 - 8.7619(-\log K)^3 \quad (2.23\text{-}3)$$

The volume of waste through which brine flows is termed the "wash-through volume". This volume is computed as an ellipsoid whose semi-axes are half the room height, an effective radius, and the effective width. The effective radius, r_{eff}, is defined as the maximum distance from the borehole where the fluid velocity is 10^{-12} m/s. The effective radius is computed through a regression equation developed from SWIFT-III computer code runs using various waste/backfill hydraulic conductivities (K in units of m/s). This parametric equation takes the form:

$$r_{eff} = 41.8976 - 3.84383(-\log K) + 0.0640027(-\log K)^2 \quad (2.23\text{-}4)$$

If the effective radius is less than half the room width the effective width is equal to the effective radius; otherwise it is set to half the room width (this is the maximum lateral axis radius possible). The fraction of radionuclides available for release (RLSFRAC, see Section 2.25) is defined as:

$$RLSFRAC = \frac{\textit{wash-through volume - volume of cuttings}}{\textit{total panel volume}} \quad (2.23\text{-}5)$$

The volume of brine which flows through the waste/backfill is the product of the flowrate through the waste/backfill and the release time.

2.24 CONTAMINATED BRINE VOLUME RELEASED DUE TO E2 INTRUSION SCENARIO (ISE2)

Intrusion scenario E2 is modeled as a single borehole penetrating the center of a waste-filled panel (Marietta et al., 1989). It is assumed that no additional sources of water or external pressurized brine pockets are intersected during the drilling process. An analytical solution is used to evaluate the cumulative volume of brine released during the release time. This equation is derived by solving the one-dimensional radial flow equation:

$$\frac{\partial \phi}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} rD \frac{\partial \phi}{\partial r} \quad (2.24\text{-}1)$$

where,

$$\phi = \textit{dimensionless hydraulic head} = \frac{[h(r,0) - h(r,t)]}{h(r,0)}$$

r = *radial direction coordinate* (m)
D = *hydraulic diffusivity* (m^2/yr).

with the following initial and boundary conditions:

$$\phi(r,t = 0) = 0 \tag{2.24-2a}$$

$$\phi(r = a,t) = \phi_a \text{ [fixed pressure head of brine in the borehole based on the distance to the culebra]} \tag{2.24-2b}$$

$$\frac{\partial\phi}{\partial r}|(r = b,t) = 0 \text{ [no flow at the edge of the panel]} \tag{2.24-2c}$$

where,

a = *radius of borehole* (m)
b = *equivalent radius of panel*
= $[(91.44m \times 7w + 30.48m \times 12w + 14w^2)/\pi]^{1/2}$ (m).

The initial hydraulic head in the panel, h(r,0) is evaluated as:

$$h(r,0) = \frac{P(r,0)}{\rho g} \tag{2.24-3}$$

where,

$h(r,t)$ = *hydraulic head at radius, r* (m)
$P(r,0)$ = *gas pressure in panel at the time of intrusion* (Pa)
ρ = *density of brine* ($1220 kg/m^3$)
g = *gravitational acceleration* ($9.80665 m/s^2$).

The solution to equation (2.24-1) subject to the initial and boundary conditions (2.24-2a,b,c) is given by (Crank, 1975, p. 86)

$$\phi = \phi_a \left[1 - \pi \sum_{n=0}^{\infty} e^{(-D\alpha_n^2 t)} J_1^2(b\alpha_n) \frac{J_0(r\alpha_n) Y_0(a\alpha_n) - J_0(a\alpha_n) Y_0(r\alpha_n)}{J_1^2(b\alpha_n) - J_0^2(a\alpha_n)}\right] \qquad (2.24\text{-}4)$$

where α_n are the roots of the equation

$$\alpha_n \left[J_1(b\alpha_n) Y_0(a\alpha_n) - J_0(a\alpha_n) Y_1(b\alpha_n)\right] = 0 \qquad (2.24\text{-}5)$$

where the J's and Y's are the Bessel functions of the first and second type respectively.

The flowrate, Q out of the panel and into the borehole is then from (Freeze and Cherry, 1979, p. 16)

$$Q = Av = -AK \frac{\partial h}{\partial r}\Big|_{r=a} = -2\pi a H K \frac{\partial h}{\partial r}\Big|_{r=a} \qquad (2.24\text{-}6)$$

where,

Q = *volumetric flowrate*(m^3/yr)
A = *area of flow* (m^2)
v = *specific discharge* (m/yr)
K = *hydraulic conductivity* (m/yr)
w = *width of rooom in panel* (m)
H = *height of room*(m).

The flowrate to the borehole as a function of time is evaluated from equation (2.24-6) as:

$$Q(t) = 2\phi_a \pi^2 a H K h(r,0) \sum_{n=1}^{\infty} \exp(-D\alpha_n^2 t)\ f(\alpha_n, a, b) \qquad (2.24\text{-}7)$$

where,

$$f(\alpha_n, a, b) = \frac{\alpha_n J_1^2(b\alpha_n)\{Y_1(a\alpha_n) J_0(a\alpha_n) - J_1(a\alpha_n) Y_0(a\alpha_n)\}}{J_1^2(b\alpha_n) - J_0^2(a\alpha_n)} \qquad (2.24\text{-}8)$$

The total volume of fluid released from the panel during release time, t_r, is evaluated by integrating equation (2.24-7) with respect to time which gives:

$$V_{fluid}(t_r) = 2\phi_a \pi^2 aHKh(r,0) \sum_{n=1}^{\infty} f(\alpha_n, a, b) \left[\frac{1 - e^{(-D\alpha_n^2 t)}}{D\alpha_n^2}\right] \qquad (2.24\text{-}9)$$

The panel is assumed to be saturated with a homogeneous fluid with the properties of WIPP brine. Since the majority of the released fluid consists of generated gases, the actual volume of brine released is evaluated as:

$$V(t_r) = \frac{V_{fluid}(t_r)\ V_{brine}}{(V_{void} + V_{brine})} \qquad (2.24\text{-}10)$$

where,

$V(t_r)$ = *volume of brine released to Culebra over the release time* (m^3)
$V_{fluid}(t_r)$ = *total fluid (brine + panel gases) released to Culebra during the release time,* t_r, *evaluated in equation* (2.24-9) (m^3)
V_{void} = *void volume in panel at intrusion time* (m^3)
V_{brine} = *volume of brine in panel at intrusion time* (m^3).

The maximum quantity of brine available for release is the total volume of brine present in the panel at the intrusion time. This approach neglects the effects of the gas expansion up the borehole.

2.25 CONTAMINATED BRINE VOLUME RELEASED DUE TO E1E2 INTRUSION SCENARIO (ISE1E2)

Intrusion scenario E1E2 is modeled as two boreholes which fully penetrate opposite ends of a room filled with waste/backfill (Marietta et al., 1989). One borehole penetrates the pressurized brine in the Castile Formation and is assumed to be plugged between the repository and the Culebra. The second borehole penetrates the same panel but does not penetrate the Castile Formation and is plugged above the Culebra. A pathway is then established for the flow of brine from the Castile Formation through the waste and up into the Culebra. The boreholes are assumed to remain at fixed hydraulic heads neglecting slight changes in elevation from the

bottom to the top of the panel. The volume of brine which flows through the waste is evaluated from the solution to the one-dimensional flow equation:

$$\frac{\partial h}{\partial t} = D \frac{\partial^2 h}{\partial x^2} \tag{2.25-1}$$

with the following initial and boundary conditions:

$$h(x,0) = h_0 = h_1 \tag{2.25-2a}$$

The hydraulic head initially in panel is equal to the hydraulic head in the borehole penetrating the Castile Formation.

$$h(0,t) = h_1 = 1337.3\ m \tag{2.25-2b}$$

The hydraulic head of the second borehole is due to the pressure in the Culebra plus the elevation.

$$h(l,t) = h_2 = 787.9\ m \tag{2.25-2c}$$

where,

h = *hydraulic head* (m)
x = *distance from the borehole penetrating the Castile along the line connecting the two boreholes*
l = *separation of the two boreholes (one room length is arbitrarily chosen as the distance separating the two boreholes, i.e.,* 91.44 m)
D = *hydraulic diffusivity* (m^2/s).

The solution to equation (2.25-1) subject to initial and boundary conditions (2.25-2a,b,c) is given by (Carslaw and Jaeger, 1959, pp. 99-100) as:

$$h(x,t) = h_1 + (h_2 - h_1)\frac{x}{l} + \frac{2}{\pi}\sum_{n=1}^{\infty}\frac{(h_2\cos n\pi - h_1)}{n}\sin\left(\frac{n\pi x}{l}\right)\exp\left(\frac{-Dn^2\pi^2 t}{l^2}\right)$$
$$+ \frac{2}{l}\sum_{n=1}^{\infty}\sin\left(\frac{n\pi x}{l}\right)\exp\left(\frac{-Dn^2\pi^2 t}{l^2}\right)\frac{h_0/(1 - \cos(n\pi))}{n\pi} \tag{2.25-3}$$

The volumetric flowrate of brine leaving the repository and flowing into the Culebra may be expressed as:

$$Q = -KA \frac{\partial h}{\partial x}\Big|_{x=l} \qquad (2.25\text{-}4)$$

where,

Q = volumetric flux of brine into the Culebra at time, t (m^3/yr)
K = hydraulic conductivity of the waste/backfill composite (m/yr)
A = cross-sectional area of the borehole connecting the waste with the Culebra (m^2)

The total volume of fluid released to the Culebra during the release time, t_r, is computed by integrating equation (2.25-4) with respect to time.

The cumulative volume of brine released to the Culebra during the release time, t_r, is thus:

$$V(t_r) = -KA \frac{(h_2 - h_1)t_r}{l} - \frac{2l}{D\pi^2} \sum_{n=1}^{\infty} \frac{(h_2\cos(n\pi) - h_1)\cos(n\pi)}{n^2} \left[\exp\left(\frac{-Dn^2\pi^2 t_r}{l^2}\right) - 1\right]$$
$$-\frac{2h_0 l}{D\pi^2} \sum_{n=1}^{\infty} \frac{(1-\cos(n\pi))\cos(n\pi)}{n^2} \left[\exp\left(\frac{-Dn^2\pi^2 t_r}{l^2}\right) - 1\right] \qquad (2.25\text{-}5)$$

The quantity of radionuclides which can potentially be released is limited to the quantity present in the volume between the two boreholes. This fraction (RLSFRAC, see Section 2.26) of the total radionuclides in the panel is evaluated as:

RLSFRAC = room width at time of borehole intrusion
× room height at time of borehole intrusion (2.25-6)
× room length / panel volume at time of intrusion.

2.26 EVALUATION OF MEASURES OF RELATIVE EFFECTIVENESS (SUMRULE)

The measure of effectiveness of an engineered alternative is evaluated for each alternative and for each of the intrusion scenarios in the subroutine SUMRULE of the Design Analysis Model. The measure of effectiveness is the sum (over all isotopes) of the ratios of the cumulative activity release of isotope "i" into the Culebra to that of the allowed activity release of isotope "i". The total activity of the WIPP radionuclide inventory was estimated by summing the activities of each radionuclide in Table 4-2 of Lappin et al. (1989). This sum is equal to 5.21 MCi. The allowed release for each radionuclide based on the CH-TRU waste inventory for the WIPP is obtained by multiplying the values in Table 1 of 40 CFR Part 191 by the factor 5.21 since the release limits

(allowed releases) are based per MCi. The allowed releases of the radionuclides are shown in Table B-5.

The release limits of radionuclides are stored in array RL in the subroutine SUMRULE. A call is made to SUMRULE after the cumulative volume of brine released to the Culebra , $V(t_R)$, and the fraction of radionuclides in the panel available for release (RLSFRAC) is evaluated for intrusion scenarios E1 and E2. The entire panel radionuclide inventory is available for release in Scenario E2; thus, the value if RLSFRAC for this scenario is equal to 1.

If the summed release is being evaluated for intrusion scenarios E1 or E1E2, then the mass of each radionuclide which can potentially be released is scaled down as:

$$M_{avail,i} = M_{panel,i}\, RLSFRAC \qquad (2.26\text{-}1)$$

where,

$M_{avail,i}$ = *mass of radionuclide "i" available for release (g)*
$M_{panel,i}$ = *mass of radionuclide "i" in a panel at the time of borehole intrusion(g)*
$RLSFRAC$ = *ratio of the wash-through volume to the total panel volume (Sections 2.23 and 2.25).*

The dissolution of radionuclides in brine is assumed to be an instantaneous process. The solubility of each radionuclide in brine is evaluated in routine RADSOLUB (Section 2.21).

The released volume, $V(t_R)$, is multiplied by the radionuclide solubilities, S_i, to evaluate the maximum mass of radionuclides which could dissolve in the released brine. If the available mass, $M_{avail,i}$ is less than what could potentially dissolve in the brine, the mass released is inventory limited. The activity of radionuclide "i" released to the Culebra with brine, $A_{brine,i}$ is calculated by multiplying the mass released by the specific activity of the radionuclide.

The activity of each radionuclide released with the cuttings from a single borehole, $A_{cut,i}$ is evaluated in subroutine CUTTINGS (Section 2.22). If the summed normalized release is being computed for intrusion scenario E1E2, then the activity released with the cuttings is twice what it is for a single borehole.

The measure of effectiveness (SUMRAD) of an engineered alternative with respect to an intrusion scenario is evaluated as:
where,

$$SUMRAD = \sum_{i=1}^{12} (A_{cut,i} + A_{brine,i}) / RL_i \qquad (2.26\text{-}2)$$

where,

$SUMRAD$ = *effectiveness measure*
RL_i = *activity release limit (allowed release) of radionuclide "i".*

TABLE B-5

ACTIVITY RELEASE LIMITS OF WIPP INVENTORY RADIONUCLIDES

RADIONUCLIDE	ACTIVITY RELEASE LIMIT (Ci)
^{240}Pu	521
^{236}U	521
^{241}Am	521
^{237}Np	521
^{233}U	521
^{229}Th	521
^{238}Pu	521
^{234}U	521
^{230}Th	52
^{226}Ra	521
^{210}Pb	521
^{239}Pu	521

The value of SUMRAD for an engineered alternative being studied is divided by the value of SUMRAD evaluated for the baseline case design to obtain a measure of effectiveness for the particular engineered alternative. These numbers cannot be used to show or disprove compliance with EPA 40 CFR Part 191 for the following reasons:

- Probabilities associated with intrusion events have not been factored into the calculations made in these analyses.

- In these evaluations, EPA Summed Normalized Releases are evaluated at the Culebra and not at the unit boundary since far-field modeling of flow and transport in the Culebra Dolomite is not being performed as part of the EATF project.

APPENDIX C

DEVELOPMENT OF THE SEAL-SYSTEM COMPONENT OF THE DESIGN ANALYSIS MODEL

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DEVELOPMENT OF THE SEAL SYSTEM COMPONENT OF THE DESIGN ANALYSIS MODEL

Introduction

The basic goal of the sealing system is to limit fluid migration in, through, and out of the repository. A multiple component system allows individual seal components to serve different functions, to be effective over different time spans, and to exist in different locations and formations in order to ensure sufficient redundant barriers are in place at all times (Stormont, 1988). The seal system objectives are accomplished by a combination of short-term and long-term seals. The short-term seals are to function for approximately 100 years after emplacement, the time of institutional control over the facility and the approximate time required for long-term seals to become functional (DOE, 1990c).

The short-term seals in drifts consist of concrete plugs and possibly crushed salt. The current design indicates that short-term seals in the upper portions of the shafts consist of swelling clay material confined by concrete bulkheads. The disturbed rock zone (DRZ) around the seals represents a potential flow path for brine. Indirect evidence that the permeability of salt may increase in the vicinity to an excavation is obtained from laboratory tests which indicate that permeability is dependent on confining stress. Kelsall et al. (1984) presents a variation in permeability with radius from the excavation. Due to the surrounding salt creep closure, the stress is expected to build up rapidly on the concrete plug, which consequently reduces permeability of the DRZ and the plug-salt interface. The long-term seals are made of crushed salt (DOE, 1990c) which is chemically and mechanically compatible with the host formation. The creep closure of the surrounding intact salt will consolidate and densify the crushed salt to a condition comparable to intact salt. Recent studies (Stormont, 1988) show that when the porosity of the crushed salt decreases to 5 percent or less, its permeability approaches that of intact salt (Figure C-1). This information indicates that crushed salt provides a tight seal in the long term.

Model Development

Two separate computer programs have been developed to model the short-term and long-term seals. The program TSEAL models the behavior of short-term seals, and the program SEAL simulates that of long-term seals. There are a number of assumptions and simplifications involved in this modeling effort:

- Analyses are for an idealized circular geometry and a homogenous media. Shafts are modeled more accurately because of geometry and the effects of stratigraphic layering on deformation. Therefore, these models should be cautiously applied to drift and panel seals.

- The backfill is emplaced to completely fill the opening.

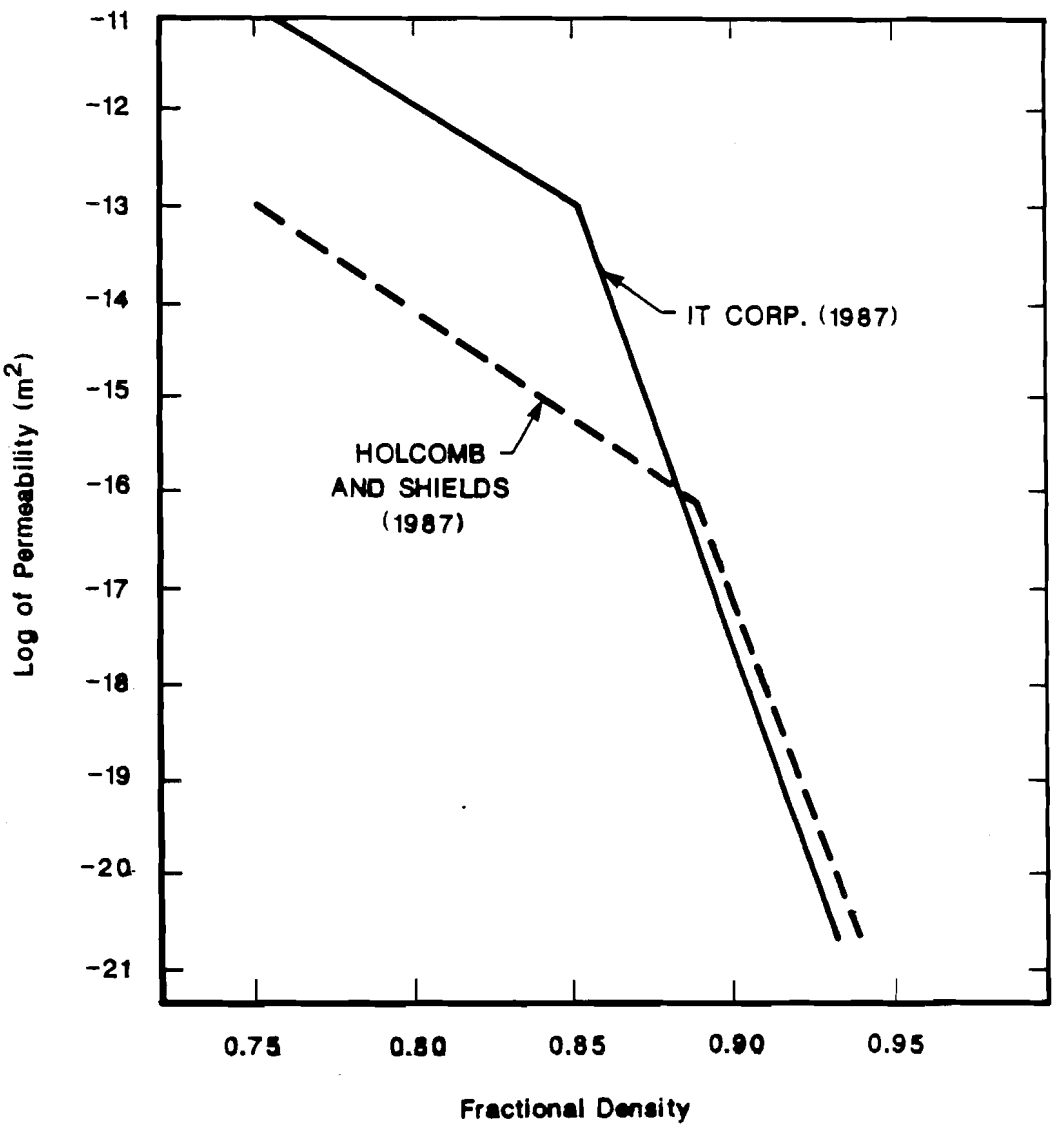

Figure C-1. Permeability Versus Fractional Density for Two Consolidation Tests on Wetted Crushed Salt (Stormont, 1988)

- The temperature at any given time is assumed to be uniform for both the intact salt and crushed salt backfill for all time.
- Thermoelastic stresses and their influence on consolidation and closure are neglected.
- Crushed salt backfill is assumed to consolidate homogeneously.
- Pore pressure will not develop as a result of wet crushed salt backfill consolidation. Furthermore, the result of the tests on wet crushed salt backfill material do not show a strong correlation between the consolidation rate and the moisture content (Sjaardema and Krieg, 1987).
- The stress field at each time step is the stationary, or steady-state stress field, which is a function of internal pressure and the far-field stress.

Intact salt, crushed salt, and concrete were modeled in the programs. The behavior of concrete has been assumed to be linear and elastic in the range of stresses expected in the repository. For the behavior of moist crushed salt, the proposed model by Sjaardema and Krieg (1987) for the hydrostatic loading of crushed salt has been used (crushed salt will not be subjected to deviatoric loading, since the cross-section of seals are assumed to be circular and the crushed salt is assumed to be consolidated homogeneously). Sjaardema and Krieg (1987) calculated the stress on crushed salt at the end of a time step, P_F, as follows:

$$P_F = \frac{-\ln}{B_1}\left\{\frac{\hat{B}\,(1+\alpha t)}{\alpha+\hat{K}+\hat{B}} + \left[e^{-B_1 P_0} - \frac{\hat{B}}{\alpha+\hat{K}+\hat{B}}\right]\exp\left\{-t\,(\hat{K}+\hat{B})\right\}\right\} \qquad \text{(C-1)}$$

where:

A, B_0, B_1, K_0, K_1 *are material constants*
P_0 = *the pressure at the beginning of the time step*
r = *the volumetric strain rate during the time step*
$\hat{B} = B_0 B_1 K_0 e^{P_0(A+K_1)}/\rho_0$
$\hat{K} = B_1 K_0 r e^{K_1 P_0}$
$\alpha = (K_1\rho_0 + A\rho_0 - 2)r$
$\beta = K_1\rho_0 r$
t = *length of time step*

And the following assumptions were used:

$$\alpha t,\ \beta t,\ rt \begin{cases} <0.5 \text{ for } <10\% \text{ error} \\ <0.1 \text{ for } < 1\% \text{ error} \end{cases}$$

Norton's law was used to model the creep behavior of the intact salt and has been expressed by Munson et al. (1989) in the following form:

$$\dot{\varepsilon}_C = \dot{\varepsilon}_{2M} \left(\frac{\sigma}{\mu}\right)^n \tag{C-2}$$

where,

$\dot{\varepsilon}_c$ = *steady-state strain rate*
$\dot{\varepsilon}_{2M}$ = $A_{2M} \exp(-Q/RT)$
A_{2M} = *creep constant*
μ = *salt shear modulus*
Q = *activation energy*
R = *universal gas constant*
T = *absolute temperature*
n = *stress exponent*
σ = *generalized stress*

Chabannes (1982) proposed a closed-form solution for a thick-wall cylinder of salt in plane strain condition. Allowing the external radius to go to infinity, a solution is obtained for a circular opening in an infinite medium of salt. The solution accounts for the secondary creep of salt which was modeled by Norton's law. Chabannes calculated the radial displacement (u_r) rate (w) at any radius, r, as follows:

$$w = \frac{du_r}{dt} = -\dot{\varepsilon}_{2M} \left[\frac{\sqrt{3}}{2}\right]^{n+1} \left[\frac{2a^{2/n}\,(P_0 - P_i)}{n \cdot \mu \cdot r^{2/n}}\right]^n \cdot r \tag{C-3}$$

where "a" is the radius of opening, P_o is the farfield stress, and P_i is the internal pressure.

The program TSEAL, which models the behavior of the temporary seal, uses Chabannes' solution to model the surrounding intact salt and assumes a linear elastic model for the behavior of concrete plugs. From the consistency of the rate of deformation between intact salt and a concrete plug, the rate of pressure change on the plug can be calculated in the form of a first-order nonlinear differential equation. This differential equation is then solved using a numerical integration scheme, and the pressure on the plug is calculated as a function of time. As a consequence of stress build-up on the concrete plug, the mean compressive stress in the DRZ will increase. Therefore, the porosity, and in turn the permeability of the DRZ, will decrease. The change in porosity at each point in time is calculated using the relaxed volumetric strain from the virgin state due to creep. The permeability of salt is then calculated using a relationship between porosity and permeability proposed by Lai (1971).

The behavior of long-term seals is modeled by the SEAL program which uses the Chabannes solution to model the surrounding intact salt. The proposed model of Sjaardema and Krieg (1987) is used to model the compaction of backfilled wet crushed salt. At each time step, the stress increase on the crushed salt due to its compaction is calculated using Equation (C-1) through an iterative procedure. The effect of stress build-up in crushed salt on the rate of creep closure is considered by modifying the internal stress in Equation (C-3) at each time step. Permeability of crushed salt at the end of each time step is obtained using a relationship between salt permeability and its fractional density (Figure C-1). The change in permeability of the DRZ is calculated as in the TSEAL program, and as explained in the previous paragraph.

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APPENDIX D

MODELING OF GAS ADVECTION INTO ANHYDRITE BEDS

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MODELING OF GAS ADVECTION INTO ANHYDRITE BEDS

Introduction

To examine the potential gas pressurization in the WIPP repository, all potential gas sources and sinks must be evaluated. One potential sink is the migration of the gases into the anhydrite layers which lie above and below the repository. The lower layer, known as Marker Bed 139 (MB 139), is located approximately 1 meter below the repository (Figure D-1). The upper layers, anhydrite beds "a" and "b," are located approximately 4 meters and 2 meters, respectively, above the repository. These anhydrite beds are considered to be made up of a disturbed zone and an intact zone. The disturbed zone is made up of fractured anhydrite caused by the repository excavation, and will exist above and below the entire repository. The intact zone is the undisturbed anhydrite, and exists beyond the area stressed by the mine operations. The anhydrite beds "a" and "b" overlying the repository are treated as a single composite layer for modeling advection. The program logic described below for MB 139 has also been used for the "a" and "b" composite bed.

Once the gas pressure in the repository has exceeded the pressure in an anhydrite bed, the gas will begin to migrate through the disturbed halite above and below the rooms and drifts into the disturbed zone of MB 139. The gas pressure will then drive the brine located in the disturbed zone (Figure D-2) into the intact marker bed, due to the pressure gradient developed by increasing gas pressure in the room. The brine is easily displaced, as the saturated capillary or threshold pressure in the disturbed marker bed is relatively small due to its enhanced permeability. However, as the brine reaches the undisturbed zone of Marker Bed 139, there is a large increase in the threshold pressure resulting from the lower permeability of this region. This threshold pressure must be exceeded in addition to the MB 139 pore pressure in order for gas to flow from the disturbed marker bed into the intact anhydrite (Figure D-3). The lower permeability does not allow the gas to displace the brine in the intact marker bed as freely as it does in the disturbed marker bed.

Assumptions

To model the gas advection from the repository through the disturbed anhydrite beds into the undisturbed anhydrite beds, the following assumptions were made:

- Each room in the repository is directly connected with the disturbed anhydrite beds above and below it (this implies that the rooms are a linked network and that the network is equalized with respect to pressure).
- The gas displaces some brine in the disturbed anhydrite beds before the gas can migrate into the undisturbed zone
- The intact anhydrite beds are initially saturated
- The gas has the properties of hydrogen

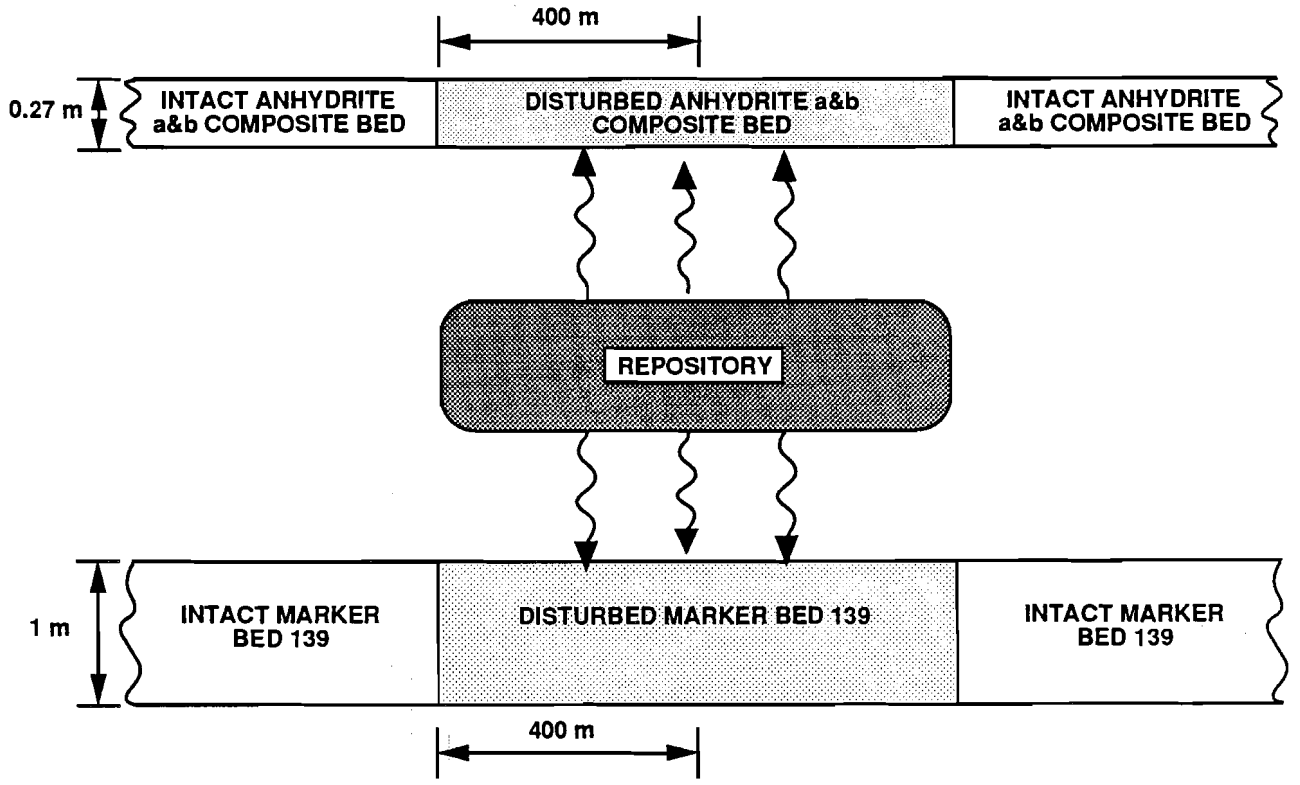

Figure D-1. Conceptual Model of Anhydrite Beds

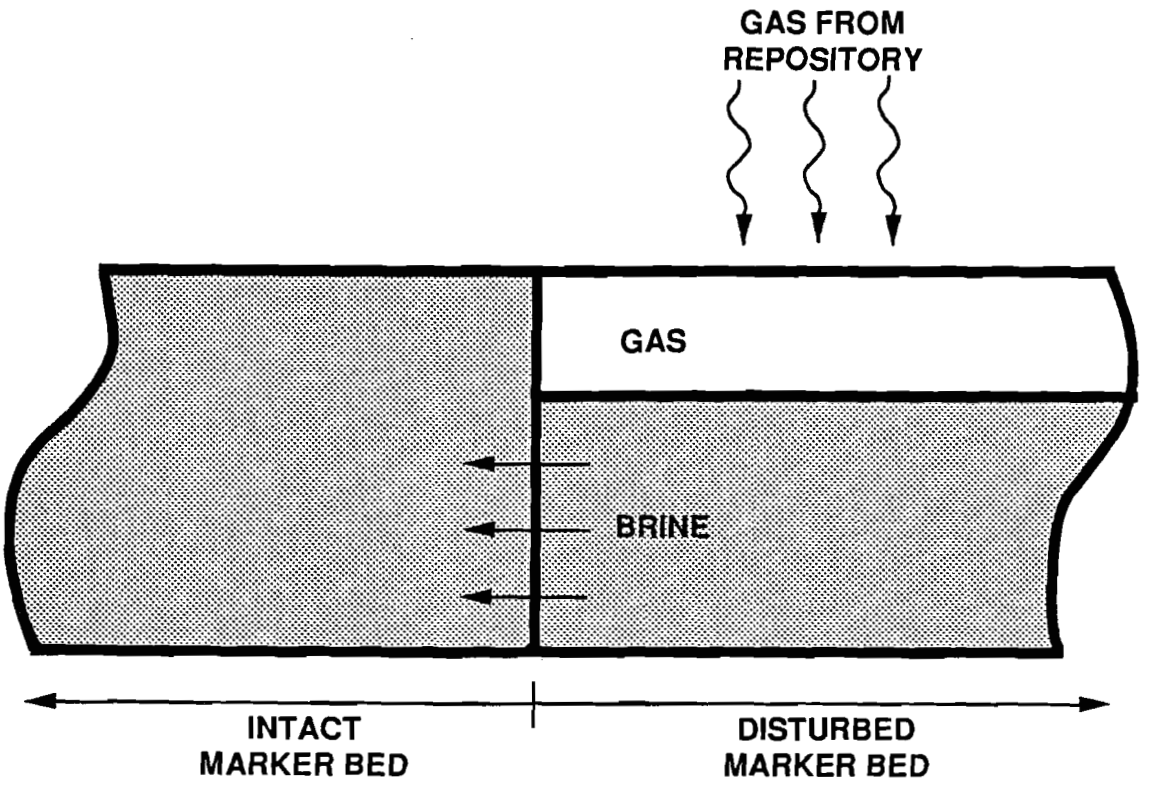

Figure D-2 . Brine Migration After Panel Pressure Exceeds
MB 139 Pore Pressure

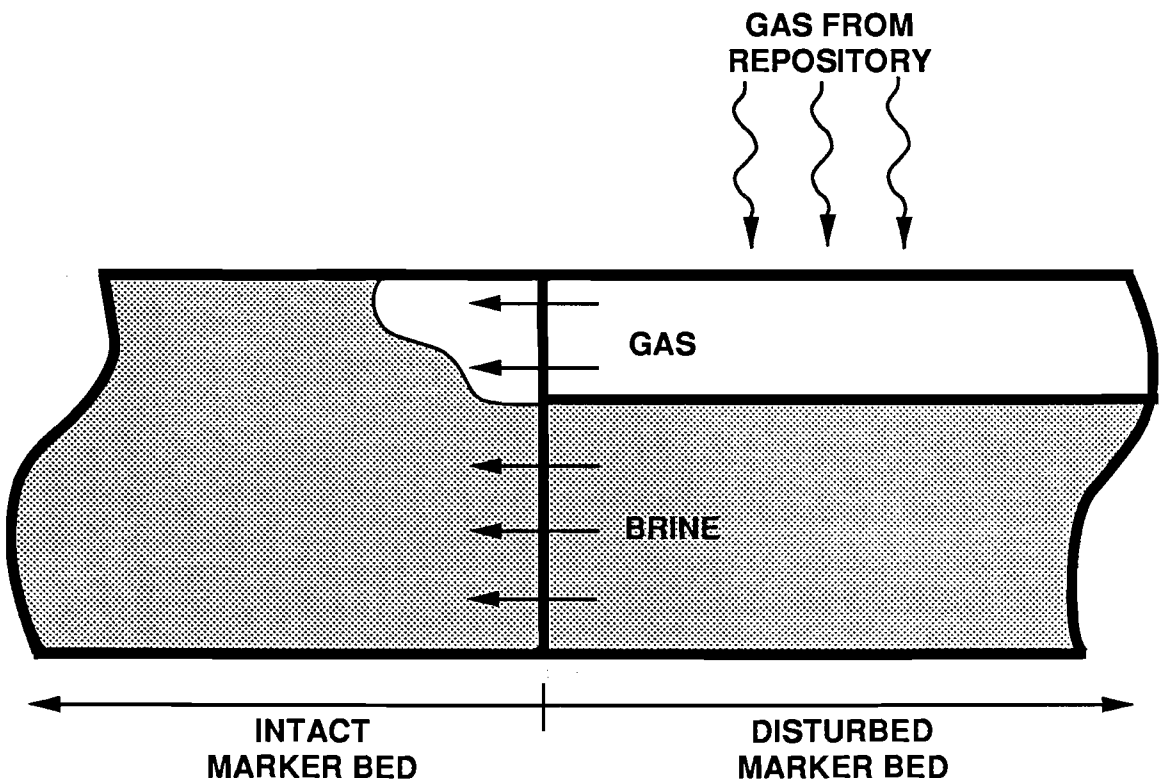

Figure D-3. Brine and Gas Migration After Panel Pressure Exceeds MB 139 Pore Pressure and Threshold Pressure

- The capillary pressure of the undisturbed anhydrite beds is always equal to the threshold pressure (saturated capillary pressure)
- The disturbed anhydrite beds are a cylinder, with a 400-meter radius
- The flow is radial
- The anhydrite beds have a constant thickness of 1 meter and 0.27 meters
- The anhydrite beds are homogeneous and isotropic
- The relative permeability curves for the intact anhydrite beds are the same as for the intact halite
- The pressure in the room remains constant
- The far-field pressure in the intact anhydrite beds remains constant
- There is no localized depressurization of the host rock.

Assuming that the gas has the physical properties of hydrogen, permits the maximum flow rates of gas into the intact anhydrite beds.

Program Description

A two-phase computer model was developed to simulate the gas advection into the intact anhydrite bed. The program developed is a versatile two-phase finite difference program which calculates the flow rate of gases in cubic meters per second, mass per second, and moles per second. The program uses the IMPES (**IM**plicit **P**ressure **E**xplicit **S**aturation) method for solving two-phase partial differential equations. This program is based upon a radial two-phase flow equation, a detailed description of which can be found in PRRC (1990).

The program allows the user to vary the important parameters such as the size of the disturbed zone, permeability of the intact anhydrite, capillary pressures, fluid properties, gas properties, boundary pressures, relative permeability curve, and the thickness of the marker bed. This flexibility facilitates the performance of sensitivity analyses on the listed parameters. This capability is particularly useful to determine the dependence of the gas advection on the different hydrologic parameters of the system.

The program was used to develop parametric equations for the gas advection rate (in moles per second) dependent on the permeability of the anhydrite beds, the far field pressure of the anhydrites, and the pressure of the room. These equations were used in the Design Analysis Model to compute the gas advection rate.

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APPENDIX E

DEVELOPMENT OF BRINE/CO_2 INTERACTION PARAMETERS

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DEVELOPMENT OF BRINE/CO_2 INTERACTION PARAMETERS

The subroutine BRINTERACT was written to address the possible role of brine as a 'sink' for the gas carbon dioxide (CO_2). Carbon dioxide will be produced by microbial activity in the waste panel rooms. If brine is available and in contact with cemented waste forms, the soluble masses of carbon dioxide and portlandite, $Ca(OH)_2$, are available to react and produce calcite ($CaCO_3$) and water (H_2O) according to the reactions:

$$CO_2 + H_2O \rightarrow HCO_3^- + H^+ \tag{E-1}$$

$$HCO_3^- + H^+ + Ca(OH)_2 \rightarrow CaCO_3 + 2H_2O \tag{E-2}$$

Combining these two reactions yields the overall reaction for the consumption process as:

$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O \tag{E-3}$$

The overall reaction progress (i.e., moles of produced $CaCO_3$ and H_2O) is limited by the availability of carbon dioxide, portlandite and brine. If any one of these components is exhausted or unavailable, the reaction progress will terminate.

The subroutine BRINTERACT begins by establishing the molar volumes of portlandite, calcite and water, and then determines if the carbon dioxide produced from microorganism respiration is greater than the equilibrium fugacity of carbon dioxide in the brine. The fugacity of carbon dioxide in the brine (0.08 atm) has been calculated with the EQ3NR/EQ6 (Wolery, 1983; Wolery, 1984) speciation/reaction-path program by equilibrating the brine with excess carbon dioxide, portlandite and calcite. A mass balance is also carried out on portlandite and water to determine if these components are present in excess and, therefore, available to react with the carbon dioxide. If all of the above conditions are met, the subroutine will continue. However, if the carbon dioxide produced by the microorganisms is less than the fugacity of carbon dioxide in the brine, or there is insufficient portlandite or water, the subroutine will terminate at this point (i.e., the reaction cannot take place). Assuming the above conditions are met, the subroutine will continue by calculating a scale factor, which relates the amount of carbon dioxide that can react to the amount of brine present. The scale factor is multiplied by the carbon dioxide present in excess of the fugacity equilibrium value to determine the number of moles available to react. It accounts for the relative proportions of void volume in the waste and brine volumes to estimate the fraction of waste that would be contacted by the brine (i.e., the fraction of cemented waste available to react). The scale factor (SCALFACT) has the form:

$$SF = 1 - [V_V / (V_V + V_B)] \tag{E-4}$$

where V_V is the void volume and V_B is the volume of brine. Therefore, if the void volume is very large relative to the volume of brine, the term in brackets approaches one and the scale factor approaches zero (i.e., the reaction will consume very little carbon dioxide if brine is limited). If the volume of brine is very large relative to the void volume, then the term in the brackets approaches zero and the scale factor approaches one. A scale factor of one would allow complete reaction of all available carbon dioxide, if not limited by portlandite.

After the number of moles of carbon dioxide available for reaction have been determined, the subroutine reacts these moles with portlandite to produce calcite and water (reaction E-2). Mass balance calculations are then performed to determine the number of moles of carbon dioxide and portlandite remaining and the number of moles of calcite and water produced. The mass of portlandite consumed is subtracted, and that of calcite added, to the total mass of solids in the panel. Water produced from the reaction is added to the total mass of liquid in the panel.

Changes in the void volume are also calculated. Void volume will decrease as this reaction progresses because water is produced and added to the volume of brine, and because the molar volume of calcite (a reaction product) is slightly greater than that of portlandite (a reactant).

After completing the mass and volume balances, the subroutine passes the moles of remaining carbon dioxide, water, portlandite, liquid and total mass of solids, void volume, and volume of brine back to the MASSGAS subroutine. This terminates the subroutine BRINTERACT. It should be noted that the reaction of carbon dioxide with cementitious materials is insignificant as a mechanism for gas dissipation. Therefore, the removal of the BRINTERACT subroutine would not have any major effect on the results. This subroutine was included for the sake of completeness.

APPENDIX F

DESIGN ANALYSIS MODEL PROGRAM VERIFICATION

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DESIGN ANALYSIS MODEL PROGRAM VERIFICATION

The EATF modeling objectives have been performed in accordance with the Quality Assurance (QA) program used by International Technology Corporation (IT Corporation). The title of the document governing this program is the "Quality Assurance Procedure for Software Development And Use At The International Technology Corporation Albuquerque Modeling Center". The purpose of this appendix is to explain how the QA program used by the EATF was applied to program verification and validation for the Design Analysis Model. Verification is the process by which the output (numerical results) of a computer program are determined to be "correct". Verification implies that the program solves the numerical problem as intended by the EATF program author. Validation implies that the theory and assumptions used in constructing the program logic constitute a correct representation of the process or system being simulated by the program ROOM-SCALE, the main component of the Design Analysis Model, as it was developed by the EATF. The software QA procedure requires that such programs be verified using one, or some combination, of the following methods, depending on the intended use of the program:

- Independent manual calculations have been performed to verify all of the program algorithms. Manual calculations were documented and verified according to Sections 6.2.1 and 6.3.1 (included below) of the International Technology Corporation, Environmental Projects Group, Engineering Operations Quality Assurance Manual, Revision 1, July, 1987 (referred to as the ITEO QA Manual).

- The subroutine ISE2.FOR was compared to the results of an "independently developed" program which performs the same calculation. The term "independent development" can mean a program developed outside IT or by an independent internal working group. If avoidable, a program should not be verified against another program developed within the originating group unless the methodology and approach are entirely different. The input to both the program being verified and the program used for verification was independently checked.

- The program results can be compared to analyses published in textbooks and journals or to the results of applicable experiments. A complete reference for such material should be provided. This method includes verification with closed-form analytical solutions.

In addition, verification procedures used by the EATF are completely documented. This documentation includes, as appropriate:

- Description of verification method used
- Identification of the specific options verified
- Set of verification comparison materials (e.g., checked manual calculations)
- Verification runs, (i.e., checked copy of the computer output)
- Results.

Validation documentation, as necessary, consists of published conclusions comparing model predictions with data from laboratory experiments, field experiments, natural analogues, and published conclusions made by external review groups. Information regarding the conditions for which the model is valid were documented.

The following are Sections 6.2.1 and 6.3.1 of the ITEO QA Manual which pertain to calculations. The relevant procedures listed in those subsections were applied to the EATF project.

Calculations

For many projects, calculations represent the most important source of information when the work is completed. They shall be legible and in a form suitable for reproduction, filing, and retrieval. Documentation shall be sufficient to permit a technically qualified individual to review and understand the calculations and verify the results.

Calculations shall be performed on IT standard calculation paper whenever possible. Exceptions to this are items such as computer output and graphs drawn on oversized paper. All calculation pages shall be individually identified with the exception of large computer output. IT calculation paper provides spaces for the originator's name and date of work, the checker's name and date, calculation subject, project number, and page number. All of this information shall be completed for each page in a uniform manner. For extra pages, such as large graphs, this information shall also be included.

Calculations should, as appropriate, include:

- Statement of calculation intent
- Discussion of modeling requirements
- Description of methodology used
- Assumptions and their justification
- Input data and equation references
- Numerical calculations, including units
- Results.

Referencing input data, particularly input data obtained externally, is extremely important as it provides the basis for calculation checking. If initial parameters are supplied by an external source, the source shall be documented. Data that are provided by telephone shall be documented using an IT telephone record sheet. A request shall be made for formal written confirmation of critical data to serve as the final documentation. Input data may provide:

- Design program or regulatory requirements

- Performance and operational requirements under various conditions

- Data previously generated for a specific site or region (e.g., geological, hydrogeological, geochemical, geotechnical, meteorological, seismological, and man-made facilities and practices)

- Data previously generated for specific materials or chemical compounds (e.g., physical, chemical, geochemical, mechanical, thermomechanical, and toxicological)

- Loadings

- Results of field and laboratory testing or other calculations

- Other information obtained from the client or literature/information surveys.

Computer printouts that become an integral part of the calculations shall be referenced in the calculations by the run number or other unique means of identification. Short computer runs and spreadsheets can be directly incorporated into the calculations by affixing the output to IT paper or directly including output of standard sheet size (8-1/2 x 11 inches).

At the end of a calculation, the results should be summarized, if this will provide clarity. Also, all pages shall be consecutively numbered. On IT calculation pages, the page numbers of individual calculations shall be completed with the indexing of sheet ___ of ___. For the compilation of a set of calculations, the combined set should be consecutively numbered in the circles in the upper right corner of the calculation pages.

Calculations which are preliminary in nature (i.e., those not contributing to final project information) shall be marked "preliminary". If "preliminary" calculations are retained for future reference, each page shall be clearly marked "preliminary". Quality control requirements with final calculations, such as checking, are not applicable to "preliminary" work. Calculations which are superseded or replaced shall be marked "void" or destroyed. If "void" calculations are retained for future reference, each page shall be clearly marked "void" and the calculations should include, as necessary, an explanatory note as to why they are "void". The explanatory note shall be signed by the originator.

For calculations, the standard IT checking process is outlined as follows.

Assignments for checking shall be made or approved by the Project Manager. Verifications shall be performed by an individual(s) other than the person who performed the original work or specified the method or input parameters to be used. The individual(s) selected shall have the technical expertise in the calculation subject necessary to verify, as appropriate, that:

- Applicable design program, regulatory, and technical requirements have been properly identified and referenced and that these requirements have been met.

- Appropriate modeling and calculational methodology have been used

- Assumptions have been adequately described and, when necessary, justified
- Input parameters have been correctly selected and incorporated into the calculation
- Information and equations from external sources have been referenced
- Numerical calculations are correct and have been completely documented
- Results are reasonable considering the input.

It is emphasized that a numerical check is not sufficient. The checker is responsible for every item on every sheet -- including the completion of the title block and page numbers. The importance of a complete and thorough review cannot be overemphasized.

To properly check calculations:

- The originator supplies the designated checker with a machine copy of the calculations. Originals should not leave the originator's possession until they are ready for final checker signing.
- The checker marks the calculation copy with a yellow marker for all items he approves.
- If the checker disagrees, for any reason, the checker crosses through the item with a red marker and writes the recommended correction or comment above it.
- The checker signs and dates all pages of the checkprints.
- The checker returns the checkprints to the originator who, in turn, reviews all recommended changes. Agreed-to corrections may be marked with a check of a third color. If a disagreement still exists, the originator adds comments to the checkprints using the third color, initials and dates the checkprints, and then confers with the checker until all differences are resolved.
- The originator corrects, or "scrubs", the calculation originals so they agree with the checkprints. A one-to-one correspondence between the originals and checkprints must exist.

- The originator gives the originals and checkprints to the checker who compares them to verify all agreed-to corrections have been made.

- When the checker is satisfied, the checker signs and dates the originals.

Checkprints shall be maintained as a part of the project file, of equal importance as the originals.

Under no circumstances shall calculations be altered after final signature by the checker. If it becomes necessary for calculations to be revised, the new pages shall be formally checked as described above.

Verification of the Design Analysis Model

The room/panel behavior simulation portion of the Design Analysis Model is comprised of a number of subroutines which are called by a main program. The shaft-seal portion of the Design Analysis Model is comprised of two programs. Each subroutine of the ROOM-SCALE model was checked individually according to one of the three methods described above, as summarized in Tables F-1 and F-2. Each of the two shaft-seal programs were verified through independent hand calculations.

Validation of the Design Analysis Model

To date, the WIPP Performance Assessment models have not been coupled to the same degree as the Design Analysis Model. Consequently, code validation requires that modules of the Design Analysis Model be validated against codes used by SNL to predict individual processes that influence repository performance. Examples include comparison of predictions of room-closure and brine-inflow rates, predicted advection of gases along undisturbed anhydrite beds and up shaft seals, and simulation of borehole intrusion consequences.

Preliminary steps have been taken to validate the Design Analysis Model against the WIPP Performance Assessment models currently under development by SNL. Closure rates predicted by the Design Analysis Model, and by SNL's adaptation of the SANCHO code, are quite similar until the repository reaches lithostatic pressure. At that point, the SANCHO code predicts reinflation of the room in response to continued gas generation, while the Design Analysis Model assumes some advection of gas along anhydrite beds but room pressures in excess of lithostatic.

Validation of other components of the Design Analysis Model are more time consuming, and will not be performed unless results from the WIPP Performance Assessment models yield relative results substantially different from those predicted by the EATF. Performance Assessment is modeling the performance of three waste types: untreated wastes, Level II treated wastes, and Level III treated wastes. If relative performance between the three waste types are similar to those predicted by the Design Analysis Model, then the model will be

validated for its intended purpose, which is to compare the effectiveness in improving repository performance using the various engineered alternatives. The Design Analysis Model cannot predict absolute performance, as that was never the objective of the model. Consequently, the Design Analysis mode cannot be validated against the suite of Performance Assessment models.

Additional Quality Assurance for This Report

An independent review group was formed to review this report. The group consisted of an engineering and management consultant, and two professors in the fields of chemical engineering and geology. The modeling procedures were reviewed by the group for consistency, and termed by them to be a technically correct representation of the process in the repository, given the limitations involved.

TABLE F-1

ROOM-SCALE COMPONENTS OF THE DESIGN ANALYSIS MODEL

SUBROUTINE	METHOD OF VERIFICATION
ROOMSCAL	Independent hand calculation
READAT	Independent hand calculation
INITIALIZE	Independent hand calculation
DIFCOEF	Independent hand calculation
BRINFLOW	Independent hand calculation
COMPACTION	Independent hand calculation
CREEP	Independent hand calculation
MASSGAS	Independent hand calculation
DIFFUSION	Independent hand calculation
ADVECTION	Independent hand calculation
VISCORR	Independent hand calculation
SHFTSEAL	Independent hand calculation
MBFLOW	Independent hand calculation
BRINTERACT	Independent hand calculation
VOLESTIM	Independent hand calculation
LKEOS	Independent hand calculation
BOREHOLE	Independent hand calculation
RADACTIM	Independent hand calculation
RADSOLUB	Independent hand calculation
ESTHCKSS	Independent hand calculation
CUTTINGS	Independent hand calculation
ISE1	Independent hand calculation
ISE2	Independently developed program
ISE1E2	Independent hand calculation
SUMRULE	Independent hand calculation
PRINTOUT	Independent hand calculation
TIMEDATE	Not Applicable

TABLE F-2

SHAFT-SEAL COMPONENTS OF THE DESIGN ANALYSIS MODEL

SUBROUTINE	METHOD OF VERIFICATION
SEAL	Independent hand calculation
TSEAL	Independent hand calculation

APPENDIX G

REPORT OF THE EXPERT PANEL ON APPLICATIONS OF CEMENT MATERIALS FOR USE AT THE WIPP

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PREFACE

The Expert Panel On Applications Of Cement Materials for use at the WIPP was convened by the EATF from May 15-17, 1990 and was composed of individuals representing many disciplines and organizations. The participants included:

CHAIRMAN AND FACILITATOR

Jonathan Myers, IT Corporation

PANEL MEMBERS	ORGANIZATION
D. R. (Rip) Anderson	Sandia National Laboratories
Ned E. Bibler	Westinghouse Savannah River Company
John Boa	U. S. Army Corps of Engineers
Barry M. Butcher	Sandia National Laboratories
Mark Gardiner	IT Corporation
Hamlin Jennings	Northwestern University
Lawrence Johnson	AECL Research/Whiteshell
Chris Langton	Westinghouse Savannah River Company
Ken E. Philipose	AECL Research/Chalk River
Lillian Wakeley	US Army Corps of Engineers

OBSERVERS

Don Blackstone	U.S. Department of Energy/WIPP Project Office
Tod Burrington	Westinghouse Electric Corporation/Waste Isolation Division
Andrew Peterson	Sandia National Laboratories
John Valdez	IT Corporation

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EXECUTIVE SUMMARY

An expert panel was convened as part of the Engineered Alternatives Task Force, to determine whether cementitous materials should be considered further for use at the WIPP to improve long-term performance and reduce uncertainties in key performance parameters. The panel included eleven members from organizations including the Army Corps of Engineers (2), Savannah River (2), Atomic Energy of Canada Ltd. (2), Sandia National Laboratories (2), Northwestern University (1), and IT Corporation (2). Observers were also present from Westinghouse and the DOE WIPP Project Office.

Specific applications of cement-based materials considered are for use as backfill, waste forms, and container material. The panel was confident that a methodology can be developed to evaluate long-term performance of cementitous material formulations for use at the WIPP, and agreed that properly formulated cement-based materials are likely to meet long-term performance criteria including permeability and shear strength. The panel also cautioned that the development of proper formulations for these applications should consider the specific environment and must take into account waste and repository characteristics.

In the case of backfill, the panel recommended the use of a concrete with a high percentage of salt aggregate to provide deformability and maintain low permeability. Several reactive components were suggested for evaluation for use as a binder, including reactive alkalis such as CaO or MgO, hygroscopic glass, Portland cement, zeolite, expansive clays, and aluminate cements. It is anticipated that such a formulation will have plastic properties that will self-seal and maintain acceptably low permeabilities under the conditions of 2,000 psi confining stress in the repository environment.

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1.0 INTRODUCTION

1.1 BACKGROUND

The Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico is an underground repository designed for the safe geologic disposal of transuranic (TRU) wastes. TRU wastes are generated from defense-related activities of the U.S. Department of Energy (DOE). The underground storage area of the WIPP repository is located 2,155 feet below the surface in the Salado Formation, composed of a bedded salt (halite) of Permian (250 million year) age. After emplacement of the waste in the WIPP storage rooms, closure of the repository occurs by the creep (plastic flow) of the surrounding salt formation. This creep is in response to the pressure gradient that exists between the far-field pressure away from the repository (referred to as the lithostatic pressure, or the pressure at the depth of the repository due to the overlying rock) and the pressure in the repository which is initially at atmospheric conditions. In a freshly excavated room, this creep rate is of the order of a few inches per year. Under ideal conditions, creep results in complete closure of the repository, and the waste is permanently encapsulated in salt and isolated from the surrounding environment.

The waste to be disposed of consists of materials such as laboratory hardware, inorganic sludges, protective clothing, plastics, rubber, resins, and tools that have become contaminated with transuranic elements, mostly plutonium, with minor amounts of americium, uranium, neptunium, and thorium. The specific isotopes of these elements that are present in WIPP waste are generally alpha emitters with long half-lives and minimal heat production, although a small volume (less than 3 percent) of the inventory is categorized as "remote-handled" waste which has moderate heat production from short-lived fission products. The majority of waste to be disposed of is presently stored in 55-gallon steel drums and a lesser number of steel boxes, at major DOE waste generation and storage sites across the country.

1.2 ENVIRONMENTAL CONDITIONS WITHIN THE REPOSITORY

The anticipated environmental conditions in the WIPP repository are summarized as follows:

- Temperature - The temperature in the repository is expected to remain constant at approximately 26°C. The average decay heat generation from the waste is less than 0.1 watt per drum which does not significantly raise the temperature above ambient. Remote-handled TRU (RH-TRU) waste has greater heat generation, however the volume of RH-TRU is less than 3 percent of the total inventory.

- Humidity - Limited volumes of brine have been observed to flow into the repository (Deal and Case, 1987). After the facility is sealed, the humidity of the room will be controlled by the thermodynamic activity of H_2O in the brine. Assuming there is a small volume of saturated brine in the sealed repository with gas above the brine, then the relative humidity in the repository will be buffered at approximately 70 percent.

- Oxygen - Although the repository will initially have an oxic environment, this oxygen is expected to be consumed in the process of microbial degradation of organic materials present in the waste, thereby eventually leading to an anoxic environment. Some oxygen is also expected to be consumed by corrosion of the mild steel drums. However, some oxygen could also be generated within the repository from the radiolytic decomposition of brine. Overall, the rate of generation of oxygen by radiolysis is expected to be less than the rate of consumption of oxygen by microbial degradation and corrosion, therefore an anoxic environment is expected to be eventually established within the repository.

- Stresses - The creep closure of salt surrounding the waste will eventually result in isostatic (nondirected) stress equal to the lithostatic pressure of about 2000 psi (15 MPa). However, since the storage rooms are 33 feet in width and only 13 feet in height, the closure rate in the ceiling-to-floor direction is greater than the closure rate in the horizontal direction. This will result in some directed stress until complete closure has taken place. Once the room has completely repressurized, isostatic conditions are expected to return.

- Brine Composition - The major elements present in the brine include Cl^- (~200,000 mg/l), Na^+ (~85,000 mg/l), Mg^{+2} (~18,000 mg/l), K^+ (~18,000 mg/l), and SO_4^{-2} (~17,000 mg/l). Br and B are also present at concentration above 1,300 mg/l. The pH is 6.1, and the total dissolved solids equal ~350,000 mg/l. The brine is saturated with respect to the minerals halite (NaCl) and anhydrite ($CaSO_4$).

1.3 REGULATORY CONSIDERATIONS

The geologic disposal of TRU waste is governed by U.S. Environmental Protection Agency (EPA) Standard 40 CFR Part 191 (EPA, 1985). This regulation sets limits on the cumulative allowable releases of radioactivity to the accessible environment over a 10,000-year period, based on predictive modeling analyses referred to as performance assessment (PA). Both undisturbed performance, as well as the consequences of inadvertent human intrusion in the form of future exploratory drilling through the storage rooms, must be considered, as mandated by the EPA Standard. In addition, the Standard requires that the uncertainties in the predicted 10,000-year cumulative release be developed by propagating uncertainties in input parameters through the calculations.

The performance assessment for the WIPP repository is being conducted by Sandia National Laboratories (SNL), and is expected to be completed by 1994 (DOE, 1990d). Work currently in progress at SNL has suggested that there might be potential problems with the current waste forms and/or repository design and that some modifications may be necessary to demonstrate compliance with the EPA Standard. In response to this concern, and based on the recommendations of the National Academy of Sciences (NAS), the DOE WIPP Project Office established the Engineered Alternatives Task Force (EATF) in September 1989. The charter of the EATF was to evaluate the effectiveness and feasibility of various modifications to the WIPP facility design and waste forms that would improve the long-term isolation capability of the repository and/or reduce uncertainties in key performance parameters (Hunt, 1990). Preliminary assessments of the long-term performance of the disposal system have

identified three key parameters that affect disposal system performance: (1) gas generation, (2) waste form and backfill permeability, and (3) waste element solubility. The importance of these parameters is discussed in the following sections.

1.4 GAS GENERATION

Preliminary assessments of the long-term performance of the disposal system have identified gas generation as one of the key parameters that might affect performance of the disposal system (DOE, 1990a). Lappin et al. (1989) discusses the possibility that up to 1,500 moles of gas can be generated per drum (or drum equivalent) of waste from anoxic corrosion, microbial degradation, and radiolysis, at rates that may be as high as 2.55 moles/drum/year. Although processes exist to dissipate excess gas pressure, these processes are currently believed to be slow relative to the current estimates of gas generation rates, resulting in gas pressures in storage rooms that may temporarily exceed lithostatic pressure. The consequences of exceeding lithostatic pressure are currently being evaluated by SNL (Lappin et al., 1989). Unless these evaluations conclusively demonstrate that either excess pressures will not occur or that excess pressures will not degrade the performance of the disposal system, some type of facility or waste form modification may be required to either eliminate or reduce the rate of gas generation.

The three main mechanisms for the generation and consumption of gases in the underground environment are: (1) corrosion of metals, (2) microbial activity, and (3) radiolysis. The potential for these mechanisms to generate gases is discussed below.

Corrosion of Metals - The primary metals that are of concern with respect to gas generation are ferrous alloys (iron and steel) and aluminum. These metals are present in the inventory as metallic waste, as well as the 55-gallon steel drums and steel boxes that contain waste. There are two general mechanisms for corrosion of metals that may operate in the underground WIPP environment. Oxic corrosion occurs when iron reacts with oxygen to form corrosion products, usually iron oxides. Anoxic corrosion occurs when iron reacts with brine or water vapor to form iron oxides or oxyhydroxides plus hydrogen. The net effect of oxic corrosion is the consumption of oxygen, and the net effect of anoxic corrosion is the production of hydrogen. Water in either a liquid or vapor state is required for anoxic corrosion and is consumed in the process, suggesting that the availability of moisture may be the rate-limiting step in this process. Cement containers can be used to replace the steel drums and boxes, thus eliminating a major source of metal in the inventory. The use of cement waste forms and/or cement backfill will raise the pH of any brine in the storage room to values which tend to reduce the corrosion rates of iron-based alloys. The use of low permeability waste forms and backfill will limit the availability of brine for corrosion.

Microbial Activity - Microbial activity can potentially break down organic materials such as paper, plastic, and wood, consuming oxygen and generating carbon dioxide and methane in the process. Sulfate reducing bacteria, if present, can generate hydrogen sulfide from sulfate present in natural brine, and nitrate reducing bacteria, if present, can generate nitrogen from nitrate salts present in the waste. The large mass of organic materials in the WIPP inventory, plus the presence of sulfate and nitrate suggest that there is a potential to eventually generate

large amounts of gases. However, the rate at which these gases are generated is a key factor in predicting pressurization of the waste storage rooms. The use of a cement waste form and/or a cement backfill may raise the pH of any moisture present in the storage room to a range where the rates of microbial activity are reduced.

Radiolysis - Radiolysis has the potential to generate hydrogen and oxygen from the decomposition of water; and carbon dioxide, carbon monoxide, hydrogen, and methane from the decomposition of organic materials. Oxygen that is generated by the decomposition of water will probably be consumed by microbial or chemical reactions, but the accumulation of hydrogen, methane, and carbon dioxide is of potential concern. The dominant form of radiation present in TRU waste is the emission of alpha particles which have a very limited range. A "matrix depletion effect" is commonly noted in alpha radiolysis experiments, where the gas generation rate decreases with time as the material that is in close proximity to the alpha source becomes depleted in volatile components. However, the matrix depletion effect has not been observed in situations where the alpha emitters are dissolved or are otherwise in intimate contact with aqueous solutions. The potential for the generation of radiolytic gases from unprocessed or incinerated waste immobilized in cement needs to be evaluated.

1.5 PERMEABILITY

A second potential problem with demonstrating regulatory compliance relates to the consequences predicted from future inadvertent human intrusion events. Some of the preliminary evaluations of compliance with the containment requirement of 40 CFR Part 191 (EPA, 1985) performed by SNL suggest that some of the current waste forms (under current interpretations of human intrusion provisions) may eventually be found to be unacceptable for disposal at the WIPP (Marietta et al., 1989). This may be due to uncertainties in key performance parameters of the waste forms. Key parameters that control the release of radionuclides during human intrusion scenarios are permeability of the waste and backfill in the storage rooms and radionuclide solubilities.

The consequences of release scenarios involving the inadvertent exploratory drilling by future generations are critically dependent on the permeability of the waste storage rooms. Panel member B. Butcher (SNL) estimated that the average permeability of the materials in the room needs to be within five orders of magnitude of the intact host rock to demonstrate compliance. However, sensitivity analyses performed subsequent to the panel meeting suggest that five orders of magnitude is in fact too high. Currently, a reduction in permeability to 10^{-18} m^2 for the backfill is recommended, and a value of 10^{-19} m^2, if possible, is preferred. Both crushed salt and crushed salt with bentonite are predicted to reach 10^{-19} m^2 within 100 years. Some proposed alternative designs that lower the permeability of the waste and backfill involve the use of cemented waste forms and/or cement backfill. A key question here is whether a low permeability cement can be relied upon to maintain an adequately low permeability in the repository environment over the 10,000-year regulatory period.

1.6 WASTE ELEMENT SOLUBILITIES

The solubilities of waste elements in the repository environment have been identified as a critical performance parameter in SNL preliminary performance assessment analyses (Marietta et al., 1989). Solubility, in this case, is defined as the maximum amount of a waste element that can be dissolved in brine that may contact the waste. Most release scenarios involve the transport of contaminated brine from the waste storage rooms to the environment. Two critical parameters that determine the consequences of such scenarios are the volume of brine available for transport and the solubility of waste elements in that volume of brine. The radionuclide releases predicted from design analysis and performance assessment models are linearly dependent upon the values chosen for waste element solubilities. Increasing the assumed solubility of a waste element by a factor of two, for example, will increase the predicted release of that element by roughly the same factor. Thus, the uncertainty in release estimates are directly proportional to the uncertainty in solubility assumptions.

Existing data on actinide element solubilities are available for dilute ground waters, but data appropriate for the brine environment at the WIPP are not available, nor is there a valid method of extrapolating solubility data obtained from dilute systems to high-strength brine environments. The current performance assessment calculations performed by SNL use a range of actinide solubilities from 10^{-3} to 10^{-9} moles/liter (Rechard et al., 1990).

Some engineered alternatives under active consideration involve the use of cemented waste forms, the use of grout backfill, and the addition of lime (CaO) to the waste drums. Advantages of cemented waste, grout, and lime is that any brine that comes in contact with these materials will undergo an increase in pH from the ambient value of approximately 6.0 up to a value of approximately 11.5. It is known that, in general, the solubilities of actinide elements are several orders of magnitude lower at pH values above 9 than at neutral pH conditions, however, the exact decrease in solubilities over this pH range in WIPP brines is unknown. The relative merits of these types of alternatives can only be fully evaluated by obtaining estimates of waste element solubilities both at the anticipated pH conditions and at the elevated pH conditions offered by these alternatives.

It should be noted, however, that the pH of the room environment can only be controlled by the use of a buffer if there is no significant movement of fluid through the repository. Such movement would eventually dissolve and remove the buffer material, limiting its effectiveness. No such migration of fluid through the repository is anticipated under undisturbed conditions. However, human intrusion scenarios that involve the connection of a storage room with an underlying brine reservoir in the Castile Formation may provide sufficient migration of brine through the room to eventually remove the buffer. In this case, the pH of the room environment would be dominated by the pH of the Castile brine.

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2.0 EVALUATION OF CEMENT-BASED MATERIALS

The mission of the Cement Materials Expert Panel was to determine whether cementitious materials should be considered further for use at the WIPP to improve long-term performance and reduce uncertainties in key performance parameters, including gas generation and permeability of the waste/backfill composite.

Specific applications considered for cementitious materials are for use as backfill to lower the permeability of the storage rooms, waste forms to immobilize waste elements in a low permeability medium, and for use as a container material to eliminate hydrogen generation from anoxic corrosion of the steel drums.

There is little doubt that cementitous materials will, at least initially, perform adequately in these roles as backfill, container, and waste forms. The critical issue is one of longevity. Values for critical parameters such as permeability of the cement must remain within an acceptable range for the 10,000-year regulatory period. The EPA standard recognizes the difficulty in quantifying the performance of a disposal system over a long period of time and allows the use of "expert judgment" in estimating performance.

A working assumption that the Panel used in evaluating candidate materials is that the more closely the materials resemble the host rock, the more they reduce chemical potential gradients, thereby minimizing any driving force for degradation of the material. Risk or uncertainty can be reduced by minimizing the use of unlike materials. It was also assumed that in the case of backfill and waste forms, rigid materials are not necessarily the best choice, since a plastic material will have self-healing properties under confined conditions.

The Panel also cautioned against using conventional construction thinking when considering the longevity of cement-based materials in the WIPP environment. The major processes that affect the physical stability of these materials in a surface environment are changes in temperature and humidity, cyclical wetting/drying and freeze/thaw, directed stresses, exposure to wind, and exposure to flowing water, which can selectively remove leachable phases in the cement. However, these processes that can promote physical degradation do not occur in the WIPP repository environment. The constant temperature and humidity, isostatic (nondirected) stress and low permeability of the host rock (which precludes flowing ground water) offer an environment that will tend to maintain the physical properties of cement-based materials. In this environment, chemical durability is the main issue. The dehydration of cement phases or the reaction of cement phases with CO_2 are processes that lead to a decrease in volume of solids. In rigid materials, these processes may lead to increases in porosity and permeability over time. However, if the material is plastic under the applied isostatic stress, then any chemical reactions that lead to a volume reduction will not necessarily result in a corresponding increase in porosity.

The following sections summarize the recommendations of the Cement Panel with respect to use of cement-based materials as a backfill, waste form, and waste container.

2.1 BACKFILL CONSIDERATIONS

A backfill material will be emplaced between and around the waste containers and will be required to eventually consolidate under lithostatic stress to a low permeability and porosity, thereby encapsulating the waste. The requirements of the backfill are as follows:

- Maintain permeability within three orders of magnitude of the intact host rock. This range of permeability will reduce the release of radionuclides in response to human intrusion events.

- Fill voids as completely as possible. This will lead to rapid reconsolidation and will minimize the accumulation of brine in the storage rooms.

- Maintain acceptable shear strength. This will reduce the volume of waste that may be brought to the surface if the storage room is breached by an exploratory drill hole.

- Minimize residual free water. This will reduce the volume of contaminated fluid that may be available for transport away from the storage room environment.

The current reference backfill is crushed salt, which has many favorable properties and may prove to be acceptable. One potential drawback however, is that crushed salt has an initially high porosity and will require a certain length of time, ranging from approximately 50 to 150 years, to reconsolidate and achieve acceptably low permeability and porosity. If performance assessment studies indicate that it is necessary to maintain low permeability and porosity during this early postclosure period, then an alternate material may need to be selected.

The recommendations of the Panel for such an alternate material is as follows:

- Use cement with a high percentage of salt aggregate. This will provide deformability, will be self-sealing, and will maintain low permeability under the anticipated 2,000-psi isostatic confining stress. Concretes with aggregate contents as high as 95 percent have been used in underground applications at the Nevada Test Site, although concretes with high salt content have not been produced to date.

- Use a WIPP brine composition as the makeup water. This will minimize concentration gradients between the backfill and the host rock.

- Use the minimum volume of brine necessary to form an emplaceable grout. This will minimize the volume of residual brine. Water/cement mass ratios of less than 0.3 have been achieved, although not with brine.

- Add the minimum amount of reactive component necessary to absorb most of the added brine when set. This will ensure that the backfill will have mechanical properties similar to that of consolidated salt. The Panel agreed that low modulus

(50 - 100 psi), self-sealing concretes have been prepared before for other applications.

Reactive components that should be considered for evaluation include: reactive alkalis such as CaO or MgO, hygroscopic glass (silica fume), hemihydrite (partially hydrated gypsum), Portland cement, zeolites, expansive clays, and aluminate cements. The Panel advised that simpler systems, such as aluminate cements are less complex than Portland-type formulations and therefore have more predictable behavior. Experiments will be required to select the reactive component and optimize the proportions of salt, brine, and reactive components. The objectives of these experiments may include the following:

- Determination of hydration capacity
- Characterization of hydrated phases
- Development of optimal emplacement techniques
- Determination of residual free brine volume
- Measurement of permeability under confining stress
- Evaluation of set time
- Determination of shear strength
- Optimization of dry mix grain size
- Measurement of initial viscosity.

The following points were made by the Panel on the anticipated performance of the recommended backfill formulation:

- Cement-based grouts can be formulated to have plastic properties that will self-seal and maintain acceptably low permeabilities under a 2,000-psi confining stress.

- Permeability and creep properties of this formulation will be similar to salt.

- No mechanism that may degrade permeability could be identified under the anticipated repository environmental conditions of constant temperature and humidity, lithostatic confining stress. Also, no ground water flow is anticipated that may dissolve and remove backfill material, with the possible exception of a human intrusion event that provides a connection with the room and a Castile brine reservoir.

2.2 WASTE FORM CONSIDERATIONS

The WIPP waste inventory can be divided into three main categories: sludges; organics (paper, plastic, wood, rubber, etc.); and inorganics (glass, metals, ceramics, etc.). If it is determined through the Performance Assessment process that the gas generation rates, permeability, shear strength, or waste element solubilities for some or all of the three waste categories are unacceptable, then some form of waste processing may be necessary to produce alternate waste forms with acceptable properties. The use of cemented waste forms provides the following potential advantages:

- Low permeability and porosity, especially if a high salt aggregate formulation of the type proposed for use as backfill is used (see Section 2.1).

- High shear strength, which will minimize release of waste in response to inadvertent exploratory drilling through the repository by future generations.

- Establishment of a more favorable chemical environment. Portland-type cement will buffer the pH of any brine that comes in contact with the waste to values in the range of approximately 12. These conditions will reduce the anoxic corrosion rate of ferrous alloys, reduce the rate of microbial degradation, and lower waste element solubilities.

Potential applications of cement-based waste forms are discussed below.

Shredding and Cementing of Organic Waste - This waste form will have a lower initial permeability and porosity than unprocessed organic waste forms, and the pH buffer effect will reduce microbial degradation rates and lower waste element solubilities.

Shredding and Cementing of Inorganic Waste - Glass, ceramic, and metallic waste forms can also be shredded or crushed and then cemented to produce a low permeability waste form. The elevated pH environment that this waste form creates will reduce the corrosion rate of ferrous-based metals, but can increase the anoxic corrosion rate of metallic aluminum. If hydrogen generation from anoxic corrosion is determined to be a problem, then cementation of metallic aluminum should be avoided.

Cemented Incinerator Ash - If it is determined that microbial gas generation must be eliminated, then some type of thermal treatment may be required to destroy the organic component of the waste. The resultant ash will need to be incorporated into a matrix to eliminate any hazard from airborne alpha particles. Cementation of incinerator ash from medical waste and low-level radioactive waste incinerators is a well-established technology that can produce a low permeability, low porosity waste form with little or no gas generation potential. The pH buffering effect of portland-type cement will have the added benefit of reducing waste element solubilities.

Cementation of Sludges - Sludges consisting of chemically precipitated metal oxides and hydroxides comprise approximately 20 percent by volume of the total WIPP inventory [based on (DOE, 1988b)]. If it is determined that the permeability of these sludges is too high, then cementation of the sludges may be required to produce a waste form with a lower permeability. Cementation of newly generated sludges can easily be accomplished by modifying the waste streams. Stored drums of sludge will need to be opened, broken into chunks, cemented and repackaged.

One concern regarding cemented waste forms is that the intimate contact between the alpha emitters and free (unbound) water in the cement matrix may yield hydrogen and oxygen from the radiolytic decomposition of the water. The Panel recommends that the gas generation potential from this process be evaluated, and, if necessary, investigate methods to reduce radiolytic gas generation. These methods may include the following:

- The addition of nitrite salts to inhibit gas generation
- The use of heat to reduce the volume of unbound water
- The use of a self-desiccating formulation to minimize unbound water
- The application of mechanical force during the curing process to press excess water from the matrix.

The panel cautioned that the influx of brine into the waste storage rooms should be avoided since such influx may cause additional radiolytic gas generation.

The following is a summary of the recommendations of the Panel on the applications of cement materials for use as waste forms.

- Cemented waste forms will be effective in reducing the initial void volume of the storage rooms, thus leading to more rapid repressurization of the repository environment. Rapid repressurization will minimize the volume of brine that may seep into the storage rooms under a pressure gradient.
- Formulations similar to those suggested for backfill should be evaluated.
- Grouting of metallic aluminum waste may generate hydrogen.

The heterogeneous nature of the waste suggests that the chemical interactions between the various waste components as they age and degrade will probably be quite complex. For this reason, the longevity of cemented waste forms is less certain than longevity of the recommended backfill formulations. The Panel cautioned that the chemical interactions between the waste and the cement matrix needs to be clearly understood or there will be no assurance that a cemented waste form will maintain desirable properties such as low permeability for 10,000 years. The Panel also stated that they have no reason to believe that aging reactions will degrade the performance of cement waste forms. However, lacking a quantitative basis for long-term waste form permeability, greater reliance should be placed on the recommended backfill formulations, rather than on cement waste forms.

2.3 CONTAINER CONSIDERATIONS

Waste containers are required for ease of handling and to contain the hazardous and radioactive materials, thus providing protection for workers and the environment. The current containers are standard 55-gallon drums, plus a lesser number of steel boxes. These

containers provide adequate protection. However, if hydrogen generation from anoxic corrosion of steel is determined to be a problem in long-term performance of the repository, then an alternate container may need to be employed.

The requirements of such an alternate container are as follows:

- The material should be easily fabricated into a container of the required shape. This can be a drum, rectangular box, or hexagonal cylinder.
- The containers should not degrade in any way that will significantly increase the permeability of the storage room environment.
- The cost of the alternate container should not be greater than a container fabricated from a noncorroding metal such as titanium.
- The container should be able to show compliance with the Department of Transportation (DOT) Type A Packaging Tests (DOT, 1989). Compliance is demonstrated by surviving a drop test and a puncture test with no loss of containment.
- The container material should either not generate gas or have an acceptably low gas generation rate in the repository environment.
- The container material should be chemically compatible with the backfill and waste forms.

The panel agreed that cement-based containers should be considered along with other materials for use as alternate containers. A wide range of properties is achievable with cement-based materials, including high flexural and compressive strength, low porosity, and low permeability.

The challenge in designing a cement-based container will be to utilize high-strength low-cost materials to minimize wall thickness and weight, as well as maximizing payload volume, while maintaining compliance with the DOT containment requirements. The Panel agreed that this goal is probably achievable through the use of reinforcement materials embedded in the cement to increase strength. This approach will allow a lighter design with thinner walls than would be possible with nonreinforced cement.

2.4 COMPARTMENTALIZATION CONCEPT

The Panel suggested that a compartmentalization concept should be considered where waste is emplaced in a series of compartments that are isolated from each other by some low permeability material. With this approach, the total volume of waste that can be released by any single event (such as intrusion by an exploratory drill hole) is limited to the volume of waste that is contained within the compartment that is breached. They further advised that the waste should be compartmentalized on several scales, including pieces of waste within

containers embedded in cement, waste containers embedded in backfill, waste compartments within rooms periodically separated by zones of thick backfill, and individual waste panels isolated by panel seals. This "fractal compartmentalization" will provide engineered upper bounds on releases resulting from a wide range of intrusion events.

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3.0 PANEL CONCLUSIONS

The Panel is confident that a methodology can be developed to evaluate the long-term performance of cementitious material formulations for use as backfill, waste forms, and containers at the WIPP. They also agree that properly formulated cement-based materials are likely to meet long-term performance criteria including low permeability and high shear strength required for backfill and waste forms, and high impact resistance required for waste containers.

In the case of backfill, the Panel provided guidance on the development and testing of a high salt aggregate formulation that will have plastic properties that will self-seal and maintain low permeabilities under a 2,000-psi confining stress.

For waste forms, the Panel recommended that shredded and cemented organic and inorganic wastes, cemented incinerator ash, and cemented sludges will produce superior waste forms if properly formulated. They did, however, caution that the development of effective formulations for waste forms must take into account the repository environment as well as the physical and chemical characteristics of the waste to be effective for the 10,000-year regulatory period.

For containers, the Panel agreed that cement-based containers should be considered along with other materials for use as alternate containers. A wide range of container properties is achievable with cement-based materials, including high flexural and compressive strength, low porosity, and low permeability, especially by incorporation of reinforcement techniques.

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APPENDIX H

REPORT OF THE WASTE CONTAINER MATERIALS PANEL

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PREFACE

The Waste Container Materials Panel, described in this report, was composed of individuals representing many disciplines and organizations. The participants included:

CHAIRMAN AND FACILITATOR

Hans Kresny, President, Solmont Corporation

PANEL MEMBERS

NAME	AFFILIATION	DISCIPLINE
Barry Butcher	Sandia National Laboratories	Performance Assessment
Noel C. Calkins	Calkins R&D Inc.	Ceramic Fabrication
Frank W. Clinard, Jr.	Los Alamos National Laboratory	Basic Ceramic Research
F. H. Froes	University of Idaho	Physical Metallurgy
Hamlin M. Jennings	Northwestern University	Cementitious Materials
Daniel C. Meess	West Valley Nuclear Services	Concrete Container Fabrication
Jonathan Myers	International Technology Corp.	Geochemistry
Rodney Palanca	Westinghouse Electric Corp. Waste Isolation Division	Waste Handling/Repository Operations
R. E. Westerman	Pacific Northwest Laboratories	Metallurgy/Corrosion

OBSERVERS

NAME	AFFILIATION
Ravi Batra	Department of Energy (DOE) WIPP Project Office
Doree Donovan	Westinghouse Electric Corporation Waste Isolation Division
Sayan Chakraborti	International Technology Corporation

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EXECUTIVE SUMMARY

The Waste Isolation Pilot Plant (WIPP) is an underground repository designed for the safe geologic disposal of transuranic (TRU) wastes generated from defense-related activities of the U. S. Department of Energy (DOE). The WIPP storage rooms are mined in a bedded salt (halite) formation and are located 2,155 feet below the surface. Once the waste is disposed in the storage rooms, complete closure of the repository occurs by the creep (plastic flow) of the salt formation, and the waste is permanently isolated from the surrounding environment.

The geologic disposal of TRU waste is governed by the U. S. Environmental Protection Agency (EPA) Standard - 40 CFR Part 191 (EPA, 1985), which sets limits on the cumulative allowable releases of radioactive isotopes to the accessible environment over a period of 10,000 years. The study done to show compliance with this regulation is referred to as performance assessment. The performance assessment for the WIPP repository is being conducted by the Sandia National Laboratories (SNL), and is expected to be completed in 1994 (DOE, 1990d). Preliminary analyses performed at SNL indicate that the current waste forms may need some modifications in order to demonstrate compliance with the EPA Standard. In response to this concern and based on the recommendations of the National Academy of Sciences, the DOE WIPP Project Office established the Engineered Alternatives Task Force (EATF) in September 1989. The charter of the EATF was to evaluate the effectiveness and feasibility of various modifications to the current waste forms and/or WIPP facility design which would improve the long-term isolation capability of the repository (Hunt, 1990).

The ongoing performance assessment studies have identified gas generation as one of the three key parameters that might affect the performance of the disposal system (DOE, 1990a). The three mechanisms for the generation and consumption of gases in the underground repository are:

- Corrosion of metals
- Microbial activity
- Radiolysis.

The corrosion of metals could take place by two general mechanisms; oxic corrosion, when iron reacts with oxygen to form oxides or oxyhydroxides, and anoxic corrosion, where iron reacts with brine or water vapor to form oxides/oxyhydroxides and hydrogen. Microbial activity has the potential to attack organic materials such as paper, plastic, and wood present in the WIPP waste inventory, consuming oxygen and generating carbon dioxide and methane in the process. Radiolysis can potentially generate hydrogen and oxygen from the decomposition of water; and carbon dioxide, carbon monoxide, hydrogen, and methane from the decomposition of organic materials.

The gases produced by the above mentioned mechanisms may result in higher than acceptable pressure in the repository, because although the excess gas pressure can be dissipated by advection through the surrounding rock, the rate of advection is believed to be

slow relative to the current estimates of gas generation rates. The effect of any excess gas pressure on the performance of the repository has not yet been conclusively determined, and is presently being studied by SNL.

The carbon steel drums and boxes that are presently being used for the storage of TRU waste are expected to corrode if they come in contact with the brine in the repository, and generate hydrogen by the process of anoxic corrosion. Although the effect of excess gas pressure is still to be determined by SNL, the EATF is studying alternate waste container materials, so that if necessary, modifications to the existing container materials can be addressed in an effective manner.

The Waste Container Materials Panel (WCMP) was convened by the EATF from August 20-21, 1990, for the preliminary identification and evaluation of alternative materials for manufacturing waste containers that would not generate gas in the WIPP environment. The panel comprised a group of technical experts from the following disciplines:

- Basic Ceramic Research
- Ceramic Fabrication
- Cementitious Materials
- Concrete Container Fabrication
- Physical Metallurgy
- Metallurgy/Corrosion
- Geochemistry
- Performance Assessment
- Waste Handling and Repository Operations.

The specific objectives of the WCMP were to:

- Identify container materials that will not generate gas in the WIPP repository environment, or generate gas at substantially lower rates as compared to the existing container material, and can be fabricated to the requirements for containment, handling, and transportation of Contact-Handled Transuranic (CH-TRU) waste.

- Evaluate the identified materials with respect to various design requirements for a waste container such as fabricability, availability, mechanical properties, etc.

This report describes the methodology used by the WCMP to accomplish the above objectives, the evaluation of the different materials, and the conclusions reached by the WCMP regarding the possibility of using alternative waste container materials that would satisfy the gas generation requirements (if gas generation is determined to be a problem by the ongoing performance assessment studies).

METHODOLOGY FOR WCMP EVALUATION

The panel members were briefed on the WIPP repository, the different constituents of TRU waste, the regulations governing the disposal of TRU waste, performance parameters such as gas generation, permeability, etc., and the possible outcomes of excess gas pressure in the storage rooms. The existing configuration for the handling and transportation of TRU waste, the U.S. Department of Transportation (DOT) Type A Packaging Tests (DOT, 1989), and the environmental conditions within the repository such as temperature, humidity, oxygen, stresses, and brine chemistry which are likely to be encountered by the waste container materials, were also explained to the panel members.

The WCMP defined the following criteria for evaluation of the alternative waste container materials:

- Fabricability - The ease with which the material can be fabricated into a container with a size and shape similar to the existing 55-gallon drums.
- Availability - The availability of material to manufacture the required number of containers per year.
- Fabrication Capacity - The existing capacity to fabricate waste containers from the given material.
- Status of Technology - The current state of technology for fabrication of the material.
- Cost - The overall cost for manufacturing a waste container including material and fabrication costs, but excluding any research and development costs that might be necessary for some materials.
- Mechanical Properties - The ability of a container made of an alternate material to survive the DOT Type A packaging tests.
- Gas Generation Potential - The total moles of gas that can be theoretically generated by thermodynamically favored reactions between the alternative material and all other species present in the repository environment.
- Gas Generation Rate - The rate at which gas might be expected to be generated from the material by either anoxic corrosion, microbial activity, or radiolysis. The panel members agreed that the rate of corrosion under anoxic conditions was a good indicator of the rate of gas generation.

Since the existing waste containers are made of mild steel, the WCMP established mild steel as the reference standard material, and evaluated each alternative material by comparing it to mild steel with respect to the criteria mentioned above.

Apart from the evaluation criteria mentioned above, the WCMP set forth the following general design requirements for waste containers to be built from alternative materials:

- Eliminate or minimize gas generation from container material for the regulatory period of 10,000 years.
- Maintain complete containment of the waste for a minimum of 25 years, (the duration of the operating life of the repository).
- Meet DOT Type A requirements.

The WCMP also made the following assumptions about the waste containers made from alternative materials:

- The alternative waste containers would be subject to the same regulations which apply to the existing containers.
- The alternative waste containers may be "free-standing" (similar to a 55-gallon drum or box), or it could be "formed" around the waste by isostatically pressing a container material such as cement around a monolithic block of processed waste.

The different classes of materials and their subcategories evaluated by the WCMP were as follows:

- Metals
  - Copper and alloys
  - Titanium and alloys
  - High-nickel alloys
  - Zirconium and alloys
  - Stainless steel
- Ceramics
  - Fired ceramics
  - Chemically bonded ceramics
  - Glass
- Cements
  - Nonreinforced cements
  - Discontinuous reinforcement
  - Continuous reinforcement

- Coatings
  - Corrosion retardation
  - Containment enhancement for monolithic waste forms
- Polymers
  - Polyethylene.

The WCMP assumed that all the brittle materials such as ceramics, cements, and glass, will be reinforced as required to provide whatever mechanical properties are deemed necessary to satisfy the DOT Type A packaging tests.

RESULTS OF WCMP EVALUATION

The evaluation of five different groups of materials (listed above) indicate that there are quite a few candidate materials which are likely to satisfy the design requirements for alternative waste containers. The WCMP believed that subsequent to the preliminary evaluation, with respect to the criteria defined earlier, there are two important characteristics that need to be verified for each of the candidate materials through development programs; the degree to which the material can satisfy the "no gas generation" requirement, and whether it can be fabricated into a container satisfying the appropriate transportation and handling requirements. Therefore, apart from cost, the WCMP summarized its evaluations of alternative materials in terms of four other criteria closely related to the verification of the above characteristics:

- Time likely to be needed to establish the effectiveness of the material in meeting the "no gas generation" requirement.
- Time likely to be needed to develop fabrication technology, and make a full-scale fabricated container.
- Probability of success in terms of the WCMP's best judgement that the material will satisfy the "no gas generation" requirement.
- Probability of success in terms of the WCMP's best judgement that the material can be fabricated into a container satisfying DOT Type A requirements.
- Cost of container in comparison to mild steel.

It was noted by the panel members that if DOT Type A requirements are to be met, then containers made of metals and polymers would probably carry the maximum payload per container. The WCMP also came to the conclusion that any research involving microbial gas generation is likely to become a long-term project because of the uncertainty associated with microbes. Therefore, whenever possible, experimental schedules for establishing the

effectiveness of a material, and efforts to establish a full-scale product, should be planned in parallel to make the most efficient use of time.

The conclusions of the WCMP are presented in Table HES-1. It should be noted that the cost estimates do not include any developmental costs or the costs of building any new facilities that might be required for some materials. Also, the estimates of schedules do not include programmatic planning time likely to be associated with the planning of research strategies, approval of schedule and budget, etc.

The summary presented in Table HES-1 is based on preliminary evaluation of these materials, and therefore represents best estimates rather than precise values. The figures in Table HES-1 provide relative estimates of the probability of the materials in meeting the effectiveness and fabricability requirements for a container, as well as the time required to verify these probabilities. The WCMP decided that copper, titanium, high-nickel alloys, zirconium alloys, ceramics, glass, and cements are all viable materials which could possibly satisfy the design requirements for an alternative waste container. However, there are some concerns associated with each material that need to be resolved.

The WCMP noted that although ceramics and cements have excellent gas generation properties as compared to metallics, and are inexpensive, waste containers made from these brittle materials are likely to have smaller internal volumes due to the thicker container walls required to satisfy DOT Type A requirements. This will result in a smaller TRU waste payload per container. In addition, if the container weight is heavier than the existing drums, then fewer containers will make up the TRUPACT-II payload, leading to increased number of waste shipments from the storage sites to the WIPP site. These factors can have large impacts on the overall program cost beyond the low unit costs required to fabricate the containers. It should also be noted that with the possible exception of cements, there is no technology presently in place to fabricate large containers from the nonmetallic materials. Therefore, the fabrication of an acceptable nonmetallic container that would satisfy the DOT Type A requirements, is likely to require long-term research and development efforts.

Among the metallics evaluated by the WCMP, with the exception of copper, there are expensive metal alloys (titanium, high-nickel, and zirconium) that have relatively fewer uncertainties associated with them, especially with respect to fabricability, and payload volume per container. Once their low anticipated corrosion rates are validated under WIPP conditions, these alloys have the potential of immediately satisfying the design requirements. Whereas, the higher end high-nickel alloys (e.g., Hastelloy C-276), and the zirconium alloys would substantially escalate program costs (roughly by $1 billion based on 600,000 mild steel drums at a cost of $50 per mild steel drum), the WCMP felt that the lower cost titanium alloys would be adequate for the purpose. Besides, under the relatively mild temperatures expected in the repository environment (~ 30°C), there is not likely to be any notable differences in corrosion properties between the relatively inexpensive titanium alloys and the more expensive ones such as zirconium and higher end high-nickel alloys.

TABLE HES-1
SUMMARY OF RESULTS

	Time to Establish Effectiveness	Time to Establish Full-Scale Product	Cost Factor[a]	Probability of Success in Establishing Effectiveness	Probability of Success in Meeting DOT Type-A Requirements
Copper & Alloys[b]	1-2 yrs.	2 yrs.	5-8 x	90%	100%
Titanium & Alloys	1-2 yrs.	2 yrs.	10-20 x	95%	100%
High-Nickel Alloys	1-2 yrs.	2 yrs.	15-35 x	97%	100%
Zirconium Alloys	1-2 yrs.	2 yrs.	35 x	98%	100%
Stainless Steel[b]	1-2 yrs.	0-1 yrs.	5-8 x	50%	100%
Free Standing Ceramics[c]	0 yrs. (validate)	4-8 yrs.	25-30 x	99.9%	30%-90%
Chem. Bonded Ceramics[c]	0 yrs. (validate)	3-5 yrs.	1-10 x	99.9%	30%-85%
Glass[c]	0 yrs. (validate)	2-4 yrs.	1-10 x	99.9%	20%-90%
Cements[c]	1-2 yrs.	2-4 yrs.	2-8 x	99.9%	30%-85%
Polymers	5 yrs.[d]	0-1 yrs.	5-10 x	Indeterminate	100%

[a] Relative to a mild steel container.
[b] Uncertainty associated with effect of microbes - not considered in duration.
[c] Reinforced as required.
[d] Should be dropped from consideration if effectiveness cannot be proven within 5 years.

The results of the WCMP should be used to:

- Select a few promising alternative materials for detailed testing regarding their fabricability and corrosion/gas generation properties
- Evaluate, with the help of appropriate experiments, the effectiveness of the selected materials for meeting the "no gas generation" requirement
- Design and demonstrate the fabricability of the selected materials (reinforced as required) into a container satisfying all transportation and handling requirements
- Estimate the total cost per container, and its impact on overall program cost for the selected materials based on the annual fabrication requirements.

Thus, the right choice of material would have to be decided by tests on a few promising materials for effectiveness and feasibility, and would also be determined by applicable cost, schedule, and transportation constraints.

1.0 INTRODUCTION

1.1 BACKGROUND

The Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico is an underground repository designed for the safe geologic disposal of transuranic (TRU) wastes. Transuranic wastes are generated from defense-related activities of the U.S. Department of Energy (DOE). The underground storage area of the WIPP repository is located 2,155 feet below the surface in a bedded salt (halite) formation. After disposal of the waste in the WIPP storage rooms, closure of the repository occurs by the creep of the surrounding salt formation. This creep is in response to the pressure gradient that exists between the far-field pressure away from the repository (referred to as the lithostatic pressure, or the pressure at the depth of the repository due to the overlying rock), and the pressure in the repository which is initially at atmospheric pressure. In a freshly excavated room, the creep is of the order of a few inches per year. Under ideal conditions, complete closure of the repository occurs due to creep, and the waste is permanently isolated from the surrounding environment.

The waste to be disposed at WIPP consists of materials such as laboratory hardware, inorganic sludges, protective clothing, plastics, rubber, resins, and tools that have become contaminated with transuranic elements, mostly plutonium with minor amounts of americium, uranium, neptunium, and thorium. The specific isotopes of these elements that are present in WIPP waste are generally alpha emitters with long half-lives and minimal heat production. The waste is presently stored in 55-gallon steel drums and a lesser number of steel boxes at ten major waste generation and storage sites across the country.

1.2 REGULATORY CONSIDERATIONS

The geologic disposal of TRU waste is governed by the U.S. Environmental Protection Agency (EPA) Standard - 40 CFR Part 191 (EPA, 1985). This regulation sets limits on the cumulative allowable releases of radioactive isotopes to the accessible environment over a period of 10,000 years. The study done to show compliance with this regulation is referred to as performance assessment. Both undisturbed performance as well as the consequences of inadvertent human intrusion in the form of future exploratory drilling must be considered, as required by the EPA Standard.

The performance assessment for the WIPP repository is being conducted by Sandia National Laboratories (SNL), and is expected to be completed by 1994 (DOE, 1990d). Work currently in progress at SNL has suggested that some modifications to the current waste forms may be necessary to demonstrate compliance with the EPA Standard (DOE, 1990a). In response to this concern, and based on recommendations of the National Academy of Sciences (NAS), the DOE WIPP Project Office established the Engineered Alternatives Task Force (EATF) in September 1989, to evaluate the effectiveness and feasibility of various modifications to the WIPP facility design and waste forms which would improve the long-term isolation capability of the repository (Hunt, 1990). Preliminary assessments of the long-term performance of the

disposal system have identified gas generation as one of the three key parameters that might affect performance of the disposal system (DOE, 1990a). The different gas generation mechanisms are discussed in the next section.

1.3 GAS GENERATION

The three main mechanisms for the generation and consumption of gases in the underground environment are:

- Corrosion of metals
- Microbial activity
- Radiolysis

Corrosion of Metals - There are two general mechanisms for corrosion that may occur in the underground WIPP environment. Oxic corrosion occurs when iron reacts with oxygen to form corrosion products such as iron oxides or oxyhydroxides. Anoxic corrosion occurs when iron reacts with brine or water vapor to form iron oxides or oxyhydroxides and hydrogen. The net effect of oxic corrosion is the consumption of oxygen, and the net effect of anoxic corrosion is the production of hydrogen. Water, in either a liquid or vapor state, is required for anoxic corrosion and is consumed in the process, suggesting that the availability of moisture may be the rate-limiting step in this process.

Microbial Activity - Microbial activity can potentially break down organic materials such as paper, plastic, and wood, consuming oxygen and generating carbon dioxide and methane in the process. Sulfate-reducing bacteria, if present, can potentially generate hydrogen sulfide from sulfate present in natural brine, and nitrate-reducing bacteria, if present, can potentially generate nitrogen from nitrate salts present in the waste. The large mass of organic materials in the WIPP waste inventory, together with the presence of sulfate and nitrate, suggest that there is a potential to eventually generate large amounts of gases.

Radiolysis - Radiolysis has the potential to generate hydrogen and oxygen from the decomposition of water; and carbon dioxide, carbon monoxide, hydrogen, and methane from the decomposition of organic materials. Oxygen that is generated by the decomposition of water will probably be consumed by microbial or chemical reactions, but the production of hydrogen, carbon dioxide, and methane is of potential concern. The form of radiation present in TRU waste is the emission of alpha particles which have a very limited range.

The carbon steel drums and boxes currently in use are expected to corrode if they come in contact with brine in the repository. The gases produced by anoxic corrosion and other mechanisms such as microbial activity and radiolysis, may result in higher than desired pressure in the repository, because although processes exist to dissipate excess gas pressure by advection through the host rock, these processes are believed to be slow relative to the current estimates of gas generation rates. The effect of excess gas pressure on the performance of the repository is presently being studied by SNL. Whether gas generation is a problem has not yet been conclusively determined. Nevertheless, alternate container

materials are being considered now by the EATF, so that if necessary, modifications can be made in a timely manner.

1.4 THE WASTE CONTAINER MATERIALS PANEL AND ITS OBJECTIVES

The Waste Container Materials Panel (WCMP) was convened by the EATF for the preliminary identification and evaluation of alternative materials for manufacturing waste containers that would not generate gas in the WIPP environment. The panel comprised a group of technical experts from different areas of materials science, and from certain areas associated with the WIPP repository and its environment. The following disciplines were represented on the panel:

- Basic Ceramic Research
- Ceramic Fabrication
- Cementitious Materials
- Concrete Container Fabrication
- Physical Metallurgy
- Metallurgy/Corrosion
- Geochemistry
- Performance Assessment
- Waste Handling and Repository Operations.

A description of the qualifications of the members of the WCMP is provided in Attachment A. The objectives of the WCMP were to:

- Identify container materials that will not generate gas in the WIPP repository environment, or will potentially generate gas at substantially lower rates as compared to the existing container material, and that can be fabricated to the requirements for containment, handling, and transportation of Contact-Handled Transuranic (CH-TRU) waste.

- Evaluate the identified materials with respect to various design requirements for a waste container such as fabricability, availability, gas generation, mechanical properties, etc.

This report describes the methodology used by the WCMP to accomplish the above objectives, the results of the WCMP deliberations, and the conclusions reached by the WCMP regarding the possibility of using alternative materials to manufacture waste containers that would meet design objectives.

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2.0 METHODOLOGY USED BY THE WASTE CONTAINER MATERIALS PANEL (WCMP)

The WCMP was convened from August 20-21, 1990. The panel members were briefed on the WIPP repository, the different constituents of TRU waste, the applicable regulations, performance parameters such as gas generation, permeability, etc., and the possible outcomes of excess gas pressure in the storage rooms. In addition, the existing configuration for the handling and transportation of TRU waste in the TRUPACT-II package (NuPac, 1989), and the U.S. Department of Transportation (DOT) 49 CFR Part 173.465 Type A Packaging Tests (DOT, 1989) were explained to the panel.

2.1 ENVIRONMENTAL CONDITIONS WITHIN THE REPOSITORY

The various environmental conditions in the WIPP repository which are most likely to be encountered by the waste container materials were outlined as follows:

- Temperature - The temperature in the repository is expected to remain constant around 26°C, which is the ambient rock temperature at the facility horizon. Radiogenic heat generation from the waste is minimal (less than 0.1 watt per drum). Remote-handled TRU (RH-TRU) waste generates a greater amount of radiogenic heat, however it constitutes only three percent of the waste inventory.

- Humidity - Limited amounts of brine have been observed to flow into the repository, and after the facility is sealed, the humidity of the room will be controlled by the evaporation of the brine. Assuming there is saturated brine in the sealed repository with air at atmospheric pressure above the brine, then the relative humidity in the repository will be approximately 70 percent.

- Oxygen - Although the repository will initially have an oxic environment, this oxygen is expected to be consumed in the process of microbial degradation of organics present in the waste, thereby eventually leading to an anoxic environment. Some oxygen is also expected to be consumed during the corrosion process of the mild steel drums. However, some oxygen could also be generated within the repository from the radiolysis of brine. Overall, since the rate of generation of oxygen by radiolysis is expected to be less than the rate of consumption of oxygen by microbial degradation and corrosion, an anoxic environment is expected within the repository after the depletion of the initial oxygen.

- Stresses - The reconsolidation of salt, which is plastic, will result in an isostatic stress equal to the lithostatic pressure of about 2000 psi (15 MPa). However, since the storage rooms are 33 feet in width and only 13 feet in height, the reconsolidation of salt in the ceiling-to-floor direction occurs much faster than the reconsolidation in a horizontal direction. This will result in some unidirectional

stress until complete closure has taken place. Once the salt has completely reconsolidated, the stress is expected to be isostatic throughout the repository, and equal to the lithostatic pressure.

- Brine - The major elements present in the brine include Cl (~200,000 mg/l), Na (~85,000 mg/l), Mg (~18,000 mg/l), K (~18,000 mg/l), and SO_4^{-2} (~17,000 mg/l). Br and B are also present at concentrations above 1,300 mg/l. The pH is 6.1, and total dissolved solids equal ~350,000 mg/l.

2.2 EVALUATION CRITERIA FOR MATERIALS

The WCMP defined the following criteria for evaluation of alternative waste container materials:

- Fabricability - The ease with which the material can be fabricated into a container with size and shape similar to a 55-gallon drum. Rectangular and hexagonal shapes were also considered.

- Availability - The availability of the raw material to manufacture the required number of containers per year (thousands of waste containers per year for several years).

- Fabrication Capacity - The existing capacity to fabricate waste containers from the given material (i.e., whether there are facilities available today which can accept a bulk order and start delivering waste containers within a reasonable time).

- Status of Technology - The current state of technology for fabrication of the material (i.e., whether the different techniques for fabrication are well understood for commercial-scale production purposes, or if the technology needs further research and development for implementation).

- Cost - The cost of a material was defined as the overall cost for manufacturing a waste container including both material and fabrication costs. Since the objective of this panel was primarily a preliminary evaluation of different prospective materials, the WCMP decided against subdividing the total cost into materials and fabrication because this would have complicated the process of evaluation to an extent well beyond the nature and scope of this panel. The WCMP also refrained from including developmental cost because of the difficulties in estimating the uncertainties associated with any research and development program. Any estimates of developmental cost at the onset could be significantly altered, if for example, there is an unexpected breakthrough in the research program. Therefore, developmental costs were not included as part of the overall cost.

- Mechanical Properties - These refer to the ability of a container made of an alternate material to survive the DOT Type A Packaging Tests (DOT, 1989). The WCMP decided to evaluate the materials in terms of certain mechanical properties (e.g., tensile strength, fracture toughness, etc.) which are required to satisfy the DOT Type A requirements. Although the WCMP could not evaluate whether meeting Type A would be a requirement or not in the future, it was decided that these requirements should be included in view of the existing WIPP Waste Acceptance Criteria (DOE, 1989b) which list the DOT Type A packaging tests as a requirement for waste containers. It was decided that any material judged to be at least equivalent to mild steel in overall mechanical properties would be rated as "adequate."

- Gas Generation Potential - This refers to the total moles of gases that can be theoretically generated by thermodynamically favored reactions between the alternative material, and all other species, given the repository environment (i.e., pressure, temperature, humidity, presence of brine, etc.). The WCMP agreed that given the potential complexity of the WIPP repository environment coupled with the regulatory period of 10,000 years, it is probably safer and conservative to assume that all reactions which are thermodynamically favored might eventually go to completion, unless adequate kinetic data is available to demonstrate that favored reactions will not occur.

- Gas Generation Rate - This is defined as the rate at which gas is expected to be generated from the material by either one of the three mechanisms discussed earlier in Section 1.3. Whereas the gas generation potential gives an indication of the total amount of gas that could be generated (provided all reactions go to completion), the gas generation rate provides a measure of how fast (or slow) this potential might be achieved. Thus, even if a given material has a high potential for gas generation, it cannot be ruled out from consideration. An alternative container material might have a rate of gas generation which is low enough that the rate of advection from the repository is adequate to prevent high gas pressures in the repository. The WCMP was not in a position to address how low the gas generation rates need to be relative to the advection rates. However, for quantitative comparisons, the WCMP agreed that the rate of corrosion of a material under anoxic conditions was a good indicator of the gas generation rate for that material.

Considering the broad spectrum of materials being evaluated (ranging from metals to ceramics to concrete), the WCMP established mild steel as the reference standard material to facilitate easy comparison between the materials. The selection of mild steel was based on two reasons:

- Since mild steel is being used for the existing waste containers, a comparison with mild steel provides an indication of the merits and disadvantages of each alternative material relative to the presently used container material.

- Since mild steel is a commonly used material for a wide variety of purposes, its properties are well documented and hence provide a firm basis for comparison.

Thus, the WCMP decided to compare all alternative materials to mild steel with respect to each evaluation criteria discussed earlier. As an example, while evaluating the fabricability of a material, the WCMP would judge whether its fabricability is easier, the same, or more difficult in comparison to mild steel.

2.3 DESIGN REQUIREMENTS FOR WASTE CONTAINERS

Apart from the specific criteria defined above for evaluation of materials, the WCMP also agreed to some general design requirements for waste containers to be built from alternative materials. These requirements were outlined as:

- Minimize or eliminate gas generation from container material for the regulatory period of 10,000 years.
- Maintain complete containment of the waste for a minimum of 25 years, (the duration of the operating life of the WIPP repository).
- Meet DOT Type A requirements.
- The containers should not degrade in any way that will significantly increase the permeability of the storage room environment.

In addition, the WCMP also made the following assumptions regarding the waste containers:

- The waste containers fabricated from alternative materials will be subjected to the same regulations which apply to the existing containers.
- The container may be "free-standing" (i.e., similar to a 55-gallon drum or box), or it could be "formed" around the waste (i.e., by isostatically pressing a container material such as cement around a monolithic block of waste).

2.4 MATERIALS SELECTED FOR EVALUATION

The WCMP initially selected five different classes of materials for evaluation. Each class of material was further subdivided into its own categories by appropriate classification schemes. Metals were classified by each metal and its alloys. Since ceramics are strongly bonded, they are all very stable materials from a gas generation standpoint, and therefore do not have any significant chemical properties to distinguish one from another. Therefore, ceramics were classified by their manufacturing method because there is a distinguishable difference between the processing techniques for different ceramics. In a similar manner, the WCMP decided to classify cements in terms of the reinforcements used in them because these lead to significant

differences in cost and properties. The different classes of materials and their subcategories evaluated by the WCMP were as follows:

- Metals
  - Copper and alloys
  - Titanium and alloys
  - High-nickel alloys
  - Zirconium and alloys
  - Stainless steels
- Ceramics
  - Fired ceramics
  - Chemically bonded ceramics
  - Glass
- Cements
  - Non-reinforced
  - Discontinuous reinforcement
  - Continuous reinforcement
- Coatings
  - Corrosion retardation
  - Containment enhancement for monolithic waste forms
- Polymers
  - Polyethylene.

Each of the above materials were evaluated with respect to the criteria described earlier in Section 2.2. The results of the evaluation are described in the next section.

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3.0 RESULTS OF THE WCMP EVALUATION OF ALTERNATIVE MATERIALS

The WCMP evaluated all the materials by comparing them to mild steel (as explained in Section 2.2), for each of the evaluation criteria described earlier. It should be noted that these evaluations were to a large extent judgmental, and are preliminary in nature. If performance assessment studies identify gas generation as an impediment to demonstrating compliance with the regulatory standard described in Section 1.2, then the evaluations of the WCMP could be used as a basis for any detailed future studies on alternative container materials.

The WCMP also established rough estimates for the cost of mild steel to set up a baseline for cost comparison of alternative materials. It was agreed by the WCMP that based on a material cost of 27 to 37 cents per pound of mild steel sheet, and a total cost of approximately $50 for a 60-lb. drum, a fabrication cost of 50 cents per pound was a reasonable assumption based on fabricating a 60-lb. drum. Thus, for cost comparisons, all materials were compared with the baseline of 77 to 87 cents per pound of finished mild steel product.

3.1 COPPER AND ALLOYS

- Fabricability - Copper is a little harder to weld than mild steel because of its high thermal conductivity, and therefore joining and handling of copper might be more difficult than mild steel. However, bearing in mind that the technology was well established, the WCMP rated the overall fabricability of copper to be about the same as that of mild steel.

- Availability - Assuming that any drums fabricated would use sheet metal as the starting material, the availability of copper and alloys was deemed to be plentiful, and equivalent to the availability of mild steel.

- Fabrication Capacity - Although the technology for fabricating copper is well established, the WCMP did not think that there are facilities available today which could start manufacturing copper drums at a short notice. Therefore the fabrication capacity of copper and alloys was judged to be "limited" in comparison to mild steel.

- Status of Technology - Since the metallurgy and fabrication of copper are quite well understood, the status of technology was deemed adequate and equivalent to mild steel.

- Cost - The cost would depend on the type of copper or its alloys being used. The cost of electrolytic copper is about $1.50/lb. Assuming the fabrication cost to be close to $50 for a 60 lb. drum, the WCMP estimated the total cost of a

copper drum to be roughly $150. This works out to be approximately 3 times that of mild steel. The WCMP also consulted the report on container materials for high level waste (Braithwaite and Molecke, 1980) where cost per unit weight of a manufactured copper container was 8.2 times that of mild steel. However, the dimensions of the container cited in this report were much larger than a 55-gallon drum, and the WCMP decided that for a smaller container the increase in cost is more likely to be 5 times that of mild steel. Overall, the WCMP agreed that a conservative estimate of 5 to 8 times that of mild steel would be a reasonable estimate for the cost of copper. It should be noted that this figure is very likely to increase if copper is alloyed with other materials.

- Mechanical Properties - Cold rolled copper will have mechanical properties very similar to that of lightly cold rolled low carbon steel, and if alloyed with 10% nickel, the properties could be very similar to mild steel. Based on these assumptions, the mechanical properties of copper were rated to be equivalent to that of mild steel. However, the WCMP agreed that the mechanical properties of a copper drum need to be verified after fabrication to determine whether copper needs alloying to enhance the properties. The alloying materials suggested for improvement were Ni (10%) or Zn (15%).

- Gas Generation Potential and Rate - Copper or copper-alloys have been found to be stable and resistant to corrosion in deaerated neutral pH conditions even under prolonged (2 months) exposure to brine at high temperature (150°C). Therefore, under deaerated conditions, it is not a gas generator (Westerman, 1988). However, the presence of any oxygen, sulfates, nitrates, or carbon dioxide open up a wide range of possibilities. The WCMP expressed concerns at the possibility of sulfates being reduced to sulfides by sulfate-reducing bacteria, which could then react with copper, resulting in the formation of copper sulfide and hydrogen. Similarly, the nitrates present in the sludges could be reduced to ammonia which in turn could cause stress corrosion cracking in copper. There were other concerns expressed about the corrosion of copper in low pH (2.0) carbonic acid solutions which could potentially form from microbial activity. The study by Braithwaite and Molecke (1980) reported corrosion rates of copper to be 25 times less than mild steel. Therefore the WCMP rated the gas generation rate of copper to be low in comparison to mild steel. Limited experiments may be required to verify these low rates.

The above scenarios notwithstanding, the potential for gas generation from copper depends entirely on the presence of a few microbially or radiolytically generated components such as CO_2, O_2, H_2S, NO^-_3, etc. The WCMP acknowledged the fact that the simultaneous presence of these species can at best be termed uncertain, and therefore agreed to rate the gas generation potential for copper as low. The WCMP recommends, however, that the effect of these species on gas generation potentials be resolved by appropriate experiments if copper is chosen as an alternative material for waste containers.

3.2 TITANIUM AND ALLOYS

- Fabricability - Titanium is a difficult material to weld, forge, or join for a variety of reasons. It has a tendency to weld to the tool during machining, leading to chipping and premature tool failure. Its low heat conductivity could increase the temperature at the tool/workpiece interface, thereby adversely affecting tool life. Also, the surface of titanium alloys is easily damaged in machining operations, especially during grinding, resulting in lower fatigue strength (Kahles et al., 1985). The WCMP agreed that the fabricability of titanium is more difficult than mild steel.

- Availability - It was estimated that based on a requirement of 600,000 drums over a period of 25 years, and a weight of 60 lbs/drum, the material required would be approximately 1.44 million lbs/year. However, it should be noted that because of the excellent corrosion resistance of titanium and its alloys, the actual amount of material required could be less than the estimated figure of 1.44 million lbs/year. This is only about 2% of the current U.S. production capacity, and therefore availability of titanium was considered to be adequate for the purpose.

- Fabrication Capacity - Facilities are available at this time to manufacture titanium drums, and there are a few companies who have fabricated drums with TiCode-12 and Grade 2 titanium. However, these have been done only on a pilot-scale, and at present no such facility exists to start delivering thousands of drums per year at a short notice. A considerable amount of scale-up effort may be required, and so the current fabrication capacity can at best be termed "limited."

- Status of Technology - Since titanium can be fabricated, and has been demonstrated for drum fabrication on a pilot-scale, the WCMP rated the technological status to be equivalent to that of mild steel.

- Cost - The report by Braithwaite and Molecke (1980) quoted the cost of a titanium container to be approximately 13 times that of mild steel. On this basis, the WCMP agreed that a cost of 10 to 20 times that of mild steel would be a reasonable assumption for titanium containers. The WCMP also noted that any alloying will increase the cost.

- Mechanical Properties - Titanium has yield stress and ultimate stress values of approximately 40% higher than those of mild steel. However, the term "mechanical properties" as defined by the WCMP also included other properties like resistance to tear (for surviving a drop test). Therefore the WCMP agreed that considering all the variables involved, the mechanical properties of titanium and its alloys are not substantially better than mild steel and rated them to be equivalent to mild steel.

- Gas Generation Potential and Rate - Titanium is susceptible to crevice corrosion under low pH conditions and temperatures ranging from 80°C to 150°C (Westerman and Telander, 1986). The product of crevice corrosion is titanium dioxide, but under anoxic conditions hydrogen will be released on the outside of the crevice. At the relatively low temperatures in the repository (around 26°C), the possibility of crevice corrosion is extremely low, especially if an alloy like TiCode-12 is used which is more resistant to crevice corrosion than the pure metal. However, it cannot be guaranteed that crevice corrosion would not occur for 10,000 years. Also, considering the definition of gas generation potential, the WCMP decided that titanium could have a relatively high gas generation potential.

  Braithwaite and Molecke (1980) reported that the rate of uniform corrosion of titanium was 70 times less than copper which in turn was 25 times less than mild steel. On this basis, the rate of corrosion (and therefore gas generation) from titanium and alloys was rated low compared to mild steel.

3.3 HIGH-NICKEL ALLOYS

These alloys, which are often called "superalloys" typically contain 40 to 75% nickel, 12 to 20% chromium, 3 to 12% molybdenum, 1 to 45% iron, and minor quantities of other metals as required for enhancing appropriate properties.

- Fabricability - Although joining or welding of these alloys is not considered to be a significant problem, they present major problems during cutting, sawing, or lathe-turning operations. The WCMP readily agreed that the fabricability of high-nickel alloys is more difficult than titanium, and definitely much more difficult than mild steel.

- Availability - The required amount is roughly equal to 2% of the existing capacity to produce these alloys. Also, since numerous facilities for producing these alloys exist in the U.S., the WCMP considered the availability of high-nickel alloys to be adequate.

- Fabrication Capacity - The fabrication technology of these alloys are well understood, but the alloys are primarily used for other purposes which have more stringent requirements (such as steam generators, etc.) There has been no need, so far, for drums made of these expensive superalloys, and therefore there is no existing fabrication capacity for superalloy drums. Although no major problems were anticipated by the WCMP, the implementation of high-nickel alloys as waste container material will definitely require the establishment of fabrication capacity.

- Status of Technology - The WCMP agreed that the metallurgical and fabrication technology for these alloys is well established, and the feasibility of scale-up to thousands of drums is not in doubt. However, fabrication technology may have

to be tailored to the production of containers depending on the chosen alloy. Since it is merely a question of time before proper facilities are constructed leading to scale-up, the status of technology for high-nickel alloys was rated to be adequate, and equivalent to mild steel.

- Cost - These alloys are very expensive and their costs exhibit a wide range of variation, depending upon the chosen alloy. Inconel-825, which is probably the cheapest of the group, is roughly 12 times more expensive than mild steel, whereas Hastelloy C-276 costs about 34 times more than mild steel. Thus, a cost of 15 to 35 times that of mild steel was considered to be a reasonable estimate by the WCMP. However, the WCMP noted that even the least expensive of these alloys might be adequate as a solution, if gas generation is determined to be a problem.

- Mechanical Properties - These alloys have excellent mechanical properties. Their tensile and yield stresses can range from 60-140 psi and 30-140 psi, respectively, depending on the alloy. Overall, the WCMP agreed that the mechanical properties were adequate for the purpose and better than mild steel.

- Gas Generation Potential and Rate - Compared to mild steel, the partial pressure of hydrogen in equilibrium with nickel is lower. If indeed the equilibrium partial pressure is low enough (2-3 atm.), then any corrosion reaction will stop at an early stage before any appreciable amount of hydrogen has been generated. However, the WCMP also recognized that apart from nickel there are chromium and iron present in these high-nickel alloys. Since both of these are much more susceptible to oxidation than nickel, the overall gas generation potential of superalloys was rated as moderate. The lower end superalloys have been shown to crevice corrode in sea water. If the lower alloys are used, they need to be investigated for pitting and crevice corrosion. Although the report by Braithwaite and Molecke (1980) cited that Inconel-825 (low end) had almost similar crevice corrosion rates as Hastelloy C-276 (high end) for an experimental period of 28 days, it did mention that the rates are dependent on the dimensions of the specimen, duration of experiment, etc. Since the lower alloys also had corrosion rates which were much lower in comparison with mild steel, the gas generation rate for all of these alloys was rated low by the WCMP.

3.4 ZIRCONIUM ALLOYS

- Fabricability - The fabricability of zirconium is very similar to titanium. It is a difficult material to machine, and was rated to be much more difficult than mild steel for the same reasons outlined earlier for titanium and alloys in Section 3.2.

- Availability - The WCMP agreed that there are plenty of facilities in operation for making zirconium sheet. However, the WCMP did not have any rough estimate of whether the production of thousands of drums would have any major impact

on the present supply of zirconium. Therefore, the availability of zirconium was assumed to be adequate, provided it does not make an impact on the present capacity.

- Fabrication Capacity - At present there is no existing capacity for making zirconium drums (i.e., there are no facilities fabricating drums made of zirconium at this time). However, since sheet metal technology for zirconium is well understood, the WCMP believes that the development of drum fabrication technology should be relatively straightforward.

- Status of Technology - The technological status for fabrication of zirconium drums was considered to be adequate by the WCMP.

- Cost - The Office of Civilian Radioactive Waste Management investigations on containers for high-level waste (Russell, et al., 1983) estimated costs of a container made of zirconium alloy (Zircaloy-702) to be 35 times that of mild steel. The WCMP thought that this was a reasonable estimate, especially when compared to the cost estimates for titanium and high-nickel alloys discussed in Sections 3.2 and 3.3, respectively.

- Mechanical Properties - Since zirconium alloys are used for fuel cladding in nuclear reactors, the WCMP agreed that its mechanical properties were definitely adequate for the purpose of containment of TRU waste for 25 years as well as for meeting DOT Type A requirements.

- Gas Generation Potential and Rate - The WCMP used the thermodynamic arguments similar to the ones used for evaluating the gas generation potential of titanium to conclude that zirconium also has a high gas generation potential.

  The corrosion rate of zirconium has been studied by Russell et al, (1983). These studies show that zirconium has exceptional corrosion resistance, and is predicted to be resistant to corrosion even at high temperatures for long periods of time. The extremely low rates of corrosion led the WCMP to conclude that zirconium will also have a very low rate of gas generation.

3.5 ALUMINUM AND ALLOYS

In view of the very low corrosion resistance of aluminum in brine, the WCMP could not justify the possibility of using aluminum as an alternative waste container material. By a unanimous decision, the WCMP eliminated aluminum from further consideration.

3.6 STAINLESS STEELS

The WCMP did express some doubts about considering stainless steels for evaluation, because of their known susceptibility to stress-corrosion cracking in solutions containing

chlorides. However, keeping in mind that the conditions at the WIPP are not going to be very extreme in nature, i.e., the temperature is expected to be below 30°C, and the fact that many stainless steels will probably adequately resist stress-corrosion cracking in the WIPP environment, the WCMP agreed to consider stainless steels for further evaluation. Also, on the basis of the study by Braithwaite and Molecke (1980) which reported that the corrosion rates of stainless steel at high temperatures in brine similar to WIPP brine is 100 times less than mild steel, the WCMP decided that the gas generation rates for stainless steel are low enough to justify its further evaluation.

- Fabricability - The fabricability of stainless steel is not much different from mild steel, and for the purposes being considered, was rated to be the same as mild steel.

- Availability - Stainless steels are widely available materials, and there is adequate supply for manufacturing thousands of drums per year.

- Fabrication Capacity - Stainless steel drums are presently produced (although not in large quantities), and Oak Ridge National Laboratory uses them on a regular basis. Although the installation of additional capacity might be needed, this is attainable, and therefore the WCMP considered fabrication capacity of stainless steel to be adequate.

- Status of Technology - The technology has been well demonstrated on a commercial scale, and is adequate for drum fabrication.

- Cost - The cost of stainless steel will depend upon the particular alloy chosen. Based on the study by Braithwaite and Molecke (1980) which quoted stainless steel to be 6 times more expensive than mild steel, the WCMP decided that considering the wide range of stainless steels available, a range of 5 to 8 times that of mild steel would be a reasonable estimate for the cost of 300 series stainless steel. It should be noted that the cost of 400 series stainless steel will be lower.

- Mechanical Properties - The WCMP decided that the mechanical properties of stainless steel were better than mild steel although not by a wide margin. Therefore, the properties were rated as "adequate."

- Gas Generation Potential and Rate - The WCMP agreed that the overall gas generation potential from stainless steel would not be much different from mild steel, and therefore rated the gas generation potential as high.

  On the issue of rate of gas generation, the Braithwaite and Molecke (1980) study was quoted as having reported that the corrosion rates of stainless steel were 100 times lower than mild steel when exposed to high magnesium brine at 250°C for 28 hours. The WCMP was hesitant to extrapolate such short-term data to

the lower temperature conditions expected at the WIPP site, because it was noted that corrosion rates do not necessarily increase with higher temperatures. Therefore the WCMP questioned the applicability of the data from Braithwaite and Molecke (1980) under WIPP conditions, and decided that the gas generation rate of stainless steel should be judged as moderate compared to mild steel. Additional testing under the WIPP conditions may be appropriate to clarify the gas generation rates from stainless steel.

3.7 FIRED CERAMICS - FREE-STANDING CONTAINER

The majority of the WCMP initially expressed doubts about the fabricability of ceramics into free-standing containers (similar to a drum). It was suggested that using ceramic materials might cause a total redesign of the container (i.e., a deviation from the standard concept of containers which are normally visualized as initially "empty" with the waste packed inside later). In contrast, ceramic containers would probably be much more attractive for a processed monolithic waste form where the container will actually gain in mechanical properties from the monolithic waste inside it. Some advantages of using alternative shapes were pointed out as well. As an example, the current cylindrical design of drums allows more void space when stacked in a storage room than a rectangular or hexagonal design. A reduction in void space using an appropriate shape (e.g., cubic) would decrease the required time for storage room reconsolidation, thereby reducing the time available for brine inflow into the repository.

Finally, the WCMP believed that given the rapid advances in the science of ceramics, there is a high probability that a fired ceramic could be formulated that can be fabricated into a free-standing container. In addition, all forms of ceramics, as well as glass and cements, could be reinforced as necessary to improve mechanical properties. On this basis, the panel members proceeded to evaluate a free-standing container made out of fired ceramics.

- Fabricability - The possibilities of firing large monolithic pieces using available microwave technology (especially for thick-walled vessels encountering temperature gradients) are becoming technologically manageable. However, although promising technologies exist, the fabrication of these materials into free-standing containers has not yet been demonstrated. Also, since these containers have to be sealed, joining the lids to the body of the containers may present considerable challenges. Therefore, the WCMP rated the fabricability of these materials to be much more difficult than mild steel.

- Availability - The basic material (i.e., fired ceramics) is widely available, and therefore its availability was judged to be adequate by the panel members.

- Fabrication Capacity - There is no current fabrication capacity for free-standing containers made out of fired ceramics. However, alternative container designs based on existing ceramics fabrication capabilities should be investigated, because there might be alternate designs which are more feasible to fabricate from ceramics than a 55-gallon drum.

- Status of Technology - The WCMP took note of the fact that although the fabricability of a 55-gallon drum has not been demonstrated, smaller pieces of alumina which have been extruded and then fired, have been obtained on a laboratory/bench-scale setup. However, it was also noted that a common rule of thumb for ceramics is that the larger the piece, the lower the quality of the ceramic. Nevertheless, the WCMP concluded that although a ceramic drum has not yet been fabricated (probably because of cost and lack of need for one), the technology does exist to make a free-standing container and appears to be adequate.

- Cost - There was not enough information available regarding developmental cost; therefore, the WCMP only considered raw materials. Since the cost of alumina is approximately $10/lb and most other fired ceramics are more expensive, a figure of 25 to 30 times that of mild steel was deemed reasonable by the panel members.

- Mechanical Properties - The majority of the panel members felt that the mechanical properties of fired ceramics were much worse than mild steel, and expressed doubts over whether a container made of a fired ceramic would survive the DOT Type A requirements. In a ceramic the atomic bond between metal and nonmetal is so strong and directionally oriented that there is no mechanism for deformation. As a result, even though the material may be strong in tension, brittleness will most likely render a container vulnerable to damage from a 4-foot drop on an unyielding surface. Thus, the WCMP rated the mechanical properties of fired ceramics to be much worse than mild steel.

- Gas Generation Potential and Rate - The WCMP decided that since all these ceramic materials are oxides, there is no chance of their generating any gas, and for all practical purposes, the gas generation potential is zero. However, since there could be hypothetical scenarios of zirconium hydride present in the waste reacting vigorously with an oxide ceramic, the WCMP was conservative and labeled the potential as "near zero" instead of zero.

3.8 CHEMICALLY BONDED CERAMICS

In a fired ceramic, the high-temperature process of firing strengthens the ceramic by allowing diffusion and shrinkage to fill the gaps in the material. The process succeeds, but introduces cracks in the material (Birchall and Kelly, 1983). Unlike fired ceramics, chemically bonded ceramics are processed at low temperatures and use water as a solvent for ions and as a medium for their diffusion. The process is similar to that of hydraulic cements (e.g., Portland cement) where solids set and harden irreversibly in the presence of water.

Application of chemically bonded ceramics to form a container around the TRU waste would probably depend heavily on the waste form. If the waste is converted to a solid monolithic

form, it might be possible to compact specially prepared powders around the waste. If the waste remains in its present loose form, compacting powder around a mold instead of the waste, to create a free standing container, might be feasible. A container made of such reactive materials as tricalcium silicate, or a mixture of tricalcium silicate and a zeolite, will combine with free water, and will also react with carbon dioxide. These characteristics can be advantageous in the repository. Some panel members expressed concerns about the permeability of the material, and also about the possible cracking of the material due to the development of nonuniform stresses when the material solidifies in contact with moist air. However, since the material has been reported to be denser than concrete or cement paste, the WCMP decided that the permeability is sufficiently low and would not be a drawback. Also, based on the fact that inspection under a confocal microscope had failed to reveal any changes in a 1/4-inch thick ceramic disk before and after immersing in water, the WCMP was assured that the material was not prone to cracking during solidification.

The WCMP recognized that the application of this concept to the containment of TRU waste requires considerable research and development. Also, the installation of a filtered vent in each container (a transportation requirement) poses significant engineering challenges. Nevertheless, the WCMP evaluated chemically bonded ceramics as candidate materials.

- Fabricability - The fabricability of chemically bonded ceramics is not difficult on a laboratory-scale, but definitely needs scaling up for manufacturing a container similar to a 55-gallon drum. However, assuming that the ease of fabricability of the material under laboratory-scale could be duplicated on a commercial scale, the WCMP rated the fabricability of this material to be similar to that of mild steel.

- Availability - The basic materials used for making this type of ceramic are certain silicates and zeolites which are widely available, and therefore the availability of raw material is comparable to mild steel and adequate.

- Fabrication Capacity - The fabricability of chemically bonded ceramics has been limited to a laboratory-scale, and there are no existing facilities which fabricate containers from these materials.

- Status of Technology - The technology needs to be developed for successful scale-up from laboratory-scale fabrication of these materials. The WCMP felt that a lot of research and development needs to be done in this area, and at best, the status of technology for chemically bonded ceramics can be termed as being "under development."

- Cost - Since the material has been fabricated only on a laboratory-scale, it was difficult for the WCMP to establish a range of cost for its commercial fabrication. It was suggested that since the cost of the raw material is approximately 2 to 3 cents per pound, a total cost of 10 cents per pound might be reasonable, including the cost of the cold-isostatic pressing needed during fabrication.

However, there was strong disagreement among the panel members regarding the cost of cold-isostatic press, and according to some panel members this step could cost as high as 25 cents/pound. Finally, the WCMP agreed that based on a conservative estimate of 25 cents/pound for the cold-isostatic press, the total cost would be close to 30 cents/pound, which was still considerably lower than the cost of mild steel. Since the cross-sectional area required for this material to satisfy DOT Type A requirements is likely to be much more than mild steel, the WCMP decided that the lower unit cost of chemically bonded ceramics would be offset by the lower amount of material required for a mild steel drum. Therefore the overall cost was rated to be similar to mild steel. However, these cost estimates should be viewed in light of the uncertainties involved in the wall thickness and weight of any container made from this material.

- Mechanical Properties - The WCMP unanimously concluded that in general, the mechanical properties of this material would not be any better than that of fired ceramics, and therefore rated these to be "much worse" as compared to mild steel.

- Gas Generation Potential and Rate - The WCMP readily agreed that this material will be exceptional in satisfying the requirements for no gas generation, because it does not generate gas by itself, and in addition also absorbs carbon dioxide and, possibly, adsorbs hydrogen as well. Thus, both gas generation potential and gas generation rate were judged to be "near zero." The WCMP also noted that this material might be useful as an effective backfill in the repository.

3.9 GLASS

Glasses are more sensitive to radiation than ceramics, and this was a concern to some panel members. However, given the fact that the majority of the isotopes of the elements present in the waste inventory are mostly alpha emitters, the WCMP decided that at such relatively low levels of radiation, the sensitivity of glass to radiation should not pose a problem. Another concern of the panel members was the possible increase in the storage room permeability resulting from crushed glass rubble after the reconsolidation of waste storage rooms. If the small broken chunks of glass cannot be further compressed by lithostatic stress, then a tortuous, interconnected path may develop for flow of brine through the waste stack.

- Fabricability - The WCMP decided that glass containers were a well established technology, and the fabricability is equivalent to mild steel.

- Availability - The availability of glass was rated to be the same as that of mild steel.

- Fabrication Capacity - Products made of glass are being fabricated widely in the U.S., and therefore the fabrication capacity was considered to be the same as that of mild steel.

- Status of Technology - This was considered to be the same as that of mild steel because of the same reasons outlined above.

- Cost - The cost of a glass container was deemed to be similar to mild steel pending confirmation of exact cost figures.

- Mechanical Properties - The mechanical properties of glass are not likely to satisfy DOT Type A requirements because of the brittle nature of glass. However, the WCMP felt that if reinforced, glass might be able to withstand DOT Type A requirements.

- Gas Generation Potential and Rate - For reasons similar to those outlined under the ceramics discussed earlier, glass was also rated to have a gas generation potential or rate near or equal to zero.

3.10 NONREINFORCED CEMENTS

The WCMP decided to evaluate cements as a general category instead of considering different types of cements (e.g., Portland cement, alumina-based cements, etc.) separately, because the characteristics of all these cements related to the criteria for evaluation are quite similar.

- Fabricability - The fabricability of cements, in general, was rated by the panel members to be as easy as fabricating mild steel, perhaps even easier.

- Availability - All basic materials needed for manufacturing cement containers are widely available, and therefore availability was not considered to pose any problem.

- Fabrication Capacity - Cementitious materials are widely fabricated all over the U.S. Specific fabrication capability to produce TRU waste containers may need to be built depending on the final container design.

- Status of Technology - The technology is believed to be established well enough to rate the status of technology equivalent to mild steel.

- Cost - Assuming a thick-walled structure and a cost of material of 2 to 3 cents/pound, the total cost of a drum was not expected to be high in comparison to mild steel. Some panel members did express concern about the greater wall thickness likely to be required for a cement drum in order to satisfy DOT Type A requirements, resulting in increased total cost. However, it was pointed out that fabrication does not have to produce a free-standing container. Rather, the waste could presumably be suspended in a bag at the bottom of a large tube that acts as a mold, and then free-flowing liquid cement poured around it. If such a fabrication process is adopted, then it has to be ensured that the density

of waste in the bag is greater than the density of the liquid cement, otherwise there is the possibility of the waste floating up during container fabrication. The WCMP noted that this would be a good example of a "formed" container where the container will actually gain in strength, if the waste inside it is in monolithic form (e.g., shredded and cemented). This method would probably not require the extra wall thickness required by a "free-standing" cement container, and based on this assumption the panel members estimated the cost to be similar to that of mild steel.

- Mechanical Properties - The mechanical properties of nonreinforced cement would be very similar to the ceramics discussed earlier, i.e., brittle and unlikely to survive a DOT Type A drop test. Therefore, the WCMP rated nonreinforced cement to be much worse than mild steel with respect to its mechanical properties.

- Gas Generation Potential and Rate - Since cement is a porous material, it might absorb water leading to potential for gas generation by radiolysis if alpha-emitters are in close contact with the water. However, the WCMP assumed very little free water present, and rated nonreinforced cement to have low overall gas generation potential and rates. The WCMP noted that Portland or alumina-based cement will also result in higher pH values of any brine that may come in contact with the containers, thereby causing decreased microbial gas generation, a reduction in the corrosion rate of ferrous materials, and a decrease in the solubility of actinides. The one drawback of cements, noted by the WCMP, is a possible increase in the corrosion rate of any aluminum present in the waste caused by the increased pH.

3.11 REINFORCED CEMENTS

A nonreinforced cement container can probably be designed to meet the DOT requirements. However, the payload volume may be small and the container weight quite high. The primary objective of using reinforcements is to improve the mechanical properties so that thinner walls can be used to satisfy DOT requirements, thus increasing usable volume and decreasing container weight. Reinforcements that were considered were subdivided into two groups:

- Discontinuous reinforcement (e.g., particulates, transformation toughening, etc.)
- Continuous reinforcement (e.g., wire, mesh, cage, etc.).

3.11.1 Discontinuous Reinforcement

The WCMP agreed that discontinuous reinforcement of cements would not change the fabricability, availability, fabrication capacity, or status of technology in comparison to the base material (i.e., nonreinforced cements). Therefore, the WCMP rated all of these properties to be similar to mild steel, and hence adequate.

- Cost - The cost will be a function of the cost of the material used for reinforcement. As an example, if rocks are used then cost will be relatively low, whereas, if the reinforcement material is carbon fibers, then cost will increase. The WCMP estimated that the cost using different reinforcement materials would range from 1 to 2 times that of mild steel.

- Mechanical Properties - The WCMP felt that the mechanical properties of reinforced cements would be adequate to meet DOT Type A requirements. However, the WCMP noted that there were a lot of uncertainties about shape, wall thickness of the container (which would probably be smaller due to reinforcement), and limitations on the maximum payload due to weight of container. All of these and their effects on the DOT Type A requirements need to be evaluated in detail.

- Gas Generation Potential and Rate - This will almost be the same as that of the base material (i.e., cement) being reinforced, with marginal variation according to the gas generation properties of the material used for reinforcement. However, due to the reinforcement, the amount of cement required per container might be less than that required for a nonreinforced container thereby decreasing the total potential for gas generation to an even lower value than nonreinforced cement.

3.11.2 Continuous Reinforcement

- Fabricability - The WCMP judged continuous reinforcement to be a more difficult and labor intensive process than discontinuous reinforcement. Automation of the reinforcing process (i.e., forming a cage/mesh, putting it in a mold, and then pouring concrete around it) is likely to be difficult, and so the WCMP rated the fabricability to range from "more difficult" to "much more difficult" in comparison with mild steel, depending on the technique used for reinforcing and the material used for reinforcement.

- Availability - There is no shortage of cements or reinforcing materials, and the availability of material was termed adequate by the panel members.

- Fabrication Capacity - Facilities are available for fabrication of reinforced concrete shapes. However, specific capabilities can be built only after a final container has been designed.

- Status of Technology - The WCMP had some doubts whether anything similar to a fiber-glass cage has ever been fabricated. However, they decided that this was more a question of engineering and set-up of fabrication facilities rather than technological development. Therefore, the status of technology was termed adequate.

- Cost - There are a wide variety of technologies available for continuous reinforcement of cements (e.g., injection molding), and therefore the cost could vary over a wide range - perhaps 2 to 3 times that of mild steel.

- Gas Generation Potential and Rate - This was rated to be low for the same reason as presented under the discussion on discontinuous reinforcements in Section 3.11.1. The WCMP also noted that using metallics as reinforcement materials should not be a cause for concern from the standpoint of corrosion, because a lot of the reinforcing material will be embedded in cement and may never come into contact with the environment. In addition, the cement is likely to raise the pH of any brine that might infiltrate through the container, and thus retard the corrosion rate.

3.12 COATINGS

Although coatings by themselves do not fall under the category of "waste container materials," the WCMP considered coatings from the standpoint of providing additional protection to the base material used for alternative waste containers. Coatings were subdivided under two categories depending on the purpose of the coating:

- Corrosion retardation for metals and alloys

- Containment enhancement for structurally weak containers (e.g., ceramics) or monolithic waste forms during waste handling and transportation.

After a brief discussion, the panel members agreed that coating metallics (especially mild steel) enhances their corrosion resistance. However, this only decreases the rate of gas generation, but has no effect on the gas generation potential. It was also pointed out by the WCMP that coatings are, at best, a temporary retardant on a time-scale of 10,000 years. Once the drums get crushed upon total reconsolidation of salt, it is very likely that part of the base metal will be exposed, and thereafter coatings would not be completely effective for stopping corrosion over a period of 10,000 years. In fact, it is extremely difficult to quantify or justify protection by coatings over such a long period of time. In view of these arguments the panel members eliminated coatings from any further evaluation, but noted that coatings that reduce corrosion rates could be a valuable approach if performance assessment studies can quantify the extent to which gas generation rates need to be reduced. The WCMP also noted that certain coatings could be used for enhancing the strength of cementitious or ceramic materials for fracture toughness. As an example, solidified monolithic waste forms inside a cementitious container, may be coated with various materials such as polymers, to assure containment during transportation and handling until the WIPP repository is decommissioned.

3.13 POLYMERS

A significant problem with polymers is proving their stability over a period of 10,000 years under the processes of microbial degradation as well as radiolysis. Obtaining the proof of

stability will require a substantial investment in research and development, and even then could not be guaranteed to be successful. Even if a polymer could be shown to withstand microbial attack in the short-term, the validity of such data is questionable over a 10,000 year period, because given the time, the microbes have the capability of adapting to new environments and attacking the organic materials present. Also, organic materials could break down by other mechanisms such as radiolysis, and then become susceptible to microbial attack. The WCMP took note of all these drawbacks of polymers, but decided that they have many desirable properties (no corrosion, toughness, etc.) to be discarded from consideration. Instead of generalizing for all polymers, the WCMP decided to evaluate polyethylene specifically, because many of its properties relevant to this evaluation were known.

Since status of technology for polymers is quite advanced, the WCMP did not have any doubts about the fabricability, availability, fabrication capacity, or the mechanical properties of polymeric containers. In fact, TRU waste stored in 55-gallon drums is actually contained in 90-mil polyethylene liners inside the drums. Although it was estimated that the cost of such a container would be 5 to 10 times that of mild steel, the WCMP expected these containers to pass DOT Type A requirements. The major concern about the use of polymeric materials, as mentioned before, was that the gas generation potential and rates were unknown to panel members. Although a lot of information is available about the radiolysis of polymers and a substantial research and development effort might not be needed in this area, the WCMP felt that these materials would require detailed investigation for microbial degradation before they can be used as a container material.

3.14 OTHER MATERIALS

Apart from the materials already discussed in Sections 3.1 to 3.13, the WCMP also examined a different material suggested by one of the panel members.

This material is based on a 10- to 20-year-old technology popularly known as "impregnation into metal." The existing 55-gallon drums are impregnated from both sides with a nonoxide ceramic containing no free oxygen (such as boron nitride) up to a thickness of 0.003 to 0.015 inch. Since radiation is not a prime concern for CH-TRU waste, there are a number of alternatives (e.g., manganese oxide, silicon oxide, etc.) that are cheaper. After impregnation, the metal surface can be coated with a polymer (polyvinylidine) for additional protection. The impregnation is done by ion-bonding the ceramic to the metal by a proprietary method. The purpose of the ion-bond is to convert the surface of the metal into a ceramic, thereby preventing corrosion.

The WCMP expressed a lot of concerns about this material, especially about its corrosion properties when crumpled during the reconsolidation of salt. Although the panel members agreed that impregnation could provide corrosion protection for the metal surface (if impregnated on both sides), they were very much concerned about the region of unimpregnated metal sandwiched between the inner and outer surfaces of the drum. The WCMP argued that after reconsolidation, the drums are most likely to rupture, leaving the unimpregnated metal at the center exposed to the corrosive environment in the repository.

Once unprotected metal is exposed the corrosion process will start, and although the rate of corrosion might be low, the impregnation techniques will be rendered ineffective in the long run. Another concern of the panel members was about the ductility of the impregnated layer. Most panel members questioned the ability of this material to withstand the bending stresses expected during room closure without developing cracks or exposing unimpregnated metal.

Overall, the panel members recognized that this could be a very promising material, especially for the purpose of reducing the rate of gas generation from corrosion, although it would not reduce the total potential of gas generation from mild steel drums. However, it appeared to the panel members that due to the proprietary nature of the technology, there was not enough information available about the material at this stage for a complete evaluation. Therefore, due to the lack of adequate information, the WCMP was unable to decide whether this technology merits further evaluation. If performance assessment studies determine that merely controlling the rate of gas generation would ensure that there is no gas generation problem, then this could be a very promising material.

A summary of the results for each material with respect to each evaluation criteria is presented in Table H-1.

TABLE H-1

EVALUATION OF ALTERNATIVE MATERIALS

	CRITERIA FOR EVALUATION							
							GAS GENERATION	
MATERIAL	FABRICABILITY[a]	AVAILA-BILITY[a]	FABRICATION CAPACITY[a]	STATUS OF TECHNOLOGY[a]	COST[a]	MECHANICAL PROPERTIES[a]	POTEN-TIAL	RATE
Copper & Alloys	Same	Same	Limited	Same	5-8x	Same	Low	Low
Titanium & Alloys	Much more difficult	Same	Limited	Same	10-20x	Same	High	Low
High-Nickel Alloys	Much more difficult	Same	None	Same	15-35x	Same	Moderate	Low
Zirconium and Alloys	Much more difficult	Same	None	Same	35x	Same	High	Low
Stainless Steels	Same	Same	Same	Same	5-8x	Same	High	Moderate
Fired Ceramics	Much more difficult	Same	None	Appears to be same	25-30x	Much worse	Near zero	Near zero
Chem. Bonded Ceramics	Same	Same	None	Being developed	Same	Much worse	Near zero	Near zero
Glass	Same	Same	Same	Same	Same	Much worse	Near zero	Near zero
Nonreinforced Cements	Same	Same	Same	Same	Same	Much worse	Low	Low
Reinforced Cements Discontinuous	Same	Same	Same	Same	1-2x	Probably same	Low	Low
Continuous	Worse	Same	Same	Same	2-5x	Probably same	Low	Low
Polyethylene	Same	Same	Same	Same	5-10x	Same	Requires Investiga-tion	Requires Investi-tion

[a]In comparison with mild steel.

4.0 CONCLUSION

The WCMP concluded that the evaluation of five different groups of materials showed that there are several candidate materials available which are capable of satisfying the design requirements for waste containers to varying degrees. In order to summarize the evaluation, the WCMP decided that there are two basic criteria that need to be addressed in detail for each one of the evaluated materials. One is the effectiveness of the material for meeting the "no gas generation" requirement; the other criterion is whether the material can be fabricated into a container satisfying the appropriate transportation and handling requirements.

The effectiveness and fabricability of different materials would have to be established through development programs of varying durations for the different materials. As an example, materials like ceramics which are brittle, are likely to take a lot more development time than a metal like copper, to establish their fabricability into an acceptable container. Therefore, the WCMP summarized its evaluations of alternative materials with respect to the following criteria:

- Time likely to be needed to establish the effectiveness of the material in meeting the "no gas generation" requirement.
- Time likely to be needed to develop fabrication technology and actually make a full-scale fabricated container.
- Probability of success in terms of the WCMP's best judgment that the material will satisfy the "no gas generation requirement."
- Probability of success in terms of the WCMP's best judgment that the material can be fabricated into a container satisfying DOT Type A requirements.
- Cost of container in comparison to mild steel.

The WCMP assumed that all the brittle materials such as ceramics, cements, and glass will be reinforced as required to provide whatever mechanical properties are deemed necessary to satisfy the DOT Type A requirements. Thus, all materials evaluated earlier under the "reinforced" prefix were not summarized separately, but rather assumed to be included in their respective base material groupings. It was noted by the panel members that if DOT Type A requirements are to be met, then containers made of metals and polymers would probably carry the maximum payload per container. The WCMP also came to the conclusion that any research involving microbial gas generation is likely to become a long-term project because of the uncertainty associated with microbes. Therefore, whenever possible, all experimental schedules for detailed evaluation of materials should be planned in parallel to make the most efficient use of time.

The conclusions of the WCMP are presented in Table H-2. It should be noted that the cost figures are taken directly from Table H-1, and do not include developmental costs, or costs

TABLE H-2
SUMMARY OF RESULTS

	Time to Establish Effectiveness	Time to Establish Full-Scale Product	Cost Factor[a]	Probability of Success in Establishing Effectiveness	Probability of Success in Meeting DOT Type-A Requirements
Copper & Alloys[b]	1-2 yrs.	2 yrs.	5-8 x	90%	100%
Titanium & Alloys	1-2 yrs.	2 yrs.	10-20 x	95%	100%
High-Nickel Alloys	1-2 yrs.	2 yrs.	15-35 x	97%	100%
Zirconium Alloys	1-2 yrs.	2 yrs.	35 x	98%	100%
Stainless Steel[b]	1-2 yrs.	0-1 yrs.	5-8 x	50%	100%
Free Standing Ceramics[c]	0 yrs. (validate)	4-8 yrs.	25-30 x	99.9%	30%-90%
Chem. Bonded Ceramics[c]	0 yrs. (validate)	3-5 yrs.	1-10 x	99.9%	30%-85%
Glass[c]	0 yrs. (validate)	2-4 yrs.	1-10 x	99.9%	20%-90%
Cements[c]	1-2 yrs.	2-4 yrs.	2-8 x	99.9%	30%-85%
Polymers	5 yrs.[d]	0-1 yrs.	5-10 x	Indeterminate	100%

[a] Relative to a mild steel container.
[b] Uncertainty associated with effect of microbes - not considered in duration.
[c] Reinforced as required.
[d] Should be dropped from consideration if effectiveness cannot be proven within 5 years.

of building any new facilities which might be required. Also, the estimates of schedules do not include programmatic planning time associated with planning of research strategy, approval of schedule and budget, etc. The conclusions of the WCMP for each material are discussed below.

Copper

It would not take a significant amount of time to evaluate the effectiveness of copper in order to reduce some of the uncertainties associated with its corrosion. Most experiments will take one to two years, depending on the extent of evaluation. However, as discussed earlier, copper could corrode if microbes reduce sulfates and nitrates in the repository. It should be noted that this uncertainty has not been included in the one to two year estimate of experimental duration. Full-scale production can probably be established in about two years, and might be done in parallel with effectiveness evaluation.

The WCMP rated the probability of success for meeting the "no gas generation" requirement using copper or its alloys to be about 90 percent. Since this figure was based purely on qualitative judgment, the WCMP decided to assign probabilities to all the materials, and then later compared them to each other in order to be assured that the relative percentages for probabilities between different materials were reasonable. The WCMP did not have any doubts about the ability of copper to satisfy DOT Type A requirements and rated the probability of success at 100 percent.

Titanium

The time to establish the effectiveness of titanium would be about one to two years. However, unlike copper, there is no microbial uncertainty with titanium. Some experiments are needed at high CO_2 overpressure in concentrated brine at the maximum temperature expected in the repository, and may be conducted at a higher temperature to accelerate data acquisition. The WCMP was confident that these experiments could be done in one to two years. The time to establish full-scale fabrication capability was estimated to be similar to that of copper, i.e., approximately two years.

The probability of success in meeting the "no gas generation" requirement for titanium was estimated to be 95 percent. Some panel members expressed concern at this high figure because of the high potential for gas generation from titanium. However, it was pointed out that the potential and probabilities are quite unrelated. As an example, even though diamond has a very high potential for oxidizing, the probability of this actually happening is very low. Also, titanium is known to be extremely corrosion resistant in a variety of environments because of a protective layer of titanium dioxide, which rapidly forms again if the surface is scratched. Although crevice corrosion can occur in brine this normally occurs at much higher temperatures than that expected in the repository. Like copper, titanium was not expected to face any problems in satisfying DOT Type A requirements and was rated to have a 100 percent probability of success.

High-Nickel Alloys

As mentioned earlier, if these alloys are to be considered as candidate container materials, then pitting and crevice corrosion of these alloys needs to be investigated as well as data about the equilibrium partial pressure of hydrogen which will stop the corrosion reaction. These alloys are extremely corrosion resistant, so that any experiments to quantify their corrosion rates will take a long time. In addition, there is also the issue of finding the optimum alloy for the given conditions. The WCMP noted these issues, and decided that it would take one to two years to establish the effectiveness of high-nickel alloys. The time for full-scale fabrication and the probability of success in meeting DOT Type A requirements were judged to be equivalent to that of copper and titanium based materials, i.e., two years and 100 percent, respectively. Since the rates of corrosion of high-nickel alloys are slower than titanium, these were judged to have a slightly higher probability of success for gas generation requirements compared to titanium, and rated at 97 percent.

Zirconium Alloys

These were considered to be similar to the high-nickel alloys, except that in recognition of their exceptional corrosion resistance, these materials were rated to have a higher probability of success (98 percent) for meeting gas generation requirements.

Stainless Steels

The time for verifying the effectiveness of stainless steel should take no more than one to two years. However, like copper, uncertainties about microbial attack are also associated with stainless steels. These uncertainties are not included in the above estimates for experimental duration. The time for full-scale production would be less than any of the other metals discussed before, because drums are being produced now for commercial purposes. Since the present production capacity is not at a level required for manufacturing thousands of drums per year, the WCMP estimated a period of approximately one year for full-scale production of stainless steel drums. Like all metals, the probability for meeting DOT Type A was rated at 100 percent. The relatively higher corrosion rates of stainless steel in comparison to titanium, zirconium, etc., reduced the probability of success in meeting gas generation requirements to 50 percent.

Free Standing (Fired) Ceramics

The WCMP felt that there was no need for any experimental studies to establish their effectiveness for meeting the "no gas generation" requirement. For all practical purposes these materials were considered to have a 99.9 percent probability of success in not generating gas. On the issue of time required for full-scale production, a broad range was noted because of a wide variety of material that can be used. As an example, a lower end material like low grade alumina could take a total of four years (two years to develop and another two years to scale-up), whereas a higher end material like toughened zirconia could take eight years. The same wide range would also apply to the probability of success in meeting DOT Type A requirements as well. The WCMP decided that the probability for low grade alumina would be about (30) percent whereas it would be considerably higher (90 percent) for a higher end material like toughened zirconia.

Chemically Bonded Ceramics

The gas generation characteristics were deemed to be similar to fired ceramics, i.e., they also were rated to have a probability of success of 99.9 percent and would not require any experimental time for verification. For full-scale production, it is conceivable that some sort of isostatic pressing technology might be developed quickly (one to two years). Once the technology for fabrication has been developed, the scaling up could take two to three years. Therefore, full-scale production could take anywhere from three to five years. Since this type of ceramics is not as tough as fired ceramics, the WCMP rated their probability of success for meeting DOT Type A to be 30 to 85 percent.

Glass

The WCMP considered the fabrication of glass to be a well-established technology, easier than any other ceramic evaluated. Full-scale production of glass containers should take one to two years. However, recognizing the fact that glass needs to be reinforced, and that design and evaluation of mechanical properties cannot be done in parallel, the WCMP estimated that two to four years is probably a more realistic figure for full-scale production. All other criteria (i.e., probability of success, etc.) were judged to be equivalent to fired ceramics for similar reasons.

Cements

If cements are to be considered as candidate materials for alternative waste containers, then the chemistry of exposing cement to brine needs to be investigated in detail. This could take one to two years. There is also the need for verifying the stability of cement for 25 years. Using some kind of accelerated degradation process, the stability could probably be verified within two years. Therefore, the WCMP felt that two to fours years would be a reasonably conservative estimate for the full-scale production of a cement container.

The probability of success for meeting gas generation requirements was rated at 99.9 percent provided that proper reinforcements (such as glass) are chosen which do not generate gas themselves. For meeting DOT Type A requirements, the WCMP felt that these can be met, although a lot will depend on a cost effective compromise between wall thickness, amount of reinforcement, and payload constraints.

Polymers

The main problem with polymers is their possible degradation under microbial attack, and radiolysis. The WCMP recognized that a given polymer might be effective, and be able to withstand microbial attack for 10,000 years. The difficulty lies in the verification of their effectiveness, because short-term research data showing lack of microbial degradation does not guarantee that such degradation would not take place over 10,000 years. Since there is a lot of uncertainty involved, the WCMP decided that if the effectiveness cannot be established within a period of five years, polymers should be dropped from further consideration as an alternative waste container material. If they are selected, the polymers should not have any problem in meeting the DOT Type A requirements, and considering their well-established technology, it should not take more than one year for full-scale production of polymer containers.

Coatings

The WCMP did not discuss coatings with respect to criteria used for summarizing other alternative materials, because coatings were considered to be a subcategory of other alternatives (a part of the process rather than a container material by themselves). It should be noted that these coatings are for surface containment of solid wastes to facilitate handling and transportation, and for retarding the corrosion rate of metallics. For example, in the case of chemically bonded ceramics there is a possibility of contaminating the powder during the process. So an option is to paint or coat the surface to isolate any contamination. Thus, coatings should be used when and wherever applicable if it indeed improves the characteristics of the container material.

It should be noted that the information presented in Table H-2 is based on preliminary evaluation of these materials, and represents educated estimates rather than precise values. The figures in Table H-2 provide relative estimates of probability of the materials in meeting the effectiveness and fabricability requirements for a container, as well as the time required to verify these probabilities. The WCMP decided that copper, titanium, high-nickel alloys, zirconium alloys, ceramics, glass, and cements were all viable materials which could possibly satisfy the design requirements for an alternative waste container. However, there are some concerns associated with each material that need to be resolved.

The WCMP noted that although ceramics and cements have excellent gas generation properties, and are inexpensive, waste containers made from these brittle materials are likely to have smaller internal volumes due to the thicker container walls required to satisfy DOT Type A requirements. This will result in a smaller TRU waste payload per container. In addition, if the container weight is heavier than the existing drums, then fewer containers will make up the TRUPACT-II payload, resulting in increased number of waste shipments from the storage sites to the WIPP site. These factors can have large impacts on the overall program costs beyond the low unit costs required to fabricate the containers. It should also be noted that with the possible exception of cements, there is no technology presently in place to fabricate large containers from the nonmetallic materials. Therefore, the fabrication of an acceptable nonmetallic container that would satisfy the DOT Type A requirements, will very likely require long-term research and development efforts.

In contrast to the nonmetallics, and with the exception of copper, there are expensive metal alloys (titanium, high-nickel, and zirconium) that have relatively fewer uncertainties associated with them, especially with respect to fabricability, and payload volume per container. Once their low anticipated corrosion rates are validated under WIPP conditions, these alloys have the potential of immediately satisfying the design requirements. Whereas, the higher end high-nickel alloys, and the zirconium alloys would substantially escalate program costs (roughly $1 billion, based on 600,000 drums and a cost of $50 for an existing mild steel drum), the WCMP felt that lower cost titanium alloys would be adequate for the purpose. Besides, under the relatively mild conditions at WIPP, there is not likely to be any notable differences in corrosion properties between the titanium alloys which are relatively inexpensive, and the more expensive ones such as zirconium and higher end high-nickel alloys.

These results of the WCMP should be used to:

- Select a few promising alternative materials for detailed testing regarding their fabricability and corrosion/gas generation properties
- Evaluate, with the help of appropriate experiments, the effectiveness of the selected materials for meeting the "no gas generation" requirement
- Design and demonstrate the fabricability of the selected materials (reinforced as required) into a container satisfying all transportation and handling requirements
- Estimate the total cost per container, and impact on overall program cost for the selected materials based on the annual fabrication requirements.

Thus, the right choice of material would have to be decided by tests on a few promising materials for both effectiveness and fabricability, and would also depend on applicable cost, schedule, and transportation constraints.

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ATTACHMENT A

QUALIFICATIONS OF PANEL MEMBERS

CHAIRMAN

Mr. Hans Kresny (Chairman and Facilitator)

Mr. Kresny is the President of Solmont Corporation, and a consultant to IT Corporation, with over 33 years of multidiscipline technical and managerial experience in the nuclear industry. His background includes engineering and project management involving major nuclear facilities and programs, institutional issues resolution between the WIPP project and 23 States, shielding and radiation analysis, and nuclear space systems and power plant design. He was also the chairman of the WIPP Engineered Alternatives Multidisciplinary Panel. Education: Bachelor of Marine Engineering.

PANEL MEMBERS

Dr. Barry M. Butcher (Performance Assessment)

Dr. Butcher is currently the Principal Investigator at Sandia National Laboratories (SNL) for WIPP programs related to the selection of backfill for the disposal rooms, development of a model for the mechanical and hydrological response of the disposal rooms, and investigation of engineered alternative concepts. He has over 30 years of experience in investigation of the dynamic behavior of materials, and is the author of over 30 publications on the subject. At SNL, he has held positions as Supervisor of the Stress Wave Research Division, and as Supervisor of the Geomechanics Division providing rock mechanics support to the WIPP and Yucca Mountain projects. Education: B.E., Civil Engineering; Ph.D., Engineering Materials (Materials Science).

Mr. Noel Calkins (Ceramic Fabrication)

Mr. Calkins has 33 years of experience as a mechanical engineer working in various areas of management, research and development, and production. The last 10 years of his experience have included working in Los Alamos National Laboratory. He has worked extensively in the area of fabrication of several materials including metals, ceramics, and composites. His process experience encompasses all traditional and non-traditional metal and ceramic removal systems, including water jet cutting, ultrasonic impact grinding, free abrasive machining (FAM), etc. He also holds patents in the areas of ceramic processing and ceramic armor. Education: B.S., Mechanical Engineering.

Dr. Frank W. Clinard, Jr. (Basic Ceramic Research)

Dr. Clinard is a Senior Laboratory Associate at Los Alamos National Laboratory (LANL) with over 25 years of technical and managerial experience in a variety of areas in materials science. His experience in LANL includes 17 years as a Project Leader for research in the area of ceramics for fusion reactor application, and as a Section Leader for irradiation effects, advanced materials, and physical ceramics. He has also been a consultant to various companies in the areas of physical properties of metals, ceramics, polymers, and ceramic

composites. Education: B.S., Mechanical Engineering; M.S., Metallurgical Engineering; Ph.D., Materials Science.

Dr. F. H. Froes (Physical Metallurgy)

Dr. Froes is the Director of the Institute for Materials and Advanced Processes at the University of Idaho, and has been active in the fields of physical metallurgy, powder metallurgy, metal matrix composites and intermetallics for over 23 years. Before assuming his position at the University of Idaho, he has held various positions supervising research in the areas of titanium, aluminum, and superalloys at the Air Force Materials Laboratory in Dayton, Ohio. He also holds in excess of 40 patents in Material Science and related fields. Education: B.S., M.S., and Ph.D., Physical Metallurgy.

Dr. Hamlin M. Jennings (Cementitious Materials)

Dr. Jennings is an Associate Professor in the Department of Civil Engineering and the Department of Materials Science and Engineering at Northwestern University. He has 15 years of teaching and research experience in the area of cementitious materials. His research has included the study of microchemistry and microstructure of various ceramics and cement-based materials using mathematical modeling and transmission electron microscopy. He has also been a member of the WIPP Cement/Grout Expert Panel which discussed the stability of cement-based materials in the WIPP environment for a period of 10,000 years. Education: B.S., Physics; Ph.D., Materials Science.

Mr. Daniel C. Meess (Concrete Container Fabrication)

Mr. Meess is currently the Design Manager of the Nuclear Waste Department, Illinois LLW Project for Westinghouse Electric Corporation. He has over 15 years of project leadership experience in goal-oriented development of advanced energy technologies, and the management of hazardous, low-level radioactive and mixed wastes with a focus on project management, developmental engineering, and technical operations. He was the Project Leader for the development, testing, and commercialization of the SUREPAK modules for the safe storage and disposal of low-level radioactive and hazardous wastes. Education: B.S., Mechanical Engineering, and Public Affairs; M.S., Mechanical Engineering.

Dr. Jonathan Myers (Geochemistry)

Dr. Myers is a Senior Technical Associate at IT Corporation with over ten years of geologic and geochemical experience solving technical problems in the field of hazardous and nuclear waste management. He has been actively involved in the WIPP and Yucca Mountain nuclear waste disposal projects, as well as the Swedish and Canadian waste disposal programs. He has also been a member of the WIPP Engineered Alternatives Multidisciplinary Panel, chairman of the WIPP Cement/Grout Expert Panel, and a participant in the WIPP Performance Assessment Program. Education: B.S. and M.S., Geology; Ph.D., Geochemistry.

Mr. Rodney Palanca (Waste Handling)

Mr. Palanca has 27 years of experience with the operation of nuclear submarine and land-based nuclear plants. He attained the rank of Lieutenant Commander in the U.S. Navy, and has supervisory and technical experience in nuclear reactor operation and testing, nuclear

instrumentation and controls, nuclear chemistry and radiological controls, training curriculum planning and scheduling. He was also a member of the WIPP Engineered Alternatives Multidisciplinary Panel. He is currently a senior engineer in the WIPP Engineered Alternatives Group. Education: B.S., Chemical Engineering, plus numerous U.S. Navy nuclear training programs.

Dr. R. E. Westerman (Metallurgy/Corrosion)

Dr. Westerman is a Senior Staff Scientist and Technical Leader of the Components Analysis Group at the Pacific Northwest Laboratories (PNL). He has 30 years of experience in the metallurgical and corrosion research of various materials, and has been involved in nuclear waste package development programs since 1977. At PNL, he has led a group involved in the selection and evaluation of metallic materials including nickel-, iron-, copper-, titanium-, and lead-based alloys, for application to engineered barrier systems for the long-term containment of nuclear waste. He has also acted in the capacity of Technical Leader of the chemical Metallurgy and Metallurgy Research Sections at PNL, either directing or contributing to a variety of programs, including the effect of hydrogen on the mechanical properties of titanium alloys and the manufacture and evaluation of alloy steel specimens made by various powder metallurgy techniques. Education: B.S., Metallurgical Engineering; Ph.D., Metallurgy.

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APPENDIX I

COMPARATIVE RISK ASSESSMENT OF ENGINEERED ALTERNATIVES

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EXECUTIVE SUMMARY

The total risk associated with various waste treatments is an important component in the evaluation of the feasibility of alternatives conducted by the Engineered Alternatives Task Force (EATF). Treatment of the wastes, prompted by the desire to improve long-term performance of the WIPP repository, will lead to some increases and decreases in different contributions to the total risk of the WIPP. It is the purpose of this study to evaluate numerically the balance between the changes in the short-term risk components and compare them to the expected improvement in the long-term risks.

This study evaluates the total risks from treating, handling, transporting, and emplacing waste in the WIPP. It then compares the total risks associated with no waste treatment (baseline case) with those associated with the four selected waste treatments, carried out at four selected site combinations. The total risk of the WIPP operations, as envisaged in the Final Supplemental Environmental Impact Statement (FSEIS) (DOE, 1990a) and Final Safety Analysis Report (FSAR) (DOE, 1989a) results in the evaluation of 124 different contributions to the total risk or risk components. These components arise from the analysis of 60 scenarios (Appendix I, Section 4.3). The risk components are written in mathematical form and their properties for different levels of treatment activities are studied. According to these properties, all risk components are then scaled appropriately to the treatments selected. Thus total risks of the WIPP for 16 treatment and location options are calculated.

The comparison of these multi-component quantities is not a trivial operation. Only two numbers can be compared at one time, and only if they are measured for the same quantity, given in the same units. A novel procedure for comparing multi-component risks was developed for this purpose, using some of the tools of Multi-Attribute Utility Theory (Appendix I, Section 3). As a consequence of inserting only risk components as attributes into this theory, and due to some special characteristics common to all risk components, a special form of utility function is selected. Based on the properties of this function, two related quantities are then defined: the consequence reduction index and its inverse, the consequence augmentation index (Appendix I, Section 3.2.2). Both indices can be interpreted as the weighted geometric average of all contributions to the total risk, relative to the same contributions to the baseline risk. A reduction index larger than one indicates a decrease in overall risk; or, more precisely, in overall consequences, an index less than one, indicates an increase. Conversely, a consequence augmentation index larger than one is an indication for an increase in overall consequences, whereas an index less than one indicates a decrease in consequences.

These indices are single, dimensionless numbers that can be compared directly. They are composites of all the risk components, weighted with a societal valuation of each particular component. Thus, a fatality will be weighted differently from an injury or the risk of some monetary losses. In deriving these societal valuations, the future application of this analysis is taken into account. In Section 6.4 and 9.0 of the main report, it becomes an integral part of the

database required to decide between the feasibility of different treatment alternatives and the plant locations. This is, thus, a technical decision. Into this decision, the societal valuations of different risk components need to be embedded. In the limited scope of this investigation it is assumed that there is one decision maker who consults with some experts to help him establish his own set of weights (Appendix I, Section 5.1). The decision maker then uses these weights in the procedure outlined to rank the total risks of the 16 treatment/location options.

In most cases, a risk comparison is part of a larger evaluation that will make a decision on engineered alternatives based on a number of criteria, among them total risk. The decision maker in that process will need to inspect the weighting process and possibly influence it in such a manner that it reflects the needs of his own multi-criteria decision analysis. In this way he becomes one of the most important members of the circle of experts consulted by the decision maker for the risk comparison, decisively influencing the weighting used in the ranking of treatment/location options.

As an additional aid in making this ranking, the relevant standard errors of all parameters are followed throughout the calculation, using algebraic methods of error propagation. The result is a set of risk reduction and augmentation indices with standard errors. Two mathematical criteria are employed to establish significant and insignificant differences between indices. More important, however, are the groupings of alternatives and the trends within groups established in this analysis (Appendix I, Section 5.1).

The results of the decision maker's evaluation are shown in Figure I.ES-1, where the consequence augmentation indices are listed in a 4 x 4 array for all 16 treatment/location options. The four location options are listed horizontally in increasing decentralization; the four treatment options are listed vertically in increasing complexity of the treatment. The left column lists the consequence augmentation factors for a single treatment center at the WIPP. For treatment at the WIPP, transportation risks are thus unchanged from the baseline case, and the sharp increase of the indices for Level III treatments (Treatment Option 4) reflects the rising influence of the treatment risks. For Treatment Option 4, the location dependence reflects the rising influence of the transport risks, mostly the reduction in normal traffic accidents due to the reduction in the number of transports when wastes are treated prior to shipment. The cells with the highest augmentation indices (greatest increase in risk due to treatment) have the lightest pattern; those with the lowest indices (here given as inverse values, that is, as consequence reduction indices) have the darkest shadings.

For Level II Treatment Options 1 and 2, the consequence augmentation indices are found to be closely grouped with overlapping errors. This signals a near independence from location and a general increase in the composite risk augmentation index to 1.5, resulting in an even shading of all the cells.

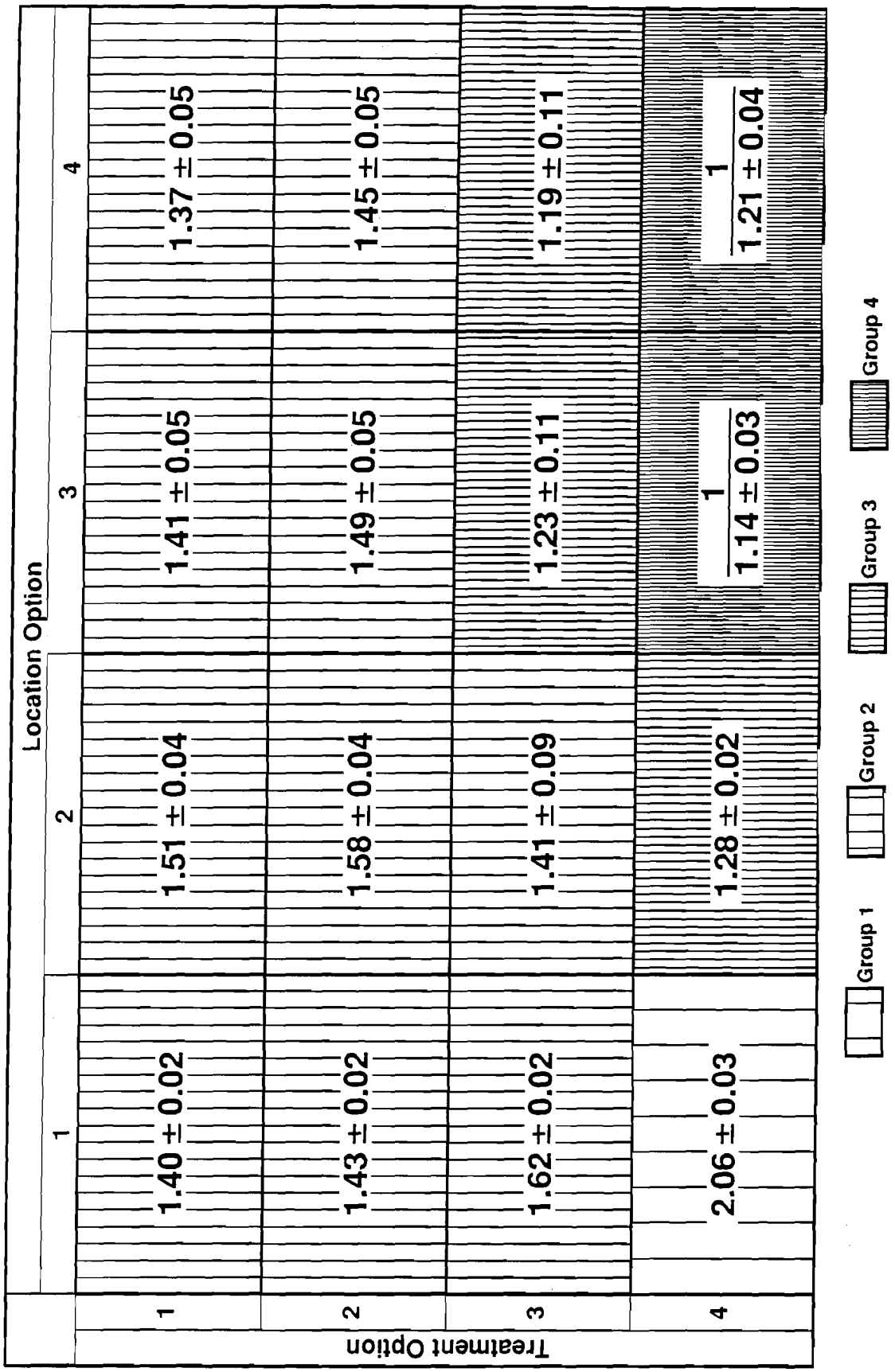

FIGURE I.ES-1 CONSEQUENCE AUGMENTATION INDICES FOR ALL TREATMENT AND LOCATION OPTIONS

For both Level III treatments (Treatment Options 3 and 4), clear trends with location are evident. Level III treatments tend to significantly reduce the required number of TRUPACT-II transports relative to the baseline, untreated waste case. For Treatment Option 3, consequence augmentation indices of about 1.6 for treatment at the WIPP decrease to indices of 1.2 for decentralized treatment. An augmentation index of 1 means equivalence with the overall baseline risk. For Treatment Option 4, this trend is much stronger and the consequence augmentation indices range from the lowest to the highest value in the array. For this manpower intensive treatment, the increased treatment risk and the reduced transportation risk lead to an augmentation index of 2 for treatment at the WIPP, and to reductions with indices near 0.8 or 1/1.2 for treatment near the originators of the waste.

In this context, it is important to realize that, although an index larger than 1 indicates an increase in consequences, the relationship is nonlinear and does not indicate an increase by this amount over the baseline risks. In fact, by virtue of the method used here, no absolute risks can be calculated for the treatment/location options.

For an evaluation of the influence of each consequence component on the value of the index, the sensitivity study in Appendix I, Section G.4 lists the factors by which each component contributes to the result. These trends and their causes show that the radiological risks are among the smallest contributions to the total risk, both in the baseline risks given in the FSEIS (DOE, 1990a) and in the risk comparison here. This arises from the valuation of society, which discounts traffic fatalities and injuries strongly, discounts occupational fatalities somewhat less, but puts strong emphasis on radiation injuries resulting in cancer and other health effects. The small size and influence of radiation risks is a testimony to effective intervention by health physicists in this respect. Thus the low but generally much larger occupational and transportation accident risks are expected to dominate most of the discussion.

Thus, in summary, Level II treatments lead to an increase in consequences, which is not sensitive to the location of that treatment. Level III treatments, on the other hand, are sensitive to location varying from increases in total risk to moderate decreases. This general insight is felt to be insensitive to most of the biases encountered here; robust even with regard to the largest source of bias, the decision maker.

1.0 INTRODUCTION

A key component in evaluating the feasibility of alternatives identified by the Engineered Alternatives Task Force (EATF) is the assessment of risk associated with the various waste treatments. Waste treatment will increase or decrease some components of the total risk of managing and transporting transuranic (TRU) wastes and of operating the WIPP. Most notably, decreases in the long-term risk components such as those due to human intrusion scenarios, can only be achieved at the price of increasing some short-term risk components, such as cancer risks; other short-term components, such as transportation risks, are decreased by some of the treatments proposed. It is the objective of this investigation to evaluate the balance of the short-term risk components and to weigh them against the improvements in the long-term risk components.

This evaluation compares the total risks inherent in managing, transporting, and emplacing differently treated wastes in the repository relative to the baseline risks associated with the shipment and emplacement of "as received" wastes. It also uses current WIPP waste container and repository designs. From the many possible treatments of the wastes, a few options were chosen to represent the span of characteristics of treated wastes, with the various components of each compared against the "baseline" to arrive at a relative risk reduction factor. One of the primary tasks of this comparative risk assessment was to scale all components of the total baseline risks to the level of activity required by the different treatment options.

A relative risk assessment of the entire WIPP operation over its operating lifetime and the subsequent post-closure period includes risks for a variety of operations, incidents, and accidents. Most prominent among them are those connected with the transportation of the wastes, the corresponding handling operations, and the emplacement of the wastes underground. While these factors are addressed in the "baseline" risk, selection of any waste treatment leads to additional risks due to handling and transportation, in addition to the risks due to the treatment. Consequently, the relative risk assessment must consider all components of the total risk.

Factors addressed by the relative risk assessment include transportation and occupational accidents, exposure to radiation either due to direct external exposure or incorporation of radioisotopes by the inhalation or ingestion route, and exposure to toxic chemical agents in the wastes. With the exception of traffic and occupational accidents not involving the radioactivity or chemical toxicity of the wastes, the risk components are all small. Traffic and occupational accidents pose larger risks, but these are essentially on the same scale as accidents in industrial operations of similar scope. For all risk components, both routine exposures and exposures under accident conditions are addressed and the corresponding risks to the public and the work force are considered. These short-term risks are evaluated both during the operational phase and as carcinogenic risks in 5 to 20 years. Long-term risks are those associated with the hypothetical human intrusion event 5,000 years after decommissioning of the WIPP (see discussion of the

Design Analysis Model in Section 2.4 of the main body of this report). These include the risks to workers involved in human intrusion scenarios and to nearby residents that are exposed to radionuclides released as a result of the intrusion.

Increased handling due to waste treatment, and thus an increase in the work force, leads to an increase in the incidence of work-related accidents, resulting in both occupational injuries and fatalities. Among these accidents, forklift accidents are quite prominent because they contribute only 1 percent to the incidence of accidents but result in 10 percent of the injuries with workdays lost (U.S. Department of Labor, 1986). Also, some waste treatments will result in an increase in the number of TRUPACT-II shipments to the WIPP (because the treatment increases the weight of the waste form, which reduces the number of drums per transport), while others decrease the number of transports relative to the "baseline" case of no waste treatment. Of all risk components, transportation risks have the largest number of expected fatalities and injuries (DOE, 1990a), and even relatively small increases/decreases will result in significant changes of both the short-term and overall risks.

The transportation risk components consist of the risks of death or injuries in accidents involving TRUPACT-II transports, as well as the health effects due to direct exposures of the transport crew and of the public to penetrating radiations. The two components due to traffic accidents are the largest risk components projected for the entire WIPP activity (DOE, 1990a). In routine transportation, public and occupational radiation exposures are limited to persons on or near the highways traveled. In accident scenarios, however, the public at larger distances downwind or downstream may also be at risk. For these rare accidents, waste treatment may offer significant risk reductions if the fraction of wastes that are released as airborne particles is minimized.

The largest contributions to the relatively small radiation risks of the actual disposal operations in the WIPP arise from direct irradiations of the work crew. These risks are not expected to be strongly affected because the same amount of radioactivity must be handled and emplaced underground, regardless of whether the wastes are treated. In the incident and accident scenarios, however, these smaller risk components could be significantly reduced. For radiation exposures, the changing risk of cancer as well as of genetic damages is addressed. For chemical toxicants, the reduced risks of both cancer and non-cancer health effects due to the destruction of Volatile Organic Compounds (VOCs) are discussed. Both the risk to workers and those to the public are addressed.

All components of the overall risk that involve the actual treatment of the wastes will lead to a small increase in the number of injuries and fatalities. These risks arise here from routine treatment operations and from regular maintenance activities. Both the workers and the public are at risk, but it is mostly occupational risks that increase when wastes are treated. This is due to the deposition of airborne wastes in the interior of the plant, the filtration, and environmental dilution which are expected to reduce public exposures substantially.

Routine exposures can be assumed to be low due to the health and safety procedures instituted at the treatment facility. The requirements of the As Low As Reasonably Achievable (ALARA) concept (International Commission on Radiological Protection, 1959) are expected to be followed rigorously. Nevertheless, penetrating radiations will lead to a low-level radiation exposure in the workplace and, consequently, an occupational risk of cancer and of genetic damage is assumed to exist. Accidental events will lead to an increase of direct external and internal exposures but for a short duration only and with a relatively low probability.

Fugitive emissions of radioactive aerosols from the enclosures of the treatment devices during routine operations will lead to a potential incorporation of radioisotopes by inhalation and ingestion, resulting in relatively small risks of cancer and genetic effects. The potential for such exposures is somewhat greater during routine maintenance operations, although personal respiratory protection and the enforcement of strict health and safety rules are expected to keep these risks low as well.

The risk of exposure to volatile chemical toxicants, both carcinogenic and non-carcinogenic, in treatment activities is expected to be higher than in any other operation because all waste enclosures such as plastic bags are opened at one point or another during treatment, allowing the volatile organics to escape. Entraining the fumes in ventilating air streams will protect worker health, and adsorptive filters in the exhaust will protect the public. The fraction of gases that penetrate to the outside may lead to health effects according to the carcinogenic or non-carcinogenic action of the toxicants. Escapes of substantial amounts of VOCs during accidental events may lead to increases of these exposures, but again for a short duration only and with a low probability of occurrence.

The basic mathematical operation in evaluating different treatment options and the location of the corresponding facilities is a comparison of the total risks for two or more different treatment/location options. This comparison is made difficult by the fact that the total risk is a multicomponent quantity. Numerical comparisons, however, can only be carried out for two quantities of the same kind, measured in the same units. Consequently, only comparisons between the same components of two total risks are possible, falling short of the goal of comparing two total risks. For that purpose, it is useful to apply some of the tools of multicriteria decision analysis to risk comparison. Formerly a branch of economics, decision analysis has over the last few decades grown into an independent discipline, which offers the basic tools needed for an application to the comparison of multicomponent total risks.

The method chosen here is based on Multi-Attribute Utility Theory (MAUT; Keeney, 1978) but modified and adapted to reflect the facts that all attributes are components of a risk and thus of a similar nature, and that risks are uncertain quantities, a characteristic that needs attention in the process of comparison. In the application of some of the tools of MAUT developed here, unusual restrictions and special considerations are imposed on the evaluation, leading to a new method of comparing and quantitatively ranking multicomponent quantities such as risks.

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2.0 BASIS FOR EATF RISK COMPARISON

2.1 GENERAL CRITERIA FOR COMPARISONS

The EATF selected 14 combinations of alternatives for analysis, far too many to be subjected to a Comparative Risk Assessment. Four forms of waste treatments were selected for assessment of risk, primarily to span the range of treatment options. Similarly, multiple choices for the location of the Treatment Facilities (TF) are being considered. Four combinations of locations were chosen, again more to span the range of options than to represent four proposed or even feasible sitings. Since the risks of transporting the wastes are the largest contributions to the total risk of WIPP activities, it is important to study a wide range of possibilities in order to be able to make use of any significant risk reductions that may arise.

The scenarios studied comprise all those discussed in the FSEIS (DOE, 1990a) and in the RADTRAN III code (Madsen et al., 1986), except for the human intrusion scenarios that occur after the WIPP is decommissioned. These were treated using the Design Analysis Model (Section 2.0 of the main body of the report) plus simplifying assumptions for radionuclide transport to the accessible environment.

In this analysis, routine operations, maintenance operations, and accidents are considered whenever the treatment requires a change relative to the baseline case. Baseline risks are not calculated in this study, but instead are taken from the risks discussed in the FSEIS and in some cases from the FSAR (DOE, 1989a). Thus a risk comparison involves the detailed discussion of a particular event, once with waste "as received," and once with waste treated in accordance with one of the four options discussed. All other parameters that define the risk of the event are kept exactly the same and cancel when calculating the relative risk reduction.

The risk comparison, therefore, is based on the evaluation of the complete mathematical expression approximating the risk and a study of the treatment dependence of each parameter. From this discussion, the scaling properties of the risk can be deduced. These properties determine how the risk will change when these parameters are given the values characteristic of the treated wastes or the treatment of the wastes.

In the FSEIS, different phases of the overall WIPP activities are distinguished. This procedure is not followed here, because to do so would incur efforts outside the limited scope of this study. In particular, it is assumed here that the WIPP activities reach an equilibrium phase in which the total activity in the wastes produced during a year is the same as the activities of the wastes transported, treated, and emplaced in the repository during that year. All risks are, therefore, expressed in terms of risk per year of equilibrium operation.

2.2 ALTERNATIVES SELECTED FOR ANALYSIS

Treatment and location alternatives are selected to span the range of options discussed in more detail in the main report.

2.2.1 Basic Considerations

The baseline case and the treatment/location alternatives selected for evaluation are described here at the minimum level of detail necessary to perform a risk analysis.

2.2.1.1 Baseline Repository and Waste ("As Received")

The baseline case for this analysis is the "proposed action" of the FSEIS, and in some cases from the FSAR. For the risk assessment, the most important assumptions about the repository are:

- Each room in a panel is filled with 6,000 drums containing "as received" waste and backfilled with crushed salt.

- After repository closure, all panel and shaft seals are in place, with crushed salt backfill.

These assumptions do not change with the four treatments selected for evaluation. In all four cases the activity in 6,000 drums of treated wastes is assumed to be higher than that for untreated wastes, the relative difference being a function of the extent to which radionuclides are concentrated during treatment.

For the risk assessment, "as received" waste is defined as follows:

- Sludges have some cement added as solidifying agents in a 55-gallon (208 L) drum. However, this does not result in a concrete monolith.

- Solid organics, metals, and glasses are in their original form, wrapped in multiple layers of high-density polyethylene inside a 90-mil (2.3 mm) liner in a 55-gallon (208 L) steel drum.

- The average drum contains 12.9 PE-Ci (477 PE-GBq) alpha activity and the corresponding average activities for emission of beta, gamma, and neutron radiation.

2.2.1.2 Treatment Alternatives For Comparison

In Section 3.0 of the main body of this report, 14 combinations of alternatives for waste treatment, waste container, backfill, and repository design are discussed. These combinations represent the range of alternatives that might improve the long-term performance of the WIPP with regard to gas generation (from anoxic corrosion of steel or microbial degradation of organics) or human intrusion. Depending on the aspect that turns out to be most critical, there is thus a set of alternatives representing different levels of effort to effect an improvement. The span of treatments is represented by the four combinations of alternatives included in this risk assessment.

In Table I.2-1 these four treatment options are summarized. The alternatives are arranged in increasing complexity and effort. Treatment Option 0 is the baseline case involving handling, transport, and emplacement of wastes as they are planned today. In Treatment Option 1, sludges are not treated at all, but combustibles, metals, and glass are shredded and cemented. Treatment Option 2 is basically the same, except that sludges are cemented as well. Treatment Options 1 and 2 are, therefore, Level II treatments, which result in a reduction in gas generation rates but no change in gas-generation potential.

Treatment Options 3 and 4, on the other hand, are Level III treatments involving the sorting of the waste and a reduction in gas-generation potential by elimination of organics through incineration and encapsulation of the ashes by cementation or vitrification. Treatment Option 3 cements the sludges, and after sorting, shreds and cements the metal/glass fraction, whereas the combustible fraction is incinerated and its ashes cemented. Treatment Option 4 is the most complex treatment considered. It vitrifies the sludges, incinerates combustibles and vitrifies their ash, and finally decontaminates the metals by melting them with frit, disposing of the metal as low-level waste, and sending only the slag enriched in radioactive isotopes to the repository.

In all of these treatments, the closure operations in the repository are assumed to be identical, i.e., the same backfill (crushed salt) is used, and the same seals for panels and the entire repository are put into place. In this form, Treatment Options 1 and 2 correspond to Alternatives 1 and 2 of the main report, whereas Treatment Option 3 corresponds to Alternative 4, and Option 4 to Alternative 8.

2.2.2 Process Descriptions for Treatment Alternatives Selected

The process descriptions given here are generic, based on general information and on some details available from similar processes.

TABLE I.2-1

ACTIVITIES FOR THE FOUR TREATMENT OPTIONS

WASTE FORMS	BASELINE 0	OPTION 1	TREATMENT OPTION 2	OPTION 3	OPTION 4
All	Retrieve/Select Waste	Retrieve/Select Waste	Retrieve/Select Waste	Retrieve/Select Waste	Retrieve/Select Waste
All	Assay and Certify	Assay and Certify	Assay and Certify	Assay and Certify	Assay and Certify
Sludges	--	--	Cement	Cement	Vitrify
Combustible Waste	--	Shred/Cement	Shred/Cement	Incinerate/ Cement Ash	Incinerate/ Vitrify Ash
Metal/Glass Waste	--	Shred/Cement	Shred/Cement	Shred/Cement	Decontaminate
All	Load in TRUPACT-II Transport	Load in TRUPACT-II Transport	Load in TRUPACT-II Transport	Load in TRUPACT-II Transport	Load in TRUPACT-II Transport
All	Unload TRUPACT-II	Unload TRUPACT-II	Unload TRUPACT-II	Unload TRUPACT-II	Unload TRUPACT-II
All	Emplace in WIPP	Emplace in WIPP	Emplace in WIPP	Emplace in WIPP	Emplace in WIPP
All	Human Intrusion After 5,000 Years	Human Intrusion After 5,000 Years	Human Intrusion After 5,000 Years	Human Intrusion After 5,000 Years	Human Intrusion After 5,000 Years

2.2.2.1 Shred and Cement Combustibles, Glass, and Metals

Risks are calculated using the following approach to shredding and cementing as one approach to waste treatment. Waste will be removed from the drums, sorted if necessary, and gravity fed into a shredder. Shredded waste will then be loaded into a feed hopper. Shredded waste and Portland cement will be simultaneously loaded into 55-gallon (208 L) drums, and mixed with an in-drum mixer. This device consists of a motor and shaft attached to the drum in place of a lid. The shaft goes into the waste/cement mixture and rotates to form a homogenous waste form.

The mixer is removed and drum lid installed. The shredding process results in an increased waste loading of 20 percent, with the cement occupying the void space within the shredded waste. The average weight of a processed drum is approximately 950 lbs (430 kg). This final waste form can be described as shredded waste encapsulated in cement.

2.2.2.2 Cement Sludges

Treatment risks assume the following approach to cementing sludges. The sludge is removed from the drums and pulverized into a granular form. The granular sludge is then mixed with cement either as an in-drum procedure or as a batch process. Cementing sludges will not result in a volume reduction. It is assumed that the volume of added cement is equivalent to the void spaces that exist in the sludge prior to reprocessing. The average weight of a processed drum is approximately 760 lbs (350 kg). The final waste form can be described as a concrete-like monolith with a homogeneous distribution of contamination. The material will be indistinguishable from cement within the monolith. For newly generated sludges this process is already in use. There may be a need for refining the process to meet particular specifications. For stored waste a new process would be required.

2.2.2.3 Incinerate and Cement Combustibles

Risks are evaluated based upon the following procedure for incinerating and cementing combustibles. Waste is removed from the containers, sorted, and fed into a shredder. After shredding, the waste will be directly fed into the incinerator. Incinerator ash is collected and mixed with cement either as an in-drum process or as a batch process. This process results in an increased waste loading of three to one. The average weight of a processed drum is approximately 1,050 lbs (480 kg). The final waste form can be described as a concrete block with a homogeneous distribution of contamination. The ash will be indistinguishable in the cement block.

2.2.2.4 Vitrify Sludges

Risks are less well defined for vitrifying sludges because the process is not fully demonstrated. For newly generated sludges it may be possible to add a melter to the end of the process that

generates the waste. For stored waste, the process is new. The sludge will be removed from the drums and pulverized into a granular form that can be fed into a microwave melter. Once processed, drums filled with melted sludge are removed from the microwave cavity and stored until cool. This process results in an increased waste loading of 9.1 to 1. The average drum of vitrified sludge weighs approximately 1,000 lbs (450 kg). The final waste form can be described as a borosilicate glass nugget. The sludge will be indistinguishable within the glass.

2.2.2.5 Incinerate and Vitrify Combustibles

Waste will be removed from the containers, sorted, and fed into a shredder. The shredding process will be the lead-in for the incinerator. After incineration, the ash will be collected and fed into the vitrification process. The vitrification process will consist of feeding ash into a microwave melter in a continuous or batch mode. Drums will then be removed from the microwave cavity and allowed to cool. This process results in an increased waste loading of 13 to 1. The average drum of processed waste is approximately 1,150 lbs (520 kg). The final waste form can be described as a borosilicate glass nugget. The incinerator ash would be an integral part of the glass.

2.2.2.6 Decontaminate Metals and Glass by Melting

The beginning of this process will involve removing all metallic components from the combustibles. This involves a sorting process in which drums will be emptied and all metallic components removed for decontamination. The remaining waste would be removed for incineration and vitrification (see Treatment Option 4). The contamination from the metal components would be homogeneously contained within a borosilicate glass nugget. This process involves melting metals and a preferential migration of the radionuclides into the slag material (borosilicate glass). The metallic waste is eliminated from the waste inventory with this process. The process results in an increased waste loading of 7.4 to 1. In the final product, the waste is in the form of a slag instead of a metal. The average weight of a drum containing slag is approximately 1,150 lbs (520 kg).

2.2.3 Location of Treatment Plants Selected

The risk assessment of the Engineered Alternatives considers the different numbers and locations of treatment plants to provide insights into the influence of these parameters on risk. According to the FSEIS, the transportation risk is the largest component of the total baseline risk. For each treatment option, the location options are varied from a single, centralized treatment facility located at the WIPP to a relatively decentralized option with local treatment facilities at all larger generator sites. The actual sites are chosen so as to best represent the multitude of possible site combinations for calculational purposes only. No other considerations were taken into account. If treatment should be required in the future, other influences and aspects would determine facility locations. The sites considered here are:

- Idaho National Engineering Laboratories (INEL)
- Rocky Flats Plant (RFP)
- Hanford Reservation (HAN)
- Savannah River Site (SRS)
- Los Alamos National Laboratories (LANL)
- Oak Ridge National Laboratories (ORNL)
- Nevada Test Site (NTS)
- Argonne National Laboratories - East (ANL)
- Lawrence Livermore National Laboratories (LLNL)
- Mound Laboratories (MOUND).

Four facility siting options are described in Table I.2-2. Only waste shipments from these ten originators will be considered in the risk assessment.

Location Option 1 (Figure I.2-1) has one treatment facility at the WIPP where all wastes are processed. For transportation, this option corresponds to the baseline case as every waste generator currently plans to send its waste to the WIPP in an untreated state. Location Option 2 (Figure I.2-2) has three regional treatment facilities located at the WIPP, RFP, and INEL. The INEL processes its own waste as well as the waste generated at HAN. The RFP processes only its own waste and the WIPP site processes all other wastes.

Location Option 3 (Figure I.2-3) has five treatment facilities. The WIPP processes waste from smaller generators such as LANL, LLNL, and NTS. The SRS acts as a regional treatment facility in the east and services ANL, MOUND, and ORNL facilities. The RFP, INEL, and HAN sites all treat their own waste before shipment to the WIPP.

Location Option 4 (Figure I.2-4) has seven treatment facilities, one at each of the major waste generators. Only smaller waste generators such as ANL, MOUND, NTS, and LLNL would ship their wastes directly to the WIPP for processing.

2.3 SCENARIOS SELECTED FOR RISK COMPARISONS

Both routine and accident exposure scenarios are considered in the risk comparison. The following descriptions are either summarized from information in the FSEIS or used in the analysis of the new treatment risks. No credit is taken for recently improved operating procedures, such as the use of a vent hood during the unloading of the TRUPACT-II containers.

2.3.1 Routine Scenarios for Baseline Risks

Routine scenarios, denoted here by the letter N, describe the day-to-day exposures to radiation and chemical toxicants.

TABLE I.2-2

LOCATION OF TREATMENT FACILITIES

LOCATION OPTION	INEL	HAN	RFP	LANL	ORNL	SRS	WIPP
1	--	--	--	--	--	--	x
2	x	--	x	--	--	--	x
3	x	x	x	--	--	x	x
4	x	x	x	x	x	x	x

x - Denotes the presence of a treatment facility.

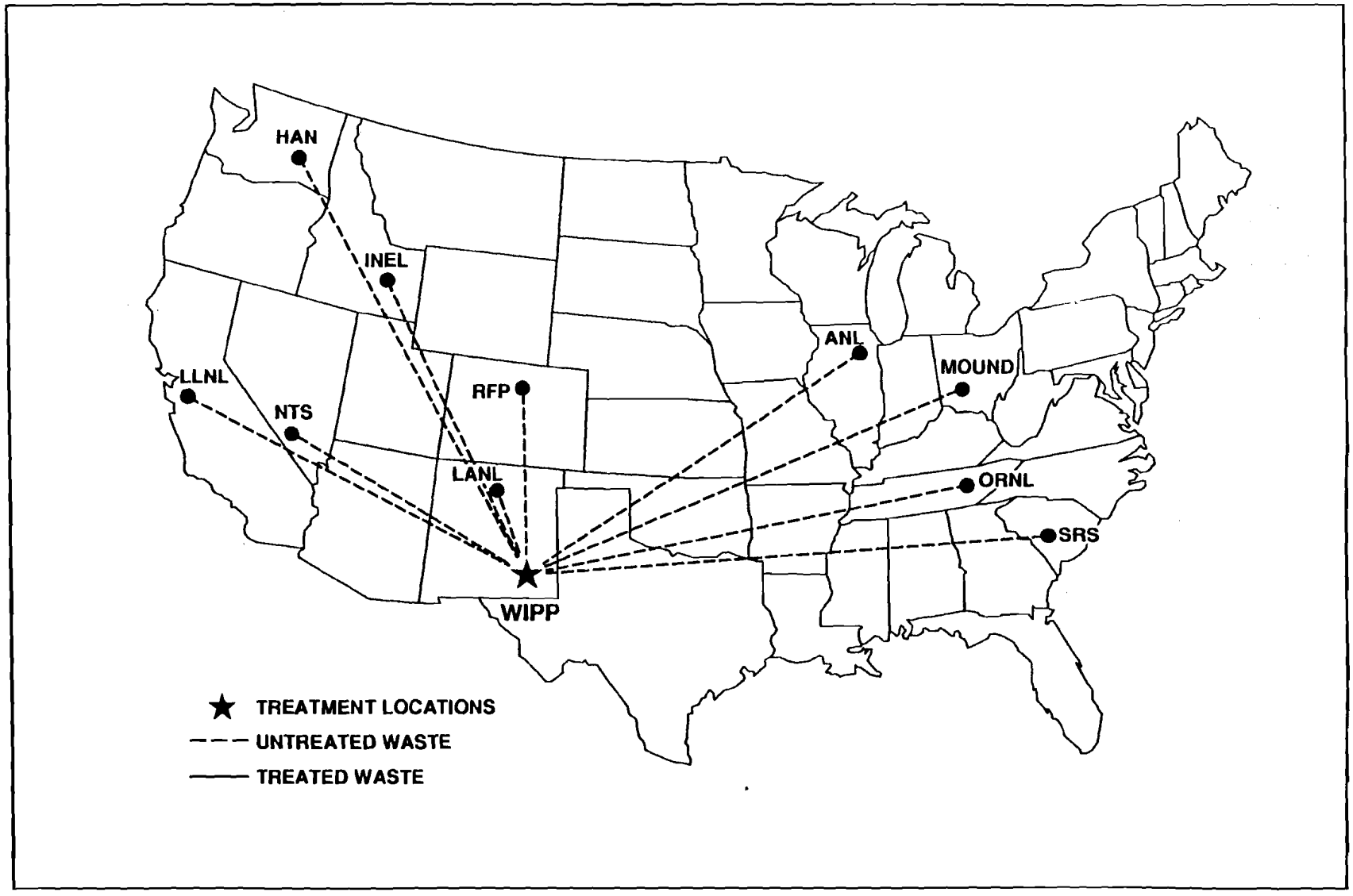

FIGURE I.2-1 TREATMENT PLANT LOCATIONS – OPTION 1

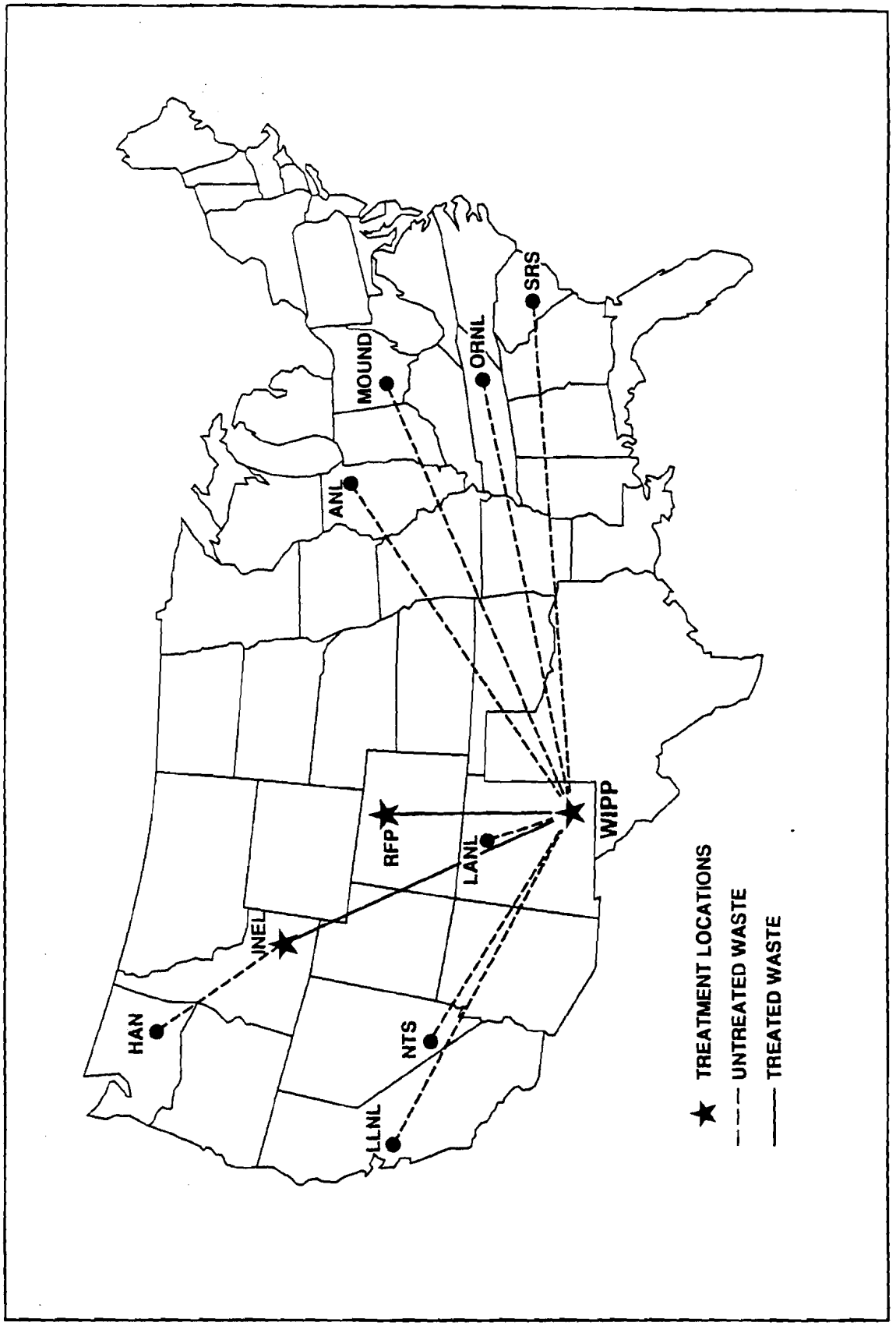

FIGURE I.2-2 TREATMENT PLANT LOCATIONS – OPTION 2

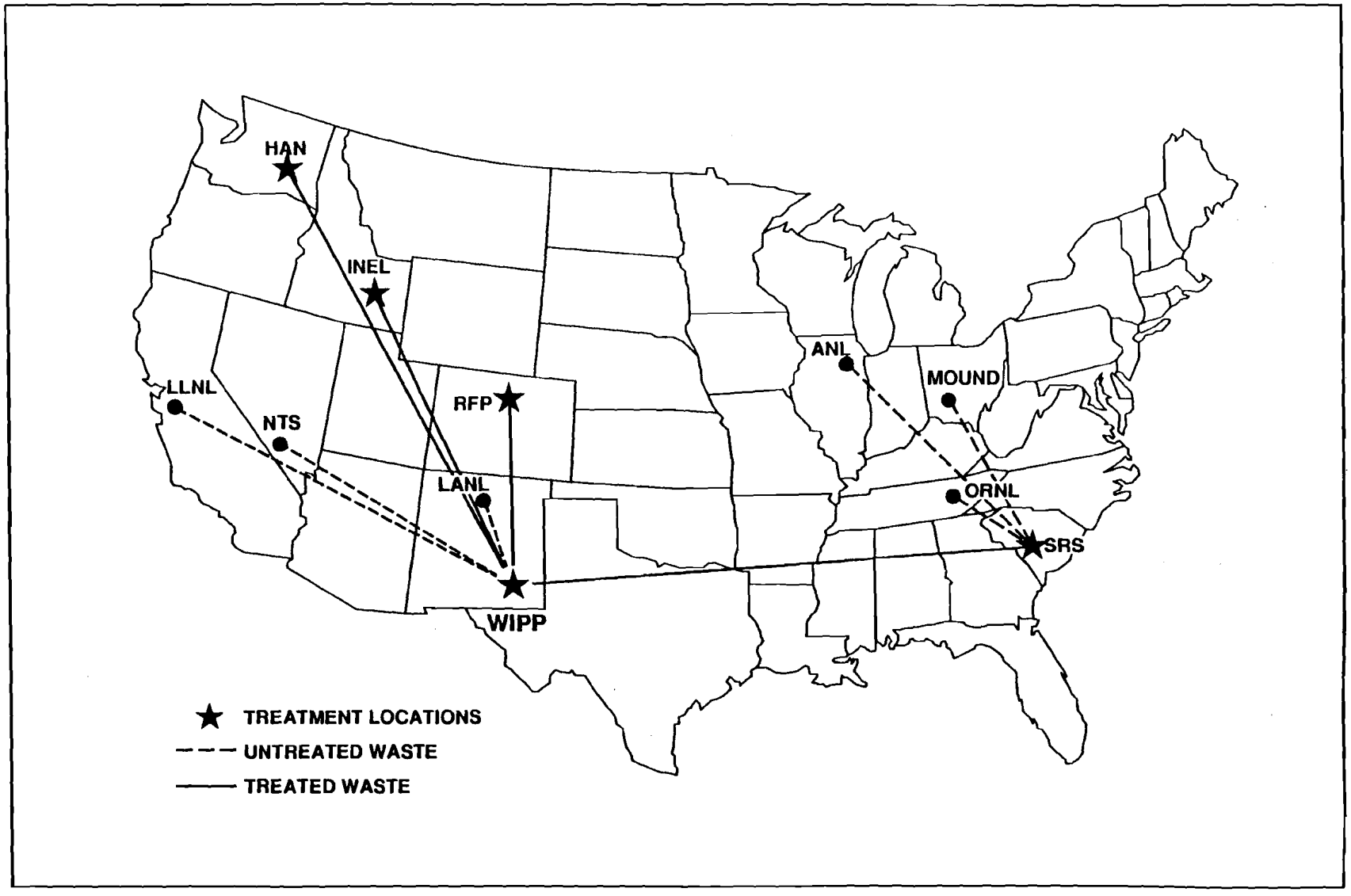

FIGURE I.2-3 TREATMENT PLANT LOCATIONS – OPTION 3

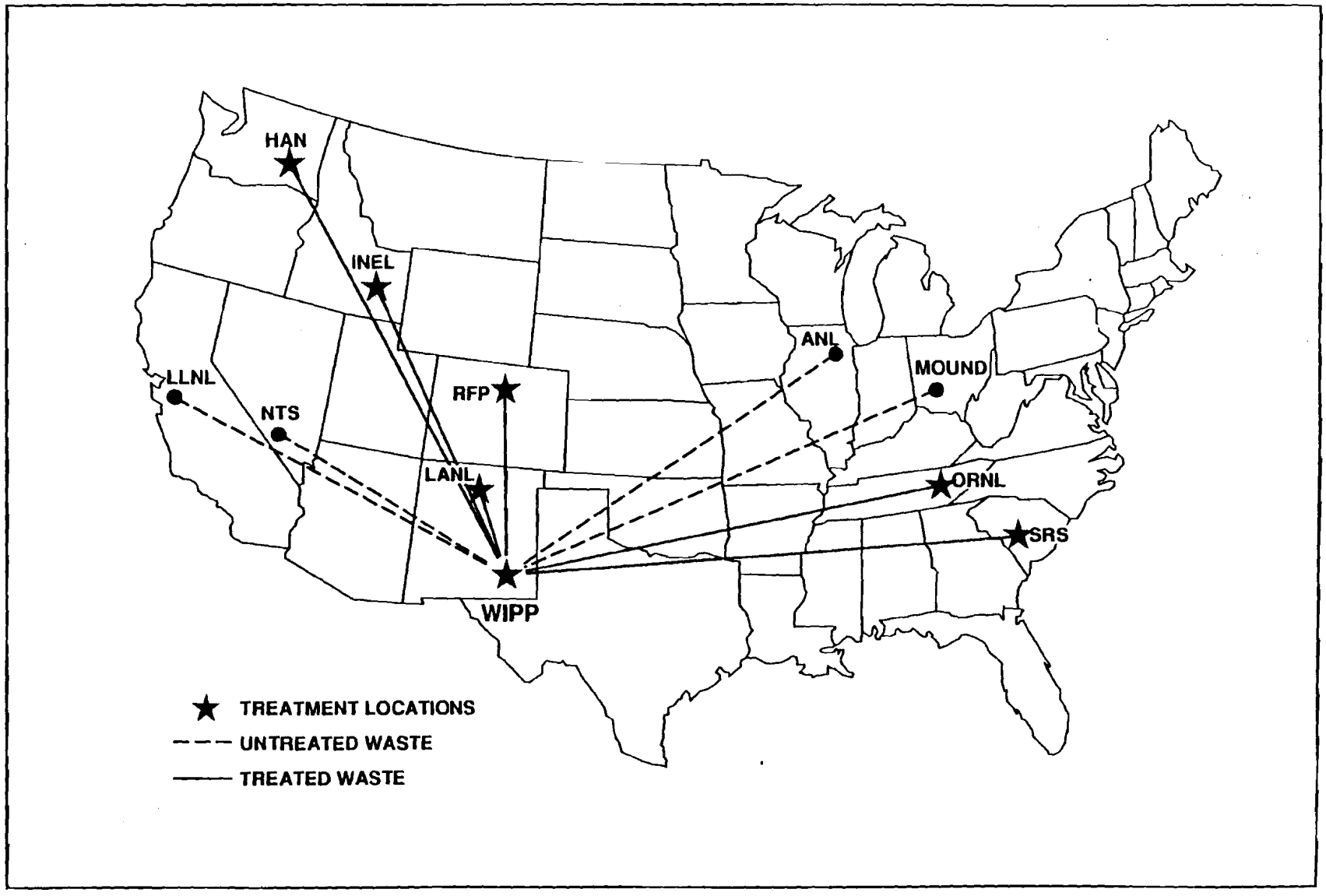

FIGURE I.2-4 TREATMENT PLANT LOCATIONS – OPTION 4

2.3.1.1 Routine Scenarios for Handling and Disposal at the WIPP

For this assessment, routine exposures are those that occur without detection by the radiation monitoring devices such as the Continuous Air Monitors (CAMs). Routine inhalation exposures that occur during waste handling operations are considered to be a continuous, chronic exposure, and workers are assumed to be without respiratory protection.

2.3.1.1.1 N1 Routine Exposure Scenario

Drums may contain surface contamination at levels below those defined in the Waste Acceptance Criteria (DOE, 1989b). Through routine handling, some contamination can be mobilized and suspended in the air. Occupational exposure results from inhalation and deposition of the suspended particles in the lung. Public exposures result from suspended particles which penetrate the High Efficiency Particulate Air (HEPA) filters and escape to the outside environment.

2.3.1.1.2 N2 Routine Exposure Scenario

In this scenario, a drum is perforated before it reaches the Waste Handling Building (WHB). During handling, but before assay and certification, small amounts are released from the drum, resuspended in the air, and subsequently inhaled by the work crew, resulting in an occupational risk. Again the public may be exposed to the particulates that escape deposition in the HEPA filters resulting in the public risk component. There is no further risk after the drum has been assayed and certified, as it is assumed that any perforation is detected by these procedures and remediated by overpacking. Recent changes in procedures (vent hood) significantly reduce this small risk.

2.3.1.1.3 N3 Routine Exposure Scenario

This scenario is identical to N1 except that the routine exposure occurs underground and results in both occupational and public risk components.

2.3.1.1.4 N4 Routine Exposure Scenario

This scenario incorporates the risk from external radiation during the unloading, assay and certification, and transport procedures in the WHB. All other elements of the scenario are the same as for Scenario N1.

2.3.1.1.5 N5 Routine Exposure Scenario

This scenario is identical to N4 except that the routine external exposure occurs underground during the unloading, transport, and disposal operations.

2.3.1.2 Routine Scenarios for Waste Transport

The routine exposure scenarios for the TRUPACT-II transports are those evaluated in the RADTRAN-III code (Madsen et al., 1986). They consist of a number of public and occupational exposure models designed to evaluate radiation exposures below regulatory limits for the general population. These models are used as baseline scenarios.

2.3.1.2.1 Routine Public Exposures Near Road Taken by the TRUPACT-II Vehicle

The public living or working in close proximity to the roads traveled by the TRUPACT-II transports are routinely exposed to the low-intensity penetrating radiations emitted by some of the radioisotopes in the wastes. Exposures depend on the distance from the road, the speed of the transport, and the population density along the road for rural, suburban, and urban sections of each route used.

2.3.1.2.2 Routine Public Exposures During Stops

During stops, due to regulation breaks or caused by road conditions, a small portion of the public will be in relatively close proximity of the TRUPACT-II transport, and will be exposed to the low-level penetrating part of the radioactivity in the wastes. These exposures can be of somewhat lengthy duration but are distributed among relatively few persons.

2.3.1.2.3 Routine Exposures Due to Public Traveling in the Opposite Direction

The public traveling in vehicles in a direction opposite to that of the TRUPACT-II transport is also exposed to the penetrating radiations from the wastes. These low-level exposures are of very short duration due to the high relative velocities of source and receptors, and take place at relatively large distances, depending on the type of road.

2.3.1.2.4 Routine Exposure Due to Public Traveling in the Same Direction

Again, an exposure of the public to the low-intensity penetrating gamma and neutron radiations of source radioisotopes in the wastes occurs. In this case, however, the exposure times may be considerably longer due to the low relative velocities and the proximity of the vehicles during passing.

2.3.1.2.5 Routine Exposure of Crew During Transport

During most of the time spent in transit, the crew is exposed continuously to the penetrating radiations emanating from the wastes in the TRUPACT-II containers. Although still relatively low, considerably below occupational exposure limits, theirs are among the highest individual occupational exposures.

2.3.1.2.6 Routine Exposures of Warehouse Personnel

Warehouse personnel at both origination and destination points are exposed to the penetrating radiations of up to a full load of drums, however, without the shielding effect of the TRUPACT-II walls. This is mitigated by a larger distance and potentially some shielding required by health and safety regulations and ALARA concerns.

2.3.2 Accident Scenarios: Assumptions and Descriptions

In this analysis, accidents are assumed to produce short exposures because extensive health and safety precautions are in place and assumed to be followed. Each accident scenario considered directly or indirectly by the risk assessment in the FSEIS will be described briefly here. Conservative assumptions are made with respect to the amount of radioactivity or chemical agent released per accident and the fraction available in respirable form. The assumptions made are uniformly on the conservative side leading to a bias in risk comparisons by overestimating the accident risks. No credit is taken for the measures planned for mitigation and control of the accident consequences. A dose calculation and a risk assessment are then made for each accident scenario postulated. Risks are calculated for both the public and occupationally exposed persons. Only accidents considered by the risk assessment in the FSEIS will be described, as others have been discounted because of extremely low probability of occurrence or because no release is postulated.

2.3.2.1 Accidents During Handling and Disposal

The accidents during handling and disposal are those denoted by the letter C in the FSEIS. The descriptions are given only in the detail required for a risk comparison.

2.3.2.1.1 Drum Drop from a Forklift in the WHB (C2 Accident)

With a certain frequency, a waste drum will be dropped from a forklift in the WHB. Waste drums are Type A packages and are designed to withstand a 4 foot drop without being damaged enough to release activity. However, it is conservatively assumed in the FSEIS that the drop results in the loss of the lid, the inner plastic liner tears, and part of the drum content is spilled. Of the wastes spilled, a fraction is suspended and available in inhalable form. The drum is assumed to contain the 12.9 PE-Ci (477 PE-GBq) cited as the average alpha radioactivity per drum. It is further assumed that the Waste Acceptance Criteria (WAC) limit of 5 percent of the total radioactivity in the drum is contained in the one weight-percent of particles with diameters less than 10 μm. Particles greater than this size are not considered to be respirable. Resuspension is assumed to cancel the depletion of activity in the room air by sedimentation or plate-out, so the total amount of suspended radioactivity in the room air reaches an equilibrium value. Between the WHB and the outside, HEPA filters are on-line that would reduce the source term to the environment by a factor of about one million.

Worker doses are estimated assuming established operating procedures and facility design. It is also assumed that the workers in the immediate area will respond as trained and immediately evacuate the area. The contamination will spread slowly and the internal deposition is, therefore, not considered to be part of the exposure. Where applicable, these assumptions will be transferred to other scenarios.

2.3.2.1.2 Two Drums Punctured by Forklift, One Drum Dropped in the WHB (C3 Accident)

It is postulated that a forklift accidentally punctures two drums with its forks and the lid of a third drum falls off as it falls from the stack. Withdrawing the forks from the drums is not advisable but is assumed to happen. For the drum with lid loss, a C2 scenario is involved; for each of the punctured drums another fraction of the waste is spilled, but from then on the probability of suspending an inhalable fraction of the activity and other assumptions are the same.

2.3.2.1.3 Transporter Hits a Pallet in the Underground Storage Area (C4 Accident)

A transporter is assumed to hit a pallet of waste drums in the underground storage area, causing the drums to fall. As in the C2 scenario, it is conservatively assumed that the lid of one of the drums is knocked off and the inner liner tears. This accident is identical to the C2 scenario with the exception that it occurs underground. HEPA filters are not assumed to be on-line as they are assumed not to be activated by the radiation detection instruments. Workers downstream from the accident would receive an inhalation dose. This part of the assessment differs from a C2 accident above ground in that there is a higher rate of air flow within the repository and there is probably a longer distance between the point of release and the workers. It is assumed that the plume is homogeneously distributed in a volume equal to 4.0 by 3.5 by 6.1 cubic meters. Conservatively, the workers are assumed to not be wearing a respirator and to be in an area not normally occupied.

2.3.2.1.4 Drum Drops from Forklift in the Underground Storage Area (C5 Accident)

This accident and its ramifications are bounded by the previously described C4 scenario.

2.3.2.1.5 Drums Punctured by Forklift, One Drum Drops in Underground Storage Area

This scenario is identical to the C3 accident scenario except that it occurs underground and that the HEPA filters are assumed to be off-line. It is further assumed that a depletion of activity occurs by plate-out and sedimentation before release to the environment. The subsequent risk to the public can be calculated from this information. The occupational worker exposure is modeled after the C4 accident scenario.

2.3.2.1.6 Fire Within a Drum Underground (C10 Accident)

Spontaneous ignition within a drum is postulated to occur only in the Underground Storage Area, because the probability rate is very low and the residence time in the WHB is brief. It is not assumed that such an event would spread to adjacent waste drums. It has been estimated that the probability of spontaneous ignition within a drum is less than 1 per 1.8 million drum-years. The drum involved in this accident is assumed here to have an average radioactivity content, contrary to the FSEIS which assumes a total alpha activity, in excess of 1,000 PE-Ci (37 PE-TBq). The spontaneous ignition is postulated to suspend some of the radioactivity content into the air underground. The deposition rate is high due to the fact that the suspended particles are in a heated state and will react with the cooler surfaces within the facility. The release to the environment and thus the amount of activity available for public exposure is estimated, assuming no HEPA filtration. There is no occupational dose postulated for this event because the waste is emplaced and stored downstream from the workers.

2.3.2.2 Accidents During Waste Transports

The accidents described here are the scenarios given in the RADTRAN code used in the FSEIS for TRUPACT-II transports.

2.3.2.2.1 Direct Consequences of Traffic Accidents

Traffic accidents, involving a TRUPACT-II transport, its crew, and members of the public and their vehicles are the largest contribution to the total risk of WIPP operations (DOE, 1990a). The number of traffic fatalities and injuries is directly related to the number of transport-kilometers and is thus sensitive to the location of the Treatment Facilities. These are the consequences of typical traffic accidents, not modified in any way by the radioactivity or chemical toxicity of the cargo.

2.3.2.2.2 Nondispersal Transportation Accidents

Nondispersal accidents mainly constitute a source of penetrating radiation with a limited range of significant exposures due to the decrease of radiation dose rate, roughly with the inverse of the square of the distance. In rare cases, close-in exposures may be incurred that cause early and late health effects such as radiation sickness, cancer, other somatic, and genetic effects. Here, the averages for accident severity, taken over the entire waste transport system and given in the FSEIS, are assumed.

2.3.2.2.3 Transportation Accident with Waste Dispersal

In this scenario, an average over large parts of the transportation system is assumed for the typical severe accident with an atmospheric suspension and dispersion of a fraction of the wastes

(see DOE, 1990a). Dispersion will subject the public to inhalation exposures and to direct exposures due to airborne radioactivity and activity deposited on the ground.

2.3.3 Routine Scenarios for Treatment Options

The modular composition of the TF allows the relatively simple evaluation of the risks for routine operations and maintenance. The same standards for health and safety, as well as ALARA, used for WIPP operations are assumed here also. Similarly, exposures to volatile chemicals are limited by forced ventilation, filters, and chemicals traps.

2.3.3.1 Occupational Accidents Typical of Industry

Risks of occupational fatalities and injuries are evaluated for the crew of the TF and the WHB. As no direct incidence data are available, information for similar industries are used. With forklift movements an integral part of the operations in handling the wastes, forklift accidents are given special attention.

2.3.3.2 Routine Radiation Exposures During Normal Operations

For routine operations with each one of the treatment devices for different waste forms, exposures to penetrating radiations are incurred. Shielding designed to satisfy health and safety criteria reduces this exposure to ALARA levels, taking into account duration of treatment and time-motion studies for the device.

Despite airlocks, some low-level airborne activity is assumed to escape from the enclosure of the device and inhaled and ingested by unprotected workers outside the enclosure. Risks are evaluated by calculating Cumulative Effective Dose Equivalents (CEDEs). The activity levels in air are assumed to be minute because they are low enough not to be detected by any of the monitors. After passing through the HEPA filters, the residual airborne activity, further diluted by atmospheric dispersion, can lead to low exposures of the public. Similarly, fugitive emissions from the device enclosures are assumed to lead to occupational exposures. Residual concentrations of VOCs after passing through filters and traps are carried outside the plant and are attenuated further by atmospheric dispersion, leading to very small public exposures to chemical toxicants.

2.3.3.3 Routine Exposures During Normal Maintenance

In routine maintenance, both external and internal exposures occur. External exposures arise from the surface contaminations of device and enclosure. Internal exposures occur by penetration or bypassing of the respirator and by ingestion. The CEDE is the quantity needed to evaluate the risk of cancer and genetic effects. Resuspended activity, after passing through HEPA filters and diluted by environmental dispersion, will lead to some public inhalation

exposures. The routine exposure to chemical agents during maintenance will be very low because treatment will reduce the presence of VOCs to negligible levels.

2.3.4 Accident Scenarios for Treatment Options

Due to the limited scope of this study and the effort required for the accident risk assessment of the six treatment devices and the appropriate accident scenarios for each, accidents in the TF are not considered in this study. Routine exposures to radiations and chemicals, as well as non-radiation, non-chemical work accidents typical of this type of industry are the only contributions to the risks of treatment taken into account. Neglecting the accident risk will lead to an underestimate of the treatment risk, and will thus introduce a bias in favor of the treatment options over the baseline case. In this type of operations, the routine risks are normally larger than the accident risks, so that this bias is not considered severe enough to invalidate the basic conclusions.

2.3.5 Human Intrusion Scenarios

The repository in an undisturbed state poses no direct risk of significance to man or environment (DOE, 1990a, 1990c). Human intrusion is needed to bring noticeable amounts of radioactivity or chemicals to the surface.

2.3.5.1 General Considerations

Human intrusion scenarios are based on the assumptions discussed in Sections 2.0 and 4.0 of the main report. Most important for the risk comparison are the following characteristics:

- The intrusion occurs 5,000 years after decommissioning of the repository.
- The hydraulic conductivity of the waste/backfill composite is the weighted geometric mean of the waste forms and backfill properties.
- The borehole conductivity is $1 \cdot 10^{-3}$ meters/second (clean sand/gravel) obtained from Table 2-2 in Freeze and Cherry (1979).
- Waste element solubilities have been assumed to be $1 \cdot 10^{-6}$ mol/liter from Table 3-10 in Marietta et. al. (1989).

The three scenarios used here are described in detail elsewhere (Marietta et al., 1989). The details relevant for a risk assessment are given here.

2.3.5.2 The E1 Scenario

The E1 scenario, shown schematically in Figure I.2-5a, assumes a borehole penetration through a waste-filled panel and continuing into or through a pressurized brine pocket existing in the Castile Formation underlying the repository. Afterwards, the drillhole is assumed to be plugged near the surface and just above the Culebra aquifer. Risks to man arise from three sources: cuttings in the drilling mud from the repository exposing the drilling crew directly; wind erosion of the dried drilling mud leading to an inhalation exposure of the nearby public; and radioactive brine contaminating the Culebra aquifer and a stock well drilled into it. This results in contaminated beef and an ingestion exposure of the public.

The model for the drill cuttings is straightforward, as is the model for the wind erosion of the dried-up mud pool and the subsequent atmospheric dispersion. The relevant quantity in both cases is the activity contained in the cross-section of the borehole and the depth of the repository (3 drums). Pressurized brine flows through the borehole and through an ellipsoidal volume of the wastes, transporting additional activity to the surface (see Section 2.2 and Appendix B.18). The contamination of the Culebra aquifer is modeled using a parametric equation relating flow rate through the waste/backfill composite to the hydraulic conductivity of the composite. This equation was developed for Section 2.2 of the main report using data from a transport model (Reeves et al., 1986).

2.3.5.3 The E2 Scenario

Scenario E2, shown in Figure I.2-5b, assumes a borehole penetrating just into the repository, not passing through. After penetration the borehole is assumed to be plugged, once near the surface and once above the Culebra aquifer. The scenarios exposing the drilling crew to direct radiation from the drill cuttings in the mud, and the subsequent public exposures are essentially unchanged. The scenario leading to the contamination of the Culebra aquifer is modeled using an analytical solution for the radial flow equation through a porous medium, simulating the borehole and the panel as concentric circles (Walton, 1989). The model is discussed in more detail in Section 2.2 of the main report and in Appendix B.18. The same model as in the E1 scenario is used to estimate the contamination in the Culebra aquifer and the stock well.

2.3.5.4 The E1E2 Scenario

The E1E2 scenario, shown schematically in Figure I.2-5c, assumes a combination of the first two scenarios; two boreholes penetrate the repository in the same panel. One borehole provides a pathway for brine flow from the Castile Formation brine pocket directly into the panel. After drilling through the repository and the brine pocket, it is assumed to be plugged near the surface and between the repository and the Culebra. The other borehole provides a pathway for the contaminated brine to reach the Culebra aquifer, as it is plugged near the surface and above the aquifer. Both boreholes provide separate sources for the exposure of the drilling crew and

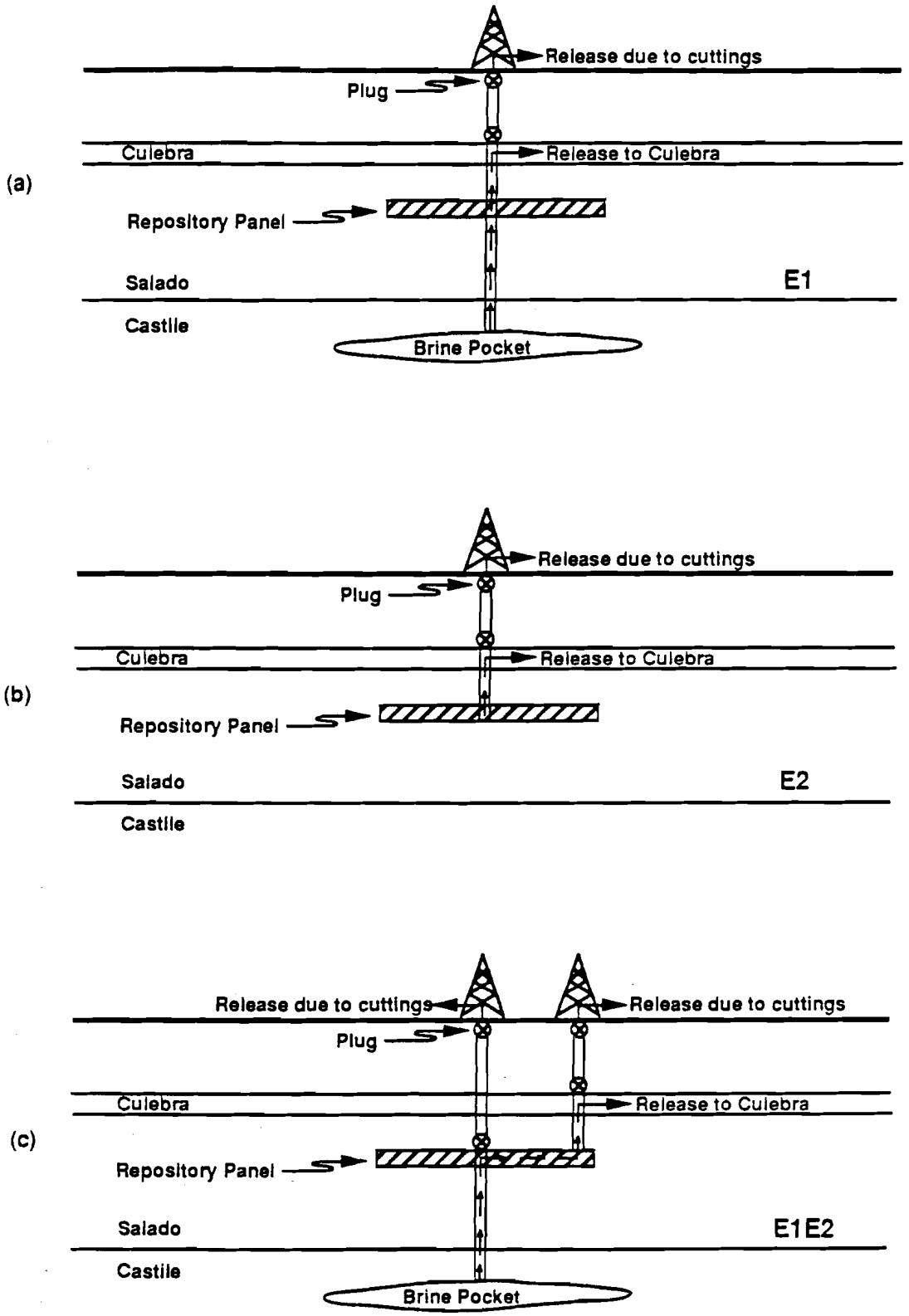

Figure I.2-5. Human Intrusion Scenarios

subsequently of the public by activities derived from drill cuttings. The contamination of the Culebra occurs by way of a flow path from the E1 borehole through the wastes to the E2 borehole and up to the Culebra. The model for the contamination of that aquifer and the stock well is the same as the one used in scenario E1.

2.4 ASSUMPTIONS FOR RISK ESTIMATES AND COMPARISONS

The assumptions presented and discussed in this section are limited to those that apply to all risk models in this study. More detailed assumptions are made when the need arises.

2.4.1 General Assumptions

Risk components may be dependent on several variables. These include treatment options, location options, routine scenarios, accident scenarios, and human intrusion or late effect scenarios. Variables such as routine and accident scenarios use the baseline cases as detailed in the FSEIS as a basis for comparison (DOE, 1990a). As stated before, the baseline cases for the human intrusion scenarios are those of the main body of this report. Treatment and location options vary the risk components but again the baseline case is used as a basis for comparison.

This study uses the same information given in the FSEIS when describing accidents, events, locations, severities, environmental conditions, and dose-effect relations. As in most of the FSEIS, risks are given as risks per year of operation, but they refer to the equilibrium phase.

The following assumptions are made for the purposes of the risk comparison mostly due to the limited scope of this study or due to lack of information on baseline risks.

- Only CH-TRU waste is considered; RH-TRU waste is not included.
- All CH-TRU waste is exclusively transported by truck.
- Risks are estimated for the equilibrium phase of operations only.
- All waste is shipped and handled in 55-gallon (208 L) drums; no other packaging is considered.
- No drums with more than average alpha activity 12.9 PE-Ci (477 PE-GBq) and the corresponding beta-, gamma- and neutron activities are taken into account.
- Maximally exposed individuals are not specifically analyzed; they are, however, included in the averaging.

- Somatic effects of radiation other than cancer are not evaluated.
- Human intrusions scenarios lead to the only post-closure effects considered.
- The FSEIS, the FSAR, and corresponding calculation briefs are the only sources used for calculation of baseline risks.

A constant value is assumed for the annual rate of activity emplacement in the repository. The annual rate of activity emplacement is an important factor for radiological risk assessment.

2.4.2 Treatment Assumptions

A treated waste has properties different from those of untreated waste resulting in changes of radiological risks. However, the following simplifications will be assumed:

- The gamma radiation spectrum and the neutron spectrum emitted by the variety of isotopes do not change with the waste form.
- The treatment of the waste is assumed not to affect isotopic leachability or isotopic composition.
- There is no attenuation of gamma radiation within the waste or its containment.
- The particle spectrum and the mean aerodynamic diameter of inhalable aerosols generated in an accident does not change with waste treatment, although the number of particles does.

All of these assumptions are basically conservative or at least neutral, because they apply to treated and untreated waste alike. However, due to their sometimes overly conservative nature, these assumptions do introduce biases, so that they should be eliminated, if possible. The spectra and the source-absorption of the gammas are conservative assumptions that can be removed by relatively simple calculations. The latter are not done here because of the limited scope of the study. The assumption of the generated particle spectrum being independent of waste treatment is borne out by the empirical particle generation model used here and thus has a low priority for replacement. The assumption of constant leachability, however, is more difficult to replace because, due to the preliminary nature of the treatment descriptions, the waste properties are not known sufficiently well to support a model for differential leachability. Note that it is a conservative assumption, which does, however, lead to an anti-treatment bias.

2.4.3 Location Assumptions

The baseline case, transportation of "as received" waste only, is the same as the Location Option 1, with the TF at the WIPP. Consequently, transportation risks are the same in both cases. Other options involve the use of additional sections of road, not traveled over in the baseline case. The assumption is made here that the fractions of travel in urban, suburban, and rural regions and all other parameters are given by the same regional averages as those given in the FSEIS.

As treatment changes the density of the wastes, and thus the number of waste shipments, there is a reduction or increase in transport-kilometers, both loaded and empty, and thus a corresponding change of the risks in some of the contributions to the total transportation risk.

2.4.4 Weight Restrictions Due to Treatment

The entire waste shipment consisting of three TRUPACT-IIs, waste, and truck/trailer assembly, must not exceed 80,000 pounds (36.2 metric tons), according to 23 CFR 658.17 (U.S. Department of Transportation, 1975). Treatment, with the corresponding volume reduction of the waste, may increase the weight of the waste form, thereby making complete utilization of the TRUPACT-II container unlikely. Each treatment option has an associated volume and weight reduction or increase, and from this information a utilization of the TRUPACT-II is obtained. Clearly, cementing of wastes increases weight to the point that complying with weight restrictions becomes an issue. The chances are greater that an increased number of shipments, above the much smaller number calculated using the volume reduction only, is required for Level II treated wastes.

Weight restrictions also seem to apply to forklift operations and forklift loading capacities. Depending on the treatment alternative, the number of forklift operations increases due to treatment. Yet, although treated drums are much heavier, a heavy-duty forklift is assumed to take care of the same number of drums as before without significant increase in accident rates.

2.4.5 Cause-Effect Functions

The cause-effect relationships for cancer due to radiation are assumed to be of the linear no-threshold type (National Research Council, 1990). Although some of the calculations in the FSEIS are using the linear-quadratic approximation of BEIR III (National Research Council, 1980), the differences at the low doses encountered here are insignificant (DOE, 1990a). The choice of the linear no-threshold hypothesis is made here, because the linear-quadratic model does not allow the use of the person-Sievert (person rem) concept. The inability to use this concept would needlessly complicate the calculation.

2.4.6 Significant Figures Given

The final values calculated are given with a number of digits determined by the standard error. Regardless of the precision of the input data, all intermediate data are given with at least one digit more than significant. This will avoid cumulation of rounding errors. Final results are normally given to one significant digit in the error because errors are rarely known to a better accuracy. This then determines the corresponding number of significant digits for the value.

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3.0 COMPARISON OF MULTI-COMPONENT RISKS

3.1 COMPARISON OF MULTI-COMPONENT RISKS

3.1.1 Definition of Risk

The concept of risk gives rise to many different definitions, which are mostly dependent on the immediate application. One of the more general definitions is that of Kaplan and Garrick (1981), which is used here. It defines risk in terms of a triplet of quantities: a scenario, a consequence, and a corresponding probability (for a more detailed description see Attachment B.21).

As an example, a risk can be defined by a scenario that postulates an exposure of the whole body of an individual to penetrating gamma rays for a short time, resulting in the consequence of leukemia five to ten years later with a probability of 0.1 percent. While more information such as the radiation dose absorbed by the body may be necessary to calculate the probability, it is implied by the value of that probability and is, therefore, not an absolutely necessary datum. Less information than the triplet, however, will result in ambiguities because the same scenario can also lead to acute radiation sickness in the short term or several other types of cancer, such as lung cancer, in the long term.

These different consequences illuminate an important property of almost all risks of an event or an activity: such risks consist of a number of different components. Only rarely is a single individual the subject of a risk assessment, and similarly, only rarely is an event completely described by one scenario. Thus, all three quantities that define a risk usually have a multi-component structure. An activity such as the operation of the WIPP entails hundreds of activities, events, and possible consequences. Also, it involves tens to hundreds of workers and, potentially, hundreds to thousands of persons in the general population. Total risks of activities such as the WIPP are thus quantities with a multi-component structure.

This multi-component structure of the total risk of an activity presents problems when the total risks of two alternate approaches, such as different waste treatments, are to be compared. Basically, it is only possible to compare two numbers, thus restricting a comparison to the values of two quantities measured in the same units. For any multi-component risk, this means that a formulation must be found to reduce the multitude of component values to one characteristic measure which then can be compared for two alternatives.

In this context, it is important to note that many decision makers prefer to compare all components of two total risks in a "seat-of-the-pants" procedure. While this may work well in many cases, it is not transparent and is, therefore, of dubious value in adversarial proceedings or other situations where decisions and their basis must be documented. The measures for risk comparison proposed here are fully transparent without unnecessarily fettering the valuation process of the decision maker. In order to accommodate decision makers that want to work with

the raw data for each component or for a decision maker on a higher level, these data are provided and discussed.

3.1.2 Uncertainties in Risk Assessment

Usually, risk calculations are beset by considerable uncertainties, which can be expressed numerically by assigning or calculating random and systematic standard errors (see for instance, Seiler, 1990). Random or statistical errors arise from many possible causes; their signs cannot be predicted, nor can they be prevented. These kinds of errors can be decreased, however, by increasing the amount of information on which the quantity is based, for example, the number of measurements taken. Systematic errors, on the other hand, usually have an identifiable cause, affect every measurement by the same mechanism, and if properly investigated, can sometimes be avoided or corrected for. They cannot, however, be decreased by increasing the number of measurements taken.

A typical example of random errors are the fluctuations in the count rate of a radiation counter exposed to a constant flux of particles. Typical systematic errors are those caused by the use of a defective scale, resulting in uniformly high or low measurements, or those caused by the use of a model that does not account for a pertinent effect, and therefore, yields systematically distorted values.

Both types of errors need to be taken into account in a risk assessment, although random errors are easier to evaluate and handle. Systematic errors are most often based on little more than an educated guess or some experimental evidence using different methods of measurement or calculation. In a comparison of risks, these standard errors play a major role in helping determine whether or not a difference between two risks is really significant. The fact of an insignificant difference in risk is an important datum in further evaluations using risk comparisons as input.

3.1.3 Comparison of a Single Risk Component

In comparing single risk components for a number of treatment/location options, it is advantageous to use a particular risk component as a baseline and perform all comparisons relative to that baseline risk. In the context of the comparison attempted here, the risk component for waste "as received" serves as baseline risk. If the comparison of the baseline risk and the risk of the alternative is in the form of a ratio, a risk reduction factor may be obtained which incorporates a number of advantages (Section B.2.2 and B.2.3). Due to the fact that risk components can be generally written as a product of a number of factors, all those that are common to both risks and do not change with treatment, will usually cancel. Among these factors are often the most uncertain ones, such as the probability of the initiating event and the probability of the consequence such as the lung cancer risk coefficient.

Risk reduction factors are, therefore, much less uncertain than absolute risks and often have a simple algebraic structure that allows the use of a simple algebraic procedure to estimate the standard errors of the result based on the standard errors of the input parameters. This process is called error propagation (Brandt, 1976; Bevington, 1969; Seiler, 1987). Also, systematic errors in quantities in the remaining factors that appear both in numerator and denominator of the ratio tend to cancel, if not completely then at least in part. This can be seen by examining a ratio with an unknown error factor in both numerator and denominator: as long as it affects both in a linear manner, the factor cancels; if its effect on both is nonlinear, it will cancel at least in part.

This risk comparison has the nature of a retrofit, imposing differently treated wastes to the risk assessment in the FSEIS. Evaluating the systematic errors in that assessment would, therefore, require an effort beyond the scope of this study. Consequently, it will be assumed that systematic errors also cancel for the largest part, leaving a small residual that does not contribute significantly to the total standard error of the risk reduction factors. The errors shown are thus exclusively of a random nature and total errors will, therefore, tend to be somewhat too small.

3.1.4 Aggregation of Risk Reduction Factors

In order to keep the number of attributes or risk components of the multi-attribute utility functions to a reasonably low number, it is often necessary to aggregate components that contribute to the same generic type of consequence. A typical example is the aggregation of risks arising from different chemicals in the same scenario, or the aggregation of various contributions to the occupational cancer risk due to transportation. As shown in more detail in Sections B.3.4 and G.1 of this Appendix, aggregation in the first case is best performed at the level of risks, that is, by combining risks and then forming risk reduction factors.

In the second case, aggregation is best performed at the level of risk reduction factors. This is especially true in the case where some the component risks are obtained from substantially different formulae. Aggregation then requires the knowledge of the values of the component risks, so that a large risk reduction factor, applied to a very small risk, cannot dominate the aggregation. Weighted averaging of the components will avoid this problem. For the averaging process over widely spread risk reduction factors, a weighted or unweighted geometric average is usually preferable over a weighted or unweighted arithmetic average (see Sections B.3.4 and C.2.1 of this Appendix).

In this aggregation phase, the decision maker responsible for the comparison first exerts his influence. It is he who decides which components to aggregate into supercomponents. This selection influences the societal valuation process and should be performed in a way that takes risk perceptions into account.

3.2 SOME TOOLS OF MULTI-ATTRIBUTE UTILITY THEORY (MAUT)

It is important for the understanding of the risk comparisons proposed that what is done here is very different from multi-attribute utility theory. Only some of its tools are being used in a manner that is designed to make the utmost of the similarities between risk components and avoid most of the criticisms of the multi-attribute utility approach.

3.2.1 Single Attribute Utility Functions

From the field of economics and economic decision theory, the concept of the *utility of a commodity* can be adapted for use in the comparison of risk components. A risk reduction factor is, according to its magnitude, assigned a utility or in other words, a usefulness or value. It should be noted that in epidemiology the inverse of the risk reduction factor is called the relative risk. According to its magnitude, it is consequently assigned a dis-utility or negative utility.

There is a relationship between the quantity of a commodity and its utility, known as the *Law of Diminishing Marginal Utility* (LDMU). It states that the slope of a utility function decreases as the commodity increases (see, for instance, Samuelson, 1973). In risk assessment, the LDMU expresses the fact that, for example, a unit increase in the relative risk is most detrimental when the risk is 1; it is less detrimental when it is 10; and even less so when it is 100. Similarly, a unit increase in the risk reduction factor is most beneficial when it is 1; somewhat less beneficial when it is 10; and so on. Graphically, this type of relationship is shown in Figure I.B-1a, in Attachment B, where, as an example, a logarithmic dependence is plotted as a function of the argument. In risk management, the LDMU expresses the fact that a unit increase in a occupational risk of one fatality, would almost certainly result in a change of health and safety procedures. A unit increase in a projected total risk of 1,000, on the other hand, would not result in any significant change of procedure. The LDMU is, therefore, an integral part of this method of risk comparison.

In a discussion in Attachment B.3.2, it is shown that the requirements of the LDMU as applied to risk comparison and the needs of error propagation result in defining a class of utility functions of which the logarithmic dependence is the simplest example (Figure I.B-1b). It is, therefore, chosen as the form of the single attribute utility function for all risk components. Pre-defining the form of the utility function in this manner is a departure from the usual practice of MAUT. It is justified by the fact that, apart from a valuation factor, all risk components are subject in the same manner to the influence of the LDMU and should thus have the same dependence.

3.2.2 Multi-Attribute Utility Functions

The combined utility function for all risk components is chosen to be a linear combination of their utility functions weighted by societal value judgments. This procedure is the simplest form that will most likely satisfy the needs of an error propagation calculation. In this manner, the value of the modified utility function, called the utility index, and its standard error are obtained. Larger

utility indices are preferred over smaller ones unless the difference is insignificant. Negative utility indices indicate an increase in overall risk over the baseline case, positive indices signal a reduction in total risk.

The weight with which the single-attribute utility functions are multiplied in the linear combination are the societal value judgements for each risk component. In another departure from the usual form of MAUT, these weights do not give a valuation of, say, a life lost to cancer, but rather a reduction in the risk of lives lost to cancer. This results in a set of weights which are quite different from the valuations usually applied in MAUT.

A mathematical analysis in Section B.3.3 of this Appendix shows that this multi-attribute utility function has a unique interpretation. It is the basis from which two quantities can be derived: the risk reduction index and its inverse, the risk augmentation index. These quantities are the weighted geometric averages of all component risk reduction factors or component relative risks, respectively. The weights are the societal valuations of small risk reductions or increases. In this report, the risk reduction index and its inverse are the quantities of choice for the comparison of risks.

3.3 RANKING AND UNCERTAINTIES

The ranking process described here is another fundamental difference to conventional multi-attribute utility theory. Here, standard errors are available and the differences between risk reduction indices are a measure of preference. Thus, ranking is not only an ordinal process but a comparison of differences and errors and yields information on the significance of these differences.

3.3.1 Calculation of Standard Errors

The propagation of the uncertainty expressed in the standard error of a parameter or a variable to the value of the function in which it appears can be evaluated using different methods. Some of these are discussed in Attachment C as far as they are needed in this study. Basically, the approach taken here allows the derivation of an analytical expression for the standard error of a risk reduction factor, the utility function, and, finally, for the risk reduction index.

For numerical procedures, numerical methods have to be used. The standard error for that particular factor in the risk equation can then be inserted into the analytical expression for the standard error of the risk. Thus, numerical procedures that evaluate the entire risk reduction factors should be avoided. For the most part, the errors are small enough to use the error propagation formula in a simple approximation for normally distributed quantities (Bevington, 1969; Brandt, 1976; Seiler, 1987b). When the relative errors get larger, standard errors given for lognormally distributed quantities can be used (see Sections C.1.1.3 and C.1.2.2 of this

Appendix). Otherwise, higher approximations for the analytical expressions may be needed (Seiler, 1987b).

In this manner, the standard errors of the risk reduction factors and the risk reduction indices can be calculated. During the process of aggregating the component risks into classes, such as public cancer risks due to waste transportation, error propagation will be taken into account also, in order to provide an unbroken chain for the influence of all pertinent uncertainties.

3.3.2 Indifference to Ranking

Ranking of utility indices with standard errors is a simple evaluation as long as the difference between two adjacent indices is large compared to either one of the standard errors. Conversely, if the difference between them is small compared to either standard error, the difference is insignificant. For differences comparable to the standard errors, the situation is more difficult. Here, the two criteria developed by Goodmann (1986) can be applied (see Sections B.4.3 and G.4.1 of this Appendix). Both are based on the fact that most of the information on the distributions of the utility indices is available for the central part of the distribution, not the tails. Thus, the criteria concentrate on the area of the mean and one or two standard errors around that mean. Using Goodmann's criteria, the utility indices are then arranged in classes of one or more indices that are insignificantly different with significant differences between the classes.

4.0 SCALING AND AGGREGATION OF RISK COMPONENTS

4.1 SCALING OF BASELINE RISKS

Most risk components discussed in the FSEIS and the FSAR are affected in some manner by the treatment of wastes at some location or other. In order to evaluate the corresponding properties, the full algebraic expression for each risk component is given. Each parameter is then evaluated as to its dependence on either the waste treatment and/or the location option. This separates the risk into a constant and a dependent part. This property of the risk equation allows the appropriate scaling of the risk to the level required by the 16 treatment/location options.

Based on the scaling properties of a risk component, the risk reduction factors and their standard errors can be calculated. Some of the parameters needed for that scaling are based on models for the processes involved in creating or modifying the risk components. These models are discussed in Attachment D.

4.1.1 Risks Due to Radiation Exposures

The risks of exposure to external radiations have public and occupational components, leading to both cancer and genetic damage in the long term, and for high doses, to acute radiation sickness in the short-term. Incorporated radioisotopes lead to internal organ doses with more focused damages and carcinogenic processes. Other somatic and short-term radiation effects are not generally considered here.

4.1.1.1 Radiation Risks in Routine Handling

Routine handling involves a number of scenarios for internal exposures, discussed in Section E.1, and external exposures, discussed in Section E.2. For internal exposures only the inhalation route is considered. Due to general health and safety procedures, the ingestion route yields much lower risks. The baseline risks are not known for all risk components, leading to difficulties with aggregation later on.

The values for the risk reduction factors show widely differing values, reflecting different scaling properties. Values for the risk reduction factors range from slightly above and below 1 in Tables E.1-1 and E.1-3, which evaluate risks due to surface contamination of the drums, to 10,000,000 in Table E.1-2, which evaluates risks due to waste leakage out of a perforated drum. This risk is subject to a dramatic risk reduction, albeit in a small risk. When these three risk reduction factors are aggregated in a supercomponent, it is important to weight them properly so as to avoid a bias due to that large value.

4.1.1.2 Radiation Risks Due to Handling Accidents

Handling accidents can lead to inhalation exposure of work crews and, after passing through HEPA filters and environmental dispersion, to exposures of the public. These risks are discussed in detail in Section E.3. Sometimes the corresponding risk reduction factors are the same; mostly they are different. The risk reduction factors for accidents are uniformly high, due to the fact that these scenarios involve inhalation exposures and treatment drastically curtails airborne particle production. The risk reduction factors range from one hundred thousand to one hundred million in Tables E.3-1, E.3-2, E.3-3 and E.3-4 and to ten and a hundred billion in Table E.3-5. The baseline risks range from 10^{-4} and 10^{-5} in most of these tables to an order of a hundred billion for a C2 accident. Proper weighting here will be essential because the largest risk reduction factors (ten and a hundred billion) are associated with an excessively small risk.

4.1.1.3 Radiation Risks in Routine Transportation

The definition of "risks from routine transportation of the wastes" is that these risks arise exclusively from exposures to penetrating radiation of the crew and of the public using the same road and living or working along that road. The risk components for waste transport are those given and discussed in the code RADTRAN III (Madsen et al., 1986). These components are discussed in more detail in Section E.6.3. The data for the calculations have also been taken from the RADTRAN code and the FSEIS. The risk reduction factors for the public along the transport route given in Table E.6-3 are approximately 1; those for public risks at stops (Table E.6-4) have ranges that do not vary significantly from 1, nor do those for the public traveling in the same and the opposite direction (Tables E.6-5 and E.6-6). This is mostly due to the fact that, regardless of treatment, the same amount of radioactivity is transported. For the same reason, occupational transportation risks involving the transport crew, the handlers, and the warehouse personnel have reduction factors that do not deviate much from unity (Tables E.6-7 to E.6-9).

4.1.1.4 Radiation Risks in Transportation Accidents

Serious transportation accidents are not expected to occur during the transportation period, but they carry the potential for population exposures. Again, the formulae and data of the RADTRAN III code were employed to evaluate the risk reduction factors for each scenario. These are discussed in detail in Section E.6.4. The risks due to direct exposure during non-dispersal accidents (Table E.6-4) again do not reduce significantly, that is, do not have risk reduction factors that deviate significantly from one. Those due to dispersal accidents, all assembled in Table E.6-10, vary from 1 to about 15. This denotes the suppression of risks due to waste dispersal in the atmosphere for the fraction of the transport which is done as treated waste.

4.1.1.5 Radiation Risks in Post-Closure Human Intrusion

Radiation risks in three human intrusion scenarios are evaluated using the models in this report rather than those of the FSEIS. There is a direct exposure of the drilling crew to radioactive cuttings. Later, there is the potential for an inhalation exposure from these dried-out cuttings and an ingestion exposure from radioactivity reaching the surface via the Culebra aquifer. This risk component is discussed in Section E.7, and the reduction factors are given in Table E.7-1. For the E1 and E2 scenarios, the factors for the drilling crew cluster closely around a value of five, given essentially by the activity mobilization for the baseline case as compared to any treatment. For the E1E2 scenario the reduction factors for the risk to the drill crew ranges from 0.1 to about 6 but are applied to a very small risk (Table E.7-2). The reduction factors for the public risk by inhalation are the same as those for the drill crew for all scenarios. For ingestion, risk reduction factors for the E1 scenario lie between ten and one hundred thousand for an exceedingly small baseline risk of $2 \cdot 10^{-13}$ (Table E.7-3); for the E2 scenario they range from 1 to 65 but for a baseline risk of $6 \cdot 10^{-11}$; and for the E1E2 scenario, the factors range from about a million to ten billion, applied to a baseline risk of $7.8 \cdot 10^{-6}$.

4.1.2 Risks Due to Chemical Toxicant Exposures

Exposures to volatile organic compounds lead to both public and occupational risks. The health effects can be carcinogenic or noncarcinogenic, depending on the chemical compound.

4.1.2.1 Chemical Risks in Routine Handling

Volatile organic compounds in the waste are vented through the carbon filters of the drums, leading to low level chronic exposures, both public and occupational. Potentially the largest exposures occur underground next to a nearly filled room with 6,000 drums. This may lead to exposures of personnel below ground, above ground near the exhaust, and of the public outside the WIPP area. Here both cancer and noncarcinogenic effects are considered. Detailed evaluations are given in Section E.4. The cancer risk reduction factors for above ground exposures are independent of the chemical and range from values near unity to about 50,000 (Table E.4-2). These factors, however, are applied to exceedingly small cancer risks near 10^{-14}. Risk reduction factors for below ground emissions have about the same range, 1 to 100,000, but some of the risks are at least in the 10^{-7} range (Table E.4-3).

For noncancer health effects, risk reduction factors are again in the range of 1 to 50,000 (Table E.4-6) but the risks assigned for workers above ground are excessively low, lying in the range of 10^{-12}; for workers below ground, they reach up to 10^{-4} (Table E.4-8).

4.1.2.2 Chemical Risks Due to Handling Accidents

In chemical accident exposures only non-carcinogenic effects are considered in the FSEIS, the short-term exposures to accidental releases being too small to result in cancer risks of any significance. The accident scenarios are discussed in detail in Section E.5. The risk reduction factors for a C2 or C3 accident range from 2 to 82,000 and are applied to very small baseline risks near 10^{-10} (Table E.5-2); those for C4, C5, and C6 accidents range from about 20 to about $1.67 \cdot 10^{6}$, still applied to risks of about 10^{-10} (Table E.5-4).

4.1.2.3 Chemical Risks in Post-Closure Human Intrusion

Only one chemical, lead, is evaluated in the post-closure human intrusion scenarios. These are discussed in detail in Section E.7.4. These morbidity baseline risks are exceedingly low and will not be pursued further.

4.1.3 Conventional Transportation Accidents

Public fatalities and injuries as direct effects of the impact in accidents involving the TRUPACT-II transports have the same risk reduction factors listed in Table E.6-2. These values range from roughly 0.5 to 4, but they are applied to the largest annual risks in the FSEIS, about 0.2 fatalities and about 3 injuries.

4.2 SCALING OF TREATMENT RISK

In this evaluation, general occupational risks, external and internal radiation exposures from routine operations and from routine maintenance are examined. For chemical toxicants, only routine operations are considered as in maintenance only traces of VOCs should be encountered. Due to the limited scope of this study, no accidental exposures of any kind are included.

4.2.1 General Occupational Risks

Working in the WHB or the TF puts the crew at risk for occupational accidents resulting in fatalities and injuries. In particular, forklift accidents are considered because they tend to have more severe consequences. These issues are discussed in detail in Section F.2. The risk reduction factors for general accidents and injuries but also for forklift fatalities and injuries lie between 0.276 and 0.076, that is between a factor of 4 and 14 below 1, indicating an increase in risk by these factors (Tables F.2-1 and F.2-2). As they are applied to sizeable baseline risks, they will have a strong influence on the risk comparison.

4.2.2 Radiation Risks in Routine Operation and Maintenance

Risks from exposure to penetrating radiations during treatment of wastes in different devices are discussed in detail in Section F.3.1 and F.3.2. The risk reduction factors for routine external exposure range from 0.1 to 0.5, that is, 2 to 10 times lower than 1; for maintenance the factors are 200 to 300 lower (Table F.3-2). By these factors, therefore, the risks are increased over the unknown baseline risk of external exposure during assay and certification. For routine internal exposures during operations, the risk reduction factors are 1/200 to 1/3000 as shown in Tables F.3-3 and F.3-4. During routine maintenance, the risk increases are factors 10,000 to 100,000 (Tables F.3-5 and F.3-6).

4.2.3 Risks in Chemical Toxicant Exposures

These risks are due to VOCs, mostly released during shredding or sorting of the wastes and penetrating through the airlocks. They are discussed in Section F.4 for both cancer and noncarcinogenic effects. The risk reduction factors show a strong increase in risk due to the mobilization of the VOCs enclosed in drums, liners, and wrappings. The risk reduction factors for the much smaller public risks are the same. For routine operations, occupational and public risks are subject to risk reduction factors of roughly 1/100,000, indicating a strong increase. The baseline risks during assay and certification are not available. This holds for both cancer and non-cancer health effects (Tables F.4-1 and F.4-2).

4.3 AGGREGATION OF RISK COMPONENTS

4.3.1 Problems of Aggregation

In this evaluation, 124 component risks are analyzed and their risk reduction factors derived. This includes all subcomponents. This number is too large to handle in a comparison and must, therefore, be lowered by aggregation. Many of these risks lead to the same consequence, and can thus be aggregated into supercomponents. Even so, it is expedient to discard some of the small risks because a larger risk of the same exposure is already being considered. Thus, genetic damage is usually smaller than the cancer risk from the same radiation exposure (National Research Council, 1980, 1988, 1990). Also, almost no information on genetic baseline risks are available in the FSEIS. These subcomponents are, therefore, not selected for aggregation. Similarly, health effects of lead poisoning for post-closure risks and the non-cancer risks due to exposure to chemical toxicant are not involved in the process either.

In this context, it is important to note that once a cure for cancer is found, cancer reverts from a fatality risk to a morbidity risk. Other somatic effects, such as lifespan shortening, and genetic effects will then become of main concern. From this point of view, genetic damages should be selected for aggregation. The main reason for not selecting these components is the fact that

the genetically relevant doses and the cumulative effective dose equivalents (CEDEs) are mostly non-linearly related and that the baseline risks are mostly unavailable.

As discussed before, the first task of the decision maker is to decide on the extent and the grouping of the aggregation of risk components. This must be done in a manner that groups components with the same societal valuations; not too detailed so as to make relative valuations difficult, and not too coarsely so as to erase significant differences.

In the case at hand, eight supercomponents are formed from the remaining 73 subcomponents:

1. Transportation fatalities
2. Transportation injuries
3. Occupational fatalities
4. Occupational injuries
5. Occupational cancers
6. Public cancers
7. Late occupational cancers
8. Late public cancers.

Six of these supercomponents are evaluated in the FSEIS. In addition, numbers 3 and 4, the occupational accident fatalities and injuries, are included here. In a comparison of treatment risks involving more or less personnel they are important and have thus been included.

In these aggregations, problems arise when no values for the baseline risk components are given in the FSEIS or the FSAR. In this case, the aggregation has to be done by unweighted averaging. A large risk reduction factor will then tend to dominate the average even if it is applied to a minute risk. This dominance can be reduced somewhat by using the geometrical average. Even so, unweighted averaging will introduce a residual bias. In the absence of data on the baseline risks, however, unweighted averaging must be used until a numerical risk value is available for the aggregate. From then on, appropriately weighted averaging will lead to the supercomponents without further bias.

After the aggregation into supercomponents, the total risks have been in effect sorted in terms of consequences, being at the same time summed over all scenarios and exposed individuals. This is the situation to which Equation (B.2.6) in Attachment B refers, where the total risk has been aggregated to form a vector of consequence components. From this point in the calculation onward, the aggregated risk reduction factors are, therefore, more aptly termed consequence reduction factors. Their numerical values are listed in Table I.4-1 as functions of treatment and location options.

TABLE I.4-1

COMPILATION OF CONSEQUENCE REDUCTION FACTORS *

CONSEQUENCE REDUCTION FACTORS	TREATMENT OPTION = 1 LOCATION 1	2	3	4	TREATMENT OPTION = 2 LOCATION 1	2	3	4
$\Gamma_{1\kappa\lambda}$	1.00 ± 0.00	0.760 ± 0.048	0.714 ± 0.057	0.715 ± 0.058	1.00 ± 0.00	0.719 ± 0.042	0.666 ± 0.048	0.666 ± 0.049
$\Gamma_{2\kappa\lambda}$	1.00 ± 0.00	0.760 ± 0.048	0.714 ± 0.057	0.715 ± 0.058	1.00 ± 0.00	0.719 ± 0.042	0.666 ± 0.048	0.666 ± 0.049
$\Gamma_{3\kappa\lambda}$	0.276 ± 0.016	0.276 ± 0.016	0.276 ± 0.016	0.276 ± 0.016	0.260 ± 0.015	0.260 ± 0.015	0.260 ± 0.015	0.260 ± 0.015
$\Gamma_{4\kappa\lambda}$	0.276 ± 0.016	0.276 ± 0.016	0.276 ± 0.016	0.276 ± 0.016	0.260 ± 0.015	0.260 ± 0.015	0.260 ± 0.015	0.260 ± 0.015
$\Gamma_{5\kappa\lambda}$	0.853 ± 0.031	0.814 ± 0.030	0.846 ± 0.031	0.852 ± 0.032	0.841 ± 0.030	0.801 ± 0.029	0.833 ± 0.030	0.840 ± 0.031
$\Gamma_{6\kappa\lambda}$	1.13 ± 0.00	2.64 ± 0.01	7.44 ± 0.02	9.47 ± 0.02	1.13 ± 0.00	2.65 ± 0.01	7.46 ± 0.02	9.49 ± 0.02
$\Gamma_{7\kappa\lambda}$	4.96 ± 0.48	4.96 ± 0.48	4.96 ± 0.48	4.96 ± 0.48	5.05 ± 0.49	5.05 ± 0.49	5.05 ± 0.49	5.05 ± 0.49
$\Gamma_{8\kappa\lambda}$	106 (2.3)	106 (2.3)	106 (2.3)	106 (2.3)	115 (2.2)	115 (2.2)	115 (2.2)	115 (2.2)

CONSEQUENCE RISK REDUCTION FACTORS	TREATMENT OPTION = 3 LOCATION 1	2	3	4	TREATMENT OPTION = 4 LOCATION 1	2	3	4
$\Gamma_{1\kappa\lambda}$	1.00 ± 0.00	1.10 ± 0.17	1.17 ± 0.26	1.18 ± 0.27	1.00 ± 0.00	2.00 ± 0.06	3.27 ± 0.21	3.51 ± 0.25
$\Gamma_{2\kappa\lambda}$	1.00 ± 0.00	1.10 ± 0.17	1.17 ± 0.26	1.18 ± 0.27	1.00 ± 0.00	2.00 ± 0.06	3.27 ± 0.21	3.51 ± 0.25
$\Gamma_{3\kappa\lambda}$	0.17 ± 0.01	0.17 ± 0.01	0.17 ± 0.01	0.17 ± 0.01	0.076 ± 0.0042	0.076 ± 0.0042	0.076 ± 0.0042	0.076 ± 0.0042
$\Gamma_{4\kappa\lambda}$	0.17 ± 0.01	0.17 ± 0.01	0.17 ± 0.01	0.17 ± 0.01	0.076 ± 0.0042	0.076 ± 0.0042	0.076 ± 0.0042	0.076 ± 0.0042
$\Gamma_{5\kappa\lambda}$	0.704 ± 0.023	0.677 ± 0.025	0.699 ± 0.027	0.704 ± 0.028	0.460 ± 0.019	0.420 ± 0.017	0.435 ± 0.018	0.452 ± 0.019
$\Gamma_{6\kappa\lambda}$	1.13 ± 0.00	2.65 ± 0.01	7.46 ± 0.02	9.49 ± 0.02	1.13 ± 0.00	2.65 ± 0.01	7.47 ± 0.02	9.50 ± 0.02
$\Gamma_{7\kappa\lambda}$	6.86 ± 1.36	6.86 ± 1.36	6.86 ± 1.36	6.86 ± 1.36	9.39 ± 0.99	9.39 ± 0.99	9.39 ± 0.99	9.39 ± 0.99
$\Gamma_{8\kappa\lambda}$	221 (2.4)	221 (2.4)	221 (2.4)	221 (2.4)	2030 (2.6)	2030 (2.6)	2030 (2.6)	2030 (2.6)

* Errors given in braces are geometric standard deviations of lognormal distributions.

4.3.2 Aggregation Into Supercomponents

4.3.2.1 Supercomponents 1 and 2: Fatalities and Injuries in Transportation Accidents

Due to volume changes resulting from treatment and thus transportation increases for Level II treatments, and transportation decreases for Level III treatments, the aggregated risk reduction factors for Supercomponent 1 range from between 0.5 and 1 for Level II treatments to values above 1 to about 4 for Level III treatments. This signals an increase in risk for Level II and a decrease for Level III. Although the departures of the factors from one are not large, they impact the largest risks in the study (0.2 fatalities and 3 injuries per year of operation) and the variations are thus of great importance. The supercomponents show little change with the location for Level II treatment, a small change in Treatment Option 3, but a substantial protective effect for Treatment Option 4 if done in distributed facilities near the originators. The aggregated risk reduction factors are listed in Table I.4-1.

4.3.2.2 Supercomponents 3 and 4: Occupational Fatalities and Injuries

The general occupational fatalities and injuries in working in the Treatment Facility and in the WHB show increases between factors of 4 to 13. These are applied to a baseline risk of $2 \cdot 10^{-3}$ fatalities and 0.5 injuries per year of operation. Due to the assumption of the model, there is no location dependence, but a steady decrease in the risk reduction factors and, therefore, a strong increase in risk for more complex treatments (Table I.4-1).

4.3.2.3 Supercomponent 5: Occupational Cancer

This supercomponent aggregates the risk reduction factors of 22 components. Due to the lack of baseline data, they have to be aggregated without weights into four intermediate components, thereby introducing a bias. Further aggregation of these four intermediate components into Supercomponent 5 introduces no further bias because of appropriate weighting. The values show risk reduction factors of about 7 for Level II treatments and about 11 for Level III treatments. There is not much variation with the location parameter, indicating the expected insensitivity of this supercomponent to the location of the TF. With increased level of treatment, however, there is a distinct gain in occupational safety.

4.3.2.4 Supercomponent 6: Public Cancers

The supercomponent for public cancers is also aggregated from 22 risk reduction factors. Again, they have to be aggregated to four intermediate components for which baseline risk values are available, incurring a bias in the unweighted portion of the averaging process. The fully aggregated risk reduction factors range from 1 to 12. Here, there is a clear trend in each treatment alternative for an improvement in public safety if the TFs are located near the originators, and a trend toward an increase in these gains with more elaborate waste treatment.

4.3.2.5 Supercomponent 7: Post-Closure Occupational Cancers

These are the unweighted aggregates of the risks to the drilling crews in the three human intrusion scenarios. The risk reduction factors range from about 5 to about 10. They are, however, applied to an exceedingly small risk of $3 \cdot 10^{-8}$.

4.3.2.6 Supercomponent 8: Post-Closure Public Cancers

This component aggregates the public cancer risks due to inhalation and ingestion of radioactivity transported over time to the surface. Substantial risk reductions are achieved by treatment, ranging from about 100 to 2,000. The baseline risk, however, is again small with an expected cancer incidence of $7 \cdot 10^{-5}$.

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5.0 COMPARISON OF THE TOTAL RISKS

5.1 SOCIETAL WEIGHTS

The weighting needed to give each component its proper valuation is not the same as the weighting used in Multi-Attribute Utility Theory. This difference arises from the fact that the argument is not a risk but a risk reduction factor, and also from the use of the logarithm of the risk reduction factor as the utility of risk reduction. The usual valuations, such as setting the widespread practice of an occupational fatality or injury equal to one-half of a public fatality or injury, have to be re-examined in the light of a risk reduction or augmentation. As discussed in Attachment B, Section B.3.5, the valuation of a particular risk reduction depends on the magnitude of the baseline risk component. In this study, most of these components are small so that the valuations are relatively weak functions of the risk values.

Within the scope of this study, and taking into account that the selection of alternatives for waste treatment is essentially a technical decision, with societal input, the decision maker charged with making the risk comparison sought advice from a group of knowledgeable persons with diverse interests and views. They made their valuations known to him as well as the rationales leading to those weights. Based on this advice, the decision maker selected his own rationales and arrived at his own weights. He treated them as decision parameters without standard errors or as stochastic quantities.

In this context, it should be borne in mind that risk assessments and risk comparisons are usually done with an ulterior motive such as a selection process in mind. Thus the decision maker for the risk comparison works for another decision maker, charged with making that selection. The environment of the criteria other than risk that enter into the selection process has an influence on the weighting in the risk comparison. This dependence arises from the cross-relationships such as the one between cost, feasibility, and some components of the consequence vector. The decision maker for the risk comparison may thus not only have to balance the advice received and his own rationales, but also the needs of the decision at the higher level.

As an example for a weighting, a risk reduction or augmentation by a factor of two for the annual number of traffic fatalities and injuries depends on the absolute baseline values of 0.2 fatalities and 3 injuries when compared to the valuation of a risk reduction or augmentation by a factor of two for the occupational risk of fatalities (0.002 per year) and injuries (0.5 per year). While the need for a reduction of the traffic risk may seem paramount, it must be seen in the context of the annual deaths and injuries due to traffic accidents. In New Mexico alone, 538 traffic fatalities and 324,962 traffic injuries occurred in 1989 (New Mexico Highway and Transportation Department, 1990). The incremental risks due to WIPP transports is 0.04 percent for fatalities and 0.01

percent for injuries. On the basis of these relationships and the relative valuations of fatalities and injuries, some of which will be severe, absolute weights of 10, 7, 5 and 4, for example, can be established by a particular expert for transportation fatalities, transportation injuries, general occupational fatalities, and occupational injuries, respectively. By considering similar relationships between all the supercomponents, a complete set of weights can be established (see Section G.2.2.1 of this Appendix).

The normalized societal weights selected by the decision maker as decision parameters are given in Table I.5-1, together with numerical values for the annual baseline risk components. These values are then used to arrive at the risk reduction or risk augmentation indices to be used in decision making. Here only the interpretation of the indices will be reported. The use made of this information is contained in the main body of this report.

5.2 COMPARISON OF THE ALTERNATIVES

5.2.1 Consequence Reduction and Augmentation Indices

The values of the consequence augmentation index $\Psi_{\kappa\lambda}$ resulting from the weighting of the previous section are given in Table I.5-2, grouped first by treatment options (first index) and then by location options (second index). The augmentation index is chosen for presentation here because there is a net increase in that index for 14 of the 16 treatment/location options, and 2 of the 14 (Options 33 and 34) are compatible with 1, which means that the overall consequence is about the same as that for the baseline case. Only two options (43 and 44) show a decrease in the index, that is, values lower than one.

An application of Goodmann's criteria of indifference (see Section G.3.1.2 of this Appendix) shows that only 12 of the 120 possible combinations of indices lead to a confirmed or possible indifference between indices. A better idea of the groupings within options can be obtained by a visual inspection of the probability distributions of the consequence augmentation indices (Figure I.5-1). These distributions give the probability of finding a given index at a particular value. Here, instead of lognormal distributions, normal distributions are used (for narrow distributions the differences are small). Thus for Level III treatments there are clear trends with regard to location. Options 31 and 41, with treatment exclusively at the WIPP, have the highest increases in the index for Treatment Options 3 and 4, respectively. For Treatment Option 3, locations near the waste originators lead to no substantial change in the indices, whereas for Treatment Option 4, a location of the facilities near the originators leads to the only decrease in overall consequence indices. Level II Treatment Options 1 and 2, with eight distributions, have indices that lie very closely together, particularly when it is considered that errors are likely to be low estimates (see Section 3.1.3). They thus lead, almost independent of location, to increases in consequence indices between 1.3 and 1.6.

TABLE I.5-1

SOCIETAL VALUATIONS, NORMALIZED WEIGHTS

RISK SUPERCOMPONENT	ANNUAL BASELINE RISK	NORMALIZED WEIGHT
1 Transportation fatalities	0.2	0.33
2 Transportation injuries	3	0.23
3 Occupational fatalities	0.002	0.17
4 Occupational injuries	0.5	0.13
5 Occupational cancers	0.005	0.033
6 Public cancer	0.02	0.10
7 Late occupational cancers	$3 \cdot 10^{-8}$	0.003
8 Late public cancers	$7 \cdot 10^{-5}$	0.007

TABLE I.5-2

RISK AUGMENTATION INDICES FOR 16 TREATMENT/LOCATION OPTIONS

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Ψ_{11}	1.40 ± 0.02	
Ψ_{12}	1.51 ± 0.04	
Ψ_{13}	1.41 ± 0.05	
Ψ_{14}	1.37 ± 0.05	
Ψ_{21}	1.43 ± 0.02	
Ψ_{22}	1.58 ± 0.04	
Ψ_{23}	1.49 ± 0.05	
Ψ_{24}	1.45 ± 0.05	
Ψ_{31}	1.62 ± 0.02	
Ψ_{32}	1.42 ± 0.09	
Ψ_{33}	1.23 ± 0.11	
Ψ_{34}	1.20 ± 0.11	
Ψ_{41}	2.06 ± 0.03	
Ψ_{42}	1.28 ± 0.02	
Ψ_{43}	0.88 ± 0.03	Decrease by a factor of 1.14 ± 0.03
Ψ_{44}	0.82 ± 0.03	Decrease by a factor of 1.21 ± 0.04

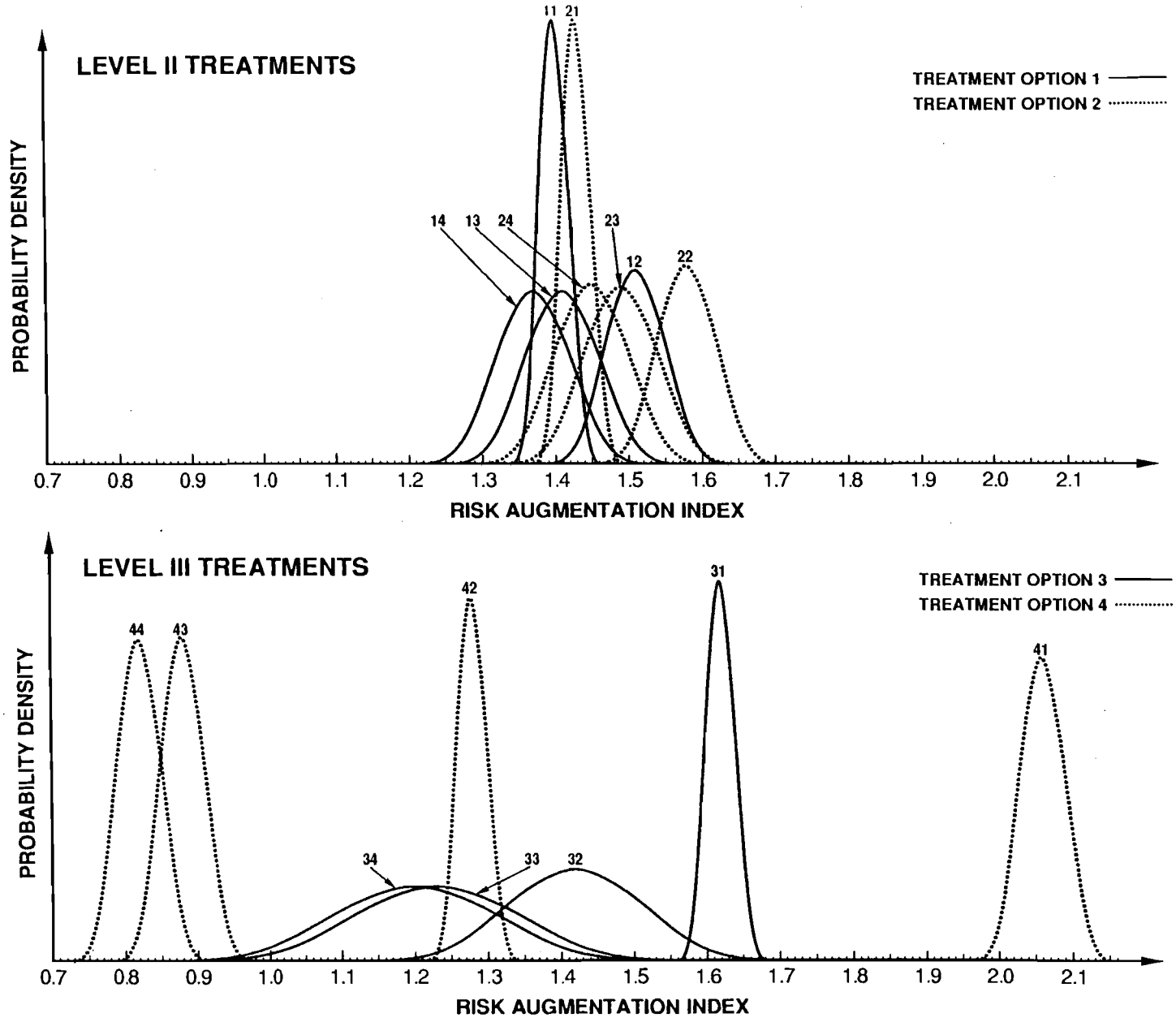

Figure I.5-1 Risk Augmentation Indices for the 16 Treatment/Location Options

The same information is once again displayed in Figure I.ES-1 in the Executive Summary, which lists facility locations in rows and treatment options in columns. There is very little variation between the values of the risk augmentation index of the Level II treatments. For Treatment Option 3, a Level III treatment, there is a trend toward the periphery (waste originators) leading down to an insignificant increase in the index. As in Figure I.5-1, there is a dramatic location dependence for Treatment Option 4, the most extensive treatment of all, leading from the largest increase in the consequence augmentation index (2.1) to the largest decrease in the index for overall risk (0.8). As an aid to the eye, the very light pattern selected in that figure for Group 1 shows the largest increase in consequence augmentation; Group 2 with a denser pattern is clustered between 1.2 and 1.5; Group 3 is almost neutral, that is, almost compatible with 1, whereas Group 4 with the densest pattern is composed of the two options that result in a consequence reduction.

5.2.2 Interpretation of the Results

An analysis of the different contributions to the consequence augmentation or reduction indices shows that the transportation risks and the occupational accident risks contribute substantially to the value of the indices. The post-closure risks due to human intrusion, on the other hand, contribute at most a few percent to the value of the indices, that is, about as much as the average standard error. For the short-term components, transportation volume increases for Level II treatment options and decreases for Level III treatments. Manpower requirements and thus general occupational accidents and injuries increase substantially from Treatment Option 1 to Treatment Option 4.

For Location Option 1, treatment at the WIPP, waste transport contributes the same risks as in the baseline case. The treatment, however, causes additional risks which result in the highest indices for the two Level III treatment options but nearly the lowest for the two Level II treatment options. The trend for more decentralized facilities for Level II treatments is undefined, for Level III treatments, however, it is clearly toward lower values. This shows the opposing influences of the transportation risks and the treatment risks.

For Level II treatment options, the modest increases in both transportation and occupational accident consequences result in an almost uniform increase in consequences with an augmentation index of about 1.5. For Level III treatment options the opposing influence of the changes in risk due to transportation and manpower are responsible for the moderate spread due to location in Treatment Option 3, and the wide spread with locations for Treatment Option 4.

An analysis of the eight factors that form the consequence reduction indices (see Section G.4) shows that the traffic accidents are responsible for most of the location-dependence in the treatment/location matrix, whereas the occupational accidents cause most of the treatment dependence. Radiological risks form only a small part of the total risk, the largest contribution being the public cancer risk in transportation accidents. This clearly reflects societal priorities

according to which radiological risks are most coherently and most successfully pushed down to low levels, whereas occupational accidents are less vigorously suppressed, and traffic accidents are attacked with only little effort. The same analysis shows post-closure cancer risks contributing a few tenths of a percent for occupational risks, and a few percent for public risks; altogether an almost negligible influence.

5.2.3 Influence of Biases

Additional, more detailed evaluations of the numbers generated for the indices meet with several difficulties. One arises from the biases due to the unweighted aggregation of many risk reduction factors. Another arises from the biases introduced by some of the model assumptions that do not give credit to treatment where credit is due, or do not assign an additional risk component where one should be assigned. The last difficulty is the weighting chosen here with values that could easily be chosen differently.

The unavoidable use of unweighted aggregation introduces biases of unknown amounts and signs. It is believed that, by the choice of supercomponents and the use of the geometrical averages, their influence is kept as small as possible. The model assumptions made for the entire risk comparison and for some parts of it also add biases of indeterminate signs and unknown magnitude. Again, they are believed to be small, but some of them could be significant.

Quite generally, these biases are due to the fact that this risk comparison is a retrofit to the FSEIS; that is, it did not grow organically out of it. Thus a lot of detail was lost, information that would be necessary for appropriate aggregation. In a different application of this method for risk comparison, this bias would not arise.

There is, however, another source of bias, at the same time more prevalent and more subtle. It arises from the widespread use of bounding calculations, worst-case models, and upper limits. Any risk values derived on this basis clearly overstates the risk, resulting in a bias. For risk comparisons it is, therefore, imperative to have risk values derived by the use of best-science models as well as their standard errors. The use of biased models and biasing assumptions should be minimized.

An unavoidable third type of bias arises from the value system of the decision maker and those of his set of advisors. The influence of either a different decision maker or a different set of advisors will result in different societal weights. The set of valuation questions have a very narrow scope, however, so that the valuations of the risk reduction factors for a given baseline risk do not vary strongly. Even that bias is not seen to be critical.

The first two biases are expected to result in perturbations of the risk augmentation indices, mostly in the nature of positive or negative shifts. It is not believed that their elimination would lead to major differences. The third bias, however, can potentially lead to more pronounced

shifts. The valuations of a different decision maker with a different set of advisors might well loosen the close association of all Level II treatment options and might even establish a small location trend. The main facts that arise from this analysis, however, are expected to remain. In sum, then, it is not thought that these effects will lead to major changes in trends, although noticeable shifts within these trends are probable.

5.2.4 Conclusions of the Risk Comparison

The risk comparison in this study results in some clear groupings and trends among the risk augmentation indices for various treatment and location options:

- The baseline risks are very small, so that even clear-cut increases in consequences still result in very small risks for all treatment and location options.

- Level II treatment options show little or no discernible trends for different locations. However they uniformly show an increase for the consequences, that is a consequence augmentation index near 1.4. In the context of interpreting these indices, it is of importance to realize that consequence reduction and augmentation indices are not linearly related to the actual set of baseline risks. Thus an index of 1.4 does not mean a 40 percent increase in the baseline risks. However, it does signify an increase in the total consequences. This nonlinearity also means that no absolute treatment risks can be inferred from these indices.

- Level III treatment options show a distinct trend in location dependence with the risk decreasing as the TFs are located closer to the waste producers. For Treatment Option 3, this results at best in total risks about equal to that of the baseline case. For Treatment Option 4, however, an actual increase to a risk augmentation index of 2.1 and decreases down to 0.8 can be realized for the two most decentralized location options, respectively.

- These increases and decreases of the societally weighted risk augmentation indices are almost independent of the long-term risks. This is due to the low valuation of the long-term risk components and their independence from the location options. It is, therefore, the balance between the short-term risk components that drives this risk comparison.

In these evaluations the standard errors of the consequence reduction or augmentation indices play an indispensable role. Even though the circumstances discussed in Section 3.1.3 lead to underestimates of the standard errors, the values quoted or somewhat larger ones would result in the conclusions given above. This is quite evident from a visual inspection of Figure I.5-1, where even a doubling of the widths would not change the groupings of the Level II treatments or the moderate to strong dispersion of the Level III treatments. This is probably the outstanding characteristic of the method of risk comparison used in this evaluation.

ATTACHMENT A

TABLE A.1
SUMMARY OF RISK COMPONENTS

Risk Component Number:	1
Risk Component Name:	Cancer Risk from Routine Internal Exposures to Ionizing Radiation in an N1 Scenario
Risk Scenario:	Surface contamination mobilized and suspended in air
Risks Addressed:	Occupational and public cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{1o} and ρ_{1p}
Annual Baseline Risk Symbol(s):	R_{1o} and R_{1p}
Appendix I Location:	Section E.1.2; Table E.1-1
Risk Component Number:	2
Risk Component Name:	Cancer Risk from Routine Internal Exposures to Ionizing Radiation in an N2 Scenario
Risk Scenario:	Perforated drum being handled
Risks Addressed:	Occupational and public cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{2o} and ρ_{2p}
Annual Baseline Risk Symbol(s):	R_{2o} and R_{2p}
Appendix I Location:	Section E.1.3; Table E.1-2
Risk Component Number:	3
Risk Component Name:	Cancer Risk from Routine Internal Exposures to Ionizing Radiation in an N3 Scenario
Risk Scenario:	Underground, drum contamination mobilized and suspended in air
Risks Addressed:	Occupational cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{3o} and ρ_{3p}
Annual Baseline Risk Symbol(s):	R_{3o} and R_{3p}
Appendix I Location:	Section E.1.4; Table E.1-3
Risk Component Number:	4
Risk Component Name:	Cancer Risk from Routine External Exposures to Ionizing Radiation in an N4 Scenario
Risk Scenario:	Handling activities in the WHB and TF
Risks Addressed:	Occupational cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{4o}
Annual Baseline Risk Symbol(s):	R_{4o}
Appendix I Location:	Section E.2.2; Table E.2-1

TABLE A.1 (Con't)

SUMMARY OF RISK COMPONENTS

Risk Component Number:	5
Risk Component Name:	Cancer Risk from Routine External Exposures to Ionizing Radiation in an N5 Scenario
Risk Scenario:	Handling activities in the WHB and TF; geometries differ from Component 4 scenario
Risks Addressed:	Occupational cancer and genetic damage
Risk Reduction Factor Symbol:	ρ_{5o}
Annual Baseline Risk Symbol:	R_{5o}
Appendix I Location:	Section E.2.3
Risk Component Number:	6
Risk Component Name:	Cancer Risk in WHB and TF Due to Accident Scenario C2
Risk Scenario:	Above ground; drum falls off forklift in WHB or TF, lid separates and liner ruptures
Risks Addressed:	Occupational and public cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{6o} and ρ_{6p}
Annual Baseline Risk Symbol(s):	R_{6o} and R_{6p}
Appendix I Location:	Section E.3.2.1; Table E.3-1
Risk Component Number:	7
Risk Component Name:	Cancer Risk in WHB or TF Due to Accident Scenario C3
Risk Scenario:	Above ground; two drums pierced, one loses lid and integrity of its liners
Risks Addressed:	Occupational and public cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{7o} and ρ_{7p}
Annual Baseline Risk Symbol(s):	R_{7o} and R_{7p}
Appendix I Location:	Section E.3.2.2; Table E.3-2
Risk Component Number:	8
Risk Component Name:	Cancer Risk Underground Due to Accident Scenario C4
Risk Scenario:	Drum knocked off a pallet in the Underground Storage Area and loses integrity
Risks Addressed:	Occupational and public cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{8o} and ρ_{8p}
Annual Baseline Risk Symbol(s):	R_{8o} and R_{8p}
Appendix I Location:	Section E.3.3.1 and Table E.3-3

TABLE A.1 (Con't)

SUMMARY OF RISK COMPONENTS

Risk Component Number:	9
Risk Component Name:	Cancer Risk Underground Due to Accident Scenario C5
Risk Scenario:	Drum knocked off a forklift
Risks Addressed:	Occupational and public cancer and genetic damage
Risk Reduction Factor Symbol:	ρ_{9o} and ρ_{9p}
Annual Baseline Risk Symbol:	R_{9o} and R_{9p}
Appendix I Location:	Section E.3.3.2; Table E.3-3
Risk Component Number:	10
Risk Component Name:	Cancer Risk Underground Due to Accident Scenario C6
Risk Scenario:	Underground; forklift pierces two drums and knocks another one down.
Risks Addressed:	Occupational and public cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{10o} and ρ_{10p}
Annual Baseline Risk Symbol(s):	R_{10o} and R_{10p}
Appendix I Location:	Section E.3.3.3; Table E.3-4
Risk Component Number:	11
Risk Component Name:	Cancer Risk Underground Due to Accident Scenario C10
Risk Scenario:	Underground; spontaneous combustion in drum, drum bursting with release of suspended particles
Risks Addressed:	Occupational and public cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{11o} and ρ_{11p}
Annual Baseline Risk Symbol(s):	R_{11o} and R_{11p}
Appendix I Location:	Section E.3.3.4; Table E.3-5
Risk Component Number:	12
Risk Component Name:	Cancer Risk Due to Routine Chemical Exposures in an N1 Scenario
Risk Scenario:	VOCs vent continuously through a filter
Risks Addressed:	Occupational and public cancer
Risk Reduction Factor Symbol(s):	ρ_{12o} and ρ_{12p}
Annual Baseline Risk Symbol(s):	R_{12o} and R_{12p}
Appendix I Location:	Section E.4.2.1; Tables E.4-1 and E.4-2

TABLE A.1 (Con't)

SUMMARY OF RISK COMPONENTS

Risk Component Number:	13
Risk Component Name:	Cancer Risk Due to Routine Chemical Exposures in an N3 Scenario
Risk Scenario:	Routine underground emissions from each drum
Risks Addressed:	Occupational (above and below ground) and public cancer
Risk Reduction Factor Symbol:	ρ_{13o}, ρ_{13a} and ρ_{13p}
Annual Baseline Risk Symbol:	R_{13o}, R_{13a} and R_{13p}
Appendix I Location:	Section E.4.2.2; Tables E.4-3 and E.4-4
Risk Component Number:	14
Risk Component Name:	Noncancer Risk in WHB Due to Routine Chemical Exposure (N1 Scenario)
Risk Scenario:	VOCs vent continuously through a filter
Risks Addressed:	Occupational and public morbidity
Risk Reduction Factor Symbol(s):	ρ_{14o}, ρ_{14a} and ρ_{14p}
Annual Baseline Risk Symbol(s):	R_{14o}, R_{14a} and R_{14p}
Appendix I Location:	Section E.4.3.1; Tables E.4-5 and E.4-6
Risk Component Number:	15
Risk Component Name:	Noncancer Risk Underground Due to Routine Chemical Exposure (N3 Scenario)
Risk Scenario:	Routine underground emissions from each drum
Risks Addressed:	Occupational and public morbidity
Risk Reduction Factor Symbol(s):	ρ_{15o}, ρ_{15a} and ρ_{15p}
Annual Baseline Risk Symbol(s):	R_{15o}, R_{15a} and R_{15p}
Appendix I Location:	Section E.4.3.2; Table E.4-7
Risk Component Number:	16
Risk Component Name:	Noncancer Risk Due to Accident Scenario C2, Above Ground Accident
Risk Scenario:	Drum dropped from forklift
Risks Addressed:	Occupational morbidity
Risk Reduction Factor Symbol(s):	ρ_{16o}
Annual Baseline Risk Symbol(s):	R_{16o}
Appendix I Location:	Section E.5.2.1; Tables E.5-1 and E.5-2

TABLE A.1 (Con't)

SUMMARY OF RISK COMPONENTS

Risk Component Number:	17
Risk Component Name:	Risk Due to Accident Scenario C3
Risk Scenario:	Two drums punctured by a forklift; third drum falls and ruptures
Risks Addressed:	Occupational morbidity
Risk Reduction Factor Symbol:	ρ_{17o}
Annual Baseline Risk Symbol:	R_{17o}
Appendix I Location:	Section E.5.2.2; Tables E.5-1 and E.5-2
Risk Component Number:	18
Risk Component Name:	Underground Risk Due to Accident Scenario C4
Risk Scenario:	Drum drops from pallet, loses lid and integrity of the liner
Risks Addressed:	Occupational morbidity
Risk Reduction Factor Symbol(s):	ρ_{18o}
Annual Baseline Risk Symbol(s):	R_{18o}
Appendix I Location:	Section E.5.3.1; Tables E.5-3 and E.5-4
Risk Component Number:	19
Risk Component Name:	Underground Risk Due to Accident Scenario C5
Risk Scenario:	Drum drops off a forklift
Risks Addressed:	Occupational morbidity
Risk Reduction Factor Symbol(s):	ρ_{19o}
Annual Baseline Risk Symbol(s):	R_{19o}
Appendix I Location:	Section E.5.3.2; Tables E.5-3 and E.5-4
Risk Component Number:	20
Risk Component Name:	Underground Risk Due to Accident Scenario C6
Risk Scenario:	Forklift pierces two drums and knocks another one down
Risks Addressed:	Occupational morbidity
Risk Reduction Factor Symbol(s):	ρ_{20o}
Annual Baseline Risk Symbol(s):	R_{20o}
Appendix I Location:	Section E.5.3.3; Tables E.5-3 and E.5-4

TABLE A.1 (Con't)

SUMMARY OF RISK COMPONENTS

Risk Component Number:	21
Risk Component Name:	Risk of Traffic Accidents
Risk Scenario:	Fatalities by impact
Risks Addressed:	Public fatalities
Risk Reduction Factor Symbol(s):	ρ_{21p}
Annual Baseline Risk Symbol(s):	R_{21p}
Appendix I Location:	Section E.6.2.1; Table E.6-2
Risk Component Number:	22
Risk Component Name:	Risk of Traffic Accidents
Risk Scenario:	Injuries by impact
Risks Addressed:	Public injuries
Risk Reduction Factor Symbol(s):	ρ_{22p}
Annual Baseline Risk Symbol(s):	R_{22p}
Appendix I Location:	Section E.6.2.2; Table E.6-2
Risk Component Number:	23
Risk Component Name:	Cancer Risk from Routine Transportation
Risk Scenario:	Risk to public near road taken by TRUPACT-II transports
Risks Addressed:	Public cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{23p}
Annual Baseline Risk Symbol(s):	R_{23p}
Appendix I Location:	Section E.6.3.2; Table E.6-3
Risk Component Number:	24
Risk Component Name:	Cancer Risk from Routine Transportation
Risk Scenario:	Risk to public during stops
Risks Addressed:	Public cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{24p}
Annual Baseline Risk Symbol(s):	R_{24p}
Appendix I Location:	Section E.6.3.3; Table E.6-4
Risk Component Number:	25
Risk Component Name:	Cancer Risk from Routine Transportation
Risk Scenario:	Risk to public traveling in the opposite direction
Risks Addressed:	Public cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{25p}
Annual Baseline Risk Symbol(s):	R_{25p}
Appendix I Location:	Section E.6.3.4; Table E.6-5

TABLE A.1 (Con't)

SUMMARY OF RISK COMPONENTS

Risk Component Number:	26
Risk Component Name:	Cancer Risk from Routine Transportation
Risk Scenario:	Risk to public traveling in the same direction as TRUPACT-II transport
Risks Addressed:	Public cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{26p}
Annual Baseline Risk Symbol(s):	R_{26p}
Appendix I Location:	Section E.6.3.5; Table E.6-6
Risk Component Number:	27
Risk Component Name:	Cancer Risk from Routine Transportation
Risk Scenario:	Cancer risk to crew during transport
Risks Addressed:	Occupational cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{27o}
Annual Baseline Risk Symbol(s):	R_{27o}
Appendix I Location:	Section E.6.3.6; Table E.6-7
Risk Component Number:	28
Risk Component Name:	Cancer Risk from Routine Transportation
Risk Scenario:	Cancer risk to waste handlers
Risks Addressed:	Occupational cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{28o}
Annual Baseline Risk Symbol(s):	R_{28o}
Appendix I Location:	Section E.6.3.7; Table E.6-8
Risk Component Number:	29
Risk Component Name:	Cancer Risk from Routine Transportation
Risk Scenario:	Cancer risk to warehouse personnel
Risks Addressed:	Occupational cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{29o}
Annual Baseline Risk Symbol(s):	R_{29o}
Appendix I Location:	Section E.6.3.8; Table E.6-9
Risk Component Number:	30
Risk Component Name:	Risks Due to Nondispersal Accidents
Risk Scenario:	Early fatalities due to nondispersal accidents
Risks Addressed:	Public fatalities (radiation syndrome)
Risk Reduction Factor Symbol(s):	ρ_{30p}
Annual Baseline Risk Symbol(s):	R_{30p}
Appendix I Location:	Section E.6.4.2.1; Table E.6-4

TABLE A.1 (Con't)

SUMMARY OF RISK COMPONENTS

Risk Component Number:	31
Risk Component Name:	Risks Due to Nondispersal Accidents
Risk Scenario:	Early morbidity due to nondispersal accidents
Risks Addressed:	Public injuries (radiation syndrome)
Risk Reduction Factor Symbol(s):	$\rho_{31\,p}$
Annual Baseline Risk Symbol(s):	$R_{31\,p}$
Appendix I Location:	Section E.6.4.2.2; Table E.6-4
Risk Component Number:	32
Risk Component Name:	Cancer Risks Due to Nondispersal Accidents
Risk Scenario:	Delayed health effects due to nondispersal accidents
Risks Addressed:	Public cancer and genetic damage
Risk Reduction Factor Symbol(s):	$\rho_{32\,p}$
Annual Baseline Risk Symbol(s):	$R_{32\,p}$
Appendix I Location:	Section E.6.4.2.3; Table E.6-4
Risk Component Number:	33
Risk Component Name:	Risks Due to Dispersal Accidents
Risk Scenario:	Risk of early fatalities due to inhalation
Risks Addressed:	Public fatalities
Risk Reduction Factor Symbol(s):	$\rho_{33\,p}$
Annual Baseline Risk Symbol(s):	$R_{33\,p}$
Appendix I Location:	Section E.6.4.3.1; Table E.6-10
Risk Component Number:	34
Risk Component Name:	Risks Due to Dispersal Accidents
Risk Scenario:	Risk of early morbidity due to inhalation
Risks Addressed:	Public injuries
Risk Reduction Factor Symbol(s):	$\rho_{34\,p}$
Annual Baseline Risk Symbol(s):	$R_{34\,p}$
Appendix I Location:	Section E.6.4.3.2; Table E.6-10
Risk Component Number:	35
Risk Component Name:	Cancer Risks Due to Dispersal Accidents
Risk Scenario:	Risk of delayed health effects due to inhalation
Risks Addressed:	Public cancer and genetic damage
Risk Reduction Factor Symbol(s):	$\rho_{35\,p}$
Annual Baseline Risk Symbol(s):	$R_{35\,p}$
Appendix I Location:	Section E.6.4.3.3; Table E.6-10

TABLE A.1 (Con't)

SUMMARY OF RISK COMPONENTS

Risk Component Number:	36
Risk Component Name:	Cancer Risks Due to Dispersal Accidents
Risk Scenario:	Risk of delayed health effects due to cloudshine
Risks Addressed:	Public cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{36p}
Annual Baseline Risk Symbol(s):	R_{36p}
Appendix I Location:	Section E.6.4.3.4; Table E.6-10

Risk Component Number:	37
Risk Component Name:	Cancer Risks Due to Dispersal Accidents
Risk Scenario:	Risk of delayed health effects due to groundshine
Risks Addressed:	Public cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{37p}
Annual Baseline Risk Symbol(s):	R_{37p}
Appendix I Location:	Section E.6.4.3.5; Table E.6-10

Risk Component Number 38 cancelled

Risk Component Number:	39
Risk Component Name:	Risk of Monetary Losses Due to Decontamination Procedures
Risk Scenario:	Potential financial losses
Risks Addressed:	Public funds
Risk Reduction Factor Symbol(s):	ρ_{39p}
Annual Baseline Risk Symbol(s):	R_{39p}
Appendix I Location:	Section E.6.5; Table E.6-10

Risk Component Number:	40
Risk Component Name:	Post-Closure Occupational Radiation Risks from Drilling Operations
Risk Scenario:	Risk of drilling operations in Scenario E1
Risks Addressed:	Occupational cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{40o}
Annual Baseline Risk Symbol(s):	R_{40o}
Appendix I Location:	Section E.7.2.1; Table E.7-1

TABLE A.1 (Con't)

SUMMARY OF RISK COMPONENTS

Risk Component Number:	41
Risk Component Name:	Post-Closure Occupational Radiation Risks from Drilling Operations
Risk Scenario:	Risk of drilling operations in Scenario E2
Risks Addressed:	Occupational cancer and genetic damage
Risk Reduction Factor Symbol(s):	$\rho_{41\,o}$
Annual Baseline Risk Symbol(s):	$R_{41\,o}$
Appendix I Location:	Section E.7.2.2; Table E.7-1
Risk Component Number:	42
Risk Component Name:	Post-Closure Occupational Radiation Risks from Drilling Operations
Risk Scenario:	Risk of drilling operations in Scenario E1E2
Risks Addressed:	Occupational cancer and genetic damage
Risk Reduction Factor Symbol(s):	$\rho_{42\,o}$
Annual Baseline Risk Symbol(s):	$R_{42\,o}$
Appendix I Location:	Section E.7.2.3; Table E.7-2
Risk Component Number:	43
Risk Component Name:	Inhalation Risks from Dried Up Ponds of Drilling Mud
Risk Scenario:	Public inhalation risk due to drilling in Scenario E1
Risks Addressed:	Public cancer and genetic damage
Risk Reduction Factor Symbol(s):	$\rho_{43\,p}$
Annual Baseline Risk Symbol(s):	$R_{43\,p}$
Appendix I Location:	Section E.7.3.2.1; Table E.7-1
Risk Component Number:	44
Risk Component Name:	Inhalation Risks from Dried Up Ponds of Drilling Mud
Risk Scenario:	Public inhalation risk due to drilling in Scenario E2
Risks Addressed:	Public cancer and genetic damage
Risk Reduction Factor Symbol(s):	$\rho_{44\,p}$
Annual Baseline Risk Symbol(s):	$R_{44\,p}$
Appendix I Location:	Section E.7.3.2.2; Table E.7-1
Risk Component Number:	45
Risk Component Name:	Inhalation Risks from Dried Up Ponds of Drilling Mud
Risk Scenario:	Public inhalation risk due to drilling in Scenario E1E2
Risks Addressed:	Public cancer and genetic damage
Risk Reduction Factor Symbol(s):	$\rho_{45\,p}$
Annual Baseline Risk Symbol(s):	$R_{45\,p}$
Appendix I Location:	Section E.7.3.2.3; Table E.7-2

TABLE A.1 (Con't)

SUMMARY OF RISK COMPONENTS

Risk Component Number:	46
Risk Component Name:	Public Ingestion Risks Due to Drilling Operations
Risk Scenario:	Public ingestion risks due to beef contaminated by stock well water in Scenario E1
Risks Addressed:	Public cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{46p}
Annual Baseline Risk Symbol(s):	R_{46p}
Appendix I Location:	Section E.7.3.3.1; Table E.7-3

Risk Component Number:	47
Risk Component Name:	Public Ingestion Risks Due to Drilling Operations
Risk Scenario:	Public ingestion risks due to beef contaminated by stock well water in Scenario E2
Risks Addressed:	Public cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{47p}
Annual Baseline Risk Symbol(s):	R_{47p}
Appendix I Location:	Section E.7.3.3.2; Table E.7-4

Risk Component Number:	48
Risk Component Name:	Public Ingestion Risks Due to Drilling Operations
Risk Scenario:	Public ingestion risks due to beef contaminated by stock well water in Scenario E1E2
Risks Addressed:	Public cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{48p}
Annual Baseline Risk Symbol(s):	R_{48p}
Appendix I Location:	Section E.7.3.3.3; Table E.7-5

Risk Component Number 49 cancelled

Risk Component Number:	50
Risk Component Name:	Post-Closure Public Ingestion Risks Due to Drilling Operations
Risk Scenario:	Public ingestion risks due to beef contaminated by stock well water in Scenario E1
Risks Addressed:	Public morbidity
Risk Reduction Factor Symbol(s):	ρ_{50p}
Annual Baseline Risk Symbol(s):	R_{50p}
Appendix I Location:	Section E.7.4.2.1; Table E.7-3

TABLE A.1 (Con't)

SUMMARY OF RISK COMPONENTS

Risk Component Number:	51
Risk Component Name:	Post-Closure Public Ingestion Risks Due to Drilling Operations
Risk Scenario:	Public ingestion risks due to beef contaminated by stock well water in Scenario E2
Risks Addressed:	Public morbidity
Risk Reduction Factor Symbol(s):	$\rho_{51\,p}$
Annual Baseline Risk Symbol(s):	$R_{51\,p}$
Appendix I Location:	Section E.7.4.2.2; Table E.7-4
Risk Component Number:	52
Risk Component Name:	Post-Closure Public Ingestion Risks Due to Drilling Operations
Risk Scenario:	Public ingestion risks due to beef contaminated by stock well water in Scenario E1E2
Risks Addressed:	Public morbidity
Risk Reduction Factor Symbol(s):	$\rho_{52\,p}$
Annual Baseline Risk Symbol(s):	$R_{52\,p}$
Appendix I Location:	Section E.7.4.2.3; Table E.7-5
Risk Component Number:	53
Risk Component Name:	Industrywide Occupational Accidents
Risk Scenario:	Fatal occupational accidents
Risks Addressed:	Occupational fatalities
Risk Reduction Factor Symbol(s):	$\rho_{53\,o}$
Annual Baseline Risk Symbol(s):	$R_{53\,o}$
Appendix I Location:	Section F.2.1.1; Table F.2-1
Risk Component Number:	54
Risk Component Name:	Industrywide Occupational Accidents
Risk Scenario:	Nonfatal accidents
Risks Addressed:	Occupational injuries
Risk Reduction Factor Symbol(s):	$\rho_{54\,o}$
Annual Baseline Risk Symbol(s):	$R_{54\,o}$
Appendix I Location:	Section F.2.1.2; Table F.2-1

TABLE A.1 (Con't)

SUMMARY OF RISK COMPONENTS

Risk Component Number:	55
Risk Component Name:	Forklift Accidents
Risk Scenario:	Fatal forklift accidents in TF
Risks Addressed:	Occupational fatalities
Risk Reduction Factor Symbol(s):	ρ_{55o}
Annual Baseline Risk Symbol(s):	R_{55o}
Appendix I Location:	Section F.2.2.2.1; Table F.2-2
Risk Component Number:	56
Risk Component Name:	Forklift Accidents
Risk Scenario:	Nonfatal forklift accidents in TF
Risks Addressed:	Occupational injuries
Risk Reduction Factor Symbol(s):	ρ_{56o}
Annual Baseline Risk Symbol(s):	R_{56o}
Appendix I Location:	Section F.2.2.2.2; Table F.2-2
Risk Component Number:	57
Risk Component Name:	Risk of Radiation Exposures
Risk Scenario:	Routine operations: External exposure in TF
Risks Addressed:	Occupational cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{57o}
Annual Baseline Risk Symbol(s):	R_{57o}
Appendix I Location:	Section F.3.1.1; Table F.3-1
Risk Component Number:	58
Risk Component Name:	Risk of Radiation Exposures
Risk Scenario:	Routine maintenance: External exposure in TF
Risks Addressed:	Occupational cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{58o}
Annual Baseline Risk Symbol(s):	R_{58o}
Appendix I Location:	Section F.3.1.2; Table F.3-2
Risk Component Number:	59
Risk Component Name:	Risk of Internal Radiation Exposures
Risk Scenario:	Occupational risks due to internal routine exposures originating from TF
Risks Addressed:	Occupational and public cancer and genetic damage
Risk Reduction Factor Symbol(s):	ρ_{59o} and ρ_{59p}
Annual Baseline Risk Symbol(s):	R_{59o} and R_{59p}
Appendix I Location:	Sections F.3.2.1.1 and F.3.2.1.2; Tables F.3-3 and F.3-4

TABLE A.1 (Con't)

SUMMARY OF RISK COMPONENTS

Risk Component Number:	60
Risk Component Name:	Risk of Internal Radiation Exposures
Risk Scenario:	Cancer risk due to maintenance operations in TF
Risks Addressed:	Occupational and public morbidity
Risk Reduction Factor Symbol(s):	ρ_{60o} and ρ_{60p}
Annual Baseline Risk Symbol(s):	R_{60o} and R_{60p}
Appendix I Location:	Sections F.3.2.2.1 and F.3.2.2.2; Tables F.3-5 and F.3-6
Risk Component Number:	61
Risk Component Name:	Risk of Cancer by Exposure to VOCs
Risk Scenario:	Routine operations in TF: Occupational and public exposures
Risks Addressed:	Occupational and public morbidity
Risk Reduction Factor Symbol(s):	ρ_{61o} and ρ_{61p}
Annual Baseline Risk Symbol(s):	R_{61o} and R_{61p}
Appendix I Location:	Sections F.4.1.1 and F.4.1.2; Tables F.4-1 and F.4-2
Risk Component Number:	62
Risk Component Name:	Risk of Noncancer Health Effects
Risk Scenario:	Routine operations in TF: Occupational and public exposures
Risks Addressed:	Occupational and public morbidity
Risk Reduction Factor Symbol(s):	ρ_{62o} and ρ_{62p}
Annual Baseline Risk Symbol(s):	R_{62o} and R_{62p}
Appendix I Location:	Sections F.4.2.1 and F.4.2.2; Table F.4-1

ATTACHMENT B

THEORETICAL BASIS FOR RISK COMPARISONS USING SOME OF THE TOOLS OF MULTI-ATTRIBUTE UTILITY THEORY

B.1 INTRODUCTION

Scenarios considered in risk assessment rarely lead to a single consequence; usually the total risk of one or more events consists of a number of different components such as fatalities, injuries, and dollars lost. Quite generally, risks are multidimensional quantities with components of widely different character, measured in different units. For two reasons, this makes the comparison of risks nontrivial: (1) a numerical comparison can only involve two numbers and (2) only numbers measured in the same units can be compared.

Therefore, for a comparison of multicomponent quantities, all components must be converted to the same units through multiplication by an appropriate scale or conversion factor, and all components must be combined in a manner prescribed by some rationale to form a single number. Two such numbers can then be compared unequivocally, provided that the algorithm used for the combination is, mathematically speaking, a well-behaved function. For rationales such as the ones discussed here, the functions used are rather simple and do not present any mathematical difficulties.

The fields of economics and decision theory offer the required rationales in the form of multi-attribute utility functions (Covello, 1987; Fishburn, 1978; Keeney, 1978; Von Neumann and Morgenstern, 1944). These functions not only convert all components to the same units, but also involve societal value judgements, for instance, by explicitly defining a dollar equivalent for a human life lost. Their function values are called utility indices and are the quantities to be used here for risk comparisons. In risk management, this generic approach was successfully used to select the three finalist sites for the high-level radioactive waste repository (Gregory and Lichtenstein, 1987; Keeney, 1987; Merkhofer and Keeney, 1987). In that selection process, a number of different attributes, such as aesthetic, cultural, and socio-economic impacts, as well as repository cost, were considered in addition to some components of the total risk. It is demonstrated here that this theoretical framework can not only be applied to comparing utility indices based on risk components alone but that the similarity of the components may be used to advantage.

It is, however, important to realize that the use made of multi-attribute utility theory proposed here differs in several significant aspects from the conventional approach. Indeed, except for the derivation, this application to the comparison of total risks has few aspects in common with the usual multi-attribute utility approach to decision making. Most important among the differences

is that the purpose of the procedure to be developed is exclusively to compare two or more risks, which are quite similar quantities. It is not the intent to make management or policy decisions, such as those indicated in the last paragraph, on the basis of often widely different criteria. As a consequence, full advantage is taken of all similarities, particularly with regard to the valuations of reductions in risk.

In the applications of multiattribute utility theory to date, ranking is based purely on the concept of *preference* without recourse to the numerical uncertainties of the utility indices; that is, the indices are treated as if they had no standard errors. Consequently, this approach is not able to make explicit use of the other basic concept of value theory: that of *indifference* to the ranking of two utility indices (Fishburn, 1978; Von Neumann and Morgenstern, 1944). In ranking risks using utility functions, the fact of indifference to ranking two alternatives is a highly significant datum, particularly if the alternatives differ in attributes other than risk, such as cost, technical viability, and reliability. In an additional procedure, these aspects can then be taken into account to make management or policy decisions.

Normally, risk comparisons are not or should not be stand-alone procedures (Seiler, 1990b). They are more likely tied into a larger framework for the evaluation of alternatives. In this environment, it is imperative that a close interaction exist between the decision makers at both levels, because the viewpoints and valuations in a stand-alone risk comparison are not the same as those in a risk comparison embedded into another study that depends on its results.

It is the purpose of this theoretical approach to apply the tools of multi-attribute utility theory to the comparison of risks, to propose a particular form of writing risks and utility functions for making these comparisons, to discuss the properties of that particular form and similar forms in detail, and, finally, to introduce an uncertainty evaluation for the utility index and apply it to two indifference criteria for the ranking process.

B.2 COMPARISONS OF RISK COMPONENTS

B.2.1 Risk as a Multicomponent Quantity

The basic quantity risk will be used here in the form defined by Kaplan and Garrick (1981),

$$R_i \equiv (S_i, C_i, P_i) , \qquad \text{(B.2.1)}$$

where S_i defines a particular scenario, C_i one of its consequences, and P_i the probability of that consequence. The complete set of I scenarios and outcomes of a given activity describes its

total risk. In set notation

$$\boldsymbol{R} = \{R_i \mid i=1,I\} = \{(S_i, C_i, P_i) \mid i=1,I\} . \qquad \text{(B.2.2)}$$

The possible scenarios S_i include different people at risk with individual risks R_i which can be summed to obtain a total risk **R** for all J possible consequences C_j, each of which is expected to occur E_j times. In other words, E_j is the expectation value for the effects in all exposed individuals. The total risk can then be written as a set of all J combinations of scenarios and consequences,

$$\boldsymbol{R} = \{R_j \mid j=1,J\} = \{(S_j, C_j, P_j) \mid j=1,J\} . \qquad \text{(B.2.3)}$$

Alternately, this total risk can be written as a vector

$$\boldsymbol{R} = (R_1, R_2, \ldots, R_j, \ldots R_J) , \qquad \text{(B.2.4)}$$

where the components R_j of the total risk are given by the same expectation value of the number of effects E_j as in Equation (B.2.3)

$$R_j = E_j , \qquad \text{(B.2.5)}$$

where the index j now has to imply both scenario and consequence. The meaning of the real number E_j can thus range from the number of traffic or latent cancer fatalities to the number of dollars necessary to clean up an accident site. Potentially, the number of components J is quite large. Methods to aggregate some of them to decrease their number to a manageable size will be discussed in the context, weighting the components in Section B.3.4. Regardless of the number of components, however, the notation of Equation (B.2.4) clearly indicates the multicomponent nature of most total risks.

The comparison of total risks is made difficult by this multi-component structure, because there exists no unique mathematical framework for comparing these risks at the present time. Yet risk comparisons are needed in many risk assessments and in most risk management activities. It is, therefore, of importance to develop tools that allow a comparison of total risks, such as an index that summarizes the combined impacts of all components of the risks being compared.

In this context, it is important to realize that the risk defined in Equation (B.2.1) and the total risk defined by Equations (B.2.3) or (B.2.4) are two different quantities. However, for want of a more appropriate term, both are usually called risks. The terminology used here is to apply the qualified term total risk to the second set of equations, defining the expectation values for each consequence. As long as the index j implies both scenario and consequence this usage will be maintained.

In the aggregation mentioned above, the number of components is reduced from J to a more manageable number J_o. This implies a summation (or integration) over the number of scenarios and over the persons exposed. The resulting quantities are more in the nature of an expectation value of a total risk than a risk, and call for a different term. Taking into account that Equations (B.2.2) and (B.2.3) contain exactly the same information, yet another formulation for this data set is

$$\boldsymbol{C} = (C_1 , C_2 , \ldots , C_j , \ldots C_{J_o}) , \tag{B.2.6}$$

where the components C_j are given by the analog to Equation (B.2.5).

$$C_j = E_j . \tag{B.2.7}$$

Note that the only real difference between Equations (B.2.4) and (B.2.6) is the range of the index j, which runs from 1 to J in Equation (B.2.4) and over the much reduced range from 1 to J_o in Equation (B.2.7). In the latter, the index runs exclusively over the different consequences C_j, selected in the aggregation process. The quantity **C** defined by Equation (B.2.6) is, therefore, termed the consequence vector.

B.2.2 Uncertainties in Risk Comparisons

In many risk assessments, the numerical analysis of uncertainties is either not performed at all or then just perfunctorily, more as an afterthought. This may in part be due to the fact that the treatment of uncertainties is often difficult; at any rate it is more involved and more delicate than the actual risk calculation (Bevington, 1969; Brandt, 1976; Iman and Helton, 1988; Seiler, 1987b). However, in any state-of-the-art risk assessment, an appropriate numerical error analysis is a central and time-consuming part of the entire effort (see Section B.4.2 and Attachment C). Also, its results should be reflected in the final quotations of the risks, even if it is only by the number of significant digits given (LaGoy, 1989).

When two or more total risks are compared, the uncertainties of each component of the total risk become of paramount importance, because the task of a risk comparison is not merely to rank risks according to some criterion or other, but rather to do so while keeping track of risks that are not significantly different from others. These comparable risks can only be assigned to a particular group but cannot be ranked within it. Failure to follow this procedure can result in considerable losses of money or other societal goods due to more efficient alternatives which were mistakenly ranked lower and consequently rejected. In order to follow the procedure outlined here, criteria that indicate an indifference to ranking need to be applied, such as Goodman's criteria of an insignificant difference (Goodmann, 1986).

The uncertainties of most risk components are usually rather large due to such uncertain factors as the probability of the primary event in a scenario or the risk coefficient for lung cancer due to high-LET irradiation of the respiratory tract by inhaled ^{238}Pu. However, closer inspection of risk

comparisons shows that these errors have the character of errors of scale which can sometimes hide even highly significant differences (Seiler, 1990b). These scale errors should either be removed by appropriate methods (Seiler, 1990b) or they can be eliminated by an appropriate normalization of the risk component.

B.2.3 Normalizing a Risk Component

The most elegant way to reduce the error of a risk component is a normalization, that is, a recalibration of the component in different units. In this operation, many common factors cancel. Quite generally, a component R_{jk} of the total risk can be separated into a product of n_j different factors F_{jkv}, often with some of the factors being sums of products,

$$R_{jk} = F_{jk1}\, F_{jk2} \cdots F_{jk}\, n_j = \prod_{v=1}^{n_j} F_{jkv} \,, \tag{B.2.8}$$

where the indices j, k, and v stand for the risk component, the alternative being compared and the risk factor, respectively. For use as a normalization quantity, a number of different risks can serve. Convenient choices are the baseline risk components, or the average of every component over all K alternatives. In this context, it is important to realize that normalization is a shift of scale that does not change relative uncertainties.

Denoting the normalization risk by the index k = 0, the normalized risk component r_{jk} is the old risk component R_{jk} measured in units of the normalization risk R_{jo} or, in the terminology of epidemiology, the new risk r_{jk} is a relative risk. In the normalization, a number of the factors in numerator and denominator will usually cancel; often only one or two factors remain. If the number of remaining factors is n_j, the relative risk is given by

$$r_{jk} \equiv \frac{R_{jk}}{R_{jo}} = \frac{F_{jk1}\, F_{jk2} \cdots F_{jkn_j}}{F_{jo1}\, F_{jo2} \cdots F_{jon_j}} = \frac{\prod_{v=1}^{n_j} F_{jkv}}{\prod_{v=1}^{n_j} F_{jov}} \,. \tag{B.2.9}$$

The error of this ratio is thus much smaller than the error of an absolute risk, and error propagation can be handled in the usual first-order or Gaussian approximation for small relative errors (Bevington, 1969; Brandt, 1976). If some relative errors are not small, higher order terms in the Taylor series may have to be used (Seiler, 1987b).

Sometimes the same parameter appears in both numerator and denominator, but does not cancel as in Equation (B.2.9), because the factor containing it is a sum of products. In this case, the error propagation formula should not be used on the absolute risks R_{jk} , but on the relative risk function $r_{jk}(\mathbf{x}) = r_{jk}(x_1, x_2, \ldots, x_P)$ with a set of P independent parameters $\{x_P\} = \{x_p \mid p = 1,P\}$

that influence the uncertainty of the final result. The Gaussian approximation, which consists of the first correction term of a multi-dimensional Taylor (Korn and Korn, 1968) expansion of $r_{jk}(\mathbf{x})$ around the point **x**, then yields

$$(\Delta r_{jk})^2 = \sum_{\kappa=1}^{P} \left(\frac{\partial r_{jk}(\{x_P\})}{\partial x_\kappa} \right)^2 (\Delta x_\kappa)^2 . \qquad \text{(B.2.10)}$$

Analogously, numerical methods (Cox and Baybutt, 1981; Helton, 1961; Iman and Helton, 1988) should focus on the relative risk r_{jk} rather than on the product of the residual factors $F_{jk\nu}$ of the absolute risks in numerator and denominator. Some of the aspects relevant to this report will be discussed in more detail in Attachment C.1.

B.3 TOOLS OF MULTI-ATTRIBUTE UTILITY FUNCTIONS

B.3.1 Decision Theory

Decision theory is a discipline grown out of economics and operations research that has developed rapidly in the last few decades. It is a system of concepts and mathematical procedures which are helpful in making decisions while pursuing multiple objectives. Some approaches are based on the economic concepts of *preference* and *utility* (Fishburn, 1978; Keeney, 1978), collectively often called value theory, and incorporate individual and societal value judgments in a mathematical framework combining different attributes.

Von Neumann and Morgenstern (1944) are credited with the primary development of modern axiomatic theory of utility functions for decision processes; more recent developments have resulted in a mature axiomatic theory. Central to this economic theory are the binary relations of preference theory based on the concepts of *preference* (the consumer prefers A to B, actually he 'strictly prefers' A to B; or in mathematical symbolism: $A \succ B$) and *indifference* (the consumer is indifferent to a choice between A and B, or in mathematical symbols: $A \sim B$). Utility functions describe the consumer's valuation of various amounts of commodities such as money, goods, and services. The numerical value of a utility function is called the utility index (Henderson and Quandt, 1971).

B.3.2 Single Attribute Utility Functions

Utility indices are used to rank alternatives; the differences between the values of different alternatives, however, are not necessarily indicative of the intensity of preference. Utility functions, as usually constructed, are thus deemed to have ordinal, but not necessarily cardinal properties (Fishburn, 1978; Henderson and Quandt, 1971; Keeney, 1978). However, for the purposes of comparing risks, cardinal properties are desirable in order to facilitate error propagation calculations and evaluate the significance of differences between utility indices.

Utility functions with the necessary properties can be constructed in a manner that avoids sizeable higher-order derivatives, for example, by using linear or logarithmic functions of gains or losses. For these functions, it is then possible to calculate standard errors for the utility indices and use them in a meaningful discussion of significant differences. The discussions here are given in terms of unaggregated risk components but hold equally well for aggregated components.

From the utility point of view a risk contribution or a number of expected health or environmental effects E_{jk} are a disutility d_{jk} or a negative utility $-u_{jk}$. If the disutility d_{jk} is assumed to be directly equal to the number of effects, it is given by the expression

$$d_{jk} = -u_{jk} = E_{jk} , \qquad \text{(B.3.1)}$$

where the indices j and k denote the component and the alternative, respectively. As long as the value of E_{jk} is larger than one but not too large, the linear utility function is a good measure for the loss of value. If E_{jk} is considerably less than one, the linear function does not give a reasonable measure for a risk reduction by - say - an order of magnitude; it undervalues that risk reduction. If E_{jk} is much larger than one, on the other hand, it will tend to overvalue a risk reduction by the same factor of ten. The same arguments can be made for a linear utility that involves normalized risks.

In economic terms, the use of the linear form disregards the relationship between the quantity of a commodity and its utility, known as the *Law of Diminishing Marginal Utility* (Fishburn, 1978; Samuelson, 1973). Put in mathematical terms, it states that the derivative of the utility decreases as the quantity of the commodity increases. Thus the use of the term 'marginal' in economics does not agree with its mathematical definition (see for instance Korn and Korn, 1968). In order to limit the use of this term to its mathematical meaning, the acronym *LDMU* will be used from now on to denote the law.

In risk management, the *LDMU* expresses the fact that, for example, a unit increase in the relative risk is most detrimental when r_{jk} is 1, it is less detrimental when r_{jk} is 10, and even less so when r_{jk} is 100. Similarly, a unit increase in the denominator is most beneficial when the relative risk is 1, less beneficial when it is 1/10, and so on. Graphically, this type of relationship is shown in Figure I.B-1a, where, as an example, a logarithmic dependence $f(x) = \log_a x$ is plotted as a function of the argument x. Given in Figure I.B-1b is its derivative, $df(x) / dx = 1 / (x \ln a)$ as a function of x. The function f(x) adds one unit of disutility for every factor, a, by which the argument x increases.

Using a logarithmic form with base, a, for the disutility inherent in a risk component leads to the second form of the utility function to be discussed here. The formulation

$$d_{jk} = \log_a r_{jk} , \qquad \text{(B.3.2)}$$

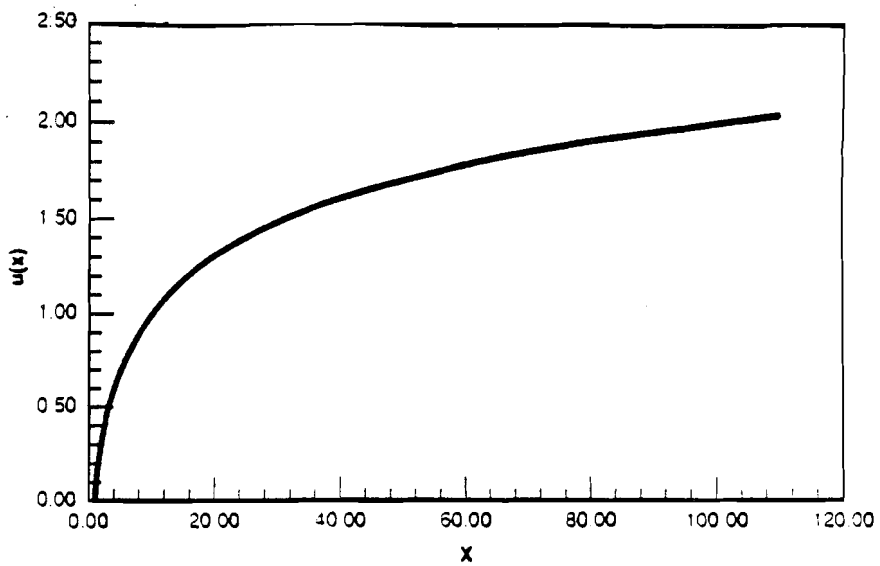

FIGURE I.B-1a. LOGARITHMIC DEPENDENCE OF A FUNCTION ON ITS ARGUMENT

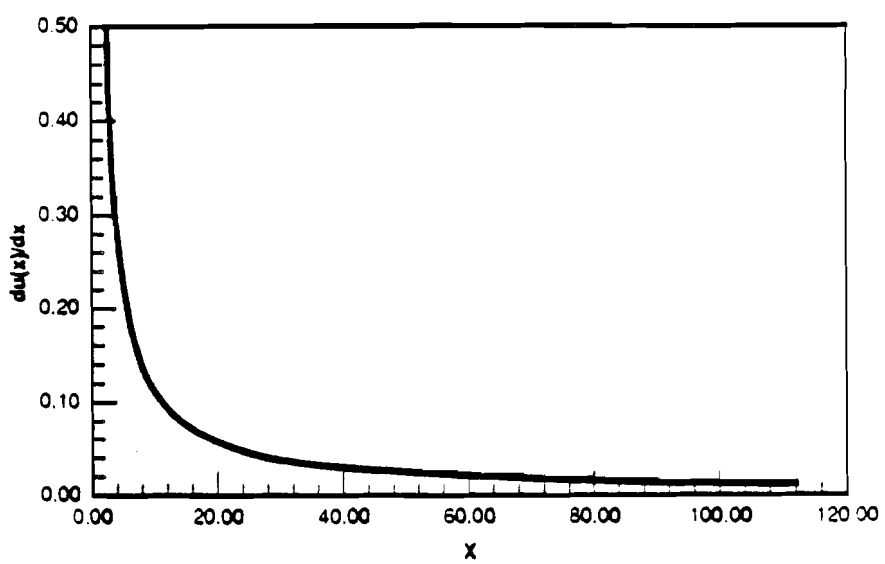

FIGURE I.B-1b. DEPENDENCE OF THE DERIVATIVE OF A FUNCTION ON ITS ARGUMENT

The *Law of Diminishing Marginal Utility* shown here (Figure I.B-1.a) for the single-attribute utility function $U(x) = \log_a x$. For each factor, a, by which the argument x increases or decreases, the utility increases or decreases by one unit. The change per unit increase of argument x, that is, its derivate $du(x)/dx = 1/(x \ln a)$ is shown in Figure I.B-1.b. As required by the *LMDU*, it continuously decreases as the argument increases.

removes the asymmetry about the point $r_{jk} = 1$, except for a sign. It is, therefore, antisymmetric with respect to unity and able to cover large variations in the relative risk r_{jk}. In fact the definition of a risk reduction factor ρ_{jk} by

$$\rho_{jk} \equiv \frac{1}{r_{jk}} = \frac{R_{jo}}{R_{jk}} , \tag{B.3.3}$$

allows the writing of the modified utility function in the form

$$\begin{aligned} \theta_{jk} &= -d_{jk} = -\log_a r_{jk} = \log_a \left(\frac{1}{r_{jk}} \right) \\ &= \log_a \rho_{jk} = \frac{ln\, \rho_{jk}}{ln\, a} = Q\, ln\, \rho_{jk} , \end{aligned} \tag{B.3.4}$$

with the definition of the 'modulus' of the logarithm with base a

$$Q \equiv \frac{1}{ln\, a} . \tag{B.3.5}$$

This type of utility function is antisymmetric in the arguments r_{jk} and ρ_{jk} and symmetric with respect to risk increases and risk reductions.

Utility functions that appear most useful in the comparison of total risks combine most of the qualities discussed above. The set of these single-attribute utility functions will be called class $\Re_s$ utility functions in this paper and is defined by the following properties:

1. Exhibiting the behavior required by the *LDMU*, and having a parameter that allows it to approximate the dependence of the utility function on the risk reduction factor.

2. Exhibiting antisymmetry with respect to an argument of unity, i.e., it is symmetric, except for the sign, with respect to $r_{jk} = 1$, and thus also $\rho_{jk} = 1$.

3. Being "mathematically well behaved functions," i.e., they are continuous, monotonic, differentiable, and have, in addition, only small values of the higher derivatives.

4. Being *measurable*, i.e., a larger difference of the utility function for two different values of the argument means a larger difference in the intensity of the preference for the higher argument over the lower one, and vice versa (Dyer and Sarin, 1979).

From the discussions above, the need for most of these properties is evident; the requirement of small higher derivatives is needed in order to justify the use of the Gaussian approximation for the propagation of errors. Together with the requirement of *measurability*, this condition assures

a meaningful mapping of the uncertainty distribution onto the utility function. Clearly, the functions discussed in Equations (B.3.2) and (B.3.4) fulfill all of these requirements, whereas Equation (B.3.1) fails with regard to the first condition, except for small deviations of the argument from unity.

B.3.3 Aggregation of Components

Among the J components of the total risk, many involve the same incident or the same type of incident, say, routine occupational whole-body exposure to low-LET radiation, as well as the same consequence, say, leukemia five to fifteen years later. The expected value of leukemia cases among the workers for several different exposure scenarios is a typical candidate for aggregating components into the single risk component of leukemia due to routine occupational low-LET whole-body radiation exposure. All contributions to this combined risk would have the same societal weight γ_i, i.e., be subject to the same valuation.

There are essentially three ways to aggregate similar components: (1) aggregate before forming the risk reduction factor; (2) aggregate risk reduction factors before forming the utility function; and (3) aggregate after forming the utility functions. Each method has its area of applicability, although in many cases the method of choice is not necessarily evident. The basic requirement for aggregation, however, is that the components lead to the same consequence, typically a health or environmental effect.

The first method is indicated, for instance, when the index j differentiates solely between individuals exposed in the same event and at risk for the same health effect. This aggregation is of the type that leads to the number E_j of health effects in Equation (B.2.5). For the aggregation labeled ξ, which combines the n_ξ components between the labels $J_{\xi-1}$ and J_ξ, with indices given by the limits $1 \le J_{\xi-1} \le J_\xi \le J$, the combined risk reduction ratio becomes a sum of products, quite likely multiplied by some common factors. This can be seen by rewriting Equation (B.3.3) as a risk reduction factor $\rho_{\xi k}$ for the combined component ξ

$$\rho_{\xi k} = \frac{\sum_{j=J_{\xi-1}}^{J_\xi} R_{jo}}{\sum_{j=J_{\xi-1}}^{J_\xi} R_{jk}} . \qquad \text{(B.3.6)}$$

The detailed derivation of the algebraic form of $\rho_{\xi k}$ and its properties are given in Attachment C.2, Aggregation of Risk Components. Also discussed there is the calculation of the error for the risk reduction factor, $\Delta \rho_{\xi k}$, which requires the application of the Gaussian approximation.

The second method should be used when it seems justified to add risk reduction factors in some appropriately weighted fashion. This is indicated in some studies where only several conditional

accident scenarios are discussed, that is, the results given are subject to the condition that the initiating event has occurred, but little information is available on the probability of that event. Also, some highly uncertain low-probability events may be more amenable to the estimation of the risk reduction factor than to the estimation of the absolute risk. In these cases, it may be useful to estimate the combined risk reduction factor as a weighted arithmetic or geometric average of the individual factors,

$$\rho_{\xi k} = \sum_{j=J_{\xi-1}}^{J_\xi} w_{\xi j}\, \rho_{jk} \,, \tag{B.3.7}$$

or

$$\rho_{\xi \kappa} = \prod_{j=J_{\xi-1}}^{J_\xi} \left(\rho_{j\kappa}\right)^{w_{\xi j}} \,. \tag{B.3.8}$$

Equations (B.3.7) and (B.3.8) do not have the usual form for weighted means because the sum of the weights is normalized to unity. Once this is taken into account, the equations assume the correct form.

The choice between the arithmetic and the geometric average depends on the characteristics of the evaluation. In risk comparisons, risk reduction factors often vary widely. In that case, a geometric mean may be preferable. For the aggregation of more densely clustered risk reduction factors, the arithmetic average may be preferable.

The problem in using Equations (B.3.7) and (B.3.8) lies in finding an adequate rationale for the determination of the weights $w_{\xi j}$. It may, however, be easier to approximate the influence of a particular risk reduction factor on a combined factor than to estimate its absolute value. In some of these cases, the relative contribution of that component to the total baseline risk of the aggregation ξ may be deemed appropriate,

$$w_{\xi j} = \frac{R_{jo}}{\sum_{v=J_{\xi-1}}^{J_\xi} R_{vo}} \,. \tag{B.3.9}$$

In other cases, equal weights may be more adequate. Generally, the second method is indicated when separate risk reduction factors are needed, but there is no rationale for a separate attribute in the multi-attribute utility function.

The third method should be used when component utilities should be added and weighted with the same societal valuation γ_j. This is often the case with the risk components targeted by the

risk reduction methods that distinguish the alternatives k. For these components a direct evaluation of the utilities is indicated. In some instances, however, these contributions to the utility index tend to overwhelm other contributions by their sheer numbers, even though they should be viewed more as a single contribution. To avoid this situation, the composite single-attribute utility function may be written as

$$u_{\xi k} = Q \sum_{\nu=J_{\xi-1}}^{J_\xi} w_{\xi\nu} \, ln(\rho_{\nu k}) \, ,$$

with relative weights $w_{\xi j}$. These weights are often most appropriate when set equal to each other, that is to

$$w_{\xi j} = \frac{1}{n_\xi} = \frac{1}{J_\xi - J_{\xi-1}} \, , \qquad \text{(B.3.11)}$$

with a sum over the n_ξ weights normalized to unity. In some situations, however, another way of weighting may be more appropriate. Some additional thoughts on the best choice of method and on the implementation of that choice are presented in Attachment C.2, Aggregation of Risk Components.

In the aggregation process from J different components down to J_o components, the terminology changes because this summation leads to a quantity in the nature of an expectation value (see Section B.2.1, above). This is recognized by the definition of the consequence reduction factor

$$\Gamma_{jk} = \Phi_a \left(\{\rho_{jk}\} \right) \, , \qquad \text{(B.3.12)}$$

aggregated by one of the functions Φ_a in Equations (B.3.7 to B.3.8) from a subset of the set of all risk reduction factors. This quantity is used in the formulation of the multi-attribute utility theory.

B.3.4 Multi-Attribute Utility Functions

Utility functions for multiple attributes, such as the risk reduction components of a relative total risk, can be written as some combination of their marginal utility functions, the modified single-attribute utilities θ_{jk}, weighted by societal value judgments (Covello, 1987; Keeney, 1978; Merkhofer and Keeney, 1987). The corresponding mathematical weights g_j express the valuation by society of different components, such as cancer fatalities, monetary losses, loss of limbs, and workdays lost in accidents. As in the case of single attribute utility functions, the value of the function is called the utility index U_k.

There are many ways to decompose the multi-attribute utility function into combinations of their marginal utilities (French, 1986; Keeney and Raiffa, 1976; Zeleny, 1982). For risk comparisons, the most interesting one is the additive decomposition. In the approach used here, two forms of the multi-attribute utility function will be discussed: both are additive, one using linear and the other logarithmic marginal utility functions. Thus

$$U_k = const \sum_{j=1}^{J_o} g_j \, \theta_{jk} \, , \tag{B.3.13}$$

where the marginal utility functions are given either by Equation (B.3.1) or Equation (B.3.4), and where const is a constant scale factor.

Apart from these properties, these multi-attribute utility functions fulfill the other conditions of what we shall call class $\Re_m$ functions:

1. Their marginal utilities are class $\Re_s$ utility functions.

2. Similar to the requirements of condition 3) for class $\Re_s$ functions, they are mathematically 'well behaved' and represent a smooth n-dimensional surface without large curvatures in (n+1)-dimensional space.

3. The utility functions are measurable, i.e., a larger difference between the function values of two alternatives means a larger difference in the intensity of preference between the two alternatives.

The exact nature of the intensity of preference (French, 1986) discussed in the third condition is not of direct relevance here, because, as stated before, the requirement of measurability is introduced in order to ascertain a meaningful mapping of the uncertainties onto the utility indices. The second condition is the reason why the multiplicative decomposition of the multiattribute utility function is not used here. Multiplicative functions have considerably more potential for large surface curvatures than additive functions.

The first additive function to be discussed here is the weighted linear combination of linear utility functions for each attribute according to Equations (B.3.1) and (B.3.4). It leads to a multi-attribute function of

$$U_k = \frac{1}{S} \sum_{j=1}^{J_o} g_j \, \rho_{jk} \, , \tag{B.3.14}$$

where S is an arbitrary normalization factor. If it is chosen as the sum of weights g_j,

$$S = \sum_{j=1}^{J_o} g_j \,, \tag{B.3.15}$$

then normalized weights γ_j can be defined by

$$\gamma_j \equiv \frac{g_j}{S} \,, \tag{B.3.16}$$

resulting in a utility index U_k that corresponds to the weighted arithmetic mean of all component utilities,

$$U_k = \sum_{j=1}^{J_o} \gamma_j \, \rho_{jk} \,. \tag{B.3.17}$$

These linear combinations of linear utility functions are best used when the total risks to be compared are rather similar in most components. In these cases, the linearity of utility with a small increase or reduction in risk is a useful concept. The range of applicability is restricted, however, because of the asymmetry with regard to the unit relative risk and the inability to give expression to the *LDMU*.

If the marginal utilities θ_{jk} are given by the logarithm of the risk reduction component according to Equation (B.3.4), the additive form yields a multi-attribute utility, $U_{k,e}$ which is the weighted arithmetic mean in a logarithmic space with base, a,

$$U_k = Q \sum_{j=1}^{J_o} \gamma_j \, \ln \rho_{jk} \,. \tag{B.3.18}$$

This function thus has the global properties required of a class $\Re_m$ function. The wide range of relative risks due to risk management and remediation efforts, often many orders of magnitude, can be covered easily by assigning an appropriate base, a, to the logarithm to be used in the marginal utility functions.

Intuitively, the use of the weighted arithmetic and the weighted logarithmic mean of the component utilities as measures of the multi-attribute utility makes sense. The first is appropriate when the values Γ_{jk} are clustered relatively closely around the value of 1, the second is more appropriate when there are wide spreads between component values.

The selection of the weighted logarithmic average in Equation (B.3.11) as the multi-attribute utility function of choice in this paper may be less obvious. It is mostly justified by the desirable properties of a class $\Re_m$ multi-attribute utility function and the fact that function (B.3.11) is the most simple representative of this class. This choice is arbitrary, but it is based on a rationale that should be sufficient for the general purpose of comparing risks.

For the comparison of risks with logarithmic utility functions, the unique property of these functions may be used directly by defining with the anti-logarithm a risk reduction index which is the weighted geometric mean of all the risk reduction factors Γ_{jk}

$$\Theta_k = a^{U_k} = \prod_{j=1}^{J_o} (\Gamma_{jk})^{\gamma_j} \tag{B.3.19}$$

or its inverse, the risk augmentation index

$$\Psi_k = a^{-U_k} = \frac{1}{\Theta_k} . \tag{B.3.20}$$

It is these quantities which will be used here for risk comparisons. In this form of the indices, contributions from the different components are the factors

$$\Phi_{jk} \equiv (\Gamma_{jk})^{\gamma_j} , \tag{B.3.21}$$

so that

$$\Theta_k = \prod_{j=1}^{J_o} \Phi_{jk} . \tag{B.3.22}$$

Writing the consequence reduction index as a product allows a simple analysis of the contribution of each component j to the index.

B.3.5 Determination of Weights

Together with the selection of the utility function, the assignment of the weights g_j is a crucial part of the comparison of risks or consequences, because it involves the numerical evaluation of societal value judgments such as the value of a human life, the true societal cost of temporarily or permanently displacing people from their home or workplace, or the losses incurred in damaging or destroying an environmental system (Covello, 1987; Edwards, 1987; Graham and Vaupel, 1981; Svenson and Karlsson, 1989). An appropriate representation of different technical and non-technical viewpoints is, therefore, of paramount importance.

This purpose is best accomplished by eliciting the judgmental values of a group of experts. In this group, the viewpoint of political authorities at the local and state level, of the regulating agencies, and the operational engineer must be represented, as well as the concerns and values of the local population, and the needs and priorities of society as a whole. The group of experts will, therefore, have to comprise technical specialists, risk assessors and managers, as well as social scientists and others that can introduce regulatory and popular concerns into the evaluation. In this context, it is important to keep in mind the use to which the comparison of total risks or consequences is put. The composition of the group of experts will be quite different for different uses, such as selection of technological alternatives for a project already decided on, or the determination of whether to do a project or not. In the second case, much more societal input is needed, whereas in the first case a corresponding viewpoint needs to be represented.

In economics and decision theory, the weights g_i or γ_i are often called value trade-offs or scaling factors, and convert the risk component given in its appropriate units into a new quantity measured in dollars. This leads to the difficult question of the monetary value of a human life (Edwards, 1987; Graham and Vaupel, 1981; Gregory and Lichtenstein, 1987; Keeney and Raiffa, 1976; Merkhofer and Keeney, 1987), and to the problem of the appropriate discount rate for that value if the life is lost to cancer in 10 or 20 years instead of being lost in an occupational accident today. These problems become paramount, if not insoluble, when - as an example - the risk comparison involves different versions of a repository for radioactive wastes, and thus needs to balance the values of money and lives lost today and 5,000 or 10,000 years from now (Graham and Vaupel, 1981; Svenson and Karlsson, 1989).

This difficulty, however, seems to arise not so much from having to make the actual value judgment, but from the practice of expressing the results of that judgment in dollars and using traditional economic methods to discount them. Recent experience has shown that monetary values are not an adequate measure of many societal issues such as health and environmental risks (Keeney, 1990a; Keeney, 1990b; Svenson and Karlsson, 1989). In public perception, many risks carry a price that cannot be measured in dollars (Slovic, 1987; Svenson and Karlsson, 1989). The concern for the safety of future generations is a typical example: since our society has decided to worry about lives that may be lost in the far-off future, it clearly assigns weights which are largely independent of absolute dollar values or meaningful discount rates. By many people, weights are more likely to be assigned on the basis of a rationale such as: every generation should take care of its own wastes and not burden future generations with problems caused by less than optimal methods of disposal.

The normalization of risk components used here side-steps the difficulty of assigning absolute dollar values. Using either the relative risks r_{jk} or the risk reduction factors Γ_{jk} for disutility or utility, respectively, involves dimensionless quantities. In weighting them, there is also an important change in the question posed: It is no longer "What is the value of a human life lost today relative to the dollar?" but rather "What is the value of a reduction by a factor F in the risk

of lives lost today relative to the same reduction in the risk of monetary losses?" Appropriate aggregation into consequence components does not change this valuation.

The value of a consequence reduction, however, still depends on the absolute value of the consequence. For a relatively large value, a reduction by a factor F is more valuable than for a value that is already small. In part, this is but an alternate form of the *LDMU*, reformulated for the fact that risk is a disutility. Class $\Re_m$ multi-attribute utility functions such as the one in Equation (B.3.11) account in part for this property and the corresponding weights should thus be assigned for the part of the function near unity, i.e., for the neighborhood of $r_{jk} = 1$ and thus also $\Gamma_{jk} = 1$. This takes care of the variability of the utility with respect to the risk reduction factor. The weighting, however, still depends on the absolute value of the baseline risk R_{jo} for that component. For the relatively small values often encountered for highly controlled operations, the dependence is usually weak. For substantial or large total consequences, with several tens or hundreds of fatalities, however, that dependence is quite strong. Thus, considering the absolute consequence component together with the consequence reduction factor will yield a meaningful weight.

There are a considerable number of methods for eliciting and evaluating expert judgment discussed in the literature (French, 1986; Keeney and Raiffa, 1976). However, the totally different type of valuation needed here will require extra care. Some aspects of importance in this particular type of consequence comparison are discussed in more detail in Attachment G.

B.4 THE RANKING PROCESS AND UNCERTAINTY

B.4.1 The Ranking Process and Its Robustness

The values of the utility indices provide a basis to establish a ranking among alternative risks. Some of these rankings, however, may be spurious because the numerical values of the uncertainties in the utility indices may be larger than or comparable to the differences by which preference is established. Due to the uncertainties of the utility functions, two risks may actually be indistinguishable and should be ranked equally.

The ranking of the set A of K different alternatives thus leads to sorting them into B indifference classes I_b with one or more members which are mutually indifferent to ranking (French, 1986). Thus, in set notation, the indifference class I_b is defined by

$$I_b = \{ \alpha \in A \mid \Theta_\alpha \sim \Theta_b \} . \qquad \text{(B.4.1)}$$

It can be shown, however, that there exists a strict preference relationship between the B indifference classes

$$I_{b_1} \succ_i I_{b_2} \succ_i \cdots \succ_i I_b \succ_i \cdots \succ_i I_B \ , \tag{B.4.2}$$

where the strict preference between indifference classes is denoted by $\succ_i$ and defined by

$$I_a \succ_i I_b \quad \Leftrightarrow \quad \alpha \succ \beta \quad \textit{for any} \quad \begin{matrix} \alpha \in I_a \\ \beta \in I_b \ , \end{matrix} \tag{B.4.3}$$

i.e., by the requirement that all elements of the preferred class are strictly preferred to all elements of the other class. On this basis, the classification in Equation (B.4.2) characterizes the ranking information needed in risk comparisons. The value of a consequence reduction index Θ_k and its uncertainty $\Delta\Theta_k$ provide the data for the uncertainty analysis of the ranking process, resulting in a ranking and a multiplicity at equal rank (French, 1986; Goodmann, 1986). The procedure is discussed in Section B.4.3.

B.4.2 Standard Error of the Utility Indices

The uncertainty $\Delta\Theta_k$ of the consequence reduction index arises from the set $\{x_P\}$ of all P stochastic quantities that enter into the calculation of the index. The Gaussian approximation (Bevington, 1969; Brandt, 1976; Seiler, 1987b) yields for the standard error

$$(\Delta\,\Theta_k)^2 = \sum_{\nu=1}^{P} \left(\frac{\partial\,\Theta_k(\{x_P\})}{\partial x_\nu} \right)^2 (\Delta\,x_\nu)^2 \ . \tag{B.4.4}$$

An analogous expression can be derived for the risk augmentation index Ψ_k.

This approximation for small errors contains only the linear term of a multidimensional Taylor series (Korn and Korn, 1968) but should suffice for most cases. If a given risk component involves larger uncertainties, an approximation which is appropriate for large errors, may be required. Examples are the use of lognormal distributions for highly uncertain parameters, the use of higher terms in the Taylor series (Seiler, 1987b), or the use of numerical methods (Cox and Baybutt, 1981; Helton, 1961; Iman and Helton, 1988).

B.4.3 Criteria for Indifferent Ranking

Two aspects of risk comparison are important in the process of ranking relative risks or risk reduction factors and using that result in risk management: the *preference* of one alternative over the other, and, conversely, an *indifference to ranking* two alternatives. Membership in these two

sets is determined by a comparison between the difference in consequence reduction indices of two risks and their uncertainties, i.e., by some kind of a statistical test.

The problem of indifference when comparing risks with overlapping probability distributions is different from that encountered in the usual statistical tests. It has been discussed in detail by Goodmann (1986), who derived two criteria for an insignificant difference between two risks by assuming that only the two first moments of the probability distributions, i.e., the means and the standard deviations, are known.

The first is based on a measure of the divergence D (X_1, X_2) between two distributions f_1 (x) and f_2 (x) derived in information theory

$$D(X_1, X_2) = \int [f_1(x) - f_2(x)] \ln\left(\frac{f_1(x)}{f_2(x)}\right) dx \ . \qquad \text{(B.4.5)}$$

The divergence is positive semi-definite, the null value being obtained only for identical distributions. As long as the divergence is smaller than a limiting value D_o,

$$D(X_1, X_2) \leq D_o \ , \qquad \text{(B.4.6)}$$

the distributions have an insignificant difference.

The second criterion is of a more statistical nature. At a preset confidence level V_0, the confidence intervals with the confidence limits $x^{(i)}_{hi}$ and $x^{(i)}_{lo}$,

$$\int_{x^{(i)}_{lo}}^{x^{(i)}_{hi}} f_i(x)\, dx = V_0 \ . \qquad \text{(B.4.7)}$$

are determined for i = 1,2. The confidence levels V_{ij} for distribution i within the confidence limits of the distribution j are then determined by,

$$\int_{x^{(j)}_{lo}}^{x^{(j)}_{hi}} f_i(x)\, dx = V_{ij} \ . \qquad \text{(B.4.8)}$$

From these cross-function confidence levels, the test quantities ε_{ij} are determined as the relative changes from the confidence level V_0,

$$\varepsilon_{ij} \equiv \frac{|V_{ij} - V_0|}{V_0} \quad . \tag{B.4.9}$$

These relative increments ε_{ij} in the confidence levels must be smaller than the limiting relative increment ε_0, resulting in the two conditions

$$\varepsilon_{ij} \leq \varepsilon_0 \ . \tag{B.4.10}$$

Criteria (B.4.6) and (B.4.10) for an insignificant difference between two probability distributions can be combined to sort a set of probability distributions into indifference classes. The limiting values for the two criteria are given in Goodmann's paper for normal and lognormal distributions.

Clearly, Goodmann's method can also be used to establish the indifference between two or more consequence reduction or augmentation indices. As long as the nature of their probability distributions can be estimated with a reasonable degree of confidence, Goodmann's criteria should yield useful results.

Values for the risk reduction indices and their standard errors can be used with Goodmann's criteria for normally or lognormally distributed quantities to establish preference or indifference to ranking between the K indices. It should be noted in this context, that in establishing indifference among three or more quantities, transitivity does not necessarily hold. Therefore, indifference to ranking has to be established for all possible pairs of a set of alternatives. These comparisons then identify the indifference classes I_b.

B.4.4 Distributions of the Consequence Reduction Indices

The errors of the risk reduction indices can be estimated using traditional methods. If it is assumed that the n_j remaining factors in numerator and denominator of the normalized risk of Equation (B.2.9) are all lognormally distributed, then the multi-attribute utility function (B.3.12) is normally distributed and the standard error can be estimated directly. According to Equation (B.3.19), the consequence reduction indices are then lognormally distributed.

Remaining factors with normal or mixed distributions in Equation (B.2.9) can give rise to problems. In that case Mellin transforms can be used (Springer, 1979) or numerical methods such as Monte Carlo calculations. However, such complex methods may not be needed. As long as the total number I of contributions to the J components of the total risk is relatively large, say 10 or so, and a sizeable fraction of these I terms contributes substantially to the total, the central limit theorem of probability theory states that the multi-attribute utility index is approximately

normally distributed (Korn and Korn, 1968). The consequence reduction indices are then lognormally distributed, and for narrow distributions, an approximate normal distribution can be used. In that case, the tables for lognormal or normal distributions in Goodmann's paper can be used to determine the limiting criteria (Goodman, 1986).

B.5 PRACTICAL APPLICATIONS

B.5.1 Utility Index as Weighted Arithmetic Mean

Practical applications of the utility function defined by Equation (B.3.10) to problems involving risk among the attributes already exist (Keeney and Raiffa, 1976). A similar approach has been suggested for the selection of routes for the transport of hazardous materials (Seiler, 1988). Although the marginal utilities in Equation (B.3.10) do not allow for the *LDMU*, the conditions for which linearity is a useful concept are met quite often, typically in a choice among pre-selected alternatives, where those with sizeable differences in important risk components are no longer present.

The evaluation of sites for the high-level radioactive waste repository, leading to a reduction of the number of sites from five to three (Keeney, 1987; Merkhofer and Keeney, 1987), is a typical example in which the less appropriate sites have already been eliminated. In this example, considerations other than risk were included also. However, the final decision by the Department of Energy dropped a number of attributes such as cost and made the decision based mostly on risk components. In these evaluations, no consideration was given to the uncertainty of the utility indices, and indices with rather small differences were ranked as different, although there is a suspicion that some of them might be indifferent to ranking.

A widely used method of multiple criterion decision making that is in many ways similar to the linear combinations of utility functions is the Analytical Hierarchy Process of Saaty (Saaty, 1980; Saaty and Vargas, 1982; Zahedi, 1986). It can be viewed as incorporating most aspects of the utility function and its weight into the weighting of the hierarchy. Formally this can be viewed as setting the marginal functions in an additive value function to unity at every level (Kamenetzky, 1982). The hierarchy process is ordinal and does not allow for the incorporation of distribution functions for the parameters, which would result in a standard error for the total weight.

B.5.2 Logarithmic Utility Functions

The utility functions most likely to meet the needs of risk comparisons are class $\Re_m$ functions. Among the functions of this class, the weighted logarithmic average of Equation (B.3.17) seems to be the easiest to use. Risk comparisons often involve components that are dramatically different due to determined attempts at risk reduction. Efforts to reduce some components of the total risk, however, almost always result in increasing some other components, often by a

considerable factor. The logarithmic dependence of Equation (B.3.17) covers these ranges quite easily. It is for these reasons that in the first practical application of the approach presented here, this function will be used in a comparison of the total risks of engineered alternatives for the treatment of transuranic wastes to be emplaced in the WIPP.

Apart from the logarithmic single-attribute utility functions, the two major differences between the approaches discussed in the last section and the one discussed here are the calculation of dimensionless relative risks or risk reduction factors, and the use of error estimates for the utility indices. The dimensionless approach avoids the necessity to estimate the value of social costs and losses in terms of dollars or some other unit, and allows a direct valuation in terms of an increase or decrease of a consequence reduction factor. The use of uncertainties allows the application of the concept of indifference to ranking, resulting in groups of indistinguishable consequence reduction indices.

B.6 DISCUSSION

Some of the tools of multi-attribute utility theory have been used to construct a framework for the comparison of multicomponent risks. Contrary to its application in economics or in public policy decisions, however, the aim is not to predict an optimal course of action for public policy or the investment behavior of an individual or a corporate entity. The intent is rather to provide a transparent method for ranking multicomponent risks, using a somewhat arbitrary but intuitively appealing rationale.

No attempt is made to arrive at a single, 'correct' solution for all segments of society. On the contrary, the ranking obtained here is clearly not unique but depends on the numerical values assigned to the weights for each risk component. This method can thus be used by anyone with a different system of societal values to derive his or her own ranking of the same risks, based on the same set of values for the marginal utility functions in Equation (B.3.13). This approach is in effect an attempt to put the comparison of risks on a rational basis without ignoring different sets of subjective, personal, or institutional valuations.

On the other hand, this method allows a direct evaluation of the influence of different value judgements on the ranking process. In many cases, the information that widely different valuations that do or do not have a drastic impact on the ranking process may be an important datum to come out of the risk comparison.

In this context, it should be noted that the method introduced here is a quite general procedure which is applicable for the comparison of many multi-component quantities. Of course, the use of class $\Re_m$ and $\Re_s$ functions must be justified for each particular case; otherwise, other classes can be defined which have the appropriate properties for the utility functions of the particular problem at hand.

Another important aspect of the method proposed here is the use of the standard errors of the consequence reduction indices to determine the significance of a difference between two total risks and, thus, to determine a possible indifference to ranking. This is a neglected aspect of comparisons which can be addressed here because of the normalization to relative risks and risk reduction factors proposed, and because both first-order and higher-order approximations are available for the calculations of error propagation.

It should be noted that these error estimates only address the random but not the systematic errors in the risk calculations. Due to their nature, the treatment of systematic errors is difficult, if it is possible at all (Seiler, 1990a). However, in the normalization process, systematic errors may cancel entirely or at least in part. Combined with the use of class $\Re_m$ multi-attribute utility functions, in particular that of Equation (B.3.17), this approach thus allows to make a routine estimate for the standard errors of the utility indices which are needed in this process.

The use of the weighted geometric mean in Equation (B.3.18) as the multi-attribute utility function of choice is, of course, arbitrary and is defensible mainly as one of the simplest choices among class $\Re_s$ and class $\Re_m$ functions. It is important in this context, to remember that the intent of the method presented here is not to make valid predictions of economic or social behavior but to provide a framework for the comparison of risks according to different valuations.

Comparisons of total risks are usually made in order to support the making of technical or public policy decisions. For that use of the comparison of the risks of alternatives, the main points are:

1. A ranking of risks is merely a decision tool; it should not and cannot replace the decision maker.

2. A ranking of risks is only rarely the sole basis for a decision; many other criteria enter into that process.

3. The existence of an insignificant difference between some total risks allows focusing on the question which of the other attributes exert the largest influence on the decision.

The ranking of several risks into a number of groups of insignificantly different utility indices can support many types of decisions. Important among them are decisions between technological options in all phases of the process of realizing a complex project. As pointed out above, an important facet of these decisions is the fact that risk is just one of the factors that influence the outcome and is by no means the most important one. In most applications where risk is introduced as one of the final decisive factors, risk assessment is not used to best advantage. A frequent use of risk comparisons in every decision phase of a project will make more appropriate use of the process (Seiler, 1990b).

In this context it is important to remember that two decision makers are involved in such a process: one at the level of the risk comparison and one at the level of the subsequent technical or policy decision. The concerns of both have to be injected into the weighting, taking into account the contribution of each consequence component. This interaction between the two decision makers is an essential step in the integration of the risk comparison into the next higher decision process.

ATTACHMENT C

UNCERTAINTIES AND AGGREGATION OF RISK COMPONENTS

C.1 PROPAGATION OF ERRORS

C.1.1 Gaussian Approximation

C.1.1.1 General Considerations

The uncertainties of parameters and variables in a function result in an uncertainty in the function value. This is called propagation of errors of the input values through the function. Analytical expressions for the propagation of errors through algebraic expressions are normally based on a number of assumptions such as the requirements that all stochastic variables contributing to the result are normally distributed, that all partial derivatives of second or higher order are very small, and that the relative errors of the stochastic variables are small. The absence of correlations between the stochastic variables makes the formulae much more manageable; however, if correlations do occur, they are assumed to be limited to correlations between only two variables.

The existence of an analytical expression for the propagation of errors, although often cumbersome algebraically, brings several advantages to the error analysis. The most important is that the algebraic properties of the expression can be studied independent of the size of the contributing standard errors. Another is that the contribution of each variable to the total uncertainty of the result can easily be isolated, making sensitivity studies relatively simple.

In numerical evaluations of differential equations and other mathematical procedures, it is obviously impossible to obtain an algebraic expression for error propagation, but numerical methods are available to obtain the necessary information (Cox and Baybutt, 1981; Iman and Helton, 1988). Often, these results can then be inserted into the algebraic expression for the rest of the calculation, thus restoring the advantages of the analytical solution.

Even so, it is generally recognized that it is more difficult and often more time consuming to determine the standard error of a stochastic variable than to actually measure it. Similarly, error propagation is a more difficult and complex procedure than the direct evaluation of the numerical value of a risk or some other quantity.

C.1.1.2 Gaussian Approximation for Normally Distributed Quantities

To study the propagation of standard errors through an arbitrary algebraic function F, it is assumed that all needed derivatives of that function with regard to its variables and parameters x_i exist. Thus,

$$F = \Phi(\boldsymbol{x}) = \Phi(x_1, \ldots x_n) , \tag{C.1.1}$$

where all parameters are normally distributed stochastic variables and parameters have a mean x_i and standard errors Δx_i. The variables can be arranged as a vector $\mathbf{x} = (x_1, \ldots x_n)$. As long as the relative errors are small, i.e., $\Delta x_i << x_i$, a multidimensional Taylor series (Korn and Korn, 1969), can be used to approximate the function $\Phi(\mathbf{x})$ and terminated after the first term. For independent variables x_i, statistical theory requires an incoherent superposition of the amplitudes (Bevington, 1969; Brandt, 1976; Seiler 1987b) in the expansion

$$(\Delta F)^2 = \sum_{i=1}^{n} \left\{ \left(\frac{\partial \Phi(\boldsymbol{x})}{\partial x_i} \right) \Delta x_i \right\}^2 . \tag{C.1.2}$$

Here the partial derivatives (in braces) are to be evaluated at the point $\mathbf{x}$. This approximation is only valid for small errors. For larger errors, additional terms in the Taylor series expansion are needed. When using higher order terms, care must be taken to ensure convergence of the series. In algebraic forms, such as $F = x^{-1}$, the pole near $x = 0$ may lead to semiconvergence or outright divergence (Seiler, 1987b).

Expression (C.1.2) assumes that the quantities x_i and their errors Δx_i are uncorrelated. If the errors Δx_i are correlated, more terms are needed in a coherent superposition of amplitudes (Bevington, 1969; Brandt, 1976; Seiler 1987b). The Gaussian approximation is then

$$(\Delta F)^2 = \sum_{i=1}^{n} \sum_{j=1}^{n} \left(\frac{\partial \Phi(\boldsymbol{x})}{\partial x_i} \right) \left(\frac{\partial \Phi(\boldsymbol{x})}{\partial x_j} \right) \sigma_{ij}^2 , \tag{C.1.3}$$

where the quantities σ_{ij}^2 are the elements of the covariance matrix between the variables x_i and x_j, and the partial derivatives are again evaluated at the point $\mathbf{x}$. The diagonal elements are the standard errors

$$\sigma_{ii}^2 = (\Delta x_i)^2 , \tag{C.1.4}$$

and the off-diagonal elements σ_{ij}^2 are the covariances which measure the degree of correlation between the corresponding variables.

C.1.1.3 Gaussian Approximation for Lognormally Distributed Quantities

A lognormal distribution for a variable x is a distribution with the property that the distribution for $\log_a x$ is a normal distribution. It is most often used in evaluating the standard error of highly uncertain stochastic variables. The lognormal distribution in linear space is characterized by a mean X and the geometrical standard deviation $\sigma_g(X)$. It is related to the upper and lower 68% limits X_+ and X_- by the relations

$$X_+ = X\,\sigma_g(X)\ , \tag{C.1.5}$$

and

$$X_- = \frac{X}{\sigma_g(X)}\ . \tag{C.1.6}$$

Similarly, the upper and lower 95% limits X_{hi} and X_{lo} are given by

$$X_{hi} = X\ \ \sigma_g^2(X)\ , \tag{C.1.7}$$

and

$$X_{lo} = \frac{X}{\sigma_g^2(X)}\ , \tag{C.1.8}$$

Error propagation using Equations (C.1.2) or (C.1.3) can be studied by a transformation of the function in Equation (C.1.1) into logarithmic space. Obviously, this is most profitable for products or products of powers, which reduce to linear combinations in logarithmic space.

C.1.1.4 Approximations for Quantities With Different Distributions

If an expression contains stochastic variables with different distributions, an algebraic approach is sometimes possible using Mellin transformations (Springer, 1979). Normally, however, numerical methods such as Monte Carlo calculations have to be used. A number of numerical procedures and spreadsheet codes have recently become available. They will not be used here, however.

C.1.2 Basic Expressions Often Used in This Report

C.1.2.1 Error Propagation for Normally Distributed Quantities

From the general equation, special expressions for error propagation in simple algebraic forms can be generated. For more complex forms, some of the more advanced tools of calculus may be needed to generate the error propagation formulae. Here, only the simplest forms will be discussed explicitly. The assumption is made that the stochastic variables x_i are uncorrelated.

C.1.2.1.1 Sums and Differences

For direct sums and differences of stochastic variables, written in a general way as

$$F_1 = \Phi_1(\boldsymbol{x}) = \sum_{i=1}^{n} (\pm 1)\, x_i \,, \tag{C.1.9}$$

where $\mathbf{x}$ is the parameter vector; $\mathbf{x} = (x_1, \ldots x_n)$ and the factor (± 1) indicates a free choice of sign for every term. The general equation then yields the expression

$$(\Delta F_1)^2 = \sum_{i=1}^{n} (\Delta x_i)^2 \,. \tag{C.1.10}$$

Thus, for sums or differences, the square of the standard error is equal to the sum of the squares of the standard errors for all terms.

Often, linear combinations of stochastic variables are encountered, such as

$$F_2 = \Phi_2(\boldsymbol{x}) = \sum_{i=1}^{n} (\pm 1)\, a_i x_i \,. \tag{C.1.11}$$

If the parameters a_i are non-stochastic parameters, the standard error is

$$(\Delta F_2)^2 = \sum_{i=1}^{n} (a_i \Delta x_i)^2 \,. \tag{C.1.12}$$

It should be noted that the expressions above are exact, because there are no second order terms in the Taylor series.

If the parameters a_i are stochastic quantities with standard errors Δa_i, however, the standard error is given by

$$(\Delta F_2)^2 = \sum_{i=1}^{n} \left\{ (a_i \Delta x_i)^2 + (x_i \Delta a_i)^2 \right\} , \qquad \text{(C.1.13)}$$

which is no longer exact, but an approximation of the Gaussian type.

C.1.2.1.2 Products and Ratios

For a function Φ which is a product of the form

$$F_3 = \Phi_3(\boldsymbol{x}) = \prod_{i=1}^{n} x_i^{\pm 1} , \qquad \text{(C.1.14)}$$

where the exponent (± 1) indicates a free choice of exponent for every factor, the application of Equation (C.1.2) yields the expression

$$\left(\frac{\Delta F_3}{F_3} \right)^2 = \sum_{i=1}^{n} \left(\frac{\Delta x_i}{x_i} \right)^2 . \qquad \text{(C.1.15)}$$

Thus for products and ratios, the square of the relative standard error is the sum of the squares of the relative standard errors of all factors. More generally, for a product of powers

$$F_4 = \Phi_4(\boldsymbol{x}) = \prod_{i=1}^{n} x_i^{p_i} , \qquad \text{(C.1.16)}$$

the basic equation for the Gaussian approximation yields

$$\left(\frac{\Delta F_4}{F_4} \right)^2 = \sum_{i=1}^{n} p_i^2 \left(\frac{\Delta x_i}{x_i} \right)^2 . \qquad \text{(C.1.17)}$$

All these equations are no longer exact but are approximations. Also, for ratios, care must be exercised with large errors due to the proximity of the pole for $1/x_i^n$ at $x = 0$. For larger errors, it is advisable to express standard errors as geometric standard deviations for lognormal distributions.

C.1.2.2 Error Propagation for Lognormally Distributed Quantities

The most appropriate application of lognormal distribution involves products of powers of variables, such as

$$F_5 = \Phi_5(\boldsymbol{x}) = \prod_{i=1}^{n} x_i^{p_i} . \tag{C.1.18}$$

In logarithmic space to base a, the function value F_5 is then a normally distributed quantity because the variables $\log_a x_i$ are normally distributed and the factors p_i are non-stochastic,

$$\log_a F_5 = \sum_{i=1}^{n} p_i \log_a x_i . \tag{C.1.19}$$

By defining the transformed variables as

$$\begin{aligned} y_5 &= \log_a F_5 , \\ y_i &= \log_a x_i , \\ S_i &= \log_a \left[\sigma_g (x_i) \right] , \end{aligned} \tag{C.1.20}$$

the function y_5 is a linear combination of normally distributed stochastic variables

$$y_5 = \sum_{i=1}^{n} p_i y_i . \tag{C.1.21}$$

This expression has the same structure as Equation (C.1.11) and the exact expression for error propagation is given by

$$(\Delta y_5)^2 = \sum_{i=1}^{n} (p_i S_i)^2 . \tag{C.1.22}$$

Transformation back into linear space yields

$$\sigma_g(F_5) = a^{\Delta y_5} , \tag{C.1.23}$$

because of the relationship

$$\Delta y_5 = \log_a \left[\sigma_g(F_5)\right] . \tag{C.1.24}$$

C.1.3 Useful Approximations for Error Propagation

C.1.3.1 Function of Normally Distributed Variables

Writing the expression for error propagation in the Gaussian approximation in the general form,

$$(\Delta f)^2 = (a\Delta\alpha)^2 + (b\Delta\beta)^2 + \ldots , \tag{C.1.25}$$

can be useful to study the influence of standard errors of different relative magnitudes. Assume that the terms on the right-hand are rearranged with ($a\Delta\alpha$) being the largest term. The expression can then be rearranged again to give

$$\begin{aligned} \Delta f &= (a\Delta\alpha)\left\{1 + \left(\frac{b\Delta\beta}{a\Delta\alpha}\right)^2 + \ldots\right\}^{1/2} \\ &= (a\Delta\alpha)\sqrt{1 + (B)^2 + \ldots} \\ &= (a\Delta\alpha)\,[1 + C] \ . \end{aligned} \tag{C.1.26}$$

This last equation can be used to obtain a limit for the ratio B which yields a negligible contribution C to the total error. Thus, setting B = 1/3 shows that a term ($b\,\Delta\beta$), which is three times smaller than ($a\Delta\alpha$), contributes only five percent to the final error. This is due to the "sums of squares" structure of Equation (C.1.2) (Seiler, 1987b). For other ratios of B, the contributions are given in Table C.1-1 and shown in Figure C.1-1. According to the judgment of the investigator, the contribution of the smaller error can be neglected for a critical ratio B, say below B = 1/3. In this context, it should be borne in mind that, as second moments of a distribution, standard errors are always more uncertain than the means themselves (first moments). It is also important to note that, according to Equation (C.1.2), the ratio B is not always the ratio of the standard errors but the ratio of the products of the derivatives with the standard errors.

TABLE C.1-1

RELATIVE CONTRIBUTION OF THE SMALLER STANDARD ERROR IN THE GAUSSIAN APPROXIMATION

RATIO B	CONTRIBUTION C
1/1	41%
1/2	12%
1/3	5%
1/4	3%
1/5	2%
1/6	1%

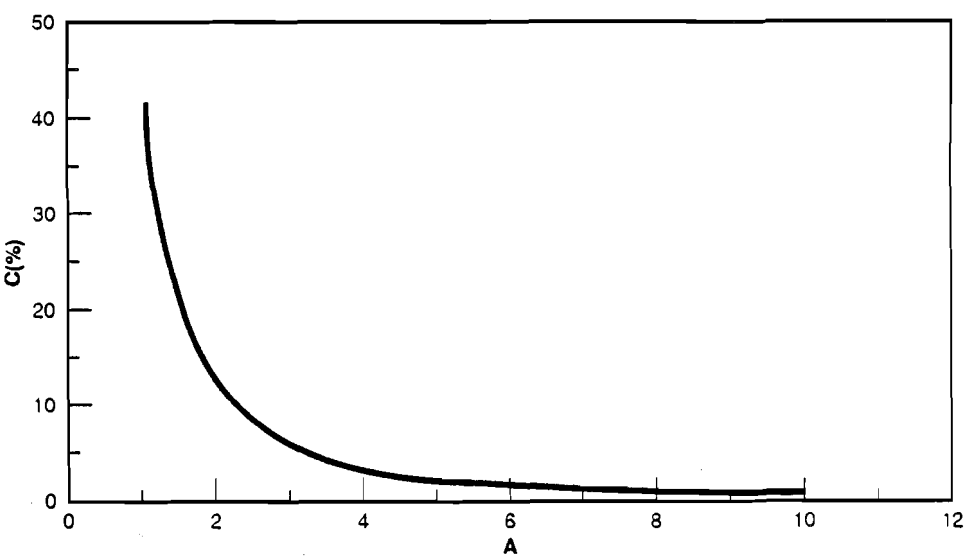

FIGURE C.1-1 Relative Contribution of the Smaller Standard Error in the Gaussian Approximation

C.1.3.2 Lognormal Distributions

Sums or differences of lognormally distributed variables are no longer lognormally distributed variables. An approximation useful for error propagation is to fit two different normal distributions to the upper and the lower parts of the lognormal distributions of each term and treat them separately. Thus, the lognormally distributed terms a_i in the sums or differences with geometric standard deviations $\sigma_g(a_i)$ have upper and lower 68% limits of

$$a_{i,hi} = a_i \, \sigma_g(a_i), \tag{C.1.27}$$

and

$$a_{i,lo} = \frac{a_i}{\sigma_g(a_i)} \, . \tag{C.1.28}$$

A normal distribution with the same limits has standard errors of

$$\Delta a_{i,hi} = \left[\sigma_g(a_i) - 1\right] \tag{C.1.29}$$

for the upper limit, and

$$\Delta a_{i,lo} = \left[1 - \frac{1}{\sigma_g(a_i)}\right] \tag{C.1.30}$$

for the lower limit. These are assigned for every term in sums or differences. The sum of a number of these terms

$$S = \sum_{i=1}^{n} (\pm 1)\, a_i \, , \tag{C.1.31}$$

where the factor (± 1) indicates an arbitrary sign for each term, has an upper limit of

$$S_{hi} = S + \sqrt{\sum_{i=1}^{n} a_i^2 \left[\sigma_g(a_i) - 1\right]^2} \, , \tag{C.1.32}$$

and a lower limit of

$$S_{lo} = S - \sqrt{\sum_{i=1}^{n} a_i^2 \left[1 - \frac{1}{\sigma_g}(a_i) \right]^2} \; . \tag{C.1.33}$$

The distribution of S is approximately normal for a large number of terms (10 to 20) according to the Central Limit Theorem (Korn and Korn, 1968). For only a few terms, the largest term is likely to determine the resulting distribution. These may thus be approximately lognormal. Similarly, if a large number of terms is dominated by one contribution, the distribution of the sum resembles a lognormal distribution.

In a lognormal approximation to the resulting distribution of the sum S, the geometric standard deviation is approximated by

$$\sigma_g(S) = \left(\frac{S_{hi}}{S_{lo}} \right)^{1/2} \; . \tag{C.1.34}$$

The mean is best derived by the first or second expression on the right-hand side

$$S \cong S_{lo} \; \sigma_g(S) = \frac{S_{hi}}{\sigma_g(S)} \; . \tag{C.1.35}$$

In a normal approximation to the resulting distribution of the sum S, the mean is given by

$$S \cong \frac{1}{2} \; (S_{hi} + S_{lo}) \; , \tag{C.1.36}$$

and the standard error by

$$\Delta S \cong \frac{1}{2} \; (S_{hi} - S_{lo}) \; . \tag{C.1.37}$$

A choice between the two approximations is best made on the basis of the actual values a_i and $\sigma_g(a_i)$ involved.

C.2 AGGREGATION OF RISK COMPONENTS

C.2.1 Weighted Averages for the Aggregation Risk Reduction Factors

C.2.1.1 Aggregations Using Weighted Arithmetic Averages

The arithmetic mean is most often used for the process of weighted averaging

$$X = \sum_{i=1}^{n} w_i x_i \ , \tag{C.2.1}$$

where the average is performed over the set $\{x_n\}$ of quantities using the normalized weights w_i

$$\sum_{i=1}^{n} w_i = 1 \ . \tag{C.2.2}$$

For the aggregations encountered in this risk assessment, baseline risk components are used to generate the weights according to

$$w_i = \frac{R_{i\delta\kappa\lambda}}{\sum_{\tau=\{n_i\}} R_{\tau\delta\kappa\lambda}} \ , \tag{C.2.3}$$

where δ = 'o' or 'p' for occupational and public, respectively, and $\{n_i\}$ is the set of baseline risks being aggregated. The aggregated risk reduction factor then becomes

$$\Gamma_{j\kappa\lambda} = \sum_{\xi=\{n_i\}} w_\xi \ \rho_{\xi\delta\kappa\lambda} \ . \tag{C.2.4}$$

Note that factors common to all component risks $R_{j\delta\kappa\lambda}$ cancel in Equation (C.2.3). This is a characteristic common to this kind of weighting processes which are independent of multiplication by an arbitrary factor. Consequently, in radiation risks, for instance, it is sufficient to know the doses in order to perform a weighted average; there is no need to actually convert doses to risks. Usually weights thus have errors that are rather small compared to those of the risks. In many cases they can be neglected in comparison to those of the risk reduction factors being aggregated. Then, the error of the aggregated risk reduction factor $\Gamma_{j\kappa\lambda}$ is given by the equation

$$\left(\Delta \Gamma_{j\kappa\lambda}\right)^2 = \sum_{\xi=\{n_j\}} \left(w_\xi \, \Delta \rho_{\xi\delta\kappa\lambda}\right)^2 . \qquad \text{(C.2.5)}$$

As long as the weight can be regarded as a non-stochastic quantity, this expression is exact and holds even for large relative errors of $\rho_{\xi\delta\kappa\lambda}$.

In cases where the standard error of the aggregation weight cannot be neglected, it is useful to note that the denominator of Equation (C.2.3), after all common factors in the numerator and denominator have been eliminated, contains one term with the same factors as the numerator. An evaluation of the standard error using the general Gaussian error propagation formula will, therefore, lead to a partial compensation of the component errors. The resulting standard error of the weighting factor Δw_ξ can then be used to calculate the error of the aggregated risk reduction factor according to Equation (C.1.13),

$$\left(\Delta \Gamma_{j\kappa\lambda}\right)^2 = \sum_{\xi=\{n_j\}} \left\{\left(w_\xi \, \Delta \rho_{\xi\delta\kappa\lambda}\right)^2 + \left(\rho_{\xi\delta\kappa\lambda} \, \Delta w_\xi\right)^2\right\}. \qquad \text{(C.2.6)}$$

This expression is not exact and holds for small relative errors of both factors only. If the relative errors of $\rho_{\xi\delta\kappa\lambda}$ and w_ξ are not small, an exact expression can be derived (Seiler, 1987b).

C.2.1.2 Aggregations Using Weighted Geometric Average

The geometric average is an arithmetic average taken in logarithmic space. Using the definition $y_i = \log_a x_i$, the weighted arithmetic mean is given by

$$Y = \sum_{i=1}^{n} w_i \, y_i . \qquad \text{(C.2.7)}$$

A transformation back into linear space leads to the expression

$$X = \prod_{i=1}^{n} x_i^{w_i} . \qquad \text{(C.2.8)}$$

The usual exponent of 1/n is not in evidence here, because the sum of the weights is normalized to unity according to Equation (C.2.2). Here again, the weights are independent of common factors. This form of weighted averaging is best employed when the values x_i are distributed over a wide range, for instance over many orders of magnitude. In such cases, the arithmetic mean has a tendency to a bias in favor of the highest value.

In the aggregation of risk reduction factors with weights given by Equation (C.2.3), the aggregated risk reduction factor is given by

$$\Gamma_{j\kappa\lambda} = \prod_{\xi=\{n_i\}} \left(\rho_{\xi\delta\kappa\lambda}\right)^{w_\xi} . \tag{C.2.9}$$

For weights with small standard errors that can be neglected compared to those of the risk reduction factors, the standard error of the aggregated risk reduction factor is

$$\left(\frac{\Delta\Gamma_{j\kappa\lambda}}{\Gamma_{j\kappa\lambda}}\right)^2 = \sum_{\xi=\{n_i\}} \left(w_\xi \frac{\Delta\rho_{\xi\delta\kappa\lambda}}{\rho_{\xi\delta\kappa\lambda}}\right)^2 . \tag{C.2.10}$$

For non-negligible but still small relative errors of the weights w_ξ, the error propagation formula yields the expression

$$\left(\frac{\Delta\Gamma_{j\kappa\lambda}}{\Gamma_{j\kappa\lambda}}\right)^2 = \sum_{\xi=\{n_i\}} \left\{\left(w_\xi \frac{\Delta\rho_{\xi\delta\kappa\lambda}}{\rho_{\xi\delta\kappa\lambda}}\right)^2 + \left(\ln \rho_{\xi\delta\kappa\lambda}\, \Delta w_\xi\right)^2\right\} . \tag{C.2.11}$$

For larger relative errors, a sufficient approximation can be obtained (Seiler, 1987b).

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ATTACHMENT D

AUXILIARY MODELS FOR HANDLING AND TREATMENT OF THE WASTES

D.1 HANDLING AND TREATMENT OF WASTE

D.1.1 Baseline Case

The baseline case assumes no treatment of the waste, either prior to or after its arrival at the WIPP facility. The waste is handled for assay and certification and transported through two separate areas: the Waste Handling Building (WHB) at ground level, and the Underground Storage Area. The baseline scenario for untreated waste comprises all routine operations and accident events incorporated in the FSEIS (DOE, 1990a). However, only average drums are considered in this report, even though the FSEIS addresses special drums, such as those with an activity of 1000 PE-Ci (37 TBq).

The handling operation that is best suited to serve as the baseline operation is the initial handling of the wastes in the Waste Handling Building, in particular the assay and certification of the waste. It is already included in the baseline, but can serve well as a standard for risk increases. Unfortunately, it is a small operation and baseline risks for many aspects are not available in the FSEIS.

D.1.1.1 Operations in the WHB

The waste is brought into the WHB in TRUPACT-II containers through entry air locks, inspected and unloaded. In the Receiving and Inspection Area, the drums are then assayed and certified, and loaded onto facility pallets. The facility pallet is subsequently transferred to the hoist air lock by forklift. The total crew working inside the WHB consists of 12 people (DOE, 1989a): 9 waste handlers, 2 health physicians, and 1 Quality Assurance person. Two forklift operations are required inside the WHB: one to transport the TRUPACT-II, one to transfer the palletized load to the hoist air lock.

All operations in the WHB are assumed to be independent of waste treatment. Drums heavier due to treatment are assumed to be handled by proportionally heavier equipment at equal risk.

D.1.1.2 Operations Underground

Once inside the hoist air lock, the facility pallet is transferred to the underground station by waste hoist. Operations below ground consist of transferring the waste to the diesel transporter and transportation to the final waste storage area. In the final waste storage area, the drums are removed from the transporter by forklift, and emplaced in the selected location. Underground

operations total two forklift and one diesel transporter operation. Total crew underground consist of four people (DOE, 1989a): two waste handlers, one health physicist, and one Quality Assurance person. In this assessment, it is assumed that neither personnel, forklift, nor transporter operations are influenced by waste treatment. For heavier drums, heavier forklifts are used.

D.1.2 Treatment Facility

In the limited scope of this study, the Treatment Facility (TF) is assumed to consist of a number of identical modules, each consisting of up to six different operational areas, according to the Treatment Option selected. According to the location option, these modules are grouped into one, three, five or seven facilities of appropriate capacity. In Level II treatments, that is, in Treatment Options 1 and 2, only two operations are needed: shredding and cementing. Additional operations are needed for the two Level III treatments. In Treatment Option 3, incineration and cementing of the ashes are added, resulting in a total of four operations: sorting, shredding, incinerating, and cementing. In the most complex Treatment Option cementing is dropped and two more operations are added: smelting and vitrifying.

The seven groups of modules are planned to operate independently from one another, regardless of their location and distribution. This model of the treatment plant, therefore, does not account for any economies of size, thereby introducing a slight bias in favor of decentralized treatment facilities. This bias is mostly monetary, but the risk is influenced mainly by potential economies of manpower, which are not addressed here.

One additional assumption is made concerning the average drum. Sludges are usually in drums by themselves. Thus the appropriate fraction of sludge-filled drums is assumed (Vetter, 1990), with the rest filled by a mix of combustibles, metals, and glasses in the proper proportions.

D.1.3 Risk Components Considered Here

The risk components associated with specific operations of handling and transportation of the waste during the waste treatment, that are discussed in the FSEIS, are included in that part of the evaluation of the total risk. The risk components considered here stem from radiation and hazardous chemicals encountered during the actual treatment process, and from general work accidents found in similar industrial operations.

As general occupational accidents and injuries, not directly related to effects of radiation and toxic chemicals, are important in comparing different levels of treatment with different manpower requirements, two risk components are added to those considered in the FSEIS: occupational accident fatalities and occupational accident and exposure injuries. These components will change with increasing manpower needed for the more complex treatments of the waste.

D.1.3.1 Radiation and Chemical Risk of the Actual Treatment Process

Despite containment of the wastes and shielding against nuclear radiation, workers are exposed to low levels of radiation and hazardous chemicals originating from the waste. Normal operational releases would encompass radiation exposures at a certain distance from the waste, and inhalation of volatile organic chemicals present in the waste. Accident releases would encompass larger radiation doses due to loss of containment for radioisotopes, and larger exposure to chemicals in the waste.

D.1.3.2 General Work Accidents in Similar Industry

The majority of the operations conducted with the waste, before, during and after the treatment process, involve handling and transportation. Within those operations, there are risks associated with manual and mechanized work, which are unrelated to the nature or composition of the waste. Since the largest number of man-hours during handling are spent on forklift operations, data for injuries and fatalities, and corresponding risk components associated with forklift operations, have been obtained. Other accidents, associated with malfunctions and breakdowns of a mechanical nature, are not treated separately, due to the assumption that such an accident would not result in direct injuries or fatalities.

Within the risk components mentioned, both public and occupational risks arising from normal operations (such as routine handling and maintenance) and accident events are taken into account.

D.1.4 Risk Components Not Considered Here

For the actual waste treatment, the risks due to operational accidents are not considered in this report, due to the large effort required for the evaluation of the overall risk associated with numerous potential accidents. This decision will tend to slightly bias the evaluation in favor of treatment. This bias, however, should not be too noticeable because the risk of process accidents is usually not very large, compared to other components.

In the evaluation of internal exposures to radioisotopes, only inhalation risks are considered. Direct ingestion risks are neglected, due to the much smaller probability of occupational ingestion of CH TRU waste. Even in the case of externally contaminated drums, where waste could come into direct contact with the handlers, protective clothing and initial radiological surveys would minimize the risk of waste ingestion. For such cases, the major component of the risk would arise from possible inhalation of suspended waste.

Also not taken into consideration, but referenced in the FSEIS and FSAR documents (DOE, 1989a), are risks arising from inhalation of diesel exhaust from the waste transporters, and from the operation and maintenance of electric-powered forklifts. It is assumed that transporters and

forklifts are electric powered and they have the appropriate power to handle the drums of the waste treatment chosen. Thus no changes are foreseen with waste treatment.

D.2 MODELS FOR TREATMENT OPERATIONS

D.2.1 General Considerations

The basic assumption in modeling treatment operations in the TF is that the same health and safety standards based on the As Low As Reasonably Achievable (ALARA) concept are observed here as in the WHB. Thus, any perceived risk will be minimized within the limits generally observed in nuclear research and industry, based on DOE and NRC guidelines.

Shielding against penetrating radiation will be based on routine time-motion studies for normal operation and maintenance. Monitors for direct radiation, continuous air monitors for high- and low-LET radiation are in operation for an early indication of potential health and safety problems. The risk of exposure to volatile organic compounds is the only one involving chemical agents that is evaluated here. Exposure to metals and halogenated and other toxic organics by ingestion or skin contamination is not treated in the FSEIS and will, therefore, not be considered.

Maintenance operations are assumed to be driven by ALARA considerations. Their frequency is aimed at keeping the contamination remaining after self-decontamination of the device within bounds. The frequency is thus assumed to be a design parameter without uncertainty. The operation and maintenance of a treatment plant results in a considerable amount of secondary wastes from operation and, above all, from maintenance (decontamination). From health physics operations in existing facilities, this secondary waste is assumed to amount to 2 to 3 percent of the wastes treated. A simple linear model that accounts for secondary wastes increases the number of drums received annually from 40,000 to 41,000, that is, feeds the secondary wastes back into the incoming waste stream. Note, however, that the baseline load remains at 40,000 drums annually.

Effluent controls are needed to bring the facility into compliance with all applicable regulations. Ventilation air is passed through HEPA filters, liquids are processed, and filters and process waste added to the secondary waste.

D.2.2 Treatment Operations

D.2.2.1 Assay and Certify Operations

This operation is the same for all drums that arrive at the TF and the WHB. No credit is taken for the easier operation at the WHB for treated waste with more reliable certification. However, increased forklift operations and general industrial risks are accounted for.

Routine and maintenance operations are defined to serve as baseline for other operations. Intra-site transport by forklift, crane, and conveyor belts is designed to minimize human exposures.

Assay and certify operations are assumed to need 0.6 man-hours per drum with a standard error of about 10 percent. For maintenance of the area, 96 ± 12 man-hours are estimated for every maintenance operation. Maintenance is estimated to be necessary after processing 1000 drums.

D.2.2.2 Sorting Operations

Sorting is needed only for Level III treatments, that is, for Treatment Options 3 and 4. It involves breaking the liners and all wrappings, allowing all gases in the headspace to vent into the containment. Sorting is either done in bubble suits inside the containment or by operators working with gloveboxes and conveyor belts.

Routine sorting is assumed to require 1.5 ± 0.15 man-hours per drum; for the maintenance of the sorter containment 96 ± 12 man-hours are estimated. It is again estimated that maintenance is needed after 1,000 drums.

D.2.2.3 Shredding Operations

The shredding operation will be doubly contained with an air lock system to transfer waste containers to the shredder. Waste containers will be additional waste, assumed to be passed through the shredder. Shredding is a high dust producing operation that will require an efficient air cleaning system, monitoring, routine cleanup, and maintenance.

Risks from exposure to penetrating radiation during routine operations are reduced by shielding. During maintenance operations, these risks are reduced by self-decontamination of devices and structures, short allowable exposure times, and frequency of decontamination. Internal exposures can occur through inhalation of suspended wastes outside the containment, and through leakage through the airlock from inside the containment.

Chemical risks are assumed to be smaller here as most volatile organics are assumed to have escaped by the time the waste reaches the shredder. The rest, partly encapsulated by solids, is assumed to be released in this operation.

Shredding operations are estimated to require 1.0 ± 0.06 man-hours per drum. For maintenance 240 ± 18 man-hours are estimated. Maintenance is assumed to be needed after every 1,000 drums.

D.2.2.4 Cementing Operations

In Treatment Option 1, only shredded metals/glasses and combustibles are cemented and in Treatment Option 2, sludges are also cemented. In Treatment Option 3, all three waste forms are cemented, but combustibles only after incineration.

The cementation process consists of metering waste and cement into drums through a system of feed hoppers. Waste and cement can be mixed within the feed system prior to loading into drums or by in-drum mixing. A protective sleeve is used to channel material from the feed system into an open drum. This sleeve prevents waste from spilling outside the drum and acts as a barrier between workers and contaminated waste. Decontamination and maintenance of cementation equipment will be more extensive if mixing occurs within the feed system, as opposed to in-drum mixing.

The cementing operation is assumed to require 0.60 ± 0.06 man-hours per drum. Maintenance is assumed to occur every 1,000 drums and need 48 ± 6 man-hours.

D.2.2.5 Incineration Operations

After sorting and shredding, combustibles are incinerated and the ashes sent to cementing in Treatment Option 3 and to vitrification in Treatment Option 4.

Waste enters the incineration process through an air-lock. From the air-lock, waste is fed into the combustion chamber by gravity or a mechanical ram. Ash resulting from the combustion process is collected in traps at the bottom of the incinerator. Ash from the incineration process becomes feed material for solidification or vitrification.

An incineration off-gas system removes any particulates, acid gases, and radionuclides which pass through the incinerator. The off-gas system is a source of secondary wastes in the form of scrubbing solutions and filters. Filters can be recycled through the incinerator, while scrubbing solutions require solidification. The incinerator and off-gas systems require routine maintenance in the form of ash removal, filter replacement, scrubbing solution treatment, etc. Decontamination activities for the incineration process tend to be labor-intensive due to the complexity and number of components comprising the system.

Normal operations are estimated to require 0.30 ± 0.03 man-hours per drum; maintenance 48 ± 6 man-hours. Maintenance is postulated to be needed every 1,000 drums.

D.2.2.6 Metal Melting Operations

After sorting and shredding, metals and glasses are melted together with frit. This operation potentially involves multiple melting operations such as an induction melter (for steels) and a

melting pot (for lead) to accommodate ranges of melting temperatures for various WIPP metallic wastes. Operators will manually feed metallic wastes into the melter. Once melting is complete (radionuclides are assumed to partition preferentially into the slag), slag is removed from the melter. The contaminated slag will not form a nonporous glass waste form and must be re-melted with glass frit to form the final homogeneous glass waste form. Decontaminated liquid metal will be poured into molds, allowed to cool, and is then packaged for disposal as Low Level Waste (LLW). Maintenance and decontamination activities will be labor intensive for metal melting processes as refractory material or the melters themselves will require periodic replacement.

Decontamination by melting is a time-consuming operation; 8.0 ± 0.6 man-hours are estimated per drum treated. Maintenance is also needed often, once after every ten melting operations; maintenance itself is estimated to require less effort, 24 ± 3 man-hours for every operation.

D.2.2.7 Vitrification Operations

Vitrification of sludges and incinerator ash can be accomplished through the use of a joule-heated melter, microwave melter, or a plasma furnace. In these processes waste and glass frit are metered into the heating chamber and melted to form a glass liquid. Feed waste does not require handling by operators for these processes. Microwave heating is an in-drum vitrification process whereas joule-heated melters and plasma furnaces utilize heating chambers. Once a drum has been filled with vitrified ash/sludge, it is placed in storage where the contents are allowed to cool. These vitrification processes have off-gas systems similar to those described in Section D.2.2.5. Microwave melting does not involve extensive maintenance and decontamination because the microwave cavity is the only component in the system subjected to contamination (aside from the off-gas system). The joule-heated melter and the plasma furnace will require labor intensive maintenance and decontamination.

Vitrification operations are estimated to require 2.0 ± 0.2 man-hours; maintenance 48 ± 6 man-hours, needed once every 200 drums.

D.2.2.8 Assembly of Manpower Needs for Operation and Maintenance

Time and manpower needs estimated for each operation and given in the preceding section are assembled in Table D.2-1. The size of the crews and the time required are estimated using operational concerns from the manpower figures. As the uncertainty of the manpower was estimated, it can be assigned exclusively to the factor time.

The maintenance schedule and the man-years of manpower needed are listed in Table D.2-2. The throughput is 41,000 drums per year, independent of treatment. For safety reasons, the smelters are assumed to be small 1-drum melting pots or furnaces, leading to a large number of maintenance operations, requiring the largest amount of manpower.

TABLE D.2-1

TIME AND MANPOWER NEEDS FOR ROUTINE OPERATIONS AND MAINTENANCE *

		ROUTINE OPERATIONS (PER DRUM HANDLED)		ROUTINE MAINTENANCE (PER OPERATION)	
v	OPERATION	MANPOWER [a]	TIME (hrs) [b]	MANPOWER [c]	TIME (hrs) [d]
0	Assay	3	0.20 ± 0.02	6	16 ± 2
1	Sort	3	0.50 ± 0.05	6	16 ± 2
2	Shred	2	0.50 ± 0.03	6	40 ± 3
3	Cement	3	0.20 ± 0.02	3	16 ± 2
4	Incinerate	3	0.10 ± 0.01	3	16 ± 2
5	Smelt	2	4.0 ± 0.3	3	8 ± 1
6	Vitrify	2	1.0 ± 0.1	3	16 ± 2

[a] This is quantity $N_{o6}^{(v)}$ used later.

[b] This is quantity $t_{57}^{(v)}$ used later.

[c] This is quantity $N_{o7}^{(v)}$ used later.

[d] This is quantity $t_{58}^{(v)}$ used later.

* Standard errors given here are based on an estimate of the relative error of the man-hours needed. Accordingly, the error is attached here to the time estimate only.

TABLE D.2-2

MAINTENANCE SCHEDULE *

v	OPERATION	FREQUENCY (PER DRUM)	NUMBER OF ANNUAL MAINTENANCE OPERATIONS ** TREATMENT OPTION 0	1	2	3	4	TIME SPENT ANNUALLY ON MAINTENANCE (MAN-YEARS) *** TREATMENT OPTION 0	1	2	3	4
0	Assay	1/1000	0 [a]	41	41	41	41	0 [a]	1.9 ± 0.2	1.9 ± 0.2	1.9 ± 0.2	1.9 ± 0.2
1	Sort	1/1000	0	0	0	33	33	0	0	0	1.5 ± 0.2	1.5 ± 0.2
2	Shred	1/1000	0	33	33	33	33	0	3.8 ± 0.3	3.8 ± 0.3	3.8 ± 0.3	3.8 ± 0.3
3	Cement	1/1000	0	33	41	30 [b]	0	0	0.8 ± 0.1	1.0 ± 0.1	0.7 ± 0.09 [b]	0
4	Incinerate	1/1000	0	0	0	16	16	0	0	0	0.4 ± 0.05	0.4 ± 0.05
5	Smelt	1/10	0	0	0	0	1640	0	0	0	0	18.9 ± 2.4
6	Vitrify	1/200	0	0	0	0	68 [c]	0	0	0	0	1.6 ± 0.2 [c]

* Assuming an annual throughput of 41,000 drums.
** This is the function $\Phi_{58\,\kappa}^{(v)}$ used later.
*** This is the function $\Phi_{60\,\kappa}^{(v)}$ used later.
a Maintenance is already included in baseline case.
b Cement ash from combustibles.
c Vitrify ash from combustibles.

D.3 MODIFICATION OF BASELINE DATA

D.3.1 Increase in Manpower Needs Due to Treatment

The manpower reduction factor $F_{m\kappa}$ is defined by

$$F_{m\kappa} = \frac{N_{01}^{(0)}}{N_{01}^{(\kappa)}}, \tag{D.3.1}$$

where $N_{01}^{(\kappa)}$ are the number of workers needed for treatment κ and $N_{01}^{(0)}$ are the 12 workers in the WHB for the baseline case. The manpower reduction factor $F_{m\kappa}$ for treatment κ is smaller than one, denoting an increase in manpower needs. On the basis of the assumption that the treatment facility is subject to the same health and safety restrictions as the Waste Handling Building, the evaluation can regard it as an extension of the WHB with additional people. The main exposures occur during handling and equipment maintenance.

The numerical values are estimated from the total number of man-years for operations and maintenance needed to treat 41,000 drums annually. Data from Tables D.2-1 and D.2-2 are used to generate the data listed in Table D.3-1. Since these values are annual needs in man-years, the totals for each treatment option can be translated directly into crew sizes, from which the ratios $F_{m\kappa}$ can be calculated.

Included in the uncertainties are systematic errors due to the differences between potential treatment facilities. This is done because $F_{m\kappa}$ is a basic quantity for the treatment that appears everywhere. These systematic uncertainties are estimated to be equal in size to the random standard errors. The latter are, therefore, multiplied by a factor of $\sqrt{2}$, according to the relation (Seiler, 1990b)

$$S_{tot}^2 = S_r^2 + S_s^2, \tag{D.3.2}$$

where S_{tot} is the total standard error, S_r the random standard error, and S_s the systematic random error. The final values and standard errors are also listed later in Table D.3-3.

D.3.2 Reduction Factor for Public Exposure

For the public risk due to emissions from the TF, the change in the risk equation appears in the function $\Phi_{idd}^{(\kappa)}$ and thus the number $N_{p1}^{(\kappa)}$ of exposed persons incorporated in that function. In a simplified model for the four locations discussed here, it will be assumed that the functions $\Phi_{idd}^{(\kappa)}$ are independent of treatment κ and depend only on the number and locations of the $N_{p1}^{(\kappa)}$

TABLE D.3-1

MANPOWER NEEDS FOR TREATMENT, MANPOWER REDUCTION FACTORS $F_{m\kappa}$ *

OPERATION	INDEX	ANNUAL WORKTIME FOR OPERATION AND MAINTENANCE (MAN-YEARS)				
		TREATMENT OPTION κ				
	v	0	1	2	3	4
Assay [a]	0	11.5	13.7 ± 1.2	13.7 ± 1.2	13.7 ± 1.2	13.7 ± 1.2
Sort	1	--	--	--	25.2 ± 2.4	25.2 ± 2.4
Shred	2	--	19.6 ± 1.0	19.6 ± 1.0	19.6 ± 1.0	19.6 ± 1.0
Cement	3	--	10.2 ± 1.0	12.8 ± 1.2	9.4 ± 0.9	--
Incinerate	4	--	--	--	2.7 ± 0.2	2.7 ± 0.2
Smelt	5	--	--	--	--	82 ± 5.3
Vitrify	6	--	--	--	--	14.7 ± 1.3
Total		11.5	43.5 ± 1.8	46.1 ± 1.9	70.6 ± 2.9	157.9 ± 6.1
Workforce [b], $N_{o1}^{(\kappa)}$		12 [c]	44 ± 3	46 ± 3	71 ± 4	158 ± 9
$F_{m\kappa}$		--	0.276 ± 0.016	0.260 ± 0.015	0.170 ± 0.010	0.0760 ± 0.0042

* Errors calculated using data from Table D.2-1.

[a] 40,000 drums processed, other entries 41,000 drums processed due to secondary wastes. No maintenance included in baseline, assumed to be included in FSEIS data.

[b] Errors increased by $\sqrt{2}$ due to the assumption of a systematic error of equal magnitude.

[c] Manpower in WHB, baseline: 12 above ground.

persons exposed. This relation is incorporated in the public exposure reduction factor

$$F_{e\kappa} \equiv \frac{\Phi_{idd}^{(0)}}{\Phi_{idd}^{(\kappa)}} = \frac{N_{p1}^{(0)}}{N_{p1}^{(\kappa)}} \ . \qquad \text{(D.3.3)}$$

Due to the increase in exposed persons, the factor $F_{e\kappa}$ is expected to be less than one. For location at the WIPP, the treatment facility will affect the same area and population. The dispersion function and the number and locations of the exposed members of the public are the same, but there are now two sources, assuming that the same health and safety concerns dictate the allowable releases for WHB and TF. For locations elsewhere, the same additional population risk is assumed to be allowed, leading to the same factor $F_{e\kappa}$, regardless of location. The exposure from handling operations is then estimated to be about twice that due to the WHB emissions alone with a random error of about 15 percent, i.e.,

$$F_{e\kappa} = 0.50 \pm 0.08 \ . \qquad \text{(D.3.4)}$$

The error is obtained from the observation that for similar operations a spread of ± 30% = 60% for a 95 percent confidence level is incompatible with the health and safety goals. This results in the standard random error of 15 percent used above.

The systematic error of the public exposure reduction factors is obviously much larger and will have to encompass the treatment/location dependence of the public exposure ratio. Rather than estimating it, it would be more profitable to amend the model to show the appropriate dependence on treatment and location.

D.3.3 Volume Reduction Factor Due to Treatment

In waste treatment, the large void spaces in the drums are reduced and in some treatment options the actual volume of the wastes is reduced also. The numerical values for the volume reduction factors, averaged over the different waste forms, are given by the weighted arithmetic average

$$F_{v\kappa} = \frac{\sum_{w=1}^{W} n_w f_{w\kappa}}{\sum_{w=1}^{W} n_w} \equiv \sum_{w=1}^{W} \eta_w f_{w\kappa} \ , \qquad \text{(D.3.5)}$$

where the definition of the weights is given by

$$\eta_w = \frac{n_w}{\sum_{\tau=1}^{W} n_\tau}, \tag{D.3.6}$$

with the normalization property

$$\sum_{\tau=1}^{W} \eta_w = 1 . \tag{D.3.7}$$

Here W is the number of different waste forms, n_w is the number of drums of waste form w produced per year, $f_{w\kappa}$ is the volume reduction factor for waste form w due to treatment κ. The relative weights, η_w, defined in the second part of Equation (D.3.5) add to unity. The values are $\eta_s = 0.2$ for sludges, and $\eta_c = \eta_m = 0.4$ for combustibles and metals, respectively (Vetter, 1990). The volume reduction factors for different waste forms are estimated on the basis of the methods reviewed for the main report. Their errors, $\Delta f_{w\kappa}$, are assigned on the basis of prudent upper and lower limits for the processes. For the total volume reduction factor $F_{v\kappa}$ the errors are

$$(\Delta F_{v\kappa})^2 = \sum_{w=1}^{W} (\eta_w \, \Delta f_{w\kappa})^2, \tag{D.3.8}$$

assuming that the standard errors of the η_w relative weights are at least a factor of three smaller than those of the individual volume reduction factors $f_{w\kappa}$.

For Treatment Option 1, which leaves sludges unaltered while combustibles and metals are shredded and cemented, the volume reduction factors are estimated to be $f_{s1} = 1 \pm 0$ for sludges, $f_{c1} = 1.2 \pm 0.2$ for combustibles, and $f_{m1} = 1.2 \pm 0.2$ for metals. The combination according to Equation (3.15) results in an average volume reduction factor of

$$F_{v1} = 1.2 \pm 0.1 . \tag{D.3.9}$$

For Treatment Option 2, which cements sludges while again shredding and cementing combustibles and metals, the volume reduction for cementing sludges is again assumed to be 1 by filling the headspace with cement. All waste forms thus have the same volume reduction factors as those of Treatment Option 1,

$$F_{v2} = 1.2 \pm 0.1 . \tag{D.3.10}$$

Treatment Option 3 cements sludges, incinerates combustibles, and cements the ashes while it shreds and cements the metals. The volume reduction is $f_{s3} = 1.0 \pm 0$ for sludges, and the overall volume reduction for the incineration of combustibles is estimated to be $f_{c3} = 3 \pm 1$. As this procedure is based on the PREPP process (Tait, 1983), which also shreds the drums, the

volume reduction factor for metals is somewhat higher than that for Treatment Options 1 and 2, and is estimated to be $f_{m3} = 2 \pm 0.5$. The composite volume reduction factor is

$$F_{v3} = 2.2 \pm 0.5 \ . \qquad \text{(D.3.11)}$$

For Treatment Option 4, which vitrifies sludges, incinerates combustibles and vitrifies their ashes, while it melts and decontaminates metals, the volume reduction factors are larger. Sludge vitrification by microwave heating is well known (Petersen et al., 1987), yielding a reduction factor of $f_{s4} = 9 \pm 1$. For metals and combustibles, the maximum fissile radionuclide content of a drum by the WAC provides the limits. If concentration is assumed to result in an average of 80 percent of the limits, the volume reduction factor is $f_{m4} = f_{c4} = 9.4 \pm 1.5$. The composite volume reduction is then

$$F_{v4} = 9.3 \pm 0.9 \ . \qquad \text{(D.3.12)}$$

These data are assembled in Table D.3-3.

D.3.4 Transportation Reduction Factor

The volume reduction factor $F_{v\kappa}$ leads to a reduction in the number of barrels handled annually by the factor $F_{v\kappa}$. The maximum transport weight is set at 80,000 pounds (36.2 metric tons), however, so that the full reduction cannot be realized. Therefore, a correction factor needs to be applied.

The number of treated drums per TRUPACT-II can be calculated using the effective payload for the 14 drums of 7,265 pounds (3.3 metric tons) and data on the weights of treated drum (see main report). The weighted average over the three waste forms is

$$n_{d\kappa} = \frac{W_0}{\sum_{\chi=1}^{3} f_w \, W_{w\kappa}} , \qquad \text{(D.3.13)}$$

where

$n_{d\kappa}$ = Number of drums per TRUPACT-II,
W_0 = Load limit of TRUPACT-II (kg),
f_w = Fraction of waste form w, and
W_w = Mass of treated drum of waste form W (kg).

These numbers are given in Table D.3-2 based on the data in the main report. The load factor $f_{t\kappa}$, that is the fraction of the 14 drums that can on average be loaded into the TRUPACT-II is

$$f_{t\kappa} = \frac{n_{d0}}{n_{d\kappa}}, \tag{D.3.14}$$

where

n_{d0} = Number of untreated drums per TRUPACT-II,
$n_{d\kappa}$ = Number of treated drums per TRUPACT-II.

The transportation reduction factor, $F_{t\kappa}$, is then calculated from the number, $n_t^{(\kappa)}$, of transports needed annually after treatment κ

$$n_t^{(\kappa)} = \frac{n_d^{(0)}}{F_{v\kappa}\, f_{t\kappa}}, \tag{D.3.15}$$

where

$n_d^{(0)}$ = Number of untreated drums handled annually,
$F_{v\kappa}$ = Volume reduction factor for treatment κ,
$f_{t\kappa}$ = TRUPACT-II load factor for treatment κ,

and with $F_{v0} = f_{t0} = 1$. The factor $F_{t\kappa}$ is then

$$F_{t\kappa} = \frac{n_t^{(0)}}{n_t^{(\kappa)}} = F_{v\kappa}\, f_{t\kappa}\,. \tag{D.3.16}$$

The relative errors of the load factor $f_{t\kappa}$, derived from the survey of a large number of drums are estimated to be a lot smaller than those of the volume reduction factor. The error of the transport reduction factor is, therefore, given by

$$\frac{\Delta F_{t\kappa}}{F_{t\kappa}} = \frac{\Delta F_{v\kappa}}{F_{v\kappa}}\,. \tag{D.3.17}$$

The numerical values for most of these factors are listed in Table D.3-2 and also in Table D.3-3.

D.3.5 Ratio of Forklift Operations

The reduction factors $F_{f\kappa}$ for forklift operations in different treatments are clearly smaller than one, and are based on an operations model that adds one forklift operation to the first treatment device

TABLE D.3-2

TRANSPORTATION REDUCTION FACTORS

TREATMENT OPTION	$n_{d\kappa}$ [a]	$f_{t\kappa}$ [b]	$F_{v\kappa}$ [c]	$F_{t\kappa}$ [d]
1	8.15	0.582	1.2 ± 0.1	0.70 ± 0.06
2	7.58	0.542	1.2 ± 0.1	0.65 ± 0.05
3	7.38	0.527	2.2 ± 0.5	1.2 ± 0.3
4	6.42	0.458	9.3 ± 0.9	4.3 ± 0.4

[a] Number of treated drums that can be transported in TRUPACT-II.
[b] Load factor of TRUPACT-II.
[c] Average volume reduction factor.
[d] Transportation reduction factor.

TABLE D.3-3

SUMMARY TABLE FOR THE REDUCTION FACTORS $F_{v\kappa}$, $F_{m\kappa}$, $F_{e\kappa}$, $F_{f\kappa}$, AND $F_{t\kappa}$

TREATMENT OPTION	$F_{v\kappa}$ [a]	$F_{m\kappa}$ [b]	$F_{e\kappa}$ [c]	$F_{f\kappa}$ [d]	$F_{t\kappa}$ [e]
1	1.2 ± 0.1	0.276 ± 0.016	0.50 ± 0.08	0.517 ± 0.010	0.70 ± 0.06
2	1.2 ± 0.1	0.260 ± 0.015	0.50 ± 0.08	0.517 ± 0.010	0.65 ± 0.05
3	2.2 ± 0.5	0.170 ± 0.010	0.50 ± 0.08	0.566 ± 0.010	1.2 ± 0.3
4	9.3 ± 0.9	0.0760 ± 0.0042	0.50 ± 0.08	0.644 ± 0.002	4.3 ± 0.4

[a] Average volume reduction factor, from Equations D.3.9 through D.3.12.
[b] Manpower reduction factor, from Table D.3-1.
[c] Public exposure reduction factor, from Equation D.3.4.
[d] Reduction factor for forklift operations, from Equations D.3.18 and D.3.19.
[e] Transportation reduction factor, from Table D.3-2.

and $1/F_{v\kappa}$ forklift operations back to the storage area to the operations in the WHB. By normalizing the latter to one, the reduction factors are

$$F_{f\kappa} = \frac{1}{\sum_{w=1}^{3} \eta_w \left\{ 1 + \frac{1}{2} \left(1 + \frac{1}{f_{w\kappa}} \right) \right\}} , \tag{D.3.18}$$

where $f_{w\kappa}$ is the volume reduction factor of treatment κ for waste form w, and η_w is the abundance of waste form w. The standard error of this expression is

$$\left(\frac{\Delta F_{f\kappa}}{F_{f\kappa}} \right)^2 = \sum_{w=1}^{3} \left(\frac{\eta_w F_{f\kappa}}{2 f_{w\kappa}} \right)^2 \left(\frac{\Delta f_{w\kappa}}{f_{w\kappa}} \right)^2 . \tag{D.3.19}$$

The parameters $f_{w\kappa}$ and η_w were given in the discussions of equations (D.3.9) to (D.3.12), resulting in the values listed in Table D.3-3. Note the implicit assumption that the number of forklift operations is independent of the final drum weight. For heavier drums, heavier forklifts are assumed to be used.

D.3.6 Particle Generation in Accidents

D.3.6.1 Particle Spectrum Generated

In the baseline waste, some fine particles are already present, while others may be generated by impacts. In treated wastes, the numbers of free particles are drastically reduced, and it is assumed here that particles are produced by impact. Empirical models have been made on the basis of experimental data for the spectrum of particles produced by impact (Bennet et al., 1980). Using data on the shattering of rocks, the model for the cumulative distribution function for particles with diameter y yields

$$\Phi_{d\kappa}(y) = c_{m\kappa} \dot{\varepsilon}_{\kappa}^{4/3} y^2 , \tag{D.3.20}$$

where $c_{m\kappa}$ is a constant of the material impacted, ε_κ is the strain or relative deformation in elastic deformation process, so that $\dot{\varepsilon}_\kappa$ is the rate at which strain builds before going beyond the fracture limit. Static strain rates are typically $10^{-4}\ s^{-1}$, while rock blasting achieves 1 to $10^3\ s^{-1}$. With the impacted drum cushioning the impact on its contents, a strain rate of $(0.10 \pm 0.03)\ s^{-1}$ is assumed for creating the perforation. A comparison of dynamic tensile fracture strengths (Grady and Hallenbach, 1979) leads to an assignment of $c_{m\kappa} = 100$ for cemented and $c_{m\kappa} = 200$ for vitrified wastes. This is based on a comparison of the dynamic tensile strengths of oil shale, for which a $c_{m\kappa}$ value is available and of several types of stone, such as sandstone, limestone and basalt. Although dynamic tensile fracture strength does not correlate well with the constant $c_{m\kappa}$ for all materials, it can provide scaling between not too different materials (Grady, 1991). Treated waste

forms, cemented or vitrified are inhomogeneous conglomerates, in many ways similar to oil shales, sandstones, limestones, and basalts. The uncertainties in these assignments for the constant $c_{m\kappa}$ are obtained from a comparison with the value 157 for oil shale. Assuming a range of 50 around the value of 100, and of 40 around the value of 200, yields error estimates of ± 12 and ± 14, respectively. The standard error of the cumulative distribution function for the constant $c_{m\kappa}$ is then

$$\left(\frac{\Delta \Phi_{d\kappa}(y)}{\Phi_{d\kappa}(y)}\right)^2 = \left(\frac{4}{3}\,\frac{\Delta \dot{\varepsilon}_\kappa}{\dot{\varepsilon}_\kappa}\right)^2 + \left(\frac{\Delta c_{m\kappa}}{c_{m\kappa}}\right)^2 . \qquad \text{(D.3.21)}$$

This model will be used to estimate the particle size distributions for all events resulting in the creation of particles from solidified wastes.

D.3.6.2 Suspendability Ratio $S_{1\kappa}$

In Section E.1.1.2 in Equation (E.1.20), the ratio of particles suspended in inhalable form for treated and untreated wastes is needed. These reduction factors for particle suspendability $S_{1\kappa}$ are estimated here on the basis of some assumptions and the model discussed in the last section. The baseline risk assumes that a perforated drum releases one percent of the waste mass, that a fraction of 10^{-3} is suspended from the floor due to the activities in the Waste Handling Building, and that 5 percent of the total activity is in inhalable form. The scenario implies that this release escapes detection by the monitoring devices. However, one percent of the mass of the average drum (DOE, 1990a) is 1.5 kg, which can hardly escape visual detection and will, therefore, be treated as an incident and not lead to a routine exposure. In order to cancel the influence of this assumption, it will be assumed here that, in the baseline case, a certain undetermined fraction of the inhalable waste which amounts to 5 percent of the activity is spilled from the perforation.

In the incident in Section E.1.1.2 involving a perforated drum with treated waste, the impact that creates the perforation also creates a certain fraction of the mass pulverized in particles of sizes below 10 μm. For diameters above 10 μm, the fraction of particles that is inhaled drops toward zero. It is now assumed that, independent of treatment, the same fraction $f_{22}^{(\kappa)}$ of these particles is spilled on the floor and the same fraction $f_{24}^{(\kappa)}$ resuspended. Thus, these factors cancel in the ratio $S_{1\kappa}$ and the only remaining factor is the fraction $f_{23}^{(\kappa)}$ of particles with diameter below 10 μm,

$$S_{1\kappa} = \frac{\phi_2^{(0)}}{\phi_2^{(\kappa)}} = \frac{f_{23}^{(0)}}{\Phi_{d\kappa}(10^{-5})} , \qquad \text{(D.3.22)}$$

with the inhalable fraction of the total activity of a drum $f_{23}^{(0)} = 0.05$ (DOE 1989b, DOE 1990a).

The inhalable fractions of the total mass generated by the impact are $(4.6 \pm 1.9) \cdot 10^{-10}$ for cemented and $(9.3 \pm 3.7) \cdot 10^{-10}$ for vitrified wastes and the corresponding reduction factors $S_{1\kappa}$ are listed in Table D.3-4.

D.3.6.3 Suspendability Ratio $S_{2\kappa}$

The suspendability reduction factors $S_{2\kappa}$ are needed in the evaluation of a C2 accident in which a drum falls off a forklift (see Section E.3.1.1). They are defined by

$$S_{2\kappa} \equiv \frac{f_{61}^{(0)}\, f_{62}^{(0)}\, f_{63}^{(0)}}{f_{61}^{(\kappa)}\, f_{62}^{(\kappa)}\, f_{63}^{(\kappa)}} \quad , \tag{D.3.23}$$

where the factors in numerator and denominator are the fraction $f_{61}^{(\kappa)}$ of the material spilling out of the drum, the fraction $f_{62}^{(\kappa)}$ of that material suspended in air, and the fraction $f_{63}^{(\kappa)}$ of the activity that is in inhalable form, i.e., with diameters less than 10 µm. The baseline scenario assumes 25 percent of the drum's content is spilled, containing a fraction of 5% inhalable activity, and that a fraction of 10^{-3} is suspended due to the dynamics of the accident. In the case of treated wastes, the particles are created in the accident by impact. The elastic deformation rate to be used in the impact model in the fall from the forklift is estimated at 0.05 s^{-1} with an error of 20 percent.

The cemented waste is fragmented, with a cumulative distribution function for the mass fraction with diameters below 10 µm of $\Phi_{d\kappa}(10^{-5}) = (1.8 \pm 0.5)\ 10^{-10}$ and for the vitrified waste the fraction is $\Phi_{d\kappa}(10^{-5}) = (3.7 \pm 1.0)\ 10^{-10}$, according to Equations (D.3.20) and (D.3.21). Assuming the fraction of $f_{62}^{(\kappa)}$ of suspended particles below 10 µm to be the same, and the fractions of waste spilled at 25 percent and 100 percent (upper limit), respectively, yields

$$S_{2\kappa} = \frac{f_{61}^{(0)}\, f_{63}^{(0)}}{f_{61}^{(\kappa)}\, f_{63}^{(\kappa)}} = \frac{f_{61}^{(0)}\, f_{63}^{(0)}}{f_{61}^{(\kappa)}\, \Phi_{d\kappa}(10^{-5})} \ . \tag{D.3.24}$$

Again, these reduction factors, given in Table D.3-4, are quite large, signalling an effective suppression of the corresponding component of the risk.

TABLE D.3-4

REDUCTION FACTORS $S_{1\kappa}$ AND $S_{2\kappa}$ IN SUSPENDED FRACTION OF INHALABLE WASTES IN AN N2 AND A C2 SCENARIO

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
S_{11}	$(0.9 \pm 0.3) \cdot 10^8$	Only 80% of drums affected
S_{12}	$(1.1 \pm 0.4) \cdot 10^8$	
S_{13}	$(1.1 \pm 0.4) \cdot 10^8$	
S_{14}	$(0.5 \pm 0.2) \cdot 10^8$	
S_{21}	$(5.4 \pm 1.4) \cdot 10^7$	Only 80% of drums affected
S_{22}	$(6.8 \pm 1.8) \cdot 10^7$	
S_{23}	$(6.8 \pm 1.8) \cdot 10^7$	$S_{2\kappa} = S_{4\kappa} = S_{6\kappa}$
S_{24}	$(3.4 \pm 0.9) \cdot 10^7$	

- The reduction factor $S_{1\kappa}$ for the fraction of waste suspended in inhalable form is defined in Equation (D.3.22).
- The reduction factor $S_{2\kappa}$ for the fraction of waste suspended in inhalable form is defined in Equation (D.3.24).

D.3.6.4 Suspendability Ratio $S_{3\kappa}$

The suspendability reduction factors $S_{3\kappa}$ are needed in the evaluation of the C3 scenario in Section E.3.1.2. The factors are defined by

$$S_{3\kappa} \equiv \frac{\phi_{31}^{(0)}}{\phi_{31}^{(\kappa)}}, \qquad \text{(D.3.25)}$$

where the factors $\phi_{31}^{(\kappa)}$ are the fractions of inhalable particles suspended in the accident.

Numerical estimates for the parameters $S_{3\kappa}$ are given in Table D.3-5 and are based on the same impact fragmentation as those in the two preceding sections. If the perforation is assumed to have been made by the tine of a forklift, two tines impacting on two drums will share the impact energy. The strain rate is thus estimated to be $(0.7 \pm 0.2)\ s^{-1}$, and equation (D.3.20) yields $(0.62 \pm 0.24) \cdot 10^{-8}$ for cemented waste and $(1.24 \pm 0.47) \cdot 10^{-8}$ for vitrified waste. The errors are calculated according to equation (D.3.21).

D.3.6.5 Suspendability Ratio $S_{10\kappa}$

The reduction factors $S_{10}^{(\kappa)}$ are needed in the evaluation of the C10 accidents (see Section E.3.1.6). They are defined there by

$$S_{10} \equiv \frac{f_{11}^{(0)}}{f_{11}^{(\kappa)}}, \qquad \text{(D.3.26)}$$

where the factors $f_{11}^{(\kappa)}$ are again the fractions of activity suspended in inhalable form.

These reduction factors are assumed to be ten times lower than the factors $S_{2\kappa}$ in the C2 and C4 scenarios. This assignment stems from the fact that the baseline inhalable suspended fraction is $f_{p0} = 1.25 \cdot 10^{-4}$, ten times higher than the fraction $\phi_6^{(0)}$ in the C2 scenario, yet for treated waste the aerosolization is assumed to be about the same. The fraction f_{p0} is derived from the 0.25 percent of the total activity which is aerosolized in the C10 scenario (DOE, 1990a) and the additional assumption that five percent of that activity is in inhalable form, that is, it has diameters below 10 µm. This is supported by the fact that no other drums are damaged, i.e., that it is a low-grade overpressure explosion that essentially does not much more than break the containment.

D.3.6.6 Suspendability Ratio $S_{33\kappa}$

The reduction factors $S_{33\kappa}$ are needed in the evaluation of the C10 scenario involving the self-ignition of pyrophoric material in a drum (see Section E.3.1.6). Therefore definition of the factor

TABLE D.3-5

SUSPENDABILITY REDUCTION FACTORS $S_{3\kappa}$, $S_{10\kappa}$, and $S_{33\kappa}$ AS A FUNCTION OF TREATMENT OPTION

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
S_{31}	$(6.4 \pm 2.5) \cdot 10^{6}$	Only 80% of drums treated
S_{32}	$(8.0 \pm 3.1) \cdot 10^{6}$	
S_{33}	$(8.0 \pm 3.1) \cdot 10^{6}$	
S_{34}	$(4.0 \pm 1.5) \cdot 10^{6}$	
S_{101}	$(5.4 \pm 1.4) \cdot 10^{8}$	Only 80% of drums treated
S_{102}	$(6.8 \pm 1.8) \cdot 10^{8}$	
S_{103}	$(6.8 \pm 1.8) \cdot 10^{8}$	
S_{104}	$(3.4 \pm 0.9) \cdot 10^{8}$	
S_{331}	$(4.0 \pm 1.6) \cdot 10^{6}$	Only 80% of drums treated
S_{332}	$(5.0 \pm 2.0) \cdot 10^{6}$	
S_{333}	$(5.0 \pm 2.0) \cdot 10^{6}$	
S_{334}	$(2.5 \pm 1.0) \cdot 10^{6}$	

- Reduction factor $S_{3\kappa}$ for fraction of waste suspended in inhalable form defined in Equation (D.3.25).
- Reduction factor $S_{10\kappa}$ for fraction of waste suspended in inhalable form defined in Equation (D.3.26).
- Reduction factor $S_{33\kappa}$ for fraction of waste suspended in inhalable form defined in Equation (D.3.27).

is again

$$S_{33\kappa} \equiv \frac{\phi_{33}^{(0)}}{\phi_{33}^{(\kappa)}} = \frac{f_{331}^{(0)} f_{332}^{(0)}}{f_{331}^{(\kappa)} f_{332}^{(\kappa)}} , \qquad \text{(D.3.27)}$$

that is the reduction in suspendability of waste in inhalable form. These values are estimated from the baseline value of $\phi_{33}^{(0)} = 2 \cdot 10^{-4}$ given in the FSEIS, Vol. II, Table D.3.29 (DOE, 1990a). If it is assumed that the accident modeled in the baseline case, essentially only mobilized radioactive fines already present in the waste and that $f_{332}^{(0)} = 0.05$ of the activity is present in sizes smaller than 10 μm, the suspended fraction is $f_{331}^{(0)} = 4 \cdot 10^{-3}$. As the mobilizing force of fire is the same in all cases, it is reasonable to assume that $f_{331}^{(\kappa)} = 4 \cdot 10^{-3}$ also. For cemented or vitrified waste, however, the small particles are no longer present and must be created by the impact.

Equation (D.3.20) can be used to determine the fraction of particles below 10 μm

$$f_{332}^{(\kappa)} = \Phi_{d\kappa}(10^{-5}) = c_{m\kappa}\, \dot{\varepsilon}_{\kappa}^{4/3}\, (10^{-10}) \quad . \qquad \text{(D.3.28)}$$

For truck accidents, higher loading rates are to be expected than from dropping or ramming drums, but here also, the overpack will soften the impact on the drum. The best estimate for $\dot{\varepsilon}_{\kappa}$ is $(1.0 \pm 0.3)\ s^{-1}$. This yields the values given in Table D.3-5.

D.3.7 Probability of a C10 Accident

A C10 accident involves the self-ignition of pyrophoric material in a drum, leading to the drum bursting open and releasing toxic materials (see Section E.3.1.6). The reduction factors $F_{p\kappa}$ for the probability of a C10 type event is defined by

$$F_{p\kappa} \equiv \frac{P_{10}^{(0)}}{P_{10}^{(\kappa)}} , \qquad \text{(D.3.29)}$$

where $P_{10}^{(0)}$ is the baseline probability for self-ignition and $P_{10}^{(\kappa)}$ is that probability after treatment. This reduction factor is estimated on the basis that the pyrophoric material is not removed from the waste except by smelting and decontamination in Treatment Option 4. Shredding increases the surface of the pyrophoric material on the one hand and cementing or vitrification reduces the oxygen available for combustion on the other. In the model used here, no credit is taken for removal of organics because they may not be needed for ignition. It is assumed that the pyrophoric material will ignite in the presence of oxygen. In the baseline case, the one event in $1.8 \cdot 10^{6}$ drum-years (DOE, 1990a) will be used to assign an annual probability of $6 \cdot 10^{-7}$ per drum. The reduction of the probability of ignition is assigned to the lack of oxygen to generate enough pressure to burst the drum. The reduction of connected void space is, therefore, assumed to be proportional to the reduction in the probability of a drum bursting open. Only in

the case of removing the pyrophoric substance by decontamination will an additional reduction of the probability by a factor of 100 ± 20 be assumed. The void space decreases from 147 L in the baseline case to three to five percent of the drum volume of 0.25 m^3, i.e., down to (10 ± 2 L). Numerical values are listed in Table D.3-6.

D.3.8 Emission of VOC Through Carbon Filter

Routine emissions of VOCs through the carbon filter of the drum are discussed in Section E.4.2.1. The reduction factors for the routine emissions of a single drum are defined by the ratio

$$F_{c\kappa j} \equiv \frac{q_{12j}^{(0)}}{q_{12j}^{(\kappa)}} \quad , \tag{D.3.30}$$

where $q_{12}^{(\kappa)}$ is the emission rate for chemical j. These ratios are estimated on the basis of the baseline emission rates and the rates after incineration of the wastes. The model used here assumes that shredding and cementing does not change the vapor pressure (saturation) in the void space, it just retards its attainment. The corresponding emission values $q_{12j}^{(\kappa)}$ for chemical j are, therefore, constant

$$q_{12j}^{(0)} = q_{12j}^{(1)} = q_{12j}^{(2)} \, , \tag{D.3.31}$$

and thus

$$F_{c1j} = F_{c2j} = 1 \pm \varepsilon \, , \tag{D.3.32}$$

where ε is a small fraction. Due to the model assumption above, ε is set to zero. It is small enough to warrant this assumption without loss of accuracy in the error calculation [see equation (C.1.26)]. Similarly, the fact of incineration to regulatory levels which requires 99.99 percent destruction effectiveness for organics (U.S. Environmental Protection Agency, 1989) or better leads to

$$q_{12j}^{(3)} = q_{12j}^{(4)} \, , \tag{D.3.33}$$

An approximation for Equation (D.3.20) can be obtained by assuming that the quantity of organics in the void connected spaces is at least sufficient to maintain saturation vapor pressure and by taking no credit for the safety margin that burning aims to achieve below regulatory limits. Thus

$$F_{c3j} = F_{c4j} = (1.0 \pm 0.3) \cdot 10^{4} \, , \tag{D.3.34}$$

None of these ratios, with a large error assigned due to the uncertainties in the assumptions above, depend on the compound, and the estimates for numerical values are listed in Table D.3-7.

TABLE D.3-6

VALUES FOR THE REDUCTION IN SELF-IGNITION RISK IN A C10 ACCIDENT AS A FUNCTION OF THE TREATMENT OPTION

QUANTITY*	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
F_{p1}	12 ± 2	Only 80 % of drums treated
F_{p2}	15 ± 3	100% of drums treated
F_{p3}	15 ± 3	100% of drums treated
F_{p4}	1500 ± 400	100% of drums treated

* The reduction factor for the probability of self-ignition $F_{p\kappa}$ is defined in Equation (D.3.29).

TABLE D.3-7

VALUES FOR THE REDUCTION FACTORS $F_{c\kappa j}$ FOR CHEMICAL EMISSIONS

CHEMICAL	QUANTITY *	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
All VOCs considered	F_{c1j}	1 ± 0	
	F_{c2j}	1 ± 0	
	F_{c3j}	$(1.0 \pm 0.3) \cdot 10^4$	
	F_{c4j}	$(1.0 \pm 0.3) \cdot 10^4$	

* Reduction factor for routine emissions of a drum (Eq. D.3.30).

D.3.9 Ratios of VOC Mass in Headspace

Venting the headspace of a drum in an accident leads to the emission of the gases accumulated there. The reduction factors $F_{g\kappa j}$ for the mass of gas j in the headspace are defined by

$$F_{g\kappa j} \equiv \frac{q_{16j}^{(0)}}{q_{16j}^{(\kappa)}} \quad , \tag{D.3.35}$$

where the quantities $q_{16j}^{(\kappa)}$ are the quantities of gas j contained in the void spaces.

The numerical values for the parameters $F_{g\kappa j}$ are again estimated by assuming a combustion efficiency of 99.99 percent for organics and by taking into account the reduction of connected void volume from 147 L to (4.0 ± 0.5) percent of the drum volume of 208 L (Butcher, 1989). The factor $F_{g\kappa j}$ for alternatives $\kappa = 1$ and 2 is then given by the ratio of the void volumes, and for Treatment Options 3 and 4 by the product of that ratio with the burn escape ratio. The numerical values are listed in Table D.3-8.

D.3.10 Location Function for Treatment Plant

In loading and unloading the TRUPACT-II containers, the handling crew is exposed to penetrating radiation from the drums. The handling is increased when the TF is located between the originator and the WIPP. This is taken into account by the location/function factor $\Phi_{28\,3\,\omega}^{(\kappa\lambda)}$ used in Section E.6.3.7. Numerical values for this function are given in Table D.3-9 and their errors in Table D.3-10. For treatment at the WIPP, one load/unload unit is incurred, equivalent to the baseline risk evaluated in the FSEIS. For treatment at the originator ω, the number of transports is reduced by the transportation reduction factor $F_{t\kappa}$ of the treatment option. For the location options with regional treatment facilities, outside suppliers incur one unit of loading and unloading of wastes "as received" and one unit reduced by the volume reduction factor $F_{t\kappa}$ of the treatment option. This evaluation is based on the assumption that the ALARA concept is fully implemented, minimizing both doses and dose-rates for the shipments reduced by the factor $F_{t\kappa}$ the higher dose-rates will then be reduced by different health and safety protocols, leaving the gain in exposure reduction intact.

D.3.11 Extension Function for Storage Time

The personnel in the warehouse used for temporary storage of the drums until they can be transported are exposed to additional penetrating radiation if the frequency of transports decreases due to treatment. This effect is taken into account in Section E.6.3.8, where the time extension function $\Phi_{29\,2\,\omega}^{(\kappa\lambda)}$ is used. Effective use of the ALARA concept is again assumed, leading to the same dose rates, but longer storage times lead to a proportionate increase in dose.

TABLE D.3-8

VALUES FOR THE REDUCTION FACTORS $F_{g\kappa j}$ FOR CHEMICAL EMISSIONS

CHEMICAL	QUANTITY*	VALUE ± STANDARD ERROR	COMMENTS/ REFERENCES
Methylene Chloride	F_{g1j}	17.7 ± 2.2	
Carbon Tetrachloride	F_{g2j}	17.7 ± 2.2	
Trichloroethylene	F_{g3j}	$(1.8 \pm 0.2) \cdot 10^5$	
Trichloroethane	F_{g4j}	$(1.8 \pm 0.2) \cdot 10^5$	
Freon			

* Reduction factor for mass of gas j in headspace after treatment option κ, according to Equation (D.3.35).

TABLE D.3-9

LOCATION FUNCTION $\Phi_{28\,3\,\omega}^{(\kappa\,\lambda)}$

ORIGINATOR	ω	λ	$\Phi_{28\,3\,\omega}^{(\kappa\,\lambda)}$	ORIGINATOR	ω	λ	$\Phi_{28\,3\,\omega}^{(\kappa\,\lambda)}$
Idaho National Engineering Laboratory, Idaho	1	1	1	Oak Ridge National Laboratory, Tennessee	6	1	1
	1	2	$1/F_{t\kappa}$		6	2	1
	1	3	$1/F_{t\kappa}$		6	3	$1 + 1/F_{t\kappa}$
	1	4	$1/F_{t\kappa}$		6	4	$1/F_{t\kappa}$
Rocky Flats Plant, Colorado	2	1	1	Nevada Test Site, Nevada	7	1	1
	2	2	$1/F_{t\kappa}$		7	2	1
	2	3	$1/F_{t\kappa}$		7	3	1
	2	4	$1/F_{t\kappa}$		7	4	1
Hanford Reservation, Washington	3	1	1	Argonne National Laboratory - East, Illinois	8	1	1
	3	2	$1 + 1/F_{t\kappa}$		8	2	1
	3	3	$1/F_{t\kappa}$		8	3	$1 + 1/F_{t\kappa}$
	3	4	$1/F_{t\kappa}$		8	4	1
Savannah River Site, South Carolina	4	1	1	Lawrence Livermore National Laboratory, California	9	1	1
	4	2	1		9	2	1
	4	3	$1/F_{t\kappa}$		9	3	1
	4	4	$1/F_{t\kappa}$		9	4	1
Los Alamos National Laboratory, New Mexico	5	1	1	Mound Laboratory, Ohio	10	1	1
	5	2	1		10	2	1
	5	3	1		10	3	$1 + 1/F_{t\kappa}$
	5	4	$1/F_{t\kappa}$		10	4	1

The location function $\Phi_{28\,3\,\omega}^{(\kappa\,\lambda)}$ evaluates the increase in handling after treatment κ of the wastes at location λ.

TABLE D.3-10

STANDARD ERRORS OF LOCATION FUNCTION $\Delta \Phi_{28\,3\,\omega}^{(\kappa\,\lambda)}$

ORIGINATOR	ω	λ	$\Delta \Phi_{28\,3\,\omega}^{(\kappa\,\lambda)}$	ORIGINATOR	ω	λ	$\Delta \Phi_{28\,3\,\omega}^{(\kappa\,\lambda)}$
Idaho National Engineering Laboratory, Idaho	1	1	0	Oak Ridge National Laboratory, Tennessee	6	1	0
	1	2	A		6	2	0
	1	3	A		6	3	A
	1	4	A		6	4	A
Rocky Flats Plant, Colorado	2	1	0	Nevada Test Site, Nevada	7	1	0
	2	2	A		7	2	0
	2	3	A		7	3	0
	2	4	A		7	4	0
Hanford Reservation, Washington	3	1	0	Argonne National Laboratory - East, Illinois	8	1	0
	3	2	A		8	2	0
	3	3	A		8	3	A
	3	4	A		8	4	0
Savannah River Site, South Carolina	4	1	0	Lawrence Livermore National Laboratory, California	9	1	0
	4	2	0		9	2	0
	4	3	A		9	3	0
	4	4	A		9	4	0
Los Alamos National Laboratory, New Mexico	5	1	0	Mound Laboratory, Ohio	10	1	0
	5	2	0		10	2	0
	5	3	0		10	3	A
	5	4	A		10	4	0

$$A = \Delta F_{1\kappa} / F_{1\kappa}^{2}$$

For the time extension functions $\Phi_{292\lambda}^{(\kappa\lambda)}$, the model assumes that for treatment at the originator, no additional storage is incurred except that mandated by the volume reduction, i.e., the additional time required to fill the 42 drums in a TRUPACT-II transport measured in units of the baseline storage time Δt_s,

$$\Phi_{292\omega}^{(\kappa\lambda)} = F_{t\kappa} \, . \tag{D.3.36}$$

For treatment at the WIPP site, the storage time is again that of the baseline case, Δt_s. For an originator going to a regional treatment facility and from there to the WIPP, the storage time at the originator remains the same, but the storage time at the treatment facility has to be added. It consists of pre-treatment storage assumed to be 1/2 Δt_s and post-treatment storage assumed to be 1/2 Δt_s $F_{t\kappa}$. Thus the total time is $\Phi_{292\omega}^{(\kappa\lambda)}\Delta t_s$ with

$$\Phi_{292\omega}^{(\kappa\lambda)} = 1 + \frac{1}{2}\left(1 + F_{t\kappa}\right) . \tag{D.3.37}$$

The functions are tabulated in Table D.3-11 and their errors in Table D.3-12.

D.4 MODELS FOR TREATMENT OPERATION

D.4.1 Accidents

D.4.1.1 Occupational Accidents

Occupational fatalities and injuries in various industries are published by the U. S. Department of Labor (1986, 1990). For the evaluation of risks of workers in the WHB or the TF, data for warehouse workers were used. The average annual rate of injuries per worker over the years 1987 and 1988 is 6.6 10^{-2} with an error of 5 percent (Tables 3 and A-1 of Ref. U.S. Department of Labor, 1990). For fatalities, the same report provides data for the years 1987 and 1988 for transportation and public utility workers. The average annual rate of occupational fatalities is 1.29 10^{-4} with a standard error estimated to be about 10 percent.

D.4.1.2 Forklift Accidents

Forklift accidents are particularly severe occupational events. Although they make up only 1 percent of the accident incidence, they are responsible for 10 percent of the workdays lost (U.S. Department of Labor, 1986). For occupational injuries, the incidence of these accidents is separated from the incidence of general occupational injuries and considered separately with a ten times higher risk coefficient. The rationale for this decision is that severe accidents are ten times more likely, but disappear in the statistical averaging in the tables. For fatalities, the same procedure is adopted, using the rationale that if accidental injuries are ten times more severe, fatalities are likely to be ten times more frequent.

TABLE D.3-11

TIME EXTENSION FUNCTION $\Phi_{29\,2\,\omega}^{(\kappa\,\lambda)}$

ORIGINATOR	ω	λ	$\Phi_{29\,2\,\omega}^{(\kappa\lambda)}$	ORIGINATOR	ω	λ	$\Phi_{29\,2\,\omega}^{(\kappa\lambda)}$
Idaho National	1	1	1	Oak Ridge	6	1	1
Engineering	1	2	$F_{t\kappa}$	National	6	2	1
Laboratory,	1	3	$F_{t\kappa}$	Laboratory,	6	3	$1 + 1/2(1+F_{t\kappa})$
Idaho	1	4	$F_{t\kappa}$	Tennessee	6	4	$F_{t\kappa}$
Rocky Flats	2	1	1	Nevada Test	7	1	1
Plant,	2	2	$F_{t\kappa}$	Site, Nevada	7	2	1
Colorado	2	3	$F_{t\kappa}$		7	3	1
	2	4	$F_{t\kappa}$		7	4	1
Hanford	3	1	1	Argonne	8	1	1
Reservation,	3	2	$1 + 1/2(1 + F_{t\kappa})$	National	8	2	1
Washington	3	3	$F_{t\kappa}$	Laboratory -	8	3	$1 + 1/2(1+F_{t\kappa})$
	3	4	$F_{t\kappa}$	East, Illinois	8	4	1
Savannah	4	1	1	Lawrence	9	1	1
River Site,	4	2	1	Livermore	9	2	1
South	4	3	$F_{t\kappa}$	National	9	3	1
Carolina	4	4	$F_{t\kappa}$	Laboratory,	9	4	1
				California			
Los Alamos	5	1	1	Mound	10	1	1
National	5	2	1	Laboratory,	10	2	1
Laboratory,	5	3	1	Ohio	10	3	$1 + 1/2(1+F_{t\kappa})$
New Mexico	5	4	$F_{t\kappa}$		10	4	1

The time extension function $\Phi_{29\,2\,\omega}^{(\kappa\,\lambda)}$ evaluates the extension of the total storage time due to treatment κ of the waste at location λ according to Equations (D.3.36) and (D.3.37).

TABLE D.3-12

ERROR OF THE TIME EXTENSION FUNCTION $\Delta \Phi_{29\,2\,\omega}^{(\kappa\lambda)}$

ORIGINATOR	ω	λ	$\Delta \Phi_{29\,2\,\omega}^{(\kappa\lambda)}$	ORIGINATOR	ω	λ	$\Delta \Phi_{29\,2\,\omega}^{(\kappa\lambda)}$
Idaho National Engineering Laboratory, Idaho	1	1	0	Oak Ridge National Laboratory, Tennessee	6	1	0
	1	2	$\Delta F_{t\kappa}$		6	2	0
	1	3	$\Delta F_{t\kappa}$		6	3	$1/2\,\Delta F_{t\kappa}$
	1	4	$\Delta F_{t\kappa}$		6	4	$\Delta F_{t\kappa}$
Rocky Flats Plant, Colorado	2	1	0	Nevada Test Site, Nevada	7	1	0
	2	2	$\Delta F_{t\kappa}$		7	2	0
	2	3	$\Delta F_{t\kappa}$		7	3	0
	2	4	$\Delta F_{t\kappa}$		7	4	0
Hanford Reservation, Washington	3	1	0	Argonne National Laboratory - East, Illinois	8	1	0
	3	2	$1/2\,\Delta F_{t\kappa}$		8	2	0
	3	3	$\Delta F_{t\kappa}$		8	3	$1/2\,\Delta F_{t\kappa}$
	3	4	$\Delta F_{t\kappa}$		8	4	0
Savannah River Site, South Carolina	4	1	0	Lawrence Livermore National Laboratory, California	9	1	0
	4	2	0		9	2	0
	4	3	$\Delta F_{t\kappa}$		9	3	0
	4	4	$\Delta F_{t\kappa}$		9	4	0
Los Alamos National Laboratory, New Mexico	5	1	0	Mound Laboratory, Ohio	10	1	0
	5	2	0		10	2	0
	5	3	0		10	3	$1/2\,\Delta F_{t\kappa}$
	5	4	$\Delta F_{t\kappa}$		10	4	0

D.4.2 Manpower Needs for Treatment

The manpower requirements to treat one drum of waste form w in device υ are needed in Section F.4.1.1. The quantity $\phi_{57\kappa}^{(w\,v)}$ denotes that effort measured in manhours expended,

$$\phi_{57\kappa}^{(w\,v)} \equiv \eta_W \; N_{06} \; t_{57}^{(v)} \; . \tag{D.4.1}$$

Here η_w is the waste form weight defined in Equation (D.3.5), N_{06} is the manpower to handle one drum (Table D.2-1), and $t_{57k}^{(v)}$ is the time required for the operation of device v. The associated standard error is approximated by the largest contribution

$$\frac{\Delta\phi_{57\kappa}^{(w\,v)}}{\phi_{57\kappa}^{(w\,v)}} = \frac{\Delta t_{57\kappa}^{(w\,v)}}{t_{57\kappa}^{(v)}} \; . \tag{D.4.2}$$

The numerical values derived for the effort $\phi_{57\kappa}^{(w\,v)}$ and its error which are needed in Section F.4.1.1, are tabulated in Table D.4-1. The two entries with footnotes are due to the ashes from incineration being added to the cementation and vitrification flow.

D.4.3 Manpower for Maintenance

The manpower needed for maintenance, defined by the manpower factor

$$\phi_{58\kappa}^{(w\,v)} \equiv \eta_w \; N_{o7}^{(v)} \; \Phi_{58\kappa}^{(v)} \; t_{58}^{(v)} \; , \tag{D.4.3}$$

where the quantities η_w are the waste fractions given in Equation (D.3.5), $N_{o7}^{(v)}$ the number of persons needed for maintenance, $\Phi_{58\kappa}^{(v)}$ the number of maintenance operations needed annually, and $t_{58}^{(v)}$ the time needed for maintenance of device v. All of these values are given in Table D.2-1 and their product is listed in Table D.4-2. Again, footnotes identify ashes being cemented or vitrified.

D.4.4 Releases Into Device Containment

Some of the treatment devices are likely to generate inert and radioactive breakup particles and suspended particles. Although the treatment apparatus must contain self-cleaning devices, a certain fraction will adhere to surfaces, leading to direct exposures to penetrating radiations during maintenance. The release fraction $f_{58\,2}^{(w\,v)}$ is estimated for the baseline case (v= 0) from the releases arising from punctured drums during the process of assay and certification. It is assumed that the entire release postulated in the FSEIS for such an event occurs during the assay and certification phase. The baseline case assumes that only a fraction of 10^{-3} of the drums is perforated and releases one percent of its total mass. It is assumed here that the

TABLE D.4-1

AVERAGE EFFORT $\phi_{57\kappa}^{(wv)}$ PER DRUM (IN MAN-HOURS) ON DEVICE v FOR TREATING WASTEFORM w IN ALTERNATIVE κ

κ	w *	v	ASSAY 0	SORT 1	SHRED 2	CEMENT 3	INCINERATE 4	SMELT 5	VITRIFY 6
0	1		0.12	0	0	0	0	0	0
	2		0.24	0	0	0	0	0	0
	3		0.24	0	0	0	0	0	0
1	1		0.12	0	0	0	0	0	0
	2		0.24	0	0.4	0.24	0	0	0
	3		0.24	0	0.4	0.24	0	0	0
2	1		0.12	0	0	0.12	0	0	0
	2		0.24	0	0.4	0.24	0	0	0
	3		0.24	0	0.4	0.24	0	0	0
3	1		0.12	0	0	0.12	0	0	0
	2		0.24	0.6	0.4	0.08 [a]	0.12	0	0
	3		0.24	0.6	0.4	0.24	0	0	0
4	1		0.12	0	0	0	0	0	0.4
	2		0.24	0.6	0.4	0	0.12	0	0.267 [b]
	3		0.24	0.6	0.4	0	0	3.2	0

* w = 1: sludges;
w = 2: combustibles;
w = 3: glass/metals.

[a] $0.24 / f_{c3} = 0.08$, cement ash.
[b] $0.8 / f_{c3} = 0.267$, vitrify ash.

TABLE D.4-2

AVERAGE ANNUAL MAINTENANCE EFFORT $\phi_{58\kappa}^{(wv)}$ (IN MAN-YEARS) ON DEVICE v FOR TREATING WASTEFORM w IN ALTERNATIVE κ

κ	w *	v	ASSAY 0	SORT 1	SHRED 2	CEMENT 3	INCINERATE 4	SMELT 5	VITRIFY 6
0	1		0.37	0	0	0	0	0	0
	2		0.74	0	0	0	0	0	0
	3		0.74	0	0	0	0	0	0
1	1		0.38	0	0	0	0	0	0
	2		0.76	0	1.90	0.38	0	0	0
	3		0.76	0	1.90	0.38	0	0	0
2	1		0.38	0	0	0.19	0	0	0
	2		0.76	0	1.90	0.38	0	0	0
	3		0.76	0	1.90	0.38	0	0	0
3	1		0.38	0	0	0.19	0	0	0
	2		0.76	0.76	1.90	0.13 [a]	0.37	0	0
	3		0.76	0.76	1.90	0.38	0	0	0
4	1		0.38	0	0	0	0	0	0.94
	2		0.76	0.76	1.90	0	0.37	0	0.63 [b]
	3		0.76	0.76	1.90	0	0	18.9	0

* w = 1: sludges;
w = 2: combustibles;
w = 3: glass/metals.

[a] Cement ash from incineration.
[b] Vitrify ash from incineration.

release thus contains a fraction of 10^{-5} of a drum mass per drum handled. For the other devices, it is assumed that health and safety concerns, particularly for maintenance, are the driving factors. Releases, therefore, have to be kept low, in order to keep maintenance frequency and the radiation dose budget of the maintenance crew low. The relatively large uncertainties in the release factors are accounted for by using a broad symmetrical Gaussian distribution but pushing it toward the upper limit of the range estimated for the quantity. The numerical values estimated for the release fractions are listed in Table D.4-3.

D.4.5 Releases From Containment

A certain fraction of the waste suspended in the containment device v is assumed to penetrate airlocks and reach the air inside the treatment unit (see Section F.3.2.1.1). The quantity $f_{59\kappa}^{(v)}$ is the fraction of waste in form w suspended and released from containment in inhalable form due to treatment v in alternative κ. This release fraction for every drum treated is estimated to be 10^{-9} in the drum. In Table D.4-4, the fraction of the drums treated at each device and the fraction escaping from containment are listed.

D.4.6 Suspension During Maintenance

During maintenance and decontamination, a certain fraction of the contamination is resuspended in air (see Section F.3.2.2.1). The fraction $f_{603}^{(wv)}$ of the waste which is resuspended during cleanup of device v is a quantity needed in that part of the risk assessment.

Numerical values of fractions $f_{603}^{(wv)}$ which are needed in the following are given in Table D.4-5. The baseline value here assumes that in maintenance operations a fraction of about (1.0 ± 0.3) 10^{-4} is resuspended. Similarly, the values from Table D.4-4 are multiplied with this factor to assess the activity remobilized during maintenance. The standard errors of the combination are estimated in the Gaussian approximation.

D.4.7 Routine Releases of VOCs During Treatment

For shredding and sorting, the drums and the liners and wrappings are opened, letting all accumulated gases escape. The gas release function $\Phi_{61j}^{(\kappa)}$ for agent j and alternative κ, is defined by

$$F_{r\kappa j} \equiv \frac{\Phi_{61j}^{(0)}}{\Phi_{61j}^{(\kappa)}}, \qquad \text{(D.4.4)}$$

where the functions $\Phi_{61j}^{(\kappa)}$ account for the gas releases from the void space. Also accounted for are the fractions of drums not opened (sludges in Treatment Option 1). The baseline releases

TABLE D.4-3

FRACTION $f_{58\,2}^{(wv)}$ OF THE WASTE RELEASED INTO THE CONTAINMENT OF DEVICE v

κ	w *	v	ASSAY 0	SORT 1	SHRED 2	CEMENT 3	INCINERATE 4	SMELT 5	VITRIFY 6
0	1		A	0	0	0	0	0	0
	2		A	0	0	0	0	0	0
	3		A	0	0	0	0	0	0
1	1		A	0	0	0	0	0	0
	2		A	0	C	C	0	0	0
	3		A	0	C	C	0	0	0
2	1		A	0	0	C	0	0	0
	2		A	0	C	C	0	0	0
	3		A	0	C	C	0	0	0
3	1		A	0	0	C	0	0	0
	2		A	C	C	B[a]	C	0	0
	3		A	C	C	C	0	0	0
4	1		A	0	0	0	0	0	C
	2		A	C	C	0	C	0	B[b]
	3		A	C	C	0	0	C	0

* w = 1: sludges;
w = 2: combustibles;
w = 3: glass/metals.

$A = (1.0 \pm 0.3) \cdot 10^{-5}$
$B = (1.0 \pm 0.3) \cdot 10^{-4}$
$C = (1.0 \pm 0.3) \cdot 10^{-3}$

[a] Cement ash from incineration
[b] Vitrify ash from incineration

TABLE D.4-4

FRACTION $f_{59\,K}^{(v)}$ OF THE WASTE ACTIVITY SUSPENDED AND RELEASED FROM CONTAINMENT OF DEVICE v

		FRACTION OF 41,000 DRUMS HANDLED ANNUALLY (PERCENT)					FRACTION $f_{59\,K}^{(v)}$ OF WASTE ACTIVITY				
	TREATMENT	TREATMENT OPTION					TREATMENT OPTION				
v	Operation	0	1	2	3	4	0	1	2	3	4
0	Assay	97.6 [a]	100	100	100	100	$(1.0 \pm 0.3)\cdot10^{-5}$	$(1.0 \pm 0.3)\cdot10^{-5}$	$(1.0 \pm 0.3)\cdot10^{-5}$	$(1.0 \pm 0.3)\cdot10^{-5}$	$(1.0 \pm 0.3)\cdot10^{-5}$
1	Sort	0	0	0	80	80	0	0	0	$(0.8 \pm 0.3)\cdot10^{-9}$	$(0.8 \pm 0.3)\cdot10^{-9}$
2	Shred	0	80	80	40	80	0	$(0.8 \pm 0.3)\cdot10^{-9}$	$(0.8 \pm 0.3)\cdot10^{-9}$	$(0.4 \pm 0.1)\cdot10^{-9}$	$(0.8 \pm 0.3)\cdot10^{-9}$
3	Cement	0	80	100	44 [b]	0	0	$(0.8 \pm 0.3)\cdot10^{-9}$	$(1.0 \pm 0.3)\cdot10^{-9}$	$(0.44 \pm 0.3)\cdot10^{-9}$	0
4	Incinerate	0	0	0	40	40	0	0	0	$(0.4 \pm 0.1)\cdot10^{-9}$	$(0.4 \pm 0.1)\cdot10^{-9}$
5	Smelt	0	0	0	0	40	0	0	0	0	$(0.4 \pm 0.1)\cdot10^{-9}$
6	Vitrify	0	0	0	0	24 [c]	0	0	0	0	$(0.24 \pm 0.07)\cdot10^{-9}$

[a] Only 40,000 drums present in baseline case.
[b] Cement ash from combustibles.
[c] Vitrify ash from combustibles.

TABLE D.4-5

FRACTION $f_{60\,3}^{(wv)}$ OF THE WASTE RELEASED WHICH IS RESUSPENDED IN MAINTENANCE OPERATIONS

κ	w *	v	ASSAY 0	SORT 1	SHRED 2	CEMENT 3	INCINERATE 4	SMELT 5	VITRIFY 6
0	1		A	0	0	0	0	0	0
	2		A	0	0	0	0	0	0
	3		A	0	0	0	0	0	0
1	1		A	0	0	0	0	0	0
	2		A	0	C	C	0	0	0
	3		A	0	C	C	0	0	0
2	1		A	0	0	C	0	0	0
	2		A	0	C	C	0	0	0
	3		A	0	C	C	0	0	0
3	1		A	0	0	C	0	0	0
	2		A	C	0	B[a]	C	0	0
	3		A	C	C	C	0	0	0
4	1		A	0	0	0	0	0	C
	2		A	C	0	0	C	0	B[b]
	3		A	C	0	0	0	C	0

* w = 1: sludges;
w = 2: combustibles;
w = 3; glass/metals.

$A = (1.0 \pm 0.3) \cdot 10^{-9}$
$B = (1.0 \pm 0.3) \cdot 10^{-8}$
$C = (1.0 \pm 0.3) \cdot 10^{-7}$

[a] Cement ash from incineration
[b] Vitrify ash from incineration

are taken to be those through the carbon filter on the drum during the assay and certification process. Table D.4-6 lists, in the second column, the release rates for the five chemical agents given in Table 5.35 of the FSEIS (DOE, 1990a). During the 0.2 hours of the process, the mass of gas given in the third column is released. The concentrations of the chemicals in the void space of the drums (147 liters) are taken from Table 5.33 of the FSEIS (DOE, 1990a) and are given in the next column together with the total mass of gas for agent j.

As expected for the slow, diffusion-limited gas release in the baseline case, the fraction of the total gas released in a short time is independent of the agent, with an average value of $(6.4 \pm 0.7) \cdot 10^{-5}$. In Table D.4-7, the values for the reduction factors for gas release $F_{r\kappa j}$ are listed. These values show the dramatic increase in releases due to handling, and demonstrate that the release reduction factors and, thus, the risk reduction factors are independent of the chemical considered. No aggregation is, therefore, needed.

D.5 HUMAN INTRUSION SCENARIOS

D.5.1 Radioactivity in Cuttings Brought to Surface

Drill cuttings brought to the surface in a human intrusion scenario will contain radioisotopes if the repository is intersected. The activity mobilized and transported to the surface for different treatments of waste is reduced by a factor

$$F_{a\kappa} = \frac{\Phi_{40\,1}^{(0)}}{\Phi_{40\,1}^{(\kappa)}}, \qquad \text{(D.5.1)}$$

where the function $\Phi_{40\,1}^{(\kappa)}$ is the time average of the activity brought to the surface. An approximation by a step function leads to a value given by the total activity mobilized. The total activity mobilized is evaluated for baseline and alternative waste using the methodology described in Section B.22 of Appendix B. The resulting values for $F_{a\kappa}$ are given in Table D.5-1. They range from about 4 for Level II treatments down to about 2 for Treatment Option 3 and to a risk increase by a factor of about 2 for Treatment Option 4.

D.5.2 Radioactivity Transported to the Culebra

After the drill hole is plugged, the connection to the Culebra aquifer may still exist, or will when the hole casing corrodes. This contamination depends not only on waste treatment but also on the drilling scenario.

D.5.2.1 The E1 Human Intrusion Scenario

In this scenario, both the repository and a brine pocket in the Castile formation are penetrated. After plugging the hole, contaminated brine can still reach the Culebra aquifer, a stock well, and

TABLE D.4-6

DATA ON RELEASE RATES AND MASS OF GASES IN DRUMS

CHEMICAL	RELEASE RATE (g/s) [a]	RELEASE OF MASS (g) [b]	GAS CONCENTRATION (g/L) [c]	MASS OF GAS IN VOID (g)	RELEASE FRACTION (12 min)
Methylene chloride	$7.8 \cdot 10^{-9}$	$5.6 \cdot 10^{-6}$	$0.5 \cdot 10^{-3}$	0.074	$7.6 \cdot 10^{-5}$
Carbon tetrachloride	$2.3 \cdot 10^{-8}$	$1.7 \cdot 10^{-5}$	$1.9 \cdot 10^{-3}$	0.28	$5.9 \cdot 10^{-5}$
Trichloro-ethylene	$9.3 \cdot 10^{-9}$	$6.7 \cdot 10^{-6}$	$0.7 \cdot 10^{-3}$	0.10	$6.5 \cdot 10^{-5}$
1,1,1-trichloroethane	$1.7 \cdot 10^{-7}$	$1.2 \cdot 10^{-4}$	$13 \cdot 10^{-3}$	1.94	$6.3 \cdot 10^{-5}$
Freon	$1.4 \cdot 10^{-8}$	$1.0 \cdot 10^{-5}$	$1.2 \cdot 10^{-3}$	0.18	$5.7 \cdot 10^{-5}$
				Average	$(6.4 \pm 0.7) \cdot 10^{-5}$

[a] From Table 5.35 of the FSEIS (DOE, 1990a); this is the rate $q_{12j}^{(0)}$.
[b] Mass released in the assay time of 0.2 hours.
[c] From Table 5.33 of the FSEIS (DOE, 1990a); this is $q_{16j}^{(0)}$.

TABLE D.4-7

REDUCTION FACTOR F_{rkj} FOR RELEASE OF AGENT j

ALTERNATIVE κ	FRACTION OF DRUMS OPENED	RELEASE FRACTION	REDUCTION FACTOR F_{rkj}
0	0.0 *	$(6.4 \pm 0.7) \cdot 10^{-5}$	--
1	0.8	0.8	$(5.1 \pm 0.6) \cdot 10^{-5}$
2	1.0	1.0	$(6.4 \pm 0.7) \cdot 10^{-5}$
3	1.0	1.0	$(6.4 \pm 0.7) \cdot 10^{-5}$
4	1.0	1.0	$(6.4 \pm 0.7) \cdot 10^{-5}$

* No drums opened routinely. Emission is that of drum releases through vent during 0.2 hours

TABLE D.5-1

REDUCTION FACTORS FOR MOBILIZED ACTIVITIES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
F_{a1}	3.9 ± 0.5	
F_{a2}	4.0 ± 0.5	
F_{a3}	2.4 ± 0.5	
F_{a4}	0.5 ± 0.5	

man via the consumption of beef. The concentration of radioactivity in the stock well and, therefore, in the beef, depends on the rate with which the activity is mobilized in the repository and transported to the Culebra aquifer. The reduction factor for this long-term mobilization and transport rate $\Phi_{46\,1}^{(\kappa)}$ is

$$F_{b\,\kappa} \equiv \frac{\Phi_{46\,1}^{(0)}}{\Phi_{46\,1}^{(\kappa)}} \,. \tag{D.5.2}$$

The solution to the two-dimensional equation governing contaminant migration in a uniform unidirectional flow from a continuous point source without adsorption or radioactive decay states that the activity concentration in the stock well is proportional to the product of the total radionuclide activity concentration entering the Culebra and the injection rate entering the Culebra (Walton, 1989). The total radionuclide activity concentration entering the Culebra was calculated by using

$$Q_T = \sum_{\alpha=1}^{A} \frac{s_\alpha \, q_\alpha \, \Phi_w}{\Phi_t} \,, \tag{D.5.3}$$

where

Q_T = Total activity concentration entering the Culebra,
s_α = Solubility of radionuclide i in brine (g m^{-3}) (evaluated in subroutine RADSOLUB of the Design Analysis Model, Section B.21 of Appendix B),
q_α = Specific activity of radionuclide i (Ci g^{-1}),
Φ_w = Flowrate of brine through the waste/backfill composite (m^3 s^{-1}), and
Φ_t = Total steady-state injection rate entering the Culebra (m^3 s^{-1}).

The steady-state flowrates Φ_w and Φ_t are evaluated through parametric equations in subroutine ISE1 of the Design Analysis Model as described in Section B.23. The numerical values for $F_{b\kappa}$ are given in Table D.5-2 with their geometric standard deviations.

TABLE D.5-2

REDUCTION FACTORS FOR MOBILIZED ACTIVITIES

SCENARIO	QUANTITY	VALUE	GSD
E1	F_{b1}	$9.5 \cdot 10^3$	(20)
	F_{b2}	$9.5 \cdot 10^3$	(20)
	F_{b3}	$9.7 \cdot 10^3$	(20)
	F_{b4}	$10.7 \cdot 10^3$	(20)
E2	F_{c1}	1.0	(3)
	F_{c2}	1.1	(3)
	F_{c3}	0.8	(5)
	F_{c4}	7.0	(50)
E1E2	F_{d1}	$6 \cdot 10^5$	(80)
	F_{d2}	$8 \cdot 10^5$	(60)
	F_{d3}	$2 \cdot 10^6$	(80)
	F_{d4}	$2 \cdot 10^8$	(40)

GSD - Geometrical Standard Deviation.

D.5.2.2 The E2 Human Intrusion Scenario

In this scenario, only the repository is penetrated. The reduction factor for the long-term mobilization and transport rate $\Phi_{471}^{(\kappa)}$ is

$$F_{c\kappa} \equiv \frac{\Phi_{471}^{(0)}}{\Phi_{471}^{(\kappa)}} . \qquad (D.5.4)$$

The release of activity from a panel to the Culebra was assumed to occur as a slug point source. The solution to the two-dimensional equation governing contaminant migration in uniform one-directional flow from a slug point source without adsorption or radioactive decay indicates that the concentration at the stock well is proportional to the total activity injected into the Culebra (Walton, 1989). The numerical values for $F_{c\kappa}$ are given in Table D.5-2 with their geometric standard deviations.

D.5.2.3 The E1E2 Human Intrusion Scenario

In this scenario, an E1 event is postulated to occur first, then an E2 event into the repressurized repository. Thus, both drill holes will, after plugging, connect to the Culebra aquifer. The reduction factor for the long-term mobilization and transport rate $\Phi_{481}^{(\kappa)}$ is

$$F_{d\kappa} \equiv \frac{\Phi_{481}^{(0)}}{\Phi_{481}^{(\kappa)}} . \qquad (D.5.5)$$

The activity concentration entering the Culebra for an alternative was assumed to be independent of an alternative and equal to the saturation activity concentration. Thus the risk reduction factor $f_{c\kappa}$ was calculated as the ratio of the volume of contaminated brine released to the Culebra for the baseline design to the total volume of contaminated brine released to the Culebra for alternative κ. Numerical values are given in Table D.5-2.

ATTACHMENT E

ROUTINE AND ACCIDENT RISKS OF TRANSPORTING, HANDLING, AND EMPLACING CH TRU WASTE

E.1 CANCER RISKS FROM ROUTINE INTERNAL EXPOSURES TO IONIZING RADIATION

E.1.1 Basic Considerations

The risks discussed in this section are risks associated with the inhalation of alpha, beta, and gamma emitters. Cumulative Effective Dose Equivalents (CEDE) are calculated and used to estimate the global lifetime cancer risks using the methodology and the data provided in ICRP 26 and ICRP 30 (International Commission on Radiological Protection, 1977 and 1979).

To determine the different risks of releases, it is essential to understand that the occupational and the public risks arise from the same source term, defined as $\{Q_i^{(k)}\}$ for scenario i and treatment/location option $k = (\kappa, \lambda)$. This source term is denoted in the formulae by the quantity in braces. Occupational and public risks are distinguished by different exposure conditions. For the occupational risks, the factor $f_{exp}^{(k)}$ takes into account the conditions of the exposure and the factor $f_{dos}^{(k)}$ accounts for the dosimetry conditions of the average worker. In order to convert the CEDE to risk in terms of latent cancer fatalities, the risk factor a_1 must be incorporated into the risk formula as a cancer risk coefficient. The basic form for the occupational cancer risk formula (denoted by subscript 'o') is then the following

$$R_{iok} = \left\{ Q_i^{(k)} \right\} f_{exp}^{(k)} \; f_{dos}^{(k)} \; a_1 \; . \qquad \text{(E.1.1)}$$

The public cancer risk formula has the same source term $\{Q_i^{(k)}\}$ and cancer risk coefficient a_1 as Equation (E.1.1). The factor $f_{dep}^{(k)}$ accounts for the depletion of activity before the filter duct. The factor $f_{rem}^{(k)}$ accounts for the removal efficiency of the high efficiency particulate air (HEPA) filters in the Waste Handling Buildling (WHB) or Treatment Facility (TF). The factor $\Phi_{i\,dd}^{(\kappa)}$ describes the environmental dispersion from the source to the various receptors via different pathways and the dosimetry for each receptor. This factor also accounts for the accumulation of a 50-year CEDE according to the computer code AIRDOS (Moore et al., 1979). The basic form for the public cancer risk formula (denoted by subscript 'p') is, therefore, given as:

$$R_{ipk} = \left\{ Q_i^{(k)} \right\} f_{dep}^{(k)} \; f_{rem}^{(k)} \; \Phi_{idd}^{(k)} \; a_1 \; . \qquad \text{(E.1.2)}$$

The function $\Phi_{i\,dd}^{(k)}$ also incorporates different types and properties of all ionizing radiations in the source term. Further, via AIRDOS, the doses for all exposed members of the public are incorporated into this function. From an inspection of Equations (E.1.1) and (E.1.2), it follows that the risk reduction factors (i.e., the inverse of the relative risks) remain the same for occupational

and public risks, provided there is no change with alternative k in the quantities of the risk formula other than the source term $\{Q_i^{(k)}\}$.

There are four major health effects arising from internal radiation exposures: acute radiation syndrome; somatic effects other than cancer; and cancer and genetic effects. In the risk assessments of the FSEIS (DOE, 1990a) and FSAR (DOE, 1989a), the acute radiation syndrome is only postulated to occur in transportation accidents of severity category VIII (RADTRAN; Madsen et al., 1986). Somatic effects, mostly manifested as a shortening of the lifespan, are well known from animal experiments, but human data are lacking for the quantification of risk. The risks of cancer and genetic damage are assumed to be proportional to different parts of the CEDE. Assuming different dosimetry factors in Equations (E.1.1) and (E.1.2) and a risk coefficient b_1 for genetic effects shows that, for scenarios in which only the source term changes with the alternatives, the risk reduction factors are the same,

$$\begin{aligned} \rho_{iok}^{(ca)} &= \rho_{iok}^{(gen)} \\ \rho_{ipk}^{(ca)} &= \rho_{ipk}^{(gen)} . \end{aligned} \qquad \text{(E.1.3)}$$

In order to simplify the equations and keep the number of equations as low as possible, the superscripts (ca) and (gen) will not be carried explicitly in the formulae. It should be noted that all quantified risks will be given in terms of per year of operation.

For the routine operations addressed in this section, it is assumed that the quantity and dispersion of contamination is low and subtle enough so that the radiation monitors, particularly the Continuous Air Monitors (CAMs) are not triggered and that normal work without special protection (respirators) continues. This assumption results in the low-level chronic exposures implied by the scenarios. Once the CAMs or other monitors are triggered, the workers don respirators and leave the area according to Health and Safety instructions, thereby ending the exposure. Such incidents are treated as accidents in Section E.3.

E.1.2 Risk From Routine Internal Exposures in an N1 Scenario

In Scenario N1, a fraction of surface contamination of the drums allowable under the Waste Acceptance Criteria (WAC) (DOE, 1989b) is mobilized by the handling of the contaminated drums and is suspended in air. Assuming constant handling activities, instantaneous mixing, and homogeneous distribution within the WHB, the specific activity in air is estimated to be at its equilibrium level. The inhalation over eight hours per workday, the deposition of particles in lung, and the dosimetry leading to effective dose equivalents are described by corresponding factors in the risk equation. The dose-effect relationship for cancer or genetic effects is assumed to be of the linear, no-threshold type. These risks do not depend on the location index λ; they vary only with treatment κ. It is assumed that nobody dons a respirator and there is no alarm sounded by the CAMs.

With these assumptions, Scenario N1 leads to Risk Component 1, with four subcomponents: occupational and public, cancer and genetic. Using the symbols

$n_r^{(\kappa)}$ = Number of drums handled routinely per year (yr^{-1}),
$f_{11}^{(\kappa)}$ = Fraction of drums externally contaminated,
$f_{12}^{(\kappa)}$ = Suspended, inhalable fraction of surface activity,
$q_1^{(\kappa)}$ = Total alpha surface activity per drum (Bq),
L_1 = Annual ventilation volume in the building (m^3),
V_1 = Annual breathing volume of worker (m^3),
$f_{13}^{(\kappa)}$ = Fraction of inhalable airborne particles deposited in lung,
$f_{14\alpha}^{(\kappa)}$ = Fraction of type α radiation in total activity,
$\Phi_{11\alpha}^{(\kappa)}$ = Dosimetry function for type α radiation (Sv Bq^{-1}),
A = Total number of different radiation types α,
$N_{o1}^{(\kappa)}$ = Number of occupationally exposed persons in WHB and TF,
f_{15} = Fraction of personnel occupationally exposed,
C_i = Constant parts of the equations,
a_1 = Cancer risk coefficient (Sv^{-1}), and
$R_{1o\kappa\lambda}$ = Risk of occupational cancer per year of operation (yr^{-1}),

the expression for the occupational cancer risk incurred for every year of operation is

$$R_{1o\kappa\lambda} = \left\{ n_r^{(\kappa)} f_{11}^{(\kappa)} f_{12}^{(\kappa)} q_1^{(\kappa)} \right\} \frac{1}{L_1} V_1 f_{13}^{(\kappa)} \left(\sum_{\alpha=1}^{A} f_{14\alpha}^{(\kappa)} \Phi_{11\alpha}^{(\kappa)} \right) f_{15} N_{o1}^{(\kappa)} a_1 , \qquad \text{(E.1.4)}$$

where the quantity in braces corresponds to the source term of Equations (E.1.1) and (E.1.2) and the four indices of the risk R are the component number 1, the risk type index, 'o' for occupational or 'p' for public, the treatment index κ, and the location index λ.

An inspection of this equation with respect to changes due to different treatment/location options shows that most of the factors do not change with κ and now with λ. Due to the assumptions about suspended particle size and activity distributions, the deposition probability and the dosimetry factors are constant. The fraction of drums contaminated is mostly dependent on work practices and these are assumed to result in a constant fraction for newly generated wastes. For old wastes, this assumption may result in an overestimate for the treatment options. The surface activity $q_1^{(\kappa)}$ is set at the maximum allowable limit (DOE, 1990a, Table A.1.1, Appendix A) and thus does not change either. The number of drums treated annually $n_r^{(\kappa)}$ changes, however, because its product with the average activity per drum $q_2^{(\kappa)}$ is the annual rate of activity emplacement Q_o in the repository and is assumed to be a constant C_o, i.e.,

$$Q_0 = n_r^{(\kappa)} q_2^{(\kappa)} = C_0 . \qquad \text{(E.1.5)}$$

The extra handling in the treatment facility, regardless of location, leads to an air concentration of radioactivity in that building. Assuming that the health and safety requirements lead to the same ventilation rates everywhere, and the modular construction of the treatment facilities, the same fraction f_{15} of the total personnel $N_{o1}^{(\kappa)}$ is assumed to be exposed. This is the crew of the module in which the exposure occurs. Therefore, the only difference lies in the number of people exposed, $N_{o1}^{(\kappa)}$. This dependence is incorporated in the manpower reduction factor

$$F_{m\kappa} \equiv \frac{N_{o1}^{(0)}}{N_{o1}^{(\kappa)}} , \tag{E.1.6}$$

which, in this simple model, is assumed to be independent of the location of the treatment facilities. The numerical values for the manpower reduction factor are given in Attachment D, Table D.3-1.

For the public risk component, the change in Equation (E.1.2) appears in the function $\Phi_{idd}^{(k)}$ and within that function in the number $N_{p1}^{(k)}$ of exposed persons. As explained in the main text, it is assumed that the functions $\Phi_{idd}^{(k)}$ are independent of treatment κ and location λ and depend only on the number and locations of the $N_{p1}^{(\kappa)}$ of persons exposed. This relation is incorporated in the public exposure reduction factor

$$F_{e\kappa} \equiv \frac{\Phi_{idd}^{(0)}}{\Phi_{idd}^{(\kappa)}} = \frac{N_{p1}^{(0)}}{N_{p1}^{(\kappa)}} . \tag{E.1.7}$$

The dependence on κ signifies the dependence on any of the four treatments. Due to this factor, the addition of risk components due to waste treatment thus leads to different reduction factors for occupational and public risk. Numerical values for this factor for these assumptions are listed in Attachment D, Table D.3-3.

With these assumptions, the scaling property of this risk component depends only on the product of the number of drums handled per year, and the number of persons exposed during handling

$$R_{1o\kappa\lambda} = C_1 \; n_r^{(\kappa)} \; N_{o1}^{(\kappa)} . \tag{E.1.8}$$

The risk reduction factor is then the ratio of the number of drums handled per unit time and the ratio of the persons exposed and is thus equal to the product of the manpower reduction factor $F_{m\kappa}$ with the volume reduction factor $F_{v\kappa}$ of the treatment defined by

$$F_{v\kappa} \equiv \frac{n_r^{(0)}}{n_r^{(\kappa)}} . \tag{E.1.9}$$

The explicit form of the risk reduction factor is

$$\rho_{1o\kappa\lambda} = \frac{R_{1o00}}{R_{1o\kappa\lambda}} = \frac{n_r^{(0)}\, N_{o1}^{(0)}}{n_r^{(\kappa)}\, N_{o1}^{(\kappa)}} = F_{v\kappa}\, F_{m\kappa}\,. \tag{E.1.10}$$

Its standard error according to the Gaussian approximation to error propagation, [Equation (C.1.15), and Seiler, 1987b, Table 1] is

$$\left(\frac{\Delta\rho_{1o\kappa\lambda}}{\rho_{1o\kappa\lambda}}\right)^2 = \left(\frac{\Delta F_{v\kappa}}{F_{v\kappa}}\right)^2 + \left(\frac{\Delta F_{m\kappa}}{F_{m\kappa}}\right)^2. \tag{E.1.11}$$

For this first risk component, the public risk for this release will be discussed in detail; later it will only be addressed if needed. Using the additional symbols

$f_{dep}^{(\kappa)}$ = Fraction of release that escapes deposition in the WHB or TF,
$f_{rem}^{(\kappa)}$ = Fraction of activity that escapes removal by the HEPA filters,
$\Phi_{1\,dd}^{(\kappa)}$ = Dispersion-dosimetry function for all $N_{p1}^{(\kappa)}$ persons exposed (Sv Bq^{-1}),
$R_{1p\kappa\lambda}$ = Risk of cancer in the public per year of operation (yr^{-1}),

it is given by the expression

$$R_{1p\kappa\lambda} = \left\{n_r^{(\kappa)}\, f_{11}^{(\kappa)}\, f_{12}^{(\kappa)}\, q_1^{(\kappa)}\right\} f_{dep}^{(\kappa)}\, f_{rem}^{(\kappa)}\, \Phi_{1dd}^{(\kappa)}\, a_1\,. \tag{E.1.12}$$

The first two factors outside the source term in braces do not change with treatment option κ, and in the source term all but the first factor have already shown to be constant by an application of Equation (E.1.5). There remains thus only the number of drums $n_r^{(\kappa)}$ handled and the number of people $N_{p1}^{(\kappa)}$ exposed in the factor $\Phi_{i\,dd}^{(\kappa)}$. Except for the substitution of the public exposure reduction factor $F_{e\kappa}$ for the factor $F_{m\kappa}$, the reduction factor for the public risk $\rho_{1p\kappa\lambda}$ and its standard error are thus the same as those for the occupational risks in Equations (E.1.10) and (E.1.11),

$$\rho_{1p\kappa\lambda} = F_{v\kappa}\, F_{e\kappa}\,, \tag{E.1.13}$$

with standard errors of

$$\left(\frac{\Delta\rho_{1p\kappa\lambda}}{\rho_{1p\kappa\lambda}}\right)^2 = \left(\frac{\Delta F_{v\kappa}}{F_{v\kappa}}\right)^2 + \left(\frac{\Delta F_{e\kappa}}{F_{e\kappa}}\right)^2. \tag{E.1.14}$$

The numerical values of the risk reduction factors and their errors are given in Table E.1-1. For the occupational risks, the risk reduction factors range from 0.3 to 0.7, signaling an increase of the risk from a factor of about 3 for the Level II treatments down to about 1.4 for the most complex treatment. These factors balance the increase of persons exposed and the decrease in the number of barrels handled. The public risks balances the same influences. However, the spread of values is wider here, ranging from an increase by a factor of 1.7 for the Level II treatments, to the same risk for Treatment Option 3, and an actual risk reduction by a factor of more than 4 for Treatment Option 4. The relative standard errors of the reduction factors for occupational risks range from 10 to 20 percent, for public risks the range is 15 to 30 percent. The only available baseline risk is relatively small.

E.1.3 Risk From Routine Internal Exposures in an N2 Exposure

In N2 Scenario, a perforated drum contaminates the WHB and the handling activities lead to a suspension of radioactivity in the air and an inhalation exposure of the work crew during a time interval that does not depend on the treatment of the wastes. With the same assumptions as in the model for Scenario N1, particularly with regard to the alarms, Risk Component 2 has four subcomponents. With the symbols

$n_r^{(\kappa)}$ = Number of drums routinely handled per year (yr^{-1}),
$f_{21}^{(\kappa)}$ = Fraction of drums perforated,
$f_{22}^{(\kappa)}$ = Fraction of waste mass spilled from perforated drum,
$f_{23}^{(\kappa)}$ = Fraction of activity in size fraction below 10 μm,
$f_{24}^{(\kappa)}$ = Fraction of spilled material which is resuspended,
$q_2^{(\kappa)}$ = Total activity in drum (Bq),
L_1 = Annual ventilation volume in WHB and TF (m^3),
V_1 = Annual breathing volume (m^3),
$f_{13}^{(\kappa)}$ = Fraction of inhalable airborne particles deposited in lung,
$f_{14\alpha}^{(\kappa)}$ = Fraction of type α radiation in total activity,
$\Phi_{11\alpha}^{(\kappa)}$ = Dosimetry factor for type α radiation ($Sv\ Bq^{-1}$),
A = Number of different radiation types α,
$N_{o1}^{(\kappa)}$ = Number of persons in WHB and TF,
f_{15} = Fraction of personnel occupationally exposed,
C_l = Constant parts of the equations,
a_1 = Cancer risk coefficient (Sv^{-1}), and
$R_{2o\kappa\lambda}$ = Occupational cancer risk per year of operation (yr^{-1}),

TABLE E.1-1

RISK REDUCTION FACTORS FOR N1 ACTIVITIES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
Occupational:		
$\rho_{1o1\lambda}$	0.331 ± 0.034	
$\rho_{1o2\lambda}$	0.312 ± 0.032	
$\rho_{1o3\lambda}$	0.374 ± 0.088	
$\rho_{1o4\lambda}$	0.707 ± 0.079	
Public:		
$\rho_{1p1\lambda}$	0.600 ± 0.108	
$\rho_{1p2\lambda}$	0.600 ± 0.108	
$\rho_{1p3\lambda}$	1.1 ± 0.31	
$\rho_{1p4\lambda}$	4.65 ± 0.87	
Annual Baseline Risks:		
Occupational:		
R_{1ooo}	$3.9 \cdot 10^{-4}$	FSEIS (DOE 1990a), Table 5.24
Public:		
R_{1poo}	--	Not available in FSEIS

the occupational risk equation is

$$R_{2o\kappa\lambda} = \left\{ n_r^{(\kappa)} f_{21}^{(\kappa)} f_{22}^{(\kappa)} f_{23}^{(\kappa)} f_{24}^{(\kappa} q_2^{(\kappa)} \right\} \frac{1}{L_1} V_1 f_{13}^{(\kappa)} \left(\sum_{\alpha=1}^{A} f_{14\alpha}^{(\kappa)} \Phi_{11\alpha}^{(\kappa)} \right) f_{15} N_{o1}^{(\kappa)} a_1 \ . \tag{E.1.15}$$

Note that, apart from the source term, the equation is the same as Equation (E.1.4). Assumption of constant annual activity disposal rate Q_o in Equation (E.1.5) and the constant factors discussed in the last section, reduce the risk to the scaling form

$$R_{2o\kappa\lambda} = C_1 f_{22}^{(\kappa)} f_{23}^{(\kappa)} f_{24}^{(\kappa)} N_{o1}^{(\kappa)} \ , \tag{E.1.16}$$

and as the first three factors after the constant are really the fraction $\phi_2^{(\kappa)}$ of the total activity which is suspended in inhalable form in a N2 scenario, the scaling relation is

$$R_{2o\kappa\lambda} = C_2 \phi_2^{(\kappa)} N_{o1}^{(\kappa)} \ , \tag{E.1.17}$$

with

$$\phi_2^{(\kappa)} \equiv f_{22}^{(\kappa)} f_{23}^{(\kappa)} f_{24}^{(\kappa)} \ . \tag{E.1.18}$$

This uses the same assumptions about the treatment facility as those made in the last section. The risk reduction factors for the occupational risks are

$$\rho_{2o\kappa\lambda} = \frac{f_{22}^{(0)} f_{23}^{(0)} f_{24}^{(0)} N_{o1}^{(0)}}{f_{22}^{(\kappa)} f_{23}^{(\kappa)} f_{24}^{(\kappa)} N_{o1}^{(\kappa)}} = S_{1\kappa} F_{m\kappa} \ , \tag{E.1.19}$$

where the reduction factor in particle resuspension, $S_{1\kappa}$, measures the reduction in suspension of waste in a N2 activity,

$$S_{1\kappa} \equiv \frac{\phi_2^{(0)}}{\phi_2^{(\kappa)}} \ . \tag{E.1.20}$$

The standard errors are

$$\left(\frac{\Delta \rho_{2o\kappa\lambda}}{\rho_{2o\kappa\lambda}}\right)^2 = \left(\frac{\Delta S_{1\kappa}}{S_{1\kappa}}\right)^2 + \left(\frac{\Delta F_{m\kappa}}{F_{m\kappa}}\right)^2 . \qquad \text{(E.1.21)}$$

Numerical values for this factor and its errors are tabulated in Attachment D in Tables D.2-2 and D.2-4.

The public risk equation uses the same symbols as those given above, and in addition

$f_{dep}^{(\kappa)}$ = Activity depletion due to deposition,
$f_{rem}^{(\kappa)}$ = Removal efficiency of HEPA filters,
$\Phi_{2dd}^{(\kappa)}$ = Dispersion-dosimetry factor for all exposed persons (Sv Bq^{-1}).

The risk is therefore given by

$$R_{2o\kappa\lambda} = \left\{ n_r^{(\kappa)} f_{21}^{(\kappa)} f_{22}^{(\kappa)} f_{23}^{(\kappa)} f_{24}^{(\kappa)} q_2^{(\kappa)} \right\} f_{dep}^{(\kappa)} f_{rem}^{(\kappa)} \Phi_{2dd}^{(\kappa)} a_1 . \qquad \text{(E.1.22)}$$

With the same constant quantities as for occupational exposure, the scaling part of the public risk is

$$R_{2p\kappa\lambda} = C_3 f_{22}^{(\kappa)} f_{23}^{(\kappa)} f_{24}^{(\kappa)} \Phi_{2dd}^{(\kappa)} = C_3 \phi_2^{(\kappa)} \Phi_{2dd}^{(\kappa)} , \qquad \text{(E.1.23)}$$

and the risk reduction factor for the public risk is

$$\rho_{2p\kappa\lambda} = \frac{f_{22}^{(0)} f_{23}^{(0)} f_{24}^{(0)} N_{p1}^{(0)}}{f_{22}^{(\kappa)} f_{23}^{(\kappa)} f_{24}^{(\kappa)} N_{p1}^{(\kappa)}} = S_{1\kappa} F_{e\kappa} , \qquad \text{(E.1.24)}$$

where the factor $F_{e\kappa}$ is given in Attachment D, in Table D.3-2. The standard error is

$$\left(\frac{\Delta \rho_{2p\kappa\lambda}}{\rho_{2p\kappa 11\lambda}}\right)^2 = \left(\frac{\Delta S_{1\kappa}}{S_{1\kappa}}\right)^2 + \left(\frac{\Delta F_{e\kappa}}{F_{e\kappa}}\right)^2 . \qquad \text{(E.1.25)}$$

Numerical values for the two factors in Equation (E.1.24) are listed in Attachment D in Tables D.3-2 and D.3-4. This results in the values for risk reduction factors given in Table E.1-2.

With an exposure reduction factor of 1/2 and a suspendability reduction factor of tens to hundreds of million, the risk reduction factors are very large, on the order of a few million to a few tens of millions. The standard errors are in the neighborhood of 20 to 30 percent. For this exposure

TABLE E.1-2

RISK REDUCTION FACTORS FOR OCCUPATIONAL AND PUBLIC RISKS IN THE N2 SCENARIOS

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
Occupational:		
$\rho_{2o1\lambda}$	$(2.48 \pm 0.84) \cdot 10^{7}$	
$\rho_{2o2\lambda}$	$(2.86 \pm 1.05) \cdot 10^{7}$	
$\rho_{2o3\lambda}$	$(1.87 \pm 0.69) \cdot 10^{7}$	
$\rho_{2o4\lambda}$	$(4.10 \pm 1.54) \cdot 10^{6}$	
Public:		
$\rho_{2p1\lambda}$	$(4.50 \pm 1.66) \cdot 10^{7}$	
$\rho_{2p2\lambda}$	$(5.50 \pm 2.19) \cdot 10^{7}$	
$\rho_{2p3\lambda}$	$(5.50 \pm 2.19) \cdot 10^{7}$	
$\rho_{2p4\lambda}$	$(2.70 \pm 1.09) \cdot 10^{7}$	
Annual Baseline Risks:		
Occupational:		
R_{2o00}	--	Not available in FSEIS
Public:		
R_{2p00}	--	Not available in FSEIS

scenario, no baseline risks are available. As the risk reduction factors here are much larger than those for Component 1, unweighted aggregation will introduce a bias later on.

E.1.4 Risk From Routine Internal Exposures in an N3 Scenario

Except for the fact that the exposure occurs underground, Scenario N3 is the same as N1. Thus, although the number of persons exposed are different, that number does not depend on treatment. The ventilation rates can also be assumed to be different due to different tasks performed but constant. The deposition and dosimetry factors, however, are the same independent of waste treatment. For this scenario, no additional risk component due to treatment of the wastes has to be considered. Risk Component 3 has four subcomponents as did the previous components. With the symbols:

$n_r^{(\kappa)}$ = Number of drums routinely handled per year (yr^{-1}),
$f_{11}^{(\kappa)}$ = Fraction of drums contaminated,
$f_{32}^{(\kappa)}$ = Fraction of surface activity suspended in inhalable form by underground handling,
$q_1^{(\kappa)}$ = Total surface activity per drum (Bq),
L_3 = Annual ventilation volume in Underground Storage Area (m^3),
V_1 = Annual breathing volume of workers (m^3),
$f_{13}^{(\kappa)}$ = Fraction of airborne particles deposited in lung,
$f_{14\alpha}^{(\kappa)}$ = Fraction of type α radiation in total activity,
$\Phi_{11\alpha}^{(\kappa)}$ = Dosimetry function for type α radiation ($Sv\ Bq^{-1}$),
A = Number of different radiation types α,
$N_{o2}^{(\kappa)}$ = Number of persons occupationally exposed underground,
C_i = Constant parts of equations,
a_1 = Cancer risk coefficient (Sv^{-1}), and
$R_{3o\kappa\lambda}$ = Risk of occupational cancer per year of operation (yr^{-1}),

the occupational cancer risk can be written as

$$R_{3o\kappa\lambda} = \left\{ n_r^{(\kappa)}\ f_{11}^{(\kappa)}\ f_{32}^{(\kappa)}\ q_1^{(\kappa)} \right\} \frac{1}{L_3}\ V_1\ f_{13}^{(\kappa)} \left(\sum_{\alpha=1}^{A} f_{14\alpha}^{(\kappa)}\ \Phi_{11\alpha}^{(\kappa)} \right) N_{o2}^{(\kappa)}\ a_1\ . \qquad \text{(E.1.26)}$$

In this scenario, the number of persons exposed does not depend on treatment and, again, the deposition fraction and the dosimetry factors remain constant as well as the suspended waste fraction $f_{32}^{(\kappa)}$. Thus in the source term, only the number of drums handled per year changes with alternatives, and the annual risk can be scaled by

$$R_{3o\kappa\lambda} = C_1\ n_r^{(\kappa)}\ . \qquad \text{(E.1.27)}$$

The risk ratio is thus the same for the occupational and public risks,

$$\rho_{3o\kappa\lambda} = \rho_{3p\kappa\lambda} = \frac{n_r^{(0)}}{n_r^{(\kappa)}} = F_{v\kappa} , \qquad \text{(E.1.28)}$$

with a standard error of

$$\Delta\rho_{3o\kappa\lambda} = \Delta\rho_{3p\kappa\lambda} = \Delta F_{v\kappa} . \qquad \text{(E.1.29)}$$

Thus the numerical values of the risk reduction factors are given by the values in Attachment D, in Table D.3-2, and are listed in Table E.1-3. Clearly, only the Treatment Option 4 leads to a risk reduction factor that is substantially different from 1.

The baseline risk of occupational cancer is $3.1 \cdot 10^{-4}$. This value is derived from the effective dose equivalent given in the FSEIS (DOE, 1990a, Vol. 1, p. 5-69, Table 5.24) of 2.5 person•rem per year of operation and uses a lifetime cancer risk coefficient of $2.8 \cdot 10^{-4}$ (DOE, 1990a, Vol. 1, p. 5-77, Table 5.29, Footnote B).

E.2 CANCER RISK FROM ROUTINE EXTERNAL EXPOSURES

E.2.1 Basic Considerations

The risks discussed here are risks of cancer due to direct external exposure to low-LET radiation. With the public far removed from the sources of external irradiation, the reduction of the public risk components will not be calculated. There are two kinds of operations in which occupational external irradiation risks arise; the first are operations aboveground in the WHB and TF, and the second are the disposal operations underground. Each of the components has two subcomponents with end points cancer and genetic damage, respectively. It is again assumed that the total activity handled per year is constant (see Equation E.1.5).

The contribution of neutrons to the external dose is taken into account by the dosimetry function which makes the assumption that the neutron source strength is proportional to the total activity in the drum. It is further assumed throughout this analysis that there is no gamma or neutron absorption occurring in the waste. The density of the untreated waste would reduce the external dose rate somewhat, so this assumption of no self absorption is slightly conservative because air shows very little absorption. If the waste is treated, the head space is reduced, the density increased and therefore the self-absorption would be greater, thus lowering the external dose rate and leading to an anti-treatment bias. The bias is small because consideration of self-absorption would make the already low risk from routine external exposures somewhat lower.

TABLE E.1-3

RISK REDUCTION FACTORS FOR OCCUPATIONAL AND PUBLIC RISKS DUE TO N3 ACTIVITIES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
Occupational:		
$\rho_{3o1\lambda}$	1.2 ± 0.1	$\rho_{3p\kappa\lambda} = \rho_{3o\kappa\lambda}$
$\rho_{3o2\lambda}$	1.2 ± 0.1	
$\rho_{3o3\lambda}$	2.2 ± 0.5	
$\rho_{3o4\lambda}$	9.3 ± 0.9	
Annual Baseline Risks:		
R_{3o00}	$7 \cdot 10^{-4}$	FSEIS (DOE, 1990a) Table 5.24, p. 5-69
R_{3p00}	--	Not available in FSEIS

E.2.2 Risk From Routine External Exposures in an N4 Scenario

Scenario N4 encompasses the handling activities in the WHB and the TF. The proximity of the workers to different drum configurations has to be considered in the time-motion study which is accounted for in the dosimetry factor. This ranges from the TRUPACT-II assembly and the management of single drums to multi-drum stacks for intermediate storage. The geometrical drum configuration factors are assumed to be independent of the waste treatment. Risk Component 4 has two subcomponents, cancer and genetic. With the symbols:

$n_r^{(\kappa)}$	=	Number of drums handled annually (yr^{-1}),
$q_4^{(\kappa)}$	=	Gamma activity per drum (Bq),
$f_{41}^{(\kappa)}$	=	Gamma activity to surface dose rate conversion factor ($Sv\ Bq^{-1}\ s^{-1}\ m^2$),
A_d	=	Number of drum assemblies,
$f_{42a}^{(\kappa)}$	=	Drum assembly factor, number of drums and geometry of assembly a,
$N_{01}^{(\kappa)}$	=	Number of persons in WHB and TF,
f_{15}	=	Fraction of personnel occupationally exposed,
$\Phi_{4a}^{(\kappa)}$	=	Dosimetry factor for all $N_{01}^{(\kappa)}$ persons exposed by assembly a (m^{-2}),
$\Delta t_{01a}^{(\kappa)}$	=	Exposure time, also, time interval for rms distance for assembly a (s),
C_i	=	Constant parts of equations,
a_1	=	Cancer risk coefficient (Sv^{-1}), and
$R_{4o\kappa\lambda}$	=	Cancer risk per year of operation (yr^{-1}),

the cancer risk for occupational external exposure in the WHB and TF is

$$R_{4o\kappa\lambda} = n_r^{(\kappa)}\ q_4^{(\kappa)}\ f_{41}^{(\kappa)} \left(\sum_{a=1}^{A_d} f_{42a}^{(\kappa)}\ \Phi_{4a}^{(\kappa)}\ \Delta t_{01a}^{(\kappa)} \right) f_{15}\ N_{01}^{(\kappa)}\ a_1\ . \qquad \text{(E.2.1)}$$

Assuming that the inverse root mean square (r.m.s.) distance in $\Phi_{4a}^{(\kappa)}$ and the drum configurations do not change, that the total activity, Q_0, disposed of per year is constant according to Equation (E.1.5), that the dosimetry does not change, and that the influence of self-absorption on the dose rate constant $f_{41}^{(\kappa)}$ can be neglected, the scaling of the risk in Equation (E.2.1) depends only on the factor $N_{01}^{(\kappa)}$, i.e., on the number of persons exposed,

$$R_{4o\kappa\lambda} = C_1\ N_{01}^{(\kappa)}\ , \qquad \text{(E.2.2)}$$

and the risk reduction factor is, therefore, equal to

$$\rho_{4o\kappa\lambda} = F_{m\kappa}\ . \qquad \text{(E.2.3)}$$

Its standard error is

$$\Delta \rho_{4o\kappa\lambda} = \Delta F_{m\kappa} \ . \tag{E.2.4}$$

The risk reduction factors are given by the data in Attachment D, Table D.3-2, and are listed in Table E.2-1. All values are smaller than 1, corresponding to an increase in risk between a factor of 3.6 and 13.

E.2.3 Risk From Routine External Exposures in an N5 Scenario

This scenario differs from N4 only in the geometries of source and surroundings and the number of people exposed; all other factors are the same. Thus, the Risk Component 5 has only one subcomponent for cancer and one for genetic damage. Using the symbols:

$n_r^{(\kappa)}$	=	Number of drums handled per year (yr^{-1}),
$q_4^{(\kappa)}$	=	Gamma activity per drum (Bq),
$f_{41}^{(\kappa)}$	=	Gamma activity to surface dose rate conversion function ($Sv\ Bq^{-1}\ s^{-1}\ m^2$),
A'_d	=	Number of different drum assemblies during disposal,
$f_{52a'}^{(\kappa)}$	=	Drum assembly function, number of drums and geometry of assembly a',
$\Phi_{5a'}^{(\kappa)}$	=	Dosimetry function for all persons underground and assembly a' (m^{-2}),
$\Delta t_{o2a'}^{(\kappa)}$	=	Exposure time, also, time interval for rms distance for assembly a' (s)
$N_{o2}^{(\kappa)}$	=	Number of persons working underground,
C_i	=	Constant parts of equations,
a_1	=	Cancer risk coefficient (Sv^{-1}), and
$R_{5o\kappa\lambda}$	=	Cancer risk per year of operation (yr^{-1}),

the cancer risk for occupational external exposure underground is given by the expression

$$R_{5o\kappa\lambda} = n_r^{(\kappa)}\ q_4^{(\kappa)}\ f_{41}^{(\kappa)} \left(\sum_{a'=1}^{A'_d} f_{52a'}^{(\kappa)}\ \Phi_{5a'}^{(\kappa)}\ \Delta t_{o2a'}^{(\kappa)} \right) N_{o2}^{(\kappa)}\ a_1 \ . \tag{E.2.5}$$

It is assumed again that the geometrical arrangements of the drums and the time-motion study do not change with waste treatment, and that the total activity disposed of per year is constant according to Equation (E.1.5). As the number of workers $N_{o2}^{(\kappa)}$ and the conversion factor $f_{41}^{(\kappa)}$ do not depend on treatment, risk in Equation (E.2.6) is independent of treatment option κ also

$$R_{5o\kappa\lambda} = C_1 \ , \tag{E.2.6}$$

and the risk reduction factor is, therefore, equal to 1

$$\rho_{5o\kappa\lambda} = 1 \ . \tag{E.2.7}$$

TABLE E.2-1

RISK REDUCTION FACTORS FOR OCCUPATIONAL RISKS DUE TO ACTIVITIES IN THE N4 SCENARIO

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
Occupational:		
$\rho_{401\lambda}$	0.276 ± 0.016	
$\rho_{402\lambda}$	0.260 ± 0.017	
$\rho_{403\lambda}$	0.170 ± 0.010	
$\rho_{404\lambda}$	0.0760 ± 0.0042	
Annual Baseline Risks:		
R_{4000}	--	Not available in FSEIS

Its standard error is, therefore, zero

$$\Delta \rho_{5o\kappa\lambda} = 0 \ . \tag{E.2.8}$$

This result is intuitively obvious because, regardless of treatment, the same amount of activity has to be handled each year. The baseline risk of cancer per year of operation is (DOE, 1990a, Table 5.24, p. 5-69)

$$R_{5ooo} = 1.5 \cdot 10^{-3} \ . \tag{E.2.9}$$

E.3 CANCER RISKS FROM ACCIDENTAL EXPOSURES TO IONIZING RADIATION

E.3.1 Basic Considerations

The comments from Section E.1.1 on the differences between public and occupational risks apply here as well, although some factors differ from those in Equations (E.1.1) and (E.1.2). For accidents as well, both occupational and public risks arise from the same source term $\{Q_i^{(\kappa)}\}$ for the event according to scenario i and treatment/location option $k = (\kappa,\lambda)$. In the formulae, the source term is again denoted by the quantity in braces, but the exposure conditions are quite different. In both cases, the annual probability rate, P_{ev}, of the initiating event is the same and is enclosed in square brackets. Also, these risks do not depend on the location of the TF but may depend strongly on the treatment.

For the occupational risks, the factor $f_{exp}^{(\kappa)}$ takes into account characteristics of the exposure, the factor $f_{dos}^{(\kappa)}$ those of the dosimetry, and the factor a_1 is the cancer risk coefficient that converts effective CEDE dose to risk. The basic form of the occupational risk is then

$$R_{io\kappa\lambda} = [P_{ev}^{(\kappa)}] \left\{ Q_i^{(\kappa)} \right\} f_{exp}^{(\kappa)} \ f_{dos}^{(\kappa)} \ a_1 \ . \tag{E.3.1}$$

For public risks, the factor $f_{dep}^{(\kappa)}$ takes into account the depletion of the activity due to deposition before the filter duct, and $f_{rem}^{(\kappa)}$ the removal efficiency of the HEPA filters. The environmental dispersion from source to the various receptors via different pathways, and the accumulation of a 50-year committed dose is, using the code AIRDOS (Moore et al., 1979), accounted for by the factor $\Phi_{i\,dd}^{(\kappa)}$ for dispersion and dosimetry. The basic form of the public risk due to the accident is then given by

$$R_{ip\kappa\lambda} = [P_{ev}^{(\kappa)}] \left\{ Q_i^{(\kappa)} \right\} f_{dep}^{(\kappa)} \ f_{rem}^{(\kappa)} \ \Phi_{idd}^{(\kappa)} \ a_1 \ . \tag{E.3.2}$$

Note that the factor $\Phi_{i\,dd}^{(\kappa)}$ accounts for the different types and properties of radiations in the source term, as well as the doses for all exposed members of the public.

As long as the last three or four factors in Equations (E.3.1) and (E.3.2), respectively, are not treatment dependent, public and occupational risk reduction factors will again be the same. However, the number of forklift operations per drum handled, the number of persons exposed, and the probability of a given type of accident will in some cases depend on the waste treatment. This situation then results in different risk reduction factors for public and occupational risks.

For accident analysis, only internal exposure is assumed to contribute substantially to the risk. External radiation will not change appreciably during the accident and exposure will cease due to evacuation. Inhalation exposures are supposed to occur without respiratory protection and for the entire time it takes for the ventilation to remove the volume of contaminated air.

E.3.2 Above Ground Accidents

These scenarios take place above ground in the WHB or in the TF regardless of location.

E.3.2.1 Risk In WHB and TF Due to Accident Scenario C2

Scenario C2 involves a drum falling off a forklift in the WHB or TF, the lid separating and the liner, if present, rupturing. Suspended particles from the debris are inhaled and deposited in lung tissue. Workers are present for the full dispersion and are assumed to not don respirators. The resulting Risk Component 6 has four subcomponents that involve cancer risk and genetic damage from both occupational and public exposures. Using the symbols:

P_2 = Probability of C2 accident per forklift operation,
$n_r^{(\kappa)}$ = Number of drums handled per year (yr^{-1}),
$n_f^{(\kappa)}$ = Number of forklift operations needed per drum handled,
$f_{61}^{(\kappa)}$ = Fraction of material spilled out of drum,
$f_{62}^{(\kappa)}$ = Fraction of spilled material suspended in air,
$f_{63}^{(\kappa)}$ = Fraction of activity in respirable form,
$q_2^{(\kappa)}$ = Total activity in average drum (Bq),
$\Phi_6^{(\kappa)}$ = Local time-integrated dispersion function in WHB and TF ($s\ L^{-1}$),
v_6 = Inhalation rate of workers in WHB and TF ($L\ s^{-1}$),
$f_{13}^{(\kappa)}$ = Fraction of particles deposited in lung,
$f_{14\alpha}^{(\kappa)}$ = Fraction of type α radiation in total activity,
$\Phi_{11\alpha}^{(\kappa)}$ = Dosimetry function for radiation type α ($Sv\ Bq^{-1}$),
A = Number of different radiation types α,
$N_{01}^{(\kappa)}$ = Number of people in the WHB and TF,
f_{15} = Fraction of personnel occupationally exposed,
C_i = Constant parts of equations,

a_1 = Cancer risk coefficient (Sv^{-1}), and
$R_{6o\kappa\lambda}$ = Occupational cancer risk per year of operations (yr^{-1}),

the risk of occupational cancer per year of operation is

$$R_{6o\kappa\lambda} = [P_2\, n_r^{(\kappa)}\, n_f^{(\kappa)}] \left\{ f_{61}^{(\kappa)}\, f_{62}^{(\kappa)}\, f_{63}^{(\kappa)}\, q_2^{(\kappa)} \right\} \Phi_6^{(\kappa)}\, v_6\, f_{13}^{(\kappa)} \left(\sum_{\alpha=1}^{A} f_{14\alpha}^{(\kappa)}\, \Phi_{11\alpha}^{(\kappa)} \right) f_{15}\, N_{o1}^{(\kappa)}\, a_1 , \tag{E.3.3}$$

where the dosimetry quantity in round brackets (the summation) again accounts for the effects of different radiation types. This model assumes that a constant fraction f_{15} of the $N_{o1}^{(\kappa)}$ workers always work in the WHB and TF area and are thus maximally exposed.

Observing a constant value of the annually emplaced activity Q_o in Equation (E.1.5), an independent dispersion function $\Phi_6^{(\kappa)}$, and a constant deposition fraction $f_{13}^{(\kappa)}$, the variable factors allow the risk to be written as scaling with

$$\begin{aligned} R_{6o\kappa\lambda} &= C_1\, f_{61}^{(\kappa)}\, f_{62}^{(\kappa)}\, f_{63}^{(\kappa)}\, n_f^{(\kappa)}\, N_{o1}^{(\kappa)} \\ &= C_1\, \phi_6^{(\kappa)}\, n_f^{(\kappa)}\, N_{o1}^{(\kappa)} , \end{aligned} \tag{E.3.4}$$

with the fraction $\phi_6^{(\kappa)}$ denoting that part of the activity which is suspended by the C2 accident in inhalable form. Thus,

$$\phi_6^{(\kappa)} \equiv f_{61}^{(\kappa)}\, f_{62}^{(\kappa)}\, f_{63}^{(\kappa)} . \tag{E.3.5}$$

This fraction, or even its reduction factor $S_{2\kappa}$,

$$S_{2\kappa} \equiv \frac{f_{61}^{(0)}\, f_{62}^{(0)}\, f_{63}^{(0)}}{f_{61}^{(\kappa)}\, f_{62}^{(\kappa)}\, f_{63}^{(\kappa)}} , \tag{E.3.6}$$

may be easier to estimate directly than the individual fractions. The risk reduction factor is, therefore,

$$\rho_{6o\kappa\lambda} = \frac{N_{o1}^{(0)}\, \phi_6^{(0)}\, n_f^{(0)}}{N_{o1}^{(\kappa)}\, \phi_6^{(\kappa)}\, n_f^{(\kappa)}} = F_{m\kappa}\, S_{2\kappa}\, F_{f\kappa} , \tag{E.3.7}$$

where $F_{f\kappa}$ is the ratio of the number of forklift operations in the handling of drums for different treatment options. The standard error is

$$\left(\frac{\Delta \rho_{6o\kappa\lambda}}{\rho_{6o\kappa\lambda}}\right)^2 = \left(\frac{\Delta S_{2\kappa}}{S_{2\kappa}}\right)^2 + \left(\frac{\Delta F_{f\kappa}}{F_{f\kappa}}\right)^2 + \left(\frac{\Delta F_{m\kappa}}{F_{m\kappa}}\right)^2 . \qquad \text{(E.3.8)}$$

As some of the factors outside the source term in the occupational risk change with alternative, the public risk is subject to different scaling, resulting in different risk reduction factors for the occupational risk.

The risk reduction factor for the public risk resulting from a C2 incident is, with the additional notation of

$f_{dep}^{(\kappa)}$ = Activity depletion due to deposition,
$f_{rem}^{(\kappa)}$ = Removal efficiency of HEPA filters,
$\Phi_{6dd}^{(\kappa)}$ = Dispersion-dosimetry factor for all exposed persons (Sv Bq^{-1}),

given by

$$R_{6p\kappa\lambda} = [\, P_2\, n_r^{(\kappa)}\, n_f^{(\kappa)} \,] \left\{ f_{61}^{(\kappa)}\, f_{62}^{(\kappa)}\, f_{63}^{(\kappa)}\, q_2^{(\kappa)} \right\} f_{dep}^{(\kappa)}\, f_{rem}^{(\kappa)}\, \Phi_{6dd}^{(\kappa)}\, a_1 . \qquad \text{(E.3.9)}$$

With the assumptions that the factors in the second row, with the exception of $N_{p1}^{(\kappa)}$ in $\Phi_{6dd}^{(\kappa)}$ are independent of κ, and using Equation (E.1.5), the scaling property of the risk is

$$R_{6p\kappa\lambda} = C_3\, \phi_6^{(\kappa)}\, n_f^{(\kappa)}\, \Phi_{6dd}^{(\kappa)} , \qquad \text{(E.3.10)}$$

resulting in a risk reduction factor for the public risk of a C2 accident of

$$\rho_{6p\kappa\lambda} = \frac{\Phi_{6dd}^{(0)}\, \phi_6^{(0)}\, n_f^{(0)}}{\Phi_{6dd}^{(\kappa)}\, \phi_6^{(\kappa)}\, n_f^{(\kappa)}} = F_{o\kappa}\, S_{2\kappa}\, F_{f\kappa} , \qquad \text{(E.3.11)}$$

with standard error

$$\left(\frac{\Delta \rho_{6p\kappa\lambda}}{\rho_{6p\kappa\lambda}}\right)^2 = \left(\frac{\Delta S_{2\kappa}}{S_{2\kappa}}\right)^2 + \left(\frac{\Delta F_{f\kappa}}{F_{f\kappa}}\right)^2 + \left(\frac{\Delta F_{o\kappa}}{F_{o\kappa}}\right)^2 . \qquad \text{(E.3.12)}$$

The ratio of forklift operations $F_{f\kappa}$ for different treatments are given in Attachment D, Table D.3-2, and the ratios $S_{2\kappa}$ in Table D.3-4. The resulting risk reduction factors are listed in Table E.3-1. They are again very large due to the factors $S_{2\kappa}$, ranging from several millions for occupational risks to several tens of millions for public risks. The relative errors for the risk reduction factors are about 30 percent. The baseline risk values show two dramatically different values. The occupational risk will be reduced from a small risk to a negligible risk. The public risk component, however, is already exceedingly small, so that a reduction, however large, is irrelevant.

E.3.2.2 Risk in WHB or TF Due to Accident Scenario C3

In Scenario C3 two drums are pierced, and one drum loses its lid and the integrity of its liners. The contamination is assumed to appear instantaneously in the air and expand across the WHB and the TF, exposing a constant fraction of the crew for a certain time. Inhalation of the activity leads to organ exposures and the risk of cancer. Escape of the activity to the outside through HEPA filters leads to public exposures. The resulting Risk Component 7 thus has four subcomponents, and with the symbols

P_3 = Probability rate of C3 accident per forklift operation ,
$n_r^{(\kappa)}$ = Number of drums handled per year (yr^{-1}),
$n_f^{(\kappa)}$ = Number of forklift operations in WHB and TF per drum,
$n_3^{(\kappa)}$ = Number of drums pierced in accident C3,
$m_3^{(\kappa)}$ = Number of drums losing lid in C3,
$f_{71}^{(\kappa)}$ = Fraction of material spilled from pierced drums,
$f_{72}^{(\kappa)}$ = Fraction of material spilled from drums with lids lost,
$f_{73}^{(\kappa)}$ = Fraction of spilled material suspended,
$f_{74}^{(\kappa)}$ = Fraction of activity in respirable form,
$q_2^{(\kappa)}$ = Total activity in average drum (Bq),
$\Phi_6^{(\kappa)}$ = Time-integrated dispersion function in WHB ($s\ L^{-1}$),
v_6 = Inhalation rate of workers ($L\ s^{-1}$),
$f_{13}^{(\kappa)}$ = Fraction of particles deposited in lung,
$f_{14\alpha}^{(\kappa)}$ = Fraction of type α radiation in total activity,
$\Phi_{11\alpha}^{(\kappa)}$ = Dosimetry function for radiation type α ($Sv\ Bq^{-1}$),
A = Number of different radiation types α,
$N_{01}^{(\kappa)}$ = Number of persons occupationally exposed in WHB and TF,
f_{15} = Fraction of personnel occupationally exposed,
C_i = Constant parts of equations,
a_1 = Cancer risk coefficient (Sv^{-1}), and
$R_{70\kappa\lambda}$ = Occupational cancer risk per year of operation (yr^{-1}),

TABLE E.3-1

RISK REDUCTION FACTORS FOR OCCUPATIONAL AND PUBLIC RISKS DUE TO C2 ACCIDENTS

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
Occupational:		
$\rho_{6o1\lambda}$	$(7.71 \pm 2.05) \cdot 10^{6}$	
$\rho_{6o2\lambda}$	$(1.03 \pm 0.28) \cdot 10^{7}$	
$\rho_{6o3\lambda}$	$(7.40 \pm 2.02) \cdot 10^{6}$	
$\rho_{6o4\lambda}$	$(1.66 \pm 0.45) \cdot 10^{6}$	
Public:		
$\rho_{6p1\lambda}$	$(1.40 \pm 0.43) \cdot 10^{7}$	
$\rho_{6p2\lambda}$	$(1.97 \pm 0.61) \cdot 10^{7}$	
$\rho_{6p3\lambda}$	$(2.18 \pm 0.68) \cdot 10^{7}$	
$\rho_{6p4\lambda}$	$(1.09 \pm 0.34) \cdot 10^{7}$	
Annual Baseline Risks:		
Occupational:		
R_{6o00}	$2.0 \cdot 10^{-4}$	FSEIS (DOE, 1990a) Table 5.28, p. 5-75
Public:		
R_{6p00}	$2.2 \cdot 10^{-11}$	FSEIS (DOE, 1990a), Table 5.28, p. 5-75

the occupational risk is

$$R_{7o\kappa\lambda} = [P_3\, n_r^{(\kappa)}\, n_f^{(\kappa)}] \left\{ (n_3^{(\kappa)}\, f_{71}^{(\kappa)} + m_3^{(\kappa)}\, f_{72}^{(\kappa)})\; f_{73}^{(\kappa)}\, f_{74}^{(\kappa)}\, q_2^{(\kappa)} \right\}$$
$$\Phi_6^{(\kappa)}\, v_6\, f_{13}^{(\kappa)} \left(\sum_{\alpha=1}^{A} f_{14\alpha}^{(\kappa)}\, \Phi_{11\alpha}^{(\kappa)} \right) f_{15}\, N_{o1}^{(\kappa)}\, a_1 \,. \tag{E.3.13}$$

As with Scenario C2 this formula is based on the assumption that the workers stay all the time inside the WHB or TF without respirators in use.

Except for $N_{o1}^{(\kappa)}$, the factors outside the source term and the event probability do not change with the treatment option κ. Using Equation (E.1.5), it is apparent that only some of the factors in the source term and probability vary with treatment options: the number of forklift operations per drum handled, the suspended fraction of the total activity, and the number of persons exposed. The risk is then

$$\begin{aligned} R_{7o\kappa\lambda} &= C_1\, n_f^{(\kappa)} \left(n_3^{(\kappa)}\, f_{71}^{(\kappa)} + m_3^{(\kappa)}\, f_{72}^{(\kappa)} \right) f_{73}^{(\kappa)}\, f_{74}^{(\kappa)}\, N_{o1}^{(\kappa)} \\ &= C_1\, n_f^{(\kappa)} \left(n_3^{(\kappa)}\, \phi_{73}^{(\kappa)} + m_3^{(\kappa)}\, \phi_{72}^{(\kappa)} \right) N_{o1}^{(\kappa)} \,, \end{aligned} \tag{E.3.14}$$

with the suspended, inhalable fraction of the activity,

$$\phi_{7\nu}^{(\kappa)} \equiv f_{7\nu}^{(\kappa)}\, f_{73}^{(\kappa)}\, f_{74}^{(\kappa)} \,. \tag{E.3.15}$$

The form of Equation (E.3.14) is not optimal for cancellation of the relatively large errors for the fractions $f_{\mu\nu}^{(\kappa)}$. This cancellation can be accomplished by regarding the pierced and the fallen drums as two separate events to be evaluated separately. After the calculation of the risk reduction factors, the effects can be superposed linearly, using some of the parameters of the event as weights. With the definition

$$S_{3\kappa} \equiv \frac{\phi_{31}^{(0)}}{\phi_{31}^{(\kappa)}} \,, \tag{E.3.16}$$

and recognizing that

$$\frac{\phi_{32}^{(0)}}{\phi_{32}^{(\kappa)}} = S_{2\kappa} , \tag{E.3.17}$$

two risk reduction factors can be calculated from Equation (E.3.14),

$$\begin{aligned} \rho_{7o\kappa\lambda\alpha} &= S_{2\kappa} F_{m\kappa} F_{f\kappa} , \\ \rho_{7o\kappa\lambda\beta} &= S_{3\kappa} F_{m\kappa} F_{f\kappa} . \end{aligned} \tag{E.3.18}$$

No risk reduction factors for additional exposures are needed because exposures due to irradiation by the radioactive cloud and exposure due to radiations from radioisotopes deposited on the ground are negligible.

Aggregation can be accomplished by a weighted average, using m_3 and n_3 as weights,

$$\rho_{7o\kappa\lambda} = \frac{1}{m_3 + n_3} \left(m_3 S_{2\kappa} + n_3 S_{3\kappa} \right) F_{m\kappa} F_{f\kappa} , \tag{E.3.19}$$

with a standard error of

$$\begin{aligned} \left(\frac{\Delta \rho_{7o\kappa\lambda}}{\rho_{7o\kappa\lambda}} \right)^2 &= \frac{\left(m_3 \Delta S_{2\kappa} \right)^2 + \left(n_3 \Delta S_{3\kappa} \right)^2}{\left(m_3 S_{2\kappa} + n_3 S_{3\kappa} \right)^2} \\ &+ \left(\frac{\Delta F_{f\kappa}}{F_{f\kappa}} \right)^2 + \left(\frac{\Delta F_{m\kappa}}{F_{m\kappa}} \right)^2 . \end{aligned} \tag{E.3.20}$$

The public risk due to a C3 accident is different and is given by

$$\begin{aligned} R_{7p\kappa} = [P_3 \, n_r^{(\kappa)} \, n_f^{(\kappa)}] \left\{ (n_3^{(\kappa)} f_{71}^{(\kappa)} + m_3^{(\kappa)} f_{72}^{(\kappa)}) \, f_{73}^{(\kappa)} \, f_{74}^{(\kappa)} \, q_2^{(\kappa)} \right\} \\ f_{dep}^{(\kappa)} \, f_{rem}^{(\kappa)} \, \Phi_{7dd}^{(\kappa)} \, a_1 , \end{aligned} \tag{E.3.21}$$

where, in addition to the symbols defined above, the definitions

$f_{dep}^{(\kappa)}$ = Activity depletion due to deposition,
$f_{rem}(\kappa)$ = Removal efficiency of HEPA filters,
$\Phi_{7dd}^{(\kappa)}$ = Dispersion-dosimetry factor for all exposed persons,

are used.

In the top row of Equation (E.3.21) the factors have the same variability as in the occupational risk; of the factors in the lower row, only $\Phi_{7dd}^{(\kappa)}$ is κ-dependent because of $N_{p1}^{(\kappa)}$. Thus the scaling property of the public risk is

$$R_{7p\kappa\lambda} = C_3\, n_f^{(\kappa)} \left(n_3^{(\kappa)}\, \phi_{31}^{(\kappa)} + m_3^{(\kappa)}\, \phi_{32}^{(\kappa)} \right) \Phi_{7dd}^{(\kappa)} . \tag{E.3.22}$$

Using the same approach to separation and re-aggregation as for the occupational risk, the risk reduction factors

$$\rho_{7p\kappa\lambda} = \frac{1}{m_3 + n_3} \left(S_{2\kappa} + S_{3\kappa} \right) F_{e\kappa}\, F_{f\kappa} , \tag{E.3.23}$$

are obtained with the standard errors

$$\left(\frac{\Delta \rho_{7p\kappa\lambda}}{\rho_{7p\kappa\lambda}} \right)^2 = \frac{\left(m_3\, \Delta S_{2\kappa} \right)^2 + \left(n_3\, \Delta S_{3\kappa} \right)^2}{\left(m_3\, S_{2\kappa} + n_3\, S_{3\kappa} \right)^2} + \left(\frac{\Delta F_{f\kappa}}{F_{f\kappa}} \right)^2 + \left(\frac{\Delta F_{e\kappa}}{F_{e\kappa}} \right)^2 . \tag{E.3.24}$$

Estimates for the numerical values for the factors $F_{f\kappa}$, $F_{e\kappa}$, $F_{m\kappa}$, $S_{2\kappa}$, and $S_{3\kappa}$ needed here are given in Attachment D, Tables D.3-3, D.3-4, and D.3-5. Based on these data, numerical values for the risk reduction factors $\rho_{7o\kappa\lambda}$ and $\rho_{7p\kappa\lambda}$ and their standard errors are given in Table E.3-2. Due to the large values of $S_{2\kappa}$ and $S_{3\kappa}$, the risk reduction factors are also very large. They range from half a million to five million for the occupational risks, and from four to eight million for the public risk. Relative standard errors are about 25 percent. Again, however, the baseline occupational risk is small and is rendered exceedingly small by the treatment. The baseline public risk is already exceedingly small, so that the large risk reduction factor is ineffectual.

TABLE E.3-2

RISK REDUCTION FACTORS FOR OCCUPATIONAL AND PUBLIC RISKS DUE TO C3 ACCIDENTS

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
Occupational:		
$\rho_{7o1\lambda}$	$(3.18 \pm 0.73) \cdot 10^{6}$	
$\rho_{7o2\lambda}$	$(4.22 \pm 0.99) \cdot 10^{6}$	
$\rho_{7o3\lambda}$	$(3.05 \pm 0.72) \cdot 10^{6}$	
$\rho_{7o4\lambda}$	$(6.84 \pm 1.59) \cdot 10^{5}$	
Public:		
$\rho_{7p1\lambda}$	$(5.20 \pm 1.43) \cdot 10^{6}$	
$\rho_{7p2\lambda}$	$(7.35 \pm 2.04) \cdot 10^{6}$	
$\rho_{7p3\lambda}$	$(8.11 \pm 2.26) \cdot 10^{6}$	
$\rho_{7p4\lambda}$	$(4.07 \pm 1.13) \cdot 10^{6}$	
Annual Baseline Risks:		
Occupational:		
R_{7ooo}	$3.6 \cdot 10^{-4}$	FSEIS (DOE, 1990a), Table 5.28, p. 5-75
Public:		
R_{7poo}	$3.9 \cdot 10^{-11}$	FSEIS, (DOE, 1990a), Table 5.28, p. 5-75

E.3.3 Underground Accidents

E.3.3.1 Risk Underground Due to Accident Scenario C4

In Scenario C4 a transporter is assumed to strike a pallet in the Underground Storage Area, knocking a drum off the pallet. As for the consequences, this scenario is identical to Scenario C2. However, as this scenario takes place underground, ventilation and inhalation rates may change, as well as the number of persons exposed. For the calculation of the public risk, no credit is taken for the filtration of the exhaust through HEPA filters. The Risk Component 8 has four subcomponents, cancer and genetic damage and occupational and public risk. With the symbols

P_4 = Probability of C4 accident per forklift operation,
$n_r^{(\kappa)}$ = Number of drums handled per year (yr^{-1}),
$n_f^{(\kappa)}$ = Number of forklift operations per drum handled,
$f_{81}^{(\kappa)}$ = Fraction of waste material spilled,
$f_{82}^{(\kappa)}$ = Fraction of spilled material suspended,
$f_{83}^{(\kappa)}$ = Fraction of activity in respirable form,
$q_2^{(\kappa)}$ = Total activity in average drum (Bq),
$\Phi_7^{(\kappa)}$ = Time-integrated dispersion function underground ($s\ L^{-1}$),
v_6 = Inhalation rate of workers ($L\ s^{-1}$),
$f_{13}^{(\kappa)}$ = Fraction of particles deposited in lung,
$f_{14\alpha}^{(\kappa)}$ = Fraction of type α radiation,
$\Phi_{11\alpha}^{(\kappa)}$ = Dosimetry factor for radiation type α ($Sv\ Bq^{-1}$),
A = Number of different radiation types α,
$N_{o2}^{(\kappa)}$ = Number of persons occupationally exposed underground,
C_i = Constant parts of equations,
a_1 = Cancer risk coefficient (Sv^{-1}),
$R_{8o\kappa\lambda}$ = Cancer risk per year of operation (yr^{-1}),

the occupational cancer risk component is given by

$$R_{8o\kappa\lambda} = [\, P_4\ n_r^{(\kappa)}\ n_f^{(\kappa)} \,] \left\{ f_{81}^{(\kappa)}\ f_{82}^{(\kappa)}\ f_{83}^{(\kappa)}\ q_2^{(\kappa)} \right\} \Phi_7^{(\kappa)}\ v_6\ f_{13}^{(\kappa)} \left(\sum_{\alpha=1}^{A} f_{14\alpha}^{(\kappa)}\ \Phi_{11\alpha}^{(\kappa)} \right) N_{o2}^{(\kappa)}\ a_1\ . \tag{E.3.25}$$

The risk is variable only in the source term because operations and personnel needed for the emplacement of waste are assumed to be independent of the physical state of the drum contents.

The changing factor is again the inhalable fraction of the suspended activity $\phi_8^{(\kappa)}$, and occupational and public risk reduction factors are, therefore, the same. Scaling depends on

$$R_{8o\kappa\lambda} = C_1 f_{81}^{(\kappa)} f_{82}^{(\kappa)} f_{83}^{(\kappa)} = C_1 \phi_8^{(\kappa)} , \tag{E.3.26}$$

where the fraction suspended in inhalable form by a C4 accident is defined by

$$\phi_8^{(\kappa)} \equiv f_{81}^{(\kappa)} f_{82}^{(\kappa)} f_{83}^{(\kappa)} . \tag{E.3.27}$$

The risk reduction ratios (public and occupational) are then simply

$$\rho_{8o\kappa\lambda} = \rho_{8p\kappa\lambda} = S_{4\kappa} , \tag{E.3.28}$$

where $S_{4\kappa}$ is the reduction in suspension for Scenario C4

$$S_{4\kappa} \equiv \frac{\phi_8^{(0)}}{\phi_8^{(\kappa)}} . \tag{E.3.29}$$

Numerically, $S_{4\kappa}$ is assumed to be equal to $S_{2\kappa}$, the reduction in the C2 accident, because only the location of the accident changes and that should not influence $S_{2\kappa}$. The values for the standard errors of the risk reduction factors are

$$\left(\frac{\Delta\rho_{8o\kappa\lambda}}{\rho_{8o\kappa\lambda}}\right)^2 = \left(\frac{\Delta\rho_{8p\kappa\lambda}}{\rho_{8p\kappa\lambda}}\right)^2 = \left(\frac{\Delta S_{4\kappa}}{S_{4\kappa}}\right)^2 . \tag{E.3.30}$$

The numerical values of the risk reduction factors, calculated with the $S_{2\kappa}$ values from Table D.3-4 in Attachment D, are given in Table E.3-3. The factors range from about 35 million to 70 million with relative standard errors of 25 to 30 percent. The baseline risks are small, both for workers and the public.

E.3.3.2 Risk Underground Due to Accident Scenario C5

Scenario C5 involves a drum knocked off a forklift. Apart from having a different annual probability rate, it has the same consequences as a C4 accident and is similar to a C2 accident except for location related factors. The Risk Component 9 also has four subcomponents, and with the symbols

P_5 = Probability of C5 accident per forklift operation,
$n_r^{(\kappa)}$ = Number of drums handled per year (yr -1),
$n_f^{(\kappa)}$ = Number of forklift operations per drum handled,

TABLE E.3-3

RISK REDUCTION FACTORS FOR OCCUPATIONAL AND PUBLIC RISKS DUE TO A C4 ACCIDENT

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
Occupational:		
$\rho_{801\lambda}$	$(5.40 \pm 1.40) \cdot 10^{7}$	$\rho_{8p\kappa\lambda} = \rho_{8o\kappa\lambda}$
$\rho_{802\lambda}$	$(6.80 \pm 1.80) \cdot 10^{7}$	$\rho_{9o\kappa\lambda} = \rho_{8o\kappa\lambda}$
$\rho_{803\lambda}$	$(6.80 \pm 1.80) \cdot 10^{7}$	$\rho_{9p\kappa\lambda} = \rho_{8o\kappa\lambda}$
$\rho_{804\lambda}$	$(3.40 \pm 0.90) \cdot 10^{7}$	
Annual Baseline Risks:		
Occupational:		
R_{8000}	$1.3 \cdot 10^{-4}$	FSEIS (DOE, 1990a), Table 5.28, p. 5-75
R_{9000}	$1.3 \cdot 10^{-4}$	FSEIS (DOE, 1990a), Table 5.28, p. 5-75
Public:		
R_{8p00}	$2.0 \cdot 10^{-5}$	FSEIS (DOE, 1990a), Table 5.28, p. 5-75
R_{9p00}	$2.0 \cdot 10^{-5}$	FSEIS (DOE, 1990a), Table 5.28, p. 5-75

$f_{91}^{(\kappa)}$ = Fraction of waste material spilled,
$f_{92}^{(\kappa)}$ = Fraction of spilled material suspended,
$f_{93}^{(\kappa)}$ = Fraction of activity in respirable form,
$q_2^{(\kappa)}$ = Total activity in average drum (Bq),
$\Phi_7^{(\kappa)}$ = Time-integrated dispersion function underground (s L -1),
v_6 = Inhalation rate of workers (L s -1),
$f_{13}^{(\kappa)}$ = Fraction of particles deposited in lung,
$f_{14\alpha}^{(\kappa)}$ = Fraction of type α radiation,
$\Phi_{11\alpha}^{(\kappa)}$ = Dosimetry factor for radiation type α (Sv Bq-1),
A = Number of different radiation types α,
$N_{o2}^{(\kappa)}$ = Number of persons occupationally exposed underground,
C_i = Constant parts of equations,
a_1 = Cancer risk coefficient (Sv -1),
$R_{9o\kappa\lambda}$ = Cancer risk per year of operation (yr -1),

the occupational risk component for a C5 scenario is

$$R_{9o\kappa\lambda} = [\, P_5 \; n_r^{(\kappa)} \; n_f^{(\kappa)} \,] \left\{ f_{91}^{(\kappa)} \; f_{92}^{(\kappa)} \; f_{93}^{(\kappa)} \; q_2^{(\kappa)} \right\} \Phi_7^{(\kappa)} \; v_6 \; f_{13}^{(\kappa)} \left(\sum_{\alpha=1}^{A} f_{14\alpha}^{(\kappa)} \; \Phi_{11\alpha}^{(\kappa)} \right) N_{o2}^{(\kappa)} \; a_1 \; . \tag{E.3.31}$$

As in the last section, the changing factors yield the same scaling properties and the same risk reduction factors

$$\rho_{9o\kappa\lambda} = \rho_{9p\kappa\lambda} = \frac{\phi_9^{(o)}}{\phi_9^{(\kappa)}} = S_{4\kappa} = \rho_{8o\kappa\lambda} \; , \tag{E.3.32}$$

where the factor $\phi_9^{(\kappa)}$ is the fraction suspended in inhalable form by a C5 accident. Its numerical value is assumed to be the same as that of $\phi_8^{(\kappa)}$ in a C4 accident. The standard error is

$$\left(\frac{\Delta \rho_{9o\kappa\lambda}}{\rho_{9o\kappa\lambda}} \right)^2 = \left(\frac{\Delta \rho_{9p\kappa\lambda}}{\rho_{9p\kappa\lambda}} \right)^2 = \left(\frac{\Delta \rho_{8o\kappa\lambda}}{\rho_{8o\kappa\lambda}} \right)^2 . \tag{E.3.33}$$

The numerical values have already been given in Table E.3-3. The baseline risks are the same as those for a C4 accident because both are assumed to occur about once a year (DOE, 1990a, Table 5.26, p. 5-72).

E.3.3.3 Risk Underground Due to Accident Scenario C6

Here a forklift pierces two drums and knocks another one down. The accident occurs in the Underground Storage Area. This scenario is identical to Scenario C3 except that the accident occurs underground. It assumes that no respirators are donned and no general exit is ordered; i.e., that the air monitors did not trigger the alarm that switches in the HEPA filters and work is continued without special precautions. The occupational exposures are modeled after a C4 scenario. This results in the Risk Component 10, which has four subcomponents. Using the symbols

P_6	=	Probability rate of C6 accident per forklift operation,
$n_r^{(\kappa)}$	=	Number of drums handled per year (yr -1),
$n_f^{(\kappa)}$	=	Number of forklift operations per drum handled,
$n_6^{(\kappa)}$	=	Number of drums pierced in accident C6,
$m_6^{(\kappa)}$	=	Number of drums losing lid in C6,
$f_{101}^{(\kappa)}$	=	Fraction of waste material spilled from pierced drums,
$f_{102}^{(\kappa)}$	=	Fraction of spilled from drums with lids lost,
$f_{103}^{(\kappa)}$	=	Fraction of spilled material suspended,
$q_2^{(\kappa)}$	=	Total activity in average drum (Bq),
$\Phi_7^{(\kappa)}$	=	Time-integrated dispersion function in Waste Storage Area (s L -1),
v_6	=	Inhalation rate of workers (L s -1),
$f_{13}^{(\kappa)}$	=	Fraction of particles deposited in lung,
$f_{14\alpha}^{(\kappa)}$	=	Fraction of type α radiation in total activity,
$\Phi_{11\alpha}^{(\kappa)}$	=	Dosimetry function for radiation type α (Sv Bq-1),
A	=	Number of different radiation types α,
$N_{o2}^{(\kappa)}$	=	Number of persons occupationally exposed underground,
C_i	=	Constant parts of equations,
a_1	=	Cancer risk coefficient (Sv -1), and
$R_{10o\kappa\lambda}$	=	Occupational cancer risk per year of operation (yr -1),

the occupational cancer risk component is given by

$$R_{10o\kappa\lambda} = [\, P_6\, n_r^{(\kappa)}\, n_f^{(\kappa)} \,] \left(n_6^{(\kappa)}\, f_{101}^{(\kappa)} + m_6^{(\kappa)}\, f_{102}^{(\kappa)} \right) \Phi_7^{(\kappa)}\, v_6\, f_{13}^{(\kappa)} \left(\sum_{\alpha=1}^{A} f_{14\alpha}^{(\kappa)}\, \Phi_{11\alpha}^{(\kappa)} \right) N_{o2}^{(\kappa)}\, a_1 \,. \tag{E.3.34}$$

As in the case of a C3 accident, this component can be written as scaling by

$$R_{10o\kappa\lambda} = C_1 \left(n_6 f_{101}^{(\kappa)} + m_6 f_{102}^{(\kappa)} \right) f_{103}^{(\kappa)} f_{103}^{(\kappa)}$$
$$= C_1 \left(n_6^{(\kappa)} \phi_{101}^{(\kappa)} + m_6^{(\kappa)} \phi_{102}^{(\kappa)} \right), \tag{E.3.35}$$

with the fraction of the activity suspended in inhalable form by a C6 accident

$$\phi_{10v}^{(\kappa)} \equiv f_{10v}^{(\kappa)} f_{103}^{(\kappa)} f_{104}^{(\kappa)} . \tag{E.3.36}$$

the risk reduction factors are then equal for public and occupational risk. However, the form of the equation is again not optimal for cancellation of the relatively large errors for the fractions $f_{\mu\nu}^{(\kappa)}$. As before (Section E.3.1.2), cancellation is accomplished by regarding the pierced and the fallen drums as two separate accidents. After the calculation of the two risk reduction factors, the effects can be superposed linearly, using number of drums involved as weights. The public risk reduction is the same as the occupational as only the $\Phi_{7v}^{(\kappa)}$ value outside the source term changed. $\Phi_{7v}^{(\kappa)}$ changes in the same way for 'o' or 'p' so that $\rho_{10o\kappa\lambda} = \rho_{10p\kappa\lambda}$. The aggregate risk reduction factor is then

$$\rho_{10o\kappa\lambda} = \rho_{10p\kappa\lambda} = \frac{1}{m_3 + n_3} \left(m_3 S_{2\kappa} + n_3 S_{3\kappa} \right), \tag{E.3.37}$$

with a standard error of

$$\left(\frac{\Delta \rho_{10o\kappa\lambda}}{\rho_{10o\kappa\lambda}} \right)^2 = \left(\frac{\Delta \rho_{10p\kappa\lambda}}{\rho_{10p\kappa\lambda}} \right)^2$$
$$= \frac{(m_3 \Delta S_{2\kappa})^2 + (n_3 \Delta S_{3\kappa})^2}{(m_3 S_{2\kappa} + n_3 S_{3\kappa}} , \tag{E.3.38}$$

The numerical values for the ratios $S_{2\kappa}$ and $S_{3\kappa}$ are given in Tables D.3-4 and D.3-5, Attachment D. The resulting reduction factors for public and occupational risks are given in Table E.3-4. They do not change much for the different treatments, ranging from 14 to 28 million, with relative errors between 25 and 30 percent. Assuming an annual occurrence of once a year, the baseline risks are given in the same table.

E.3.3.4 Risk Underground Due to Accident Scenario C10

Scenario C10 involves the spontaneous combustion in the contents of a drum, and the subsequent bursting of the drum leads to a release of suspended particles that reach the surface, disperse, and are inhaled by the public downwind. Note that, due to the assumptions in Section

TABLE E.3-4

RISK REDUCTION FACTORS FOR OCCUPATIONAL AND PUBLIC RISKS DUE TO C6 ACCIDENTS

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
Occupational:		
$\rho_{10o1\lambda}$	$(2.23 \pm 0.50) \cdot 10^{7}$	$\rho_{10p\kappa\lambda} = \rho_{10o\kappa\lambda}$
$\rho_{10o2\lambda}$	$(2.80 \pm 0.63) \cdot 10^{7}$	
$\rho_{10o3\lambda}$	$(2.80 \pm 0.63) \cdot 10^{7}$	
$\rho_{10o4\lambda}$	$(1.40 \pm 0.32) \cdot 10^{7}$	
Annual Baseline Risks:		
Occupational:		
R_{10o00}	$2.3 \cdot 10^{-4}$	FSEIS (DOE 1990a), Table 5.28, p. 5-75
Public:		
R_{10p00}	$3.4 \cdot 10^{-5}$	FSEIS (DOE 1990a), Table 5.28, p. 5-75

E.1.1, the occupational risk is subject to the same reduction factors as the public risk, and could, therefore, be considered here. However, no worker exposure is assumed, because workers below ground are supposed to be upstream of the release. In the FSEIS this scenario is assumed to involve only public exposures because the disposal time is short compared to the time while a drum is open.

Still, due to the considerations above, the Risk Component 11 has four subcomponents. With the symbols:

P_{10}	=	Probability rate of C10 event per drum per year (yr^{-1}),
$n_c^{(\kappa)}$	=	Average number of drums in undealed drifts,
$f_{11}^{(\kappa)}$	=	Fraction of activity mobilized in inhalable form,
$q_2^{(\kappa)}$	=	Average activity per drum (Bq),
$f_{dep}^{(\kappa)}$	=	Depletion factor due to deposition before the filter duct,
$f_{rem}^{(\kappa)}$	=	Transmission of the HEPA FILTERS
$\Phi_{11\,dd}^{(\kappa)}$	=	Environmental dispersion and dosimetry factor ($Sv\ Bq^{-1}$),
C_i	=	Constant parts of equations,
a_1	=	Cancer risk factor (Sv^{-1}), and
$R_{11\,p\kappa\lambda}$	=	Cancer risk per year of operation (yr^{-1}),

the public cancer risk per year of operation is

$$R_{11\,p\kappa\lambda} = \left\{ [\, P_{10}^{(\kappa)}\, n_c^{(\kappa)} \,]\, f_{11}^{(\kappa)}\, q_2^{(\kappa)} \right\} f_{dep}^{(\kappa)}\, f_{rem}^{(\kappa)}\, \Phi_{11\,dd}^{(\kappa)}\, a_1 \,. \tag{E.3.39}$$

Here, the event probability depends on the treatment option κ. If it is assumed that the product of $n_c^{(\kappa)}\, q_2^{(\kappa)}$ = const, i.e., that the same amounts of activity are stored in a given time interval regardless of treatment, and that the product of the dispersion function $\Phi_{11\,dd}^{(\kappa)}$ with the two preceding factors does not depend on the waste treatment, then the risk scales as

$$R_{11\,p\kappa\lambda} = C_1\, P_{10}^{(\kappa)}\, f_{11}^{(\kappa)} \,, \tag{E.3.40}$$

and the risk reduction factors are

$$\rho_{11\,p\kappa\lambda} = \rho_{11\,o\kappa\lambda} = \frac{P_{10}^{(0)}\, f_{11}^{(0)}}{P_{10}^{(\kappa)}\, f_{11}^{(\kappa)}} \equiv F_{p\kappa}\, S_{10\kappa} \,, \tag{E.3.41}$$

where $F_{p\kappa}$ is the reduction factor for the probability of a drum fire and $S_{10\kappa}$ is the reduction factor

for the suspendabilities in inhalable form. The standard error is then

$$\left(\frac{\Delta \rho_{11 o \kappa \lambda}}{\rho_{11 o \kappa \lambda}}\right)^2 = \left(\frac{\Delta \rho_{11 p \kappa \lambda}}{\rho_{11 p \kappa \lambda}}\right)^2 = \left(\frac{\Delta F_{p \kappa}}{F_{p \kappa}}\right)^2 + \left(\frac{\Delta S_{10 \kappa}}{S_{10 \kappa}}\right)^2 . \qquad \text{(E.3.42)}$$

Estimates for the values $S_{10\kappa}$ and $F_{p\kappa}$ are given in Attachment D, Tables D.3-5 and D.3-6. On the basis of these data, numerical values for the risk reduction factors are calculated and tabulated in Table E.3-5. These risk reduction factors are very high, varying from six billion to 500 billion, but they are applied to an extremely small risk of $1 \cdot 10^{-11}$, and are, therefore, practically meaningless.

E.4 RISKS FROM ROUTINE CHEMICAL EXPOSURES

E.4.1 Basic Considerations

In the FSEIS, five representative volatile organic chemical agents are identified. Three of these are carcinogens: methylene chloride, carbon tetrachloride, and trichloroethylene (HEAST, 1990). All of these compounds are B2 carcinogens; that is, they are suspected to be human carcinogens on the basis of animal data. For these agents, only cancer risks are considered. For noncarcinogens, a "morbidity risk" is estimated on the basis of the hazard index. This is based on the assumption that every reference level $L_j^{(ref)}$ for agent j corresponds to some particular risk value. As long as risk reduction factors are calculated before the aggregation of the effects of these chemical agents, the accuracy of these risks is of no consequence because these risks cancel. The two noncarcinogens of concern here are 1,1,1-trichloroethane and Freon (HEAST, 1990).

The risk equations are given here for individual agents, that is, for different values of the chemical index j. For cases of exposures to multiple agents, no interactions are assumed. As shown by Seiler (1987b), this is a reasonable assumption at these low exposures and low effects because even strongly synergistic interaction terms tend to be very small. It is only at higher doses and thus higher effects that interaction effects become more prominent. The occupational risks are parameterized in analogy to Equation (E.1.1) by

$$R_{i o \kappa \lambda j} = \left\{ Q_{ij}^{(\kappa)} \right\} f_{exp}^{(\kappa)} \; f_{dos\,j}^{(\kappa)} \; c_j \, , \qquad \text{(E.4.1)}$$

where the agent is denoted by the index j, the treatment option by the index κ, the type of exposure by the index 'o' or 'p', denoting occupational or public exposure, and the risk component by the index i. The quantity in braces, $Q_{ij}^{(\kappa)}$, is the source strength of the release, $f_{exp}^{(\kappa)}$ characterizes the exposure, $f_{dos}^{(\kappa)}$ the dosimetry, and c_j is the risk coefficient for chemical agents.

TABLE E.3-5

RISK REDUCTION FACTORS FOR OCCUPATIONAL AND PUBLIC RISKS DUE TO C10 ACCIDENTS

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
Occupational:		
$\rho_{11o1\lambda}$	$(6.48 \pm 2.00) \cdot 10^{9}$	$\rho_{11o\kappa\lambda} = \rho_{11p\kappa\lambda}$
$\rho_{11o2\lambda}$	$(1.02 \pm 0.34) \cdot 10^{10}$	
$\rho_{11o3\lambda}$	$(1.02 \pm 0.34) \cdot 10^{10}$	
$\rho_{11o4\lambda}$	$(5.10 \pm 1.92) \cdot 10^{11}$	
Annual Baseline Risks:		
Occupational:		
R_{11o00}	--	No exposure postulated
Public:		
R_{11p00}	$5.9 \cdot 10^{-7}$	FSEIS (DOE, 1990a), Table 5.28, p. 5.75 *

* The risk given in the reference was calculated for a 1000 PE-Ci (37 TBq) drum as a conditional probability. The value given here assumes an average drum with 12.6 PE-Ci (466 PE-GBq) and includes the probability of the event (10^{-7}) per year and assumes 6,000 drums per panel.

The corresponding public risk equation is

$$R_{ip\kappa\lambda j} = \left\{ Q_{ij}^{(\kappa)} \right\} f_{dep}^{(\kappa)} \; f_{rem}^{(\kappa)} \; \Phi_{iddj}^{(\kappa)} \; c_j \; , \tag{E.4.2}$$

with the notation of

$f_{dep}^{(\kappa)}$ = Activity depletion due to deposition,
$f_{rem}^{(\kappa)}$ = Removal efficiency of HEPA filters, and
$\Phi_{iddj}^{(\kappa)}$ = Dispersion-dosimetry function for agent j.

Again, as long as the option-dependent terms are only those in the source term, public and occupational risk components have the same risk reduction factors. If the number of exposed persons is treatment-dependent, as for some occupational risks, the two risk reduction factors will be different.

E.4.2 Cancer Risk From Routine Handling

E.4.2.1 Risk Due To An N1 Scenario

Volatile Organic Compounds (VOCs) in drums will vent continuously through a filter, causing an exposure, mostly in enclosed spaces. With a certain average number of drums in the WHB and TF, an equilibrium exposure atmosphere can be estimated. These factors, however, apply to risk components that differ by several orders of magnitude. Similarly, venting of the gases outside the buildings leads to public exposures. Thus Risk Component 12 has two subcomponents, occupational and public cancer risks, for each of the three carcinogenic agents j. Using the symbols

$n_a^{(\kappa)}$ = Number of drums present on average in WHB,
$q_{12j}^{(\kappa)}$ = Quantity of chemical j released per unit time per drum (mg s^{-1}),
$\Phi_{121}^{(\kappa)}$ = WHB and TF dispersion function for all chemicals (s m^{-3}),
V_2 = Respiratory volume per day (m^3 day^{-1}),
f_{12j} = Probability of absorption of chemical j into body of receptor,
M = Receptor body mass (kg),
$N_{o1}^{(\kappa)}$ = Number of persons in WHB and TF,
f_{15} = Fraction of personnel occupationally exposed,
c_j = Cancer potency factor for lifetime exposure to chemical j (kg day mg^{-1}),
f_1 = Exposure time correction factor for one year (yr^{-1}),
C_i = Constant parts of equations, and
$R_{12o\kappa\lambda j}$ = Occupational cancer risk per year of operation (yr^{-1}),

the occupational risk component is

$$R_{12o\kappa\lambda j} = \left\{ n_a^{(\kappa)} \, q_{12j}^{(\kappa)} \right\} \Phi_{121}^{(\kappa)} \, V_2 \, f_{12j} \, \frac{1}{M} \, f_{15} \, N_{o1}^{(\kappa)} \, c_j \, f_t \, . \tag{E.4.3}$$

In the source term, both factors vary. Of the other factors, the dispersion function $\Phi_{121}^{(\kappa)}$ can be assumed constant, and with the variable factors combining to form the total release rate in the WHB, the risk scales according to

$$R_{12o\kappa\lambda j} = C_1 \, n_a^{(\kappa)} \, q_{12j}^{(\kappa)} \, N_{o1}^{(\kappa)} \, , \tag{E.4.4}$$

and the reduction factors are the ratios of these products

$$\rho_{12o\kappa\lambda j} = \frac{n_a^{(0)} \, q_{12j}^{(0)} \, N_{o1}^{(0)}}{n_a^{(\kappa)} \, q_{12j}^{(\kappa)} \, N_{o1}^{(\kappa)}} = F_{v\kappa} \, F_{c\kappa j} \, F_{m\kappa} \, , \tag{E.4.5}$$

where the quantity $F_{v\kappa}$ is the volume reduction factor, $F_{m\kappa}$ the manpower reduction factor, and $F_{c\kappa j}$ is defined as the reduction factor for the emission rates for chemical j for an individual drum

$$F_{c\kappa j} \equiv \frac{q_{12j}^{(0)}}{q_{12j}^{(\kappa)}} \, . \tag{E.4.6}$$

This factor is modeled in Section D.3.8 of Attachment D. The standard errors of the risk reduction factors are

$$\left(\frac{\Delta \rho_{12o\kappa\lambda j}}{\rho_{12o\kappa\lambda j}} \right)^2 = \left(\frac{\Delta F_{v\kappa}}{F_{v\kappa}} \right)^2 + \left(\frac{\Delta F_{c\kappa j}}{F_{c\kappa j}} \right)^2 + \left(\frac{\Delta F_{m\kappa}}{F_{m\kappa}} \right)^2 \, . \tag{E.4.7}$$

For the calculation of the public risk for routine emission of chemicals, the following additional symbols are needed

$f_{out}^{(\kappa)}$ = Deposition losses before reaching the outside atmosphere,
$\Phi_{12dd}^{(\kappa)}$ = Dispersion-dosimetry function for the persons exposed downwind (s day^{-1}).

Note that the dispersion-dosimetry function is assumed to be the same for all agents j. With these quantities, the public risk for chemical j is

$$R_{12p\kappa\lambda j} = \left\{ n_a^{(\kappa)} \, q_{12j}^{(\kappa)} \right\} f_{out}^{(\kappa)} \, \Phi_{12dd}^{(\kappa)} \, \frac{1}{M} \, c_j \, f_t \, . \tag{E.4.8}$$

Again, the only treatment dependent factors are the two quantities in the source term and the dispersion-dosimetry term, giving the risk the scaling structure

$$R_{12p\kappa\lambda j} = C_2 \, n_a^{(\kappa)} \, q_{12j}^{(\kappa)} \, \Phi_{12dd}^{(\kappa)} \, , \tag{E.4.9}$$

leading to the reduction factors

$$\rho_{12p\kappa\lambda j} = \frac{n_a^{(0)} \, q_{12j}^{(0)} \, \Phi_{12dd}^{(0)}}{n_a^{(\kappa)} \, q_{12j}^{(\kappa)} \, \Phi_{12dd}^{(\kappa)}} = F_{v\kappa} \, F_{c\kappa j} \, F_{e\kappa} \, , \tag{E.4.10}$$

with the standard errors

$$\left(\frac{\Delta \rho_{12p\kappa\lambda j}}{\rho_{12p\kappa\lambda j}} \right)^2 = \left(\frac{\Delta F_{v\kappa}}{F_{v\kappa}} \right)^2 + \left(\frac{\Delta F_{c\kappa j}}{F_{c\kappa j}} \right)^2 + \left(\frac{\Delta F_{e\kappa}}{F_{e\kappa}} \right)^2 . \tag{E.4.11}$$

The volume and manpower reduction factors are given in Attachment D, Table D.3-3, whereas estimates for the emission reduction factors $F_{c\kappa j}$ are given in Table D.3-6. The values calculated for the risk reduction factors using these parameters are given in Table E.4-1. The occupational risks for the three agents were obtained from Table 5.43 of the FSEIS (DOE, 1990a) by dividing the 20-year risks by 20.

As discussed in Section E.4.1, the risk reduction factors for different chemicals are aggregated at this level. Thus

$$\rho_{12o\kappa\lambda} = \sum_{j=1}^{3} g_{12oj} \, \rho_{12o\kappa\lambda j} \, , \tag{E.4.12}$$

with the weights

$$g_{12oj} = \frac{R_{12o00j}}{\sum_{i=1}^{3} R_{12o00j}} \, , \tag{E.4.13}$$

and errors

$$(\Delta \rho_{12o\kappa\lambda})^2 = \sum_{j=1}^{3} (g_{12oj}\, \Delta \rho_{12o\kappa\lambda j})^2 \,. \qquad \text{(E.4.14)}$$

Note that for risk reduction factors that are independent of the agent j, all sets of weights g_{12oj} will lead to the same result $\rho_{12o\kappa\lambda}$ and $\Delta \rho_{12o\kappa\lambda}$. This arises from the fact that Equation (E.4.14) is valid for independent errors only, which is not the case here. The correct formula is obtained by an inspection of Equation E.4.12 for $\rho_{12o\kappa\lambda}$ independent of j.

The corresponding equations for the aggregation of the public risk reduction factors $\rho_{12p\kappa\lambda}$ are obtained by substituting the index 'o' by 'p' in Equations (E.4.11) and (E.4.12). The numerical values of the baseline risks are given in Table E.4-1, and the final aggregated values in Table E.4-2. The risk reduction factors for the occupational risk indicate an increase in risk for Level II Treatments of about a factor of 3, whereas for public risks the increase is reduced to a factor of 1.7. For Level III Treatments, there is a risk reduction of about 4,000 and 7,000 for occupational risks and of about 11,000 and 46,000 for public risks. Increases and decreases are practically irrelevant, however, because they apply to an exceedingly small risk. This statement can be justified by the observation that the two baseline risks, applied to the entire world population ($5 \cdot 10^9$ persons) would give rise to an expectation of a few times 10^{-4} cancers at best.

E.4.2.2 Risk Underground Due To N3 Scenario

Routine emissions from each drum lead to releases underground, similar to Scenario N1, except for the underground environment and the far larger number of drums involved. Risk Component 13 also has three subcomponents, occupational, both below ground and above ground, and public cancer risks for each of the three carcinogenic agents j. Using the symbols

$n_b^{(\kappa)}$ = Number of drums present on average in underground drift,
$q_{12j}^{(\kappa)}$ = Quantity of chemical j released per unit time per drum (mg s^{-1}),
$\Phi_{131}^{(\kappa)}$ = Underground dispersion function for all chemicals (s m^{-3}),
V_2 = Respiratory volume per workday (m^3 day^{-1}),
f_{12j} = Probability of absorption of chemical j into body of receptor,
M = Receptor body mass (kg),
$N_{o2}^{(\kappa)}$ = Number of persons exposed underground,
c_j = Cancer potency factor for lifetime exposure to chemical j (kg day mg^{-1}),
f_t = Exposure time correction factor for one year,
C_j = Constant parts of equations, and
$R_{13o\kappa\lambda j}$ = Underground occupational cancer risk per year of operation (yr^{-1}),

TABLE E.4-1

RISK REDUCTION FACTORS FOR N1 ACTIVITIES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
Occupational:		
$\rho_{12o1\lambda j}$	0.331 ± 0.034	$\rho_{14\chi\kappa\lambda j} = \rho_{12\chi\kappa\lambda j}$ with χ = o, p
$\rho_{12o2\lambda j}$	0.312 ± 0.032	
$\rho_{12o3\lambda j}$	3740 ± 1420	
$\rho_{12o4\lambda j}$	7070 ± 2260	
Public:		
$\rho_{12p1\lambda j}$	0.600 ± 0.108	
$\rho_{12p2\lambda j}$	0.600 ± 0.108	
$\rho_{12p3\lambda j}$	11000 ± 4500	
$\rho_{12p4\lambda j}$	46500 ± 16400	
Annual Baseline Risks: *		
Occupational:		
R_{12o001}	$1.5 \cdot 10^{-15}$	FSEIS (DOE, 1990a), Table 5.43
R_{12o002}	$4.1 \cdot 10^{-14}$	FSEIS (DOE, 1990a), Table 5.43
R_{12o003}	$1.7 \cdot 10^{-15}$	FSEIS (DOE, 1990a), Table 5.43
Public:		
R_{12p001}	$2.4 \cdot 10^{-15}$	FSEIS (DOE, 1990a), Table 5.43
R_{12p002}	$6.5 \cdot 10^{-14}$	FSEIS (DOE, 1990a), Table 5.43
R_{12p003}	$2.7 \cdot 10^{-15}$	FSEIS (DOE, 1990a), Table 5.43

* The baseline risks from the FSEIS (DOE, 1990a, Table 5.43), were divided by 20 years to convert them to annual risks.

TABLE E.4-2

AGGREGATED RISK REDUCTION FACTORS FOR CARCINOGENIC CHEMICALS IN N1 ACTIVITIES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
Occupational:		
$\rho_{12o1\lambda}$	0.331 ± 0.034	
$\rho_{12o2\lambda}$	0.312 ± 0.032	
$\rho_{12o3\lambda}$	3740 ± 1420	
$\rho_{12o4\lambda}$	7070 ± 2260	
Public:		
$\rho_{12p1\lambda}$	0.600 ± 0.108	
$\rho_{12p2\lambda}$	0.600 ± 0.108	
$\rho_{12p3\lambda}$	11000 ± 4500	
$\rho_{12p4\lambda}$	46500 ± 16400	
Annual Baseline Risks:		
Occupational:		
R_{12o00}	$4.4 \cdot 10^{-14}$	Aggregated data from Table E.4-1
Public:		
R_{12p00}	$7.0 \cdot 10^{-14}$	Aggregated data from Table E.4-1

the underground occupational risk component is

$$R_{13o\kappa\lambda j} = \left\{ n_b^{(\kappa)} \, q_{12j}^{(\kappa)} \right\} \Phi_{131}^{(\kappa)} \, V_2 \, f_{12j} \, \frac{1}{M} \, N_{o2}^{(\kappa)} \, c_j \, f_t \, . \qquad \text{(E.4.15)}$$

Assuming both $\Phi_{131}^{(\kappa)}$ and $N_{o2}^{(\kappa)}$ to be constant and recognizing that the variable factors combine to form a constant total release rate underground, the risk scales according to

$$R_{13o\kappa\lambda j} = C_1 \, n_b^{(\kappa)} \, q_{12j}^{(\kappa)} \, . \qquad \text{(E.4.16)}$$

The reduction factors are again the ratios of these release rates, which are the same for underground occupational and public risk. This leads to risk reduction factors

$$\rho_{13o\kappa\lambda j} = \rho_{13p\kappa\lambda j} = \frac{n_b^{(0)} \, q_{12j}^{(0)}}{n_b^{(\kappa)} \, q_{12j}^{(\kappa)}} = F_{v\kappa} \, F_{c\kappa j} \, , \qquad \text{(E.4.17)}$$

where $F_{v\kappa}$ is the volume reduction factor, and $F_{c\kappa j}$ is the reduction factor for the emissions of chemical j defined by Equation (E.4.6). The standard errors are

$$\left(\frac{\Delta \rho_{13o\kappa\lambda j}}{\rho_{13o\kappa\lambda j}} \right)^2 = \left(\frac{\Delta F_{v\kappa}}{F_{v\kappa}} \right)^2 + \left(\frac{\Delta F_{c\kappa j}}{F_{c\kappa j}} \right)^2 . \qquad \text{(E.4.18)}$$

The reduction factors for waste volume and emissions of compound j are calculated using the same constants as for Component 12, listed in Tables D.3-3 and D.3-6 of Attachment D. They are given in Table E.4-3.

The routine emissions from drums underground also lead to exposures of workers aboveground. This is the third subcomponent of Risk Component 13. Using the symbols

$n_b^{(\kappa)}$ = Number of drums present on average in underground drift,
$q_{12j}^{(\kappa)}$ = Quantity of chemical j released per unit time per drum (mg s^{-1}),
$\Phi_{132}^{(\kappa)}$ = Underground/above ground dispersion function for all chemicals (s m^{-3}),
V_2 = Respiratory volume per workday (m^3 day^{-1}),
f_{12j} = Probability of absorption of chemical j into body of receptor,
M = Receptor body mass (kg),
$N_{o3}^{(\kappa)}$ = Number of persons exposed aboveground from underground source,
c_j = Cancer potency factor for lifetime exposure to chemical j (mg/(kg day)),
f_t = Exposure time correction factor for one year (yr^{-1}),
C_i = Constant parts of equations, and
$R_{13a\kappa\lambda j}$ = Above ground occupational cancer risk from underground N3 activities per year, of operation (yr^{-1}),

TABLE E.4-3

RISK REDUCTION FACTORS FOR N3 ACTIVITIES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
Occupational (underground):		
$\rho_{13o1\lambda j}$	1.20 ± 0.10	$\rho_{13p\kappa\lambda j} = \rho_{13o\kappa\lambda j}$
$\rho_{13o2\lambda j}$	1.20 ± 0.10	
$\rho_{13o3\lambda j}$	22000 ± 8300	$\rho_{13a\kappa\lambda j} = \rho_{13o\kappa\lambda j}$
$\rho_{13o4\lambda j}$	93000 ± 29300	
Annual Baseline Risks: *		
Occupational (underground):		
R_{13o001}	$2.2 \cdot 10^{-8}$	FSEIS (DOE, 1990a), Table 5.43
R_{13o002}	$6.0 \cdot 10^{-7}$	
R_{13o003}	$2.4 \cdot 10^{-8}$	
Public:		
R_{13p001}	$4.6 \cdot 10^{-13}$	FSEIS (DOE, 1990a), Table 5.43
R_{13p002}	$1.3 \cdot 10^{-11}$	
R_{13p003}	$5.0 \cdot 10^{-13}$	
Occupational (Above ground):		
R_{13a001}	$5.5 \cdot 10^{-13}$	FSEIS (DOE, 1990a), Table 5.43
R_{13a002}	$1.5 \cdot 10^{-11}$	
R_{13a003}	$6.0 \cdot 10^{-13}$	

* The baseline risks from the FSEIS (DOE, 1990a, Table 5.43), were divided by 20 years to convert them to annual risks.

the above ground occupational risk component from underground operations is

$$R_{13a\kappa\lambda j} = \left\{ n_b^{(\kappa)} \, q_{12j}^{(\kappa)} \right\} \Phi_{132}^{(\kappa)} \, V_2 \, f_{12j} \, \frac{1}{M} \, N_{o3}^{(\kappa)} \, c_j \, f_t \, , \tag{E.4.19}$$

and with $N_{o3}^{(\kappa)}$ constant, and the variable factors again combining to form the total release rate underground, the risk scales as

$$R_{13a\kappa\lambda j} = C_1 \, n_b^{(\kappa)} \, q_{12j}^{(\kappa)} \, . \tag{E.4.20}$$

The reduction factors are again the same as for underground workers

$$\rho_{13a\kappa\lambda j} = \rho_{13o\kappa\lambda j} = \frac{n_b^{(o)} \, q_{12j}^{(o)}}{n_b^{(\kappa)} \, q_{12j}^{(\kappa)}} = F_{v\kappa} \, F_{c\kappa j} \, . \tag{E.4.21}$$

The standard errors are

$$\left(\frac{\Delta \rho_{13a\kappa\lambda j}}{\rho_{13a\kappa\lambda j}} \right)^2 = \left(\frac{\Delta F_{v\kappa}}{F_{v\kappa}} \right)^2 + \left(\frac{\Delta F_{c\kappa j}}{F_{c\kappa j}} \right)^2 \, . \tag{E.4.22}$$

The reduction factors and the baseline risks are the same as those given in Table E.4-3.

Again, the three different risk reduction factors for the carcinogenic chemicals are aggregated at this level. Thus

$$\rho_{13\chi\kappa\lambda} = \sum_{j=1}^{3} g_{13\chi j} \, \rho_{13\chi\kappa\lambda j} \, , \tag{E.4.23}$$

with the indices χ = o, p, and a, that stand for occupational (underground), public, and occupational (above ground), respectively. The weights used here are defined by

$$g_{13\chi j} = \frac{R_{13\chi 00j}}{\sum_{i=1}^{3} R_{13\chi 00i}} \, . \tag{E.4.24}$$

and the standard errors are

$$\left(\Delta \rho_{13\chi\kappa\lambda} \right)^2 = \sum_{j=1}^{3} \left(g_{13\chi j} \, \Delta \rho_{13\chi\kappa\lambda j} \right)^2 \, . \tag{E.4.25}$$

Again, this equation is not valid if the risk reduction factors are independent of agent j. The correct formula is obtained by inspection of Equation (E.4.23) for that case.

The numerical values of the baseline risks are given in Table E.4-3, and the final aggregated values in Table E.4-4. The risk reduction factors for Level II treatments are close to 1, whereas they are 20,000 and 90,000 for the two Level III treatments. The relative errors for Level II treatment risk reduction factors are about 7 percent; those for Level III treatments are about 30 percent. Still, the baseline risks are very small to exceedingly small. The largest risk occurs for the workers underground.

E.4.3 Noncancer Risk Due to Routine Chemical Exposure

E.4.3.1 Noncancer Risk In WHB Due to N1 Scenario

This component of the risk has exposure conditions identical to those in Section E.4.2, only the action of the chemical agent on the human organism is different. The two non-carcinogenic agents considered are Freon and 1,1,1-trichloroethylene. Risk Component 14, therefore, consists of two subcomponents, occupational and public risk. With the symbols

$n_a^{(\kappa)}$ = Number of drums present on average in WHB and TF,
$q_{12j}^{(\kappa)}$ = Quantity of chemical j released per drum and per unit time (mg s^{-1}),
$\Phi_{121}^{(\kappa)}$ = Dispersion function for all chemicals in WHB (s m^{-3}),
V_2 = Worker respiratory volume per workday (m^3 day^{-1}),
f_{12j} = Transfer probability for absorption of chemical j into body,
M = Receptor body mass (kg),
$L_j^{(ref)}$ = Reference level for chemical j (mg (kg day)$^{-1}$),
r_{oj} = Risk of reference level $L_j^{(ref)}$,
$N_{o1}^{(\kappa)}$ = Number of persons in WHB and TF,
f_{15} = Fraction of personnel occupationally exposed,
f_t = Exposure time correction factor for one year (yr^{-1}),
C_i = Constant parts of equations, and
$R_{14o\kappa\lambda j}$ = Occupational risk of noncancer health effects per year of operation (yr^{-1}),

the occupational risk component for agent j is

$$R_{14o\kappa\lambda j} = \left\{ n_a^{(\kappa)} \, q_{12j}^{(\kappa)} \right\} \Phi_{121}^{(\kappa)} \, V_2 \, f_{12j} \, \frac{1}{M \, L_j^{(ref)}} \, f_{15} \, N_{o1}^{(\kappa)} r_{oj} \, f_t \, , \qquad \text{(E.4.26)}$$

and with all but $N_{o1}^{(\kappa)}$ and the two factors in the source term constant, as before, the risk can be scaled as

$$R_{14o\kappa\lambda j} = C_1 \left\{ n_a^{(\kappa)} \, q_{12j}^{(\kappa)} \right\} N_{o1}^{(\kappa)} \, . \qquad \text{(E.4.27)}$$

TABLE E.4-4

AGGREGATED RISK REDUCTION FACTORS FOR CARCINOGENIC CHEMICALS IN N3 ACTIVITIES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
Occupational:		
$\rho_{13o1\lambda}$	1.20 ± 0.1	$\rho_{13p\kappa\lambda} = \rho_{13o\kappa\lambda}$
$\rho_{13o2\lambda}$	1.20 ± 0.1	$\rho_{13a\kappa\lambda} = \rho_{13o\kappa\lambda}$
$\rho_{13o3\lambda}$	22000 ± 8300	
$\rho_{13o4\lambda}$	93000 ± 29300	
Annual Baseline Risks:		
Occupational Underground:		
R_{13o00}	$6.5 \cdot 10^{-7}$	Aggregated from data in Table E.4-3
Public:		
R_{13p00}	$1.4 \cdot 10^{-11}$	Aggregated from data in Table E.4-3
Occupational Above Ground:		
R_{13a00}	$1.6 \cdot 10^{-11}$	Aggregated from data in Table E.4-3

This results in risk reduction factors that are again the same ratios as in the N1 and N3 scenarios for the cancer risk. This time, however, they are evaluated for the non-carcinogenic chemicals 4 and 5,

$$\rho_{14\,o\kappa\lambda j} = \frac{n_a^{(0)}\, q_{12j}^{(0)}\, N_{o1}^{(0)}}{n_a^{(\kappa)}\, q_{12j}^{(\kappa)}\, N_{o1}^{(\kappa)}} \tag{E.4.28}$$

$$= F_{v\kappa}\, F_{c\kappa j}\, F_{m\kappa}\,,$$

with standard errors of

$$\left(\frac{\Delta\rho_{14\,o\kappa\lambda j}}{\rho_{14\,o\kappa\lambda j}}\right)^2 = \left(\frac{\Delta F_{v\kappa}}{F_{v\kappa}}\right)^2 + \left(\frac{\Delta F_{c\kappa j}}{F_{c\kappa j}}\right)^2 + \left(\frac{\Delta F_{m\kappa}}{F_{m\kappa}}\right)^2 . \tag{E.4.29}$$

For the calculation of the public risk, again a few more symbols need to be defined

$f_{out}^{(\kappa)}$ = Deposition losses before reaching the outside atmosphere,
$\Phi_{14\,dd}^{(\kappa)}$ = Dispersion-dosimetry function for the $N_{p2}^{(\kappa)}$ persons exposed (s day^{-1}).

With these quantities, the public risk is

$$R_{14\,p\kappa\lambda j} = \left\{ n_a^{(\kappa)}\, q_{12j}^{(\kappa)} \right\} f_{out}^{(\kappa)}\, \Phi_{14\,dd}^{(\kappa)}\, \frac{1}{M\, L_j^{(ref)}}\, r_{oj}\,, \tag{E.4.30}$$

where only the source term and the dispersion-dosimetry factor are treatment dependent. The risk can, therefore, be written in the form

$$R_{14\,p\kappa\lambda j} = C_2 \left\{ n_a^{(\kappa)}\, q_{12j}^{(\kappa)} \right\} \Phi_{14\,dd}^{(\kappa)}\,, \tag{E.4.31}$$

to denote its scaling properties. The risk reduction factor is then

$$\rho_{14\,p\kappa\lambda j} = \frac{n_a^{(0)}\, q_{12j}^{(0)}\, \Phi_{14\,dd}^{(0)}}{n_a^{(\kappa)}\, q_{12j}^{(\kappa)}\, \Phi_{14\,dd}^{(\kappa)}} \tag{E.4.32}$$

$$= F_{v\kappa}\, F_{c\kappa j}\, F_{e\kappa}\,.$$

The standard errors are given by

$$\left(\frac{\Delta \rho_{14p\kappa\lambda j}}{\rho_{14p\kappa\lambda j}}\right)^2 = \left(\frac{\Delta F_{v\kappa}}{F_{v\kappa}}\right)^2 + \left(\frac{\Delta F_{c\kappa j}}{F_{c\kappa j}}\right)^2 + \left(\frac{\Delta F_{e\kappa}}{F_{e\kappa}}\right)^2 . \qquad \text{(E.4.33)}$$

The values of the constants are again given in Attachment D. Numerical values for the occupational and corresponding public risk reduction factors are given in Table E.4-5. The risk reduction factors are the same as those given in Table E.4-1 for $\rho_{12o\kappa\lambda j}$ and $\rho_{12p\kappa\lambda j}$.

The occupational risks for a 20-year operation are obtained from the hazard indices given in FSEIS (DOE, 1990a, Table 5.43) by a division by 20 and converted to annual risks by making the assumption that the risk corresponding to the reference level is 10^{-4} for occupational exposures and 10^{-5} for exposures of the public. These baseline risks are different from those given in Table E.4-1 for R_{12ooj} and R_{12poj} even though the risk reduction factors are the same. These differences in risks, however, will result in different values after aggregation.

Again, the risk reduction factors for the two noncarcinogenic chemicals are aggregated at this level. Thus

$$\rho_{14\chi\kappa\lambda} = \sum_{j=4}^{5} g_{14\chi j}\, \rho_{14\chi\kappa\lambda j} , \qquad \text{(E.4.34)}$$

with χ being either 'o' or 'p', and the weights

$$g_{14\chi j} = \frac{R_{14\chi oj}}{\sum_{j=4}^{5} R_{14\chi oj}} , \qquad \text{(E.4.35)}$$

with the standard errors

$$(\Delta \rho_{14\chi\kappa\lambda})^2 = \sum_{j=4}^{5} (g_{14\chi j}\, \Delta \rho_{14\chi\kappa\lambda j})^2 . \qquad \text{(E.4.36)}$$

The numerical values of the baseline risks are given in Table E.4-5, and the final aggregated values are listed in Table E.4-6. As for Risk Component 12, Level II treatments have small risk reduction factors near 1, whereas Level III treatments have values of 10,000 and 50,000. However, they are applied to risks one hundred times larger than those in Table E.4-2.

E.4.3.2 Noncancer Risk Underground Due to an N3 Scenario

This component of the risk has exposure conditions identical to those in Section E.4.2.1. Risk Component 15, therefore, consists of two subcomponents. With the symbols:

TABLE E.4-5

RISK REDUCTION FACTORS FOR OCCUPATIONAL AND PUBLIC NONCANCER RISK IN N1 ACTIVITIES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
Occupational:		
$\rho_{14o1\lambda4}$	0.331 ± 0.034	$\rho_{14o\kappa\lambda4} = \rho_{14o\kappa\lambda5}$
$\rho_{14o2\lambda4}$	0.312 ± 0.032	
$\rho_{14o3\lambda4}$	3740 ± 1420	
$\rho_{14o4\lambda4}$	7070 ± 2260	
Public:		
$\rho_{14p1\lambda5}$	0.600 ± 0.108	$\rho_{14p\kappa\lambda5} = \rho_{14p\kappa\lambda4}$
$\rho_{14p2\lambda5}$	0.600 ± 0.108	
$\rho_{14p3\lambda5}$	11000 ± 4500	
$\rho_{14p4\lambda5}$	46500 ± 16400	
Annual Baseline Risks: *		
Occupational:		
R_{14o004}	$6.0 \cdot 10^{-12}$	FSEIS (DOE, 1990a), Table 5.44
R_{14o005}	$1.0 \cdot 10^{-13}$	
Public:		
R_{14p004}	$2.1 \cdot 10^{-12}$	FSEIS (DOE, 1990a), Table 5.44
R_{14p005}	$3.4 \cdot 10^{-14}$	

* The data in Table 5.44 are divided by 20 to obtain the risk per year of operation.

TABLE E.4-6

AGGREGATION OF RISK REDUCTION FACTORS FOR NONCARCINOGENIC CHEMICALS IN N1 ACTIVITIES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
Occupational:		
$\rho_{14o1\lambda j}$	0.331 ± 0.034	$\rho_{12o\kappa\lambda j} = \rho_{14o\kappa\lambda j}$
$\rho_{14o2\lambda j}$	0.312 ± 0.032	$\rho_{12p\kappa\lambda j} = \rho_{14p\kappa\lambda j}$
$\rho_{14o3\lambda j}$	3740 ± 1420	
$\rho_{14o4\lambda j}$	7070 ± 2260	
Public:		
$\rho_{14p1\lambda j}$	0.600 ± 0.108	
$\rho_{14p2\lambda j}$	0.600 ± 0.108	
$\rho_{14p3\lambda j}$	11000 ± 4500	
$\rho_{14p4\lambda j}$	46500 ± 16400	
Annual Baseline Risks:		
Occupational:		
R_{14o00}	$6.1 \cdot 10^{-12}$	Aggregated from data in Table E.4-5
Public:		
R_{14p00}	$2.13 \cdot 10^{-12}$	Aggregated from data in Table E.4-5

$n_b^{(\kappa)}$ = Number of drums present on average in unsealed waste disposal drifts,
$q_{12j}^{(\kappa)}$ = Quantity of chemical j released per drum and per unit time (mg s^{-1}),
$\Phi_{132}^{(\kappa)}$ = Underground dispersion function for all chemicals (s m^{-3}),
V_2 = Worker respiratory volume per workday (m^3 day^{-1}),
f_{12j} = Transfer probability for absorption of chemical j into body,
M = Receptor body mass (kg),
$L_j^{(ref)}$ = Reference level for chemical j (mg (kg day)$^{-1}$),
$N_{o3}^{(\kappa)}$ = Number of persons exposed above ground from underground source,
r_{oj} = Risk of reference level $L^{(ref)}$,
f_t = Exposure time correction factor for one year (yr^{-1}),
C_i = Constant parts of equations, and
$R_{15o\kappa\lambda j}$ = Risk of noncancer health effects per year of operations (yr^{-1}),

the underground occupational risk of noncancer health effects for N3 operations is

$$R_{15o\kappa\lambda j} = \left\{ n_b^{(\kappa)} \, q_{12j}^{(\kappa)} \right\} \Phi_{132}^{(\kappa)} \, V_2 \, f_{12j} \, N_{o3}^{(\kappa)} \, \frac{1}{M \, L_j^{(ref)}} \, r_{oj} \, f_t \, . \tag{E.4.37}$$

With all but the source term constant, the risk scales as

$$R_{15o\kappa\lambda j} = C_1 \left\{ n_b^{(\kappa)} \, q_{12j}^{(\kappa)} \right\} , \tag{E.4.38}$$

and results in risk reduction factors that are again the ratios of the global release rates

$$\begin{aligned} \rho_{15o\kappa\lambda j} = \rho_{15p\kappa\lambda j} &= \frac{n_b^{(0)} \, q_{12j}^{(0)}}{n_b^{(\kappa)} \, q_{12j}^{(\kappa)}} = F_{v\kappa} \, F_{c\kappa j} \\ &= \rho_{13o\kappa\lambda j} = \rho_{13p\kappa\lambda j} , \end{aligned} \tag{E.4.39}$$

with standard errors of

$$\left(\frac{\Delta \rho_{15o\kappa\lambda j}}{\rho_{15o\kappa\lambda j}} \right)^2 = \left(\frac{\Delta F_{v\kappa}}{F_{v\kappa}} \right)^2 + \left(\frac{\Delta F_{c\kappa j}}{F_{c\kappa j}} \right)^2 . \tag{E.4.40}$$

Although the risk reduction factors for chemical j are the same as those for the N3 scenario for carcinogens, weighted aggregation will lead to different values. This subcomponent of the risk has an N3 release scenario but includes transport to the surface and exposure of workers there.

With the symbols

$n_b^{(\kappa)}$ = Number of drums present on average in unsealed waste disposal drifts,
$q_{12j}^{(\kappa)}$ = Quantity of chemical j released per drum and per unit time (mg s^{-1}),
$\Phi_{132}^{(\kappa)}$ = Underground dispersion function for all chemicals (s m^{-3}),
V_2 = Worker respiratory volume per workday (m^3 day^{-1}),
f_{12j} = Transfer probability for absorption of chemical j into body,
M = Receptor body mass (kg),
$L_j^{(ref)}$ = Reference level for chemical j (mg (kg day)$^{-1}$),
r_{oj} = Risk of reference level $L^{(ref)}$,
f_t = Exposure time correction factor for one year (yr^{-1}),
$N_{o3}^{(\kappa)}$ = Number of persons exposed above ground,
C_i = Constant parts of equations, and
$R_{15a\kappa\lambda j}$ = Risk of noncancer health effects per year of operations (yr^{-1}),

the above ground occupational risk of noncancer health effects for N3 operations is

$$R_{15a\kappa\lambda j} = \left\{ n_b^{(\kappa)} \, q_{12j}^{(\kappa)} \right\} \Phi_{132}^{(\kappa)} \, V_2 \, f_{12j} \, N_{o3}^{(\kappa)} \, \frac{1}{M \, L_j^{(ref)}} \, r_{oj} \, f_t \, . \qquad \text{(E.4.41)}$$

With all but the source term constant, the risk can also be written as

$$R_{15a\kappa\lambda j} = C_1 \left\{ n_b^{(\kappa)} \, q_{12j}^{(\kappa)} \right\} , \qquad \text{(E.4.42)}$$

which again results in the same risk reduction factors as those for Component 13

$$\rho_{15a\kappa\lambda j} = \rho_{15o\kappa\lambda j} = \rho_{13o\kappa\lambda j} = \rho_{13p\kappa\lambda j} \, , \qquad \text{(E.4.43)}$$

with standard errors

$$\left(\frac{\Delta \rho_{15a\kappa\lambda j}}{\rho_{15a\kappa\lambda j}} \right)^2 = \left(\frac{\Delta \rho_{15o\kappa j}}{\rho_{15o\kappa j}} \right)^2 = \left(\frac{\Delta F_{v\kappa}}{F_{v\kappa}} \right)^2 + \left(\frac{\Delta F_{c\kappa j}}{F_{c\kappa j}} \right)^2 . \qquad \text{(E.4.44)}$$

The equations for the risk reduction factors and their errors are the same as those for component 13. They are evaluated, however, for noncarcinogenic compounds 4 and 5. The numerical values are listed in Table E.4-7. The values for the baseline risks per year of operation given in the same table are taken from the FSEIS (DOE, 1990a).

The occupational risks for a 20-year operation are obtained from the hazard indices given in FSEIS (DOE, 1990a, Table 5.44) by a division by 20, and converted to annual risks by making

TABLE E.4-7

RISK REDUCTION FACTORS FOR OCCUPATIONAL AND PUBLIC NONCANCER HEALTH EFFECTS FROM N3 ACTIVITIES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
Occupational (Below ground):		
$\rho_{15o1\lambda j}$	0.331 ± 0.034	j = 4, 5
$\rho_{15o2\lambda j}$	0.312 ± 0.032	
$\rho_{15o3\lambda j}$	3740 ± 1420	
$\rho_{15o4\lambda j}$	7070 ± 2260	
Public:		
$\rho_{15p1\lambda j}$	0.600 ± 0.108	
$\rho_{15p2\lambda j}$	0.600 ± 0.108	
$\rho_{15p3\lambda j}$	11000 ± 4500	
$\rho_{15p4\lambda j}$	46500 ± 16400	
Occupational (Above ground):		
$\rho_{15a1\lambda j}$	0.331 ± 0.035	
$\rho_{15a2\lambda j}$	0.312 ± 0.033	
$\rho_{15a3\lambda j}$	3740 ± 1420	
$\rho_{15a4\lambda j}$	7070 ± 2260	
Annual Baseline Risks: *		
Occupational (Below ground):		
R_{15o004}	$9.0 \cdot 10^{-5}$	FSEIS (DOE, 1990a), Table 5.44
R_{15o005}	$1.5 \cdot 10^{-8}$	
Public:		
R_{15p004}	$4.1 \cdot 10^{-10}$	FSEIS (DOE, 1990a), Table 5.44
R_{15p005}	$6.5 \cdot 10^{-12}$	
Occupational (Above ground):		
R_{15a004}	$2.2 \cdot 10^{-9}$	FSEIS (DOE, 1990a), Table 5.44
R_{15a005}	$3.6 \cdot 10^{-11}$	

* The annual baseline risks are obtained from the FSEIS (DOE, 1990a), Table 5.44, by dividing the values listed by 20 years.

the assumption that the risk corresponding to the reference level is 10^{-4} for occupational exposures and 10^{-5} for exposures of the public.

As discussed before, the risk reduction factors for different chemicals are aggregated at this level.

Thus

$$\rho_{15\chi\kappa\lambda} = \sum_{j=4}^{5} g_{15\chi j}\, \rho_{15\chi\kappa\lambda j}\,, \tag{E.4.45}$$

with the weights

$$g_{15\chi j} = \frac{R_{15\chi 00j}}{\sum_{j=4}^{5} R_{15\chi 00j}}\,, \tag{E.4.46}$$

and standard errors

$$(\Delta\rho_{15\chi\kappa\lambda})^2 = \sum_{j=4}^{5} (g_{15\chi j}\, \Delta\rho_{15\chi\kappa\lambda j})^2\,. \tag{E.4.47}$$

Note again that, for factors $\rho_{15o\kappa 3j}$ independent of agent j, this formula is not valid. The replacement is straightforward from a discussion of Equation (E.4.45) for this case.

The numerical values of the baseline risks are given in Table E.4-7, and the final aggregated values in Table E.4-8. For every risk reduction factor, the Level II treatments yield values near 1, whereas Level III treatments have values of several thousands to several tens of thousands. The occupational baseline risk is exceedingly small for underground workers and three to four orders of magnitude smaller for above ground occupational exposures and public exposures.

E.5 RISKS FROM CHEMICAL ACCIDENT EXPOSURES

E.5.1 Basic Considerations

For the accident scenarios involving chemicals, no cancer risks are calculated because the exposure times are too short, i.e., the doses are too low to yield any sizeable effects. Thus only noncancer risks are estimated, which are mostly based on Threshold Limit Values (TLVs) and Immediate Danger to Life and Health (IDLHs) in the FSEIS (DOE, 1990a). Here TLV-based hazard indices will be used exclusively to characterize the low-level occupational risks. These are already very low, so that public risks would be lower still. In these accidents, breaching the containment by losing the lid or piercing the drum is assumed to release the entire gas in the headspace at once, leading to a local exposure of the work crew. For the C10 scenario, the

TABLE E.4-8

AGGREGATED RISK REDUCTION FACTORS FOR NONCARCINOGENIC HEALTH EFFECTS DUE TO N3 ACTIVITIES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
Occupational (Below ground):		
$\rho_{15o1\lambda}$	0.331 ± 0.034	
$\rho_{15o2\lambda}$	0.312 ± 0.032	
$\rho_{15o3\lambda}$	3740 ± 1420	
$\rho_{15o4\lambda}$	7070 ± 2260	
Public:		
$\rho_{15p1\lambda}$	0.600 ± 0.108	
$\rho_{15p2\lambda}$	0.600 ± 0.108	
$\rho_{15p3\lambda}$	11000 ± 4500	
$\rho_{15p4\lambda}$	46500 ± 16400	
Occupational (Above ground):		
$\rho_{15a1\lambda}$	0.331 ± 0.034	
$\rho_{15a2\lambda}$	0.312 ± 0.032	
$\rho_{15a3\lambda}$	3740 ± 1420	
$\rho_{15a4\lambda}$	7070 ± 2260	
Annual Baseline Risks:		
R_{15o00}	$9.15 \cdot 10^{-5}$	Aggregated from data in Table E.4-7
R_{15p00}	$4.17 \cdot 10^{-10}$	
R_{15a00}	$2.24 \cdot 10^{-9}$	

same assumption is made as for the case of radioactivity; the probability of occupational exposure is considered too small, so that neither an occupational nor a public risk is calculated for a C10 accident.

E.5.2 Above Ground Accidents

E.5.2.1 Risk Due To Accident Scenario C2

Dropping a drum from the forklift leads to a loss of lid and liner containment and release of the headspace gas. This is Risk Component 16 with only one sub-component, occupational risk. Using the symbols

P_2 = Probability of C2 accident per forklift operation,
$n_r^{(\kappa)}$ = Number of drums handled routinely per year (yr^{-1}),
$n_f^{(\kappa)}$ = Number of forklift operations per drum handled,
$q_{16j}^{(\kappa)}$ = Quantity of chemical j contained in and released from void space (mg),
$\Phi_{161}^{(\kappa)}$ = Accident dispersion function in WHB and TF for all chemicals (m^{-3}),
$L_j^{(ref)}$ = TLV for chemical j ($mg\ m^{-3}$),
r_{oj} = Risk associated with short term exposure to reference level $L_j^{(ref)}$,
$N_{o1}^{(\kappa)}$ = Number of people in WHB and TF,
f_{15} = Fraction of personnel occupationally exposed,
C_i = Constant parts of equations, and
$R_{16o\kappa\lambda j}$ = Noncancer health risk per year of operation (yr^{-1}),

the occupational risk for a C2 accident is

$$R_{16o\kappa\lambda j} = \left\{ [P_2\ n_r^{(\kappa)}\ n_f^{(\kappa)}]\ q_{16j}^{(\kappa)} \right\} \Phi_{161}^{(\kappa)} \frac{1}{L_j^{(ref)}} f_{15}\ r_{oj}\ N_{o1}^{(\kappa)} . \qquad \text{(E.5.1)}$$

The dispersion function $\Phi_{161}^{(\kappa)}$ is not dependent on waste treatment. Apart from the number of people exposed, the product of the only factors that change is the total mass of gas j contained in the headspace of the drums handled each year

$$R_{16o\kappa\lambda j} = C_1\ n_r^{(\kappa)}\ q_{16j}^{(\kappa)}\ n_f^{(\kappa)}\ N_{o1}^{(\kappa)} . \qquad \text{(E.5.2)}$$

The risk reduction factor is then the product of the volume reduction factor $F_{v\kappa}$, the reduction factor $F_{g\kappa j}$ for the mass of gas in the headspace, defined by

$$F_{g\kappa j} \equiv \frac{q_{16j}^{(0)}}{q_{16j}^{(\kappa)}} , \tag{E.5.3}$$

and the factors $F_{f\kappa}$ and $F_{m\kappa}$,

$$\rho_{16o\kappa\lambda j} = \frac{n_r^{(0)}\, q_{16j}^{(0)}\, n_f^{(0)}\, N_{o1}^{(0)}}{n_r^{(\kappa)}\, q_{16j}^{(\kappa)}\, n_f^{(\kappa)}\, N_{o1}^{(\kappa)}} = F_{v\kappa}\, F_{g\kappa j}\, F_{f\kappa}\, F_{m\kappa} . \tag{E.5.4}$$

The error of the risk reduction factor is

$$\left(\frac{\Delta \rho_{16o\kappa\lambda j}}{\rho_{16o\kappa\lambda j}}\right)^2 = \left(\frac{\Delta F_{v\kappa}}{F_{v\kappa}}\right)^2 + \left(\frac{\Delta F_{g\kappa j}}{F_{g\kappa j}}\right)^2 + \left(\frac{\Delta F_{f\kappa}}{F_{f\kappa}}\right)^2 + \left(\frac{\Delta F_{m\kappa}}{F_{m\kappa}}\right)^2 . \tag{E.5.5}$$

The numerical values for the reduction factors $F_{g\kappa j}$ are listed in Table D.3-8 of Attachment D. Use of these parameters results in the reduction factors in Table E.5-1. The baseline TLV-based hazard indices are taken from Table 5.46 of the FSEIS (DOE, 1990a) and multiplied with a factor of 10^{-4} for conversion to an approximate risk. The accuracy of this factor is of no concern in the weighting because in the method used for the aggregation, all common factors such as this one cancel.

Aggregation of the risk reduction factors for different chemicals is done at this level. For C2 and C3 accidents, the aggregation procedure is the same, and using the symbol i for Components 16 or 17,

$$\rho_{io\kappa\lambda} = \sum_{j=4}^{5} g_{ioj}\, \rho_{io\kappa\lambda j} , \tag{E.5.6}$$

with the weights

$$g_{ioj} = \frac{R_{io00j}}{\sum_{\tau=4}^{5} R_{io00\tau}} , \tag{E.5.7}$$

TABLE E.5-1

VALUES FOR THE REDUCTION FACTORS FOR CHEMICAL EMISSIONS

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{16o1\lambda4}$	3.03 ± 0.49	$\rho_{16o\kappa\lambda4} = \rho_{16o\kappa\lambda5}$
$\rho_{16o2\lambda4}$	3.20 ± 0.52	$\rho_{17o\kappa\lambda j} = \rho_{16o\kappa\lambda j}$
$\rho_{16o3\lambda4}$	$(4.3 \pm 1.1) \cdot 10^{4}$	
$\rho_{16o4\lambda4}$	$(8.2 \pm 1.3) \cdot 10^{4}$	
Annual Baseline Risks: *		
R_{16o004}	$1.7 \cdot 10^{-10}$	FSEIS (DOE, 1990a),
R_{16o005}	$1.0 \cdot 10^{-11}$	Table 5.46
R_{17o004}	$5.0 \cdot 10^{-10}$	FSEIS (DOE, 1990a),
R_{17o005}	$3.1 \cdot 10^{-11}$	Table 5.46

* The values in Table 5.46 of the FSEIS (DOE, 1990a) are multiplied by the risk of 10^{-4} for the occupational reference level.

and the standard errors

$$(\Delta \rho_{i o \kappa \lambda})^2 = \sum_{j=4}^{5} (g_{i o j} \; \Delta \rho_{i o \kappa \lambda j})^2 \; . \qquad \text{(E.5.8)}$$

Note again that this equation is valid only for risk reduction factors that depend on agent j. For j-independent factors, the numerical values of the baseline risks are given in Table E.5-1, and the final aggregated values in Table E.5-2. Here, Level II risk reduction factors lie near 3, and factors for Level III treatments between about 40,000 and 80,000. Relative errors for Level II factors are about 15 percent; for Level III factors they are about 30 percent. The baseline risks are exceedingly small.

E.5.2.2 Risk Due To Accident Scenario C3

In this scenario two drums are punctured by a forklift. The third drum falls and ruptures as a result of the impact. The release of the headspace gases results in Risk Component 17. With the symbols

P_3 = Probability of C3 accident per forklift operation,
$n_r^{(\kappa)}$ = Number of drums handled routinely per year (yr^{-1}),
$n_f^{(\kappa)}$ = Number of forklift operations per drum handled,
n_3 = Number of headspaces vented in C3 accident,
$q_{16j}^{(\kappa)}$ = Quantity of chemical j released from headspace of a drum (mg),
$\Phi_{121}^{(\kappa)}$ = Dispersion function in WHB and TF for all chemicals (m^{-3}),
$L_j^{(ref)}$ = TLV for chemical j ($mg\ m^{-3}$),
r_{oj} = Risk associated with short term exposure to reference level $L_j^{(ref)}$,
$N_{o1}^{(\kappa)}$ = Number of people in WHB and TF,
f_{15} = Fraction of personnel occupationally exposed,
C_1 = Constant parts of equations, and
$R_{17o\kappa\lambda j}$ = Health risk per year of operation (yr^{-1}),

the occupational risk component is

$$R_{17o\kappa\lambda j} = \left\{ [P_3 \; n_r^{(\kappa)} \; n_f^{(\kappa)}] \; n_3 \; q_{16j}^{(\kappa)} \right\} \Phi_{121}^{(\kappa)} \; \frac{1}{L_j^{(ref)}} \; r_{oj} \; f_{15} \; N_{o1}^{(\kappa)} \; . \qquad \text{(E.5.9)}$$

The dispersion function $\Phi_{121}^{(\kappa)}$ is assumed to be independent of treatment. The product of the treatment dependent factors is the total quantity of gas j in the headspace of the drums handled annually multiplied by the number of forklift operations and the number of people exposed. The

TABLE E.5-2

AGGREGATED RISK REDUCTION FACTORS FOR NONCARCINOGENIC CHEMICALS IN C2 ACCIDENTS

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{16o1\lambda}$	3.03 ± 0.49	$\rho_{16o\kappa\lambda j} = \rho_{17o\kappa\lambda j}$
$\rho_{16o2\lambda}$	3.20 ± 0.52	
$\rho_{16o3\lambda}$	$(4.3 \pm 1.1) \cdot 10^{4}$	
$\rho_{16o4\lambda}$	$(8.2 \pm 1.3) \cdot 10^{4}$	
Annual Baseline Risks:		
R_{16o00}	$1.8 \cdot 10^{-10}$	Aggregated from data in Table E.5-1
R_{17o00}	$5.3 \cdot 10^{-10}$	

risk component scales as

$$R_{17o\kappa\lambda j} = C_1 \; n_r^{(\kappa)} \; q_{16j}^{(\kappa)} \; n_f^{(\kappa)} \; N_{o1}^{(\kappa)} \; . \qquad \text{(E.5.10)}$$

This is the same dependence as the one for Component 16. The risk reduction factor is, therefore,

$$\rho_{17o\kappa\lambda j} = \rho_{16o\kappa\lambda j} \; , \qquad \text{(E.5.11)}$$

and its error

$$\Delta\rho_{17o\kappa\lambda j} = \Delta\rho_{16o\kappa\lambda j} \; . \qquad \text{(E.5.12)}$$

The numerical values for the risk reduction factors are given in Table E.5-2 for Component 16. The baseline risks are derived from the values given in Table 5.46 of the FSEIS (DOE, 1990a, p. 5-99) by means of multiplication by an occupational reference level risk of 10^{-4}. Due to different weighting, the aggregated values in Table E.5-2 are different for the two risk reduction factors.

E.5.3 Underground Accidents

E.5.3.1 Risk Due To Accident Scenario C4

In this scenario a drum drops and loses its lid and the integrity of the liner due to the collision of a transporter with a pallet of drums. This leads to Risk Component 18, which, using the symbols

P_4 = Probability of C4 accident per forklift operation,
$n_r^{(\kappa)}$ = Number of drums handled routinely per year (yr^{-1}),
$n_f^{(\kappa)}$ = Number of forklift operations per drum handled,
n_4 = Number of headspaces vented in C4 accident,
$q_{16j}^{(\kappa)}$ = Quantity of chemical j released from headspace of a drum (mg),
$\Phi_{141}^{(\kappa)}$ = Underground dispersion function for all chemicals (m^{-3}),
$L_j^{(ref)}$ = TLV for chemical j ($mg\ m^{-3}$),
r_{oj} = Risk associated with short term exposure to reference level $L_j^{(ref)}$,
$N_{o2}^{(\kappa)}$ = Number of people exposed in Underground Storage Area,
C_1 = Constant parts of equations, and
$R_{18o\kappa\lambda j}$ = Health risk per year of operation (yr^{-1}),

leads to an occupational risk of a C4 accident of

$$R_{18o\kappa\lambda j} = \left\{ [P_4\ n_r^{(\kappa)}\ n_f^{(\kappa)}]\ n_4\ q_{16j}^{(\kappa)} \right\} \Phi_{141}^{(\kappa)}\ \frac{1}{L_j^{(ref)}}\ r_{oj}\ N_{o2}^{(\kappa)}\ . \qquad \text{(E.5.13)}$$

The factors $n_f^{(\kappa)}$ and $\Phi_{141}^{(\kappa)}$ are assumed to be constant, and the variable part is the total annual headspace at risk. The risk thus scales as

$$R_{18o\kappa\lambda j} = C_1\ n_r^{(\kappa)}\ q_{16j}^{(\kappa)}\ , \qquad \text{(E.5.14)}$$

and the risk reduction factor is

$$\rho_{18o\kappa\lambda j} = \frac{n_r^{(0)}\ q_{16j}^{(0)}}{n_r^{(\kappa)} q_{16j}^{(\kappa)}} = F_{v\kappa}\ F_{g\kappa j}\ , \qquad \text{(E.5.15)}$$

with standard errors

$$\left(\frac{\Delta \rho_{18o\kappa\lambda j}}{\rho_{18o\kappa\lambda j}} \right) = \left(\frac{\Delta F_{v\kappa}}{F_{v\kappa}} \right)^2 + \left(\frac{\Delta F_{g\kappa j}}{F_{g\kappa j}} \right)^2 . \qquad \text{(E.5.16)}$$

The numerical values of the risk reduction factors and the baseline risks derived from Table 5.46 of the FSEIS (DOE, 1990a) are listed in Table E.5-3.

Again, aggregation of the risk reduction factors for different chemicals is done at this level. For C4, C5, and C6 accidents, the aggregation procedure is the same, and using the symbol i for Components 18, 19, or 20,

$$\rho_{io\kappa\lambda} = \sum_{j=4}^{5} g_{ioj}\ \rho_{io\kappa\lambda j}\ , \qquad \text{(E.5.17)}$$

with the weights

$$g_{ioj} = \frac{R_{io00j}}{\sum_{\tau=4}^{5} R_{io00\tau}}\ , \qquad \text{(E.5.18)}$$

TABLE E.5-3

VALUES FOR THE REDUCTION FACTORS FOR CHEMICAL EMISSIONS DURING ACCIDENTS C4, C5, AND C6

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{18o1\lambda4}$	21.2 ± 3.2	$\rho_{18o\kappa\lambda4} = \rho_{18o\kappa\lambda5}$
$\rho_{18o2\lambda4}$	21.2 ± 3.2	$\rho_{19o\kappa\lambda j} = \rho_{18o\kappa\lambda j}$
$\rho_{18o3\lambda4}$	$(3.96 \pm 1.00) \cdot 10^{5}$	$\rho_{20o\kappa\lambda j} = \rho_{18o\kappa\lambda j}$
$\rho_{18o4\lambda4}$	$(1.67 \pm 0.25) \cdot 10^{6}$	
Annual Baseline Risks: *		
R_{18o004}	$2.4 \cdot 10^{-10}$	FSEIS (DOE, 1990a),
R_{18o005}	$1.5 \cdot 10^{-11}$	Table 5.46
R_{19o004}	$2.4 \cdot 10^{-10}$	FSEIS (DOE, 1990a),
R_{19o005}	$1.5 \cdot 10^{-11}$	Table 5.46
R_{20o004}	$7.2 \cdot 10^{-10}$	FSEIS (DOE, 1990a),
R_{20o005}	$4.5 \cdot 10^{-11}$	Table 5.46

* The values in Table 5.46 of the FSEIS (DOE, 1990a) are multiplied by the risk of 10^{-4} for the occupational reference level.

and standard errors

$$(\Delta \rho_{i o \kappa \lambda})^2 = \sum_{j=4}^{5} (g_{i o j} \; \Delta \rho_{i o \kappa \lambda j})^2 \; . \qquad \text{(E.5.19)}$$

The numerical values of the baseline risks are given in Table E.5-3, and the final aggregated values in Table E.5-4. The risk reduction factors are about 21 for Level II treatments, about 400,000 for Treatment 3 and about 1.7 million for Treatment Alternative 4. These factors are applied to exceedingly small baseline risks of several times 10^{-10}.

E.5.3.2 Risk Due to Accident Scenario C5

A C5 accident in Risk Component 19 is essentially the same event as a C4 accident, except that the cause is a drop off a forklift. Apart from the probability of a C5 accident per forklift operation, all the factors are, therefore, the same as Component 18, i.e., as for the C4 accident. Thus

$$\rho_{19 o \kappa \lambda j} = \rho_{18 o \kappa \lambda j} \; , \qquad \text{(E.5.20)}$$

and

$$\Delta \rho_{19 o \kappa \lambda j} = \Delta \rho_{18 o \kappa \lambda j} \; . \qquad \text{(E.5.21)}$$

The risk reduction factors are thus given by Table E.5-3 and the baseline risks are the values given there. The aggregated risk reduction factors are given in Table E.5-4.

E.5.3.3 Risk Underground Due To Accident Scenario C6

In this scenario, leading to Risk Component 20, the headspaces of three drums are vented, because two are pierced and one loses its lid. Except for the probability of a C6 accident per forklift operation and the number of headspaces vented, all the factors are the same as for Components 18 and 19. Consequently, the risk reduction factors are the same as for the C3 accident of Component 18. Thus

$$\rho_{20 o \kappa \lambda j} = \rho_{18 o \kappa \lambda j} \; , \qquad \text{(E.5.22)}$$

and

$$\Delta \rho_{20 o \kappa \lambda j} = \Delta \rho_{18 o \kappa \lambda j} \; . \qquad \text{(E.5.23)}$$

The risk reduction factors are thus given in Table E.5-3 and the baseline risks shown there are derived from Table 5.46 of the FSEIS (DOE, 1990a), which gives estimated daily intakes at the receptor location in mg (kg day)$^{-1}$. The aggregated risk reduction factors are given in Table E.5-4.

TABLE E.5-4

AGGREGATED RISK REDUCTION FACTORS FOR NONCARCINOGENIC CHEMICALS IN C4, C5, AND C6 ACCIDENTS

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{18o1\lambda}$	21.2 ± 3.2	$\rho_{19o\kappa\lambda j} = \rho_{18o\kappa\lambda j}$
$\rho_{18o2\lambda}$	21.2 ± 3.2	$\rho_{20o\kappa\lambda j} = \rho_{18o\kappa\lambda j}$
$\rho_{18o3\lambda}$	$(3.96 \pm 1.00) \cdot 10^{5}$	
$\rho_{18o4\lambda}$	$(1.67 \pm 0.25) \cdot 10^{6}$	
Annual Baseline Risks:		
R_{18000}	$2.6 \cdot 10^{-10}$	Aggregated from data in Table E.5-3
R_{19000}	$2.6 \cdot 10^{-10}$	
R_{20000}	$7.7 \cdot 10^{-10}$	

E.6 PROPERTIES OF TRANSPORTATION RISKS

E.6.1 Basic Considerations

The transportation risk calculated in the FSEIS and in this study are based on the transportation risk methodology found in RADTRAN III (Madsen et al., 1986). RADTRAN III is a revised version of the RADTRAN code (Taylor and Daniel, 1977) which was developed in conjunction with the Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Means (USNRC 1977b). RADTRAN III combines meteorological, demographic, health physics, economic, transportation, packaging, and material factors to obtain the expected radiological risks resulting from transportation of radioactive material.

Two principal computations are performed by the code: the radiological impact due to "incident free" transport and due to vehicular accidents. There are several submodels used in the RADTRAN III code. The material model describes the physical character of the waste and measures the radiotoxicity of the dispersed materials. The transportation model used in RADTRAN III describes accident rates, traffic patterns, and shipment information. Accident rates are given for types of accident and population zone in which they occur. The traffic patterns contain the fraction of travel which occurs on various types of road, population zones, and time of day. The shipment information gives the number of persons per vehicle, separation distances, and timing data.

An accident severity and package release model describes eight categories of accident severity and the fractional release of material from packaging and determines the expected release of each accident. An atmospheric dispersion model uses basic dispersion calculations provided by the user to evaluate concentrations at receptor sites.

The population distribution model specifies population densities in three population zones, rural, suburban, and urban, as well as certain other areas such as pedestrian walkways. The health effects model, finally, considers health effects due to exposure to different radiations such as early fatalities, early morbidities, latent cancer fatalities, and genetic effects.

In transportation, the treatment alternative κ influences the risks mostly through the effect of waste volume reduction on the number of transports and through the reduction of the suspension fraction of wastes in an accident; the location option λ exerts influence mainly through the partition of the total distance, from the originator to the WIPP into the portion travelled as untreated waste and the portion covered as treated waste.

The largest transportation risks are those incurred in traffic accidents in which the TRUPACT-II transport is involved but its containment not breached. The risks are, therefore, those of normal traffic accidents involving truck transports. In the FSEIS, recent studies made in 23 states were considered in this context and systemwide averages computed. As the different location options

involve additional transport in the same general area, it is a reasonable assumption that the extra transportation distances do not alter these averages in an appreciable way.

The risk formulae in this section are those coded in RADTRAN III, generalized to yield the corresponding risks for treated and untreated wastes. In the FSEIS, transportation risks were estimated using an earlier version, RADTRAN II (Madsen, et al, 1983). The parameter values used for the calculations in this section are listed in Tables E.6-1a and E.6-1b.

E.6.2 Risk of Traffic Accidents

E.6.2.1 Risk Of Fatalities

Traffic fatalities, involving the TRUPACT-II transport, its crew, and both members and vehicles of the general population, are modeled to be proportional to the total distance traveled. This results in Risk Component 21 which is expressed with the symbols

p_a	=	Probability density of a fatal accident per unit length of road (m^{-1}),
Ω	=	Number of waste producers,
$L_{0\omega}^{(\lambda)}$	=	Distance traveled as untreated waste from originator ω (m),
$L_{1\omega}^{(\lambda)}$	=	Distance traveled as treated waste from originator ω (m),
$L_{t\omega}^{(\lambda)}$	=	Total transport distance for originator ω in location option λ (m),
$f_{21\omega}$	=	Fraction of total annual waste produced by originator ω,
$n_t^{(\kappa)}$	=	Number of transports per year for treatment option κ (yr^{-1}),
$F_{t\kappa}$	=	Transport reduction factor for treatment κ, and
$R_{21pk\lambda}$	=	Annual risk of traffic fatalities (yr^{-1}),

in the equation

$$R_{21p\kappa\lambda} = p_a \sum_{\omega=1}^{\Omega} f_{21\omega} \left\{ L_{0\omega}^{(0)} n_t^{(0)} + L_{1\omega}^{(\lambda)} n_t^{(\kappa)} \right\} . \qquad \text{(E.6.1)}$$

TABLE E.6-1a

RADTRAN GENERAL INPUT DATA

SYMBOL	PARAMETER	CH TRU TRUCK
N_{o3}	Number of crewmen	2
N_{p1}	Number of people exposed while stopped	50
N_{p2}	Number of people per vehicle	2
τ	Time to catch up to TRUPACT-II (seconds)	2
v_i	Speed (km/hr):	
v_3	Urban population zone	24
v_2	Suburban population zone	40
v_1	Rural population zone	88
d_i	Population density, people/km^2	
d_3	Urban population zone	3861
d_2	Suburban population zone	719
d_1	Rural population zone	6
$r_{max\,i}$	r max (m):	
$r_{max\,3}$	Urban population zone	800
$r_{max\,2}$	Suburban population zone	800
$r_{max\,1}$	Rural population zone	800
$r_{min\,i}$	r min (m):	
$r_{min\,3}$	Urban population zone	5
$r_{min\,2}$	Suburban population zone	27
$r_{min\,1}$	Rural population zone	27
$N_{25\,i}$	One-way traffic count (vehicles/hr):	
$N_{25\,3}$	Urban population zone	2800
$N_{25\,2}$	Suburban population zone	780
$N_{25\,1}$	Rural population zone	470

TABLE E.6-1b
LIST OF RADTRAN PARAMETERS USED IN THIS STUDY

PARAMETER	INEL	RFP	HANFORD	SRS	LANL	ORNL	NTS	ANL-E	LLNL	MOUND
$L_{1\omega}^{(\lambda)}$ (km)										
$L_{1\omega}^{(0)}$	2433.6	1398.4	3060.8	2536.0	548.8	2160.0	2057.6	2219.2	2332.8	2355.2
$L_{1\omega}^{(1)}$	2433.6	1398.4	3060.8	2536.0	548.8	2160.0	2057.6	2219.2	2332.8	2355.2
$L_{1\omega}^{(2)}$	2433.6	1398.4	3363.2	2536.0	548.8	2160.0	2057.6	2219.2	2332.8	2355.2
$L_{1\omega}^{(3)}$	2433.6	1398.4	3060.8	2536.0	548.8	2920.0	2057.6	3763.2	2332.8	3422.4
$L_{1\omega}^{(4)}$	2433.6	1398.4	3060.8	2536.0	548.8	2160.0	2057.6	2219.2	2332.8	2355.2
$L_{1\omega}^{(\lambda)}$ (km)										
$L_{1\omega}^{(0)}$	0	0	0	0	0	0	0	0	0	0
$L_{1\omega}^{(1)}$	0	0	0	0	0	0	0	0	0	0
$L_{1\omega}^{(2)}$	2433.6	1398.4	2433.6	0	0	0	0	0	0	0
$L_{1\omega}^{(3)}$	2433.6	1398.4	3060.8	2536.0	0	2536.0	0	2536.0	0	2536.0
$L_{1\omega}^{(4)}$	2433.6	1398.4	3060.8	2536.0	548.8	2160.0	0	0	0	0
$L_{0\omega}^{(\lambda)}$ (km)										
$L_{0\omega}^{(0)}$	2433.6	1398.4	3060.8	2536.0	548.8	2160.0	2057.6	2219.2	2332.8	2355.2
$L_{0\omega}^{(1)}$	2433.6	1398.4	3060.8	2536.0	548.8	2160.0	2057.6	2219.2	2332.8	2355.2
$L_{0\omega}^{(2)}$	0	0	929.6	2536.0	548.8	2160.0	2057.6	2219.2	2332.8	2355.2
$L_{0\omega}^{(3)}$	0	0	0	0	548.8	384.0	2057.6	1227.2	2332.8	886.4
$L_{0\omega}^{(4)}$	0	0	0	0	0	0	2057.6	2219.2	2332.8	2355.2
$f_{11\omega}^{(\lambda)}$										
$f_{11\omega}^{(0)}$	0	0	0	0	0	0	0	0	0	0
$f_{11\omega}^{(1)}$	0	0	0	0	0	0	0	0	0	0
$f_{11\omega}^{(2)}$	0.85	0.823	0.85	0	0	0	0	0	0	0
$f_{11\omega}^{(3)}$	0.85	0.823	0.857	0.743	0	0.743	0	0.743	0	0.743
$f_{11\omega}^{(4)}$	0.85	0.823	0.857	0.743	0.901	0.786	0	0	0	0

TABLE E.6-1b
LIST OF RADTRAN PARAMETERS USED IN THIS STUDY
(CONTINUED)

PARAMETER	INEL	RFP	HANFORD	SRS	LANL	ORNL	NTS	ANL-E	LLNL	MOUND
$f_{12\omega}^{(\lambda)}$										
$f_{12\omega}^{(0)}$	0	0	0	0	0	0	0	0	0	0
$f_{12\omega}^{(1)}$	0	0	0	0	0	0	0	0	0	0
$f_{12\omega}^{(2)}$	0.138	0.157	0.138	0	0	0	0	0	0	0
$f_{12\omega}^{(3)}$	0.138	0.157	0.134	0.251	0	0.251	0	0.251	0	0.251
$f_{12\omega}^{(4)}$	0.138	0.157	0.134	0.251	0.099	0.207	0	0	0	0
$f_{13\omega}^{(\lambda)}$										
$f_{13\omega}^{(0)}$	0	0	0	0	0	0	0	0	0	0
$f_{13\omega}^{(1)}$	0	0	0	0	0	0	0	0	0	0
$f_{13\omega}^{(2)}$	0.012	0.02	0.012	0	0	0	0	0	0	0
$f_{13\omega}^{(3)}$	0.012	0.02	0.009	0.006	0	0.006	0	0.006	0	0.006
$f_{13\omega}^{(4)}$	0.012	0.02	0.009	0.006	0	0.007	0	0	0	0
$f_{01\omega}^{(\lambda)}$										
$f_{01\omega}^{(0)}$	0.85	0.823	0.857	0.743	0.901	0.786	0.868	0.781	0.862	0.754
$f_{01\omega}^{(1)}$	0.85	0.823	0.857	0.743	0.901	0.786	0.868	0.781	0.862	0.754
$f_{01\omega}^{(2)}$	0	0	0.852	0.743	0.901	0.786	0.868	0.781	0.862	0.754
$f_{01\omega}^{(3)}$	0	0	0	0	0.901	0.766	0.868	0.766	0.862	0.766
$f_{01\omega}^{(4)}$	0	0	0	0	0	0	0.868	0.781	0.862	0.754
$f_{02\omega}^{(\lambda)}$										
$f_{02\omega}^{(0)}$	0.138	0.157	0.134	0.251	0.099	0.207	0.112	0.218	0.101	0.241
$f_{02\omega}^{(1)}$	0.138	0.157	0.134	0.251	0.099	0.207	0.112	0.218	0.101	0.241
$f_{02\omega}^{(2)}$	0	0	0.1284	0.251	0.099	0.207	0.112	0.218	0.101	0.241
$f_{02\omega}^{(3)}$	0	0	0	0	0.099	0.2293	0.112	0.2293	0.101	0.2293
$f_{02\omega}^{(4)}$	0	0	0	0	0	0	0.112	0.218	0.101	0.241

TABLE E.6-1b
LIST OF RADTRAN PARAMETERS USED IN THIS STUDY
(CONTINUED)

PARAMETER	INEL	RFP	HANFORD	SRS	LANL	ORNL	NTS	ANL-E	LLNL	MOUND
$f_{03\omega}^{(\lambda)}$										
$f_{03\omega}^{(0)}$	0.012	0.02	0.009	0.006	0	0.007	0.02	0.001	0.037	0.005
$f_{03\omega}^{(1)}$	0.012	0.02	0.009	0.006	0	0.007	0.02	0.001	0.037	0.005
$f_{03\omega}^{(2)}$	0	0	0.0196	0.006	0	0.007	0.02	0.001	0.037	0.005
$f_{03\omega}^{(3)}$	0	0	0	0	0	0.0048	0.02	0.0048	0.037	0.0048
$f_{03\omega}^{(4)}$	0	0	0	0	0	0	0.02	0.001	0.037	0.005
$f_{25i\omega}^{(\lambda)}$										
$f_{251\omega}$	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
$f_{252\omega}$	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
$f_{253\omega}$	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
$g_{25i\omega}$										
$g_{252\omega}$	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
$g_{253\omega}$	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
$h_{25i\omega}$										
$h_{252\omega}$	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
$h_{253\omega}$	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
$f_{21\omega}$	0.194	0.365	0.148	0.126	0.099	0.011	0.004	0.001	0.046	0.007

The form for the risk reduction factor is thus

$$\rho_{21\,p\kappa\lambda} = \frac{n_t^{(0)} \sum_{\omega=1}^{\Omega} f_{21\,\omega}\, L_{t\omega}^{(0)}}{\sum_{\omega=1}^{\Omega} f_{21\,\omega} \left(L_{0\omega}^{(\lambda)}\, n_t^{(0)} + L_{1\omega}^{(\lambda)}\, n_t^{(\kappa)} \right)}$$

$$= \frac{\sum_{\omega=1}^{\Omega} f_{21\,\omega}\, L_{t\omega}^{(0)}}{\sum_{\omega=1}^{\Omega} f_{21\,\omega} \left(L_{0\omega}^{(\lambda)} + L_{1\omega}^{(\lambda)} \frac{1}{F_{t\kappa}} \right)} \equiv \frac{V_{21\,00}}{V_{21\,\kappa\lambda}} \,. \tag{E.6.2}$$

The definition of the quantities $V_{21\,\kappa\lambda}$ in the last part of the equation are needed for the error calculations. Assuming that the errors of the distances and the waste fractions are much smaller than the error of the transport reduction factor, only the latter need be considered (see Attachment C, Equation C.1.26). The standard error of the risk reduction factor for this case is then

$$\left(\frac{\Delta \rho_{21\,p\kappa\lambda}}{\rho_{21\,p\kappa\lambda}} \right) = \frac{\Delta F_{t\kappa}}{V_{21\,\kappa\lambda}\, F_{t\kappa}^2} \sum_{\omega=1}^{\Omega} f_{21\,\omega}\, L_{1\omega}^{(\lambda)} \,. \tag{E.6.3}$$

The risk reduction factors for the four treatment alternatives and the four location options are given in Table E.6-2. The values of the risk reduction factors for Location Option 1 (TF at the WIPP) are equal to 1 because the transports are the same as those in the baseline case. For Level II treatments, there is an increase in this risk component; for Treatment 3, the risk component is about constant, whereas for Treatment Option 4, there are modest risk reductions of factors 2 or 3. These reductions, however, are applied to the largest baseline risk components and are thus of great importance.

E.6.2.2 Risk Of Injuries

The expression for Risk Component 22, evaluating the risk of traffic injuries in accidents involving the TRUPACT-II, is the same as Equation (E.6.1) except for the linear probability density for accident injuries, p_i, that replaces the probability density p_a for fatal accidents. The risk reduction factors are, therefore, the same and are given in Table E.6-2. The baseline risk component for traffic injuries, on the other hand, is given by the value taken from the FSEIS executive summary, divided by 20 to obtain a risk per year of operation, reduced to apply for CH-TRU waste only, and entered in Table E.6-2.

TABLE E.6-2

RISK REDUCTION FACTORS AND BASELINE RISK OF TRAFFIC DEATHS AND INJURIES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{21\,p\,11}$	1	$\rho_{22\,p\,\kappa\,\lambda} = \rho_{21\,p\,\kappa\,\lambda}$
$\rho_{21\,p\,12}$	0.760 ± 0.048	
$\rho_{21\,p\,13}$	0.714 ± 0.057	
$\rho_{21\,p\,14}$	0.715 ± 0.058	
$\rho_{21\,p\,21}$	1	
$\rho_{21\,p\,22}$	0.720 ± 0.042	
$\rho_{21\,p\,23}$	0.666 ± 0.048	
$\rho_{21\,p\,24}$	0.666 ± 0.049	
$\rho_{21\,p\,31}$	1	
$\rho_{21\,p\,32}$	1.10 ± 0.17	
$\rho_{21\,p\,33}$	1.17 ± 0.26	
$\rho_{21\,p\,34}$	1.18 ± 0.27	
$\rho_{21\,p\,41}$	1	
$\rho_{21\,p\,42}$	2.00 ± 0.06	
$\rho_{21\,p\,43}$	3.27 ± 0.21	
$\rho_{21\,p\,44}$	3.51 ± 0.25	
Annual Baseline Risks:		
$R_{21\,p\,00}$	0.2	FSEIS (DOE, 1990a),
$R_{22\,p\,00}$	3	Table D.4.6, p. D-108

E.6.3 Cancer Risk From Routine Transportation Radiation Exposures

E.6.3.1 Basic Considerations

Incident-free radiological risks occur during routine transportation and are the result of public and occupational exposures to external radiation far below regulatory levels. These low doses will fall below natural background radiation levels (DOE, 1990a, D.3.2.2, p. D-62).

The public may be exposed during stops, near the road taken by the TRUPACT-II transport, or from travelling in the same or opposite direction from the transport. Routine occupational exposures result from external radiation from the transportation itself, during waste handling procedures and also exposures to warehouse personnel. The above-mentioned radiological exposures result from exposure to untreated waste. Even when the waste is treated, the source term (activity) will dictate the risk. It is assumed here that there is no shielding or self-attenuation of gamma radiation in either the treated or the untreated waste.

Due to the assumption that the total annual activity handled is independent of treatment,

$$Q_o = q_2^{(\kappa)} \, n_d^{(\kappa)} \, n_t^{(\kappa)} = const \, , \qquad \text{(E.6.4)}$$

where $q_2^{(\kappa)}$ is the average activity per drum, $n_d^{(\kappa)}$ is the number of drums in the TRUPACT-II container, and $n_t^{(\kappa)}$ is the number of annual TRUPACT-II transports, and Q_o is the total activity produced, handled, and emplaced in the WIPP in an equilibrium situation. In essence, this is thus the same condition as the one expressed by Equation (E.1.5). Weight limitations are introduced in post-treatment transportation by the transportation reduction factor.

E.6.3.2 Cancer Risk To Public Near Road Taken by TRUPACT-II Transports

The public near the roads travelled by the TRUPACT-II transports is routinely exposed to the penetrating part of the radioactivity. The corresponding cancer and genetic risks are the two subcomponents of Risk Component 23. The symbols used in modeling this component are:

$q_2^{(\kappa)}$	=	Total activity per drum (Bq),
$n_d^{(\kappa)}$	=	Number of drums per TRUPACT-II transport (3 TRUPACT-II containers, 42 drums),
$n_t^{(\kappa)}$	=	Number of shipments per year (yr^{-1}),
$f_{21\omega}$	=	Fraction of waste generated by originator ω,
Ω	=	Number of originators,
$L_{0\omega}^{(\lambda)}$	=	Distance travelled as untreated waste from originator ω (m),
$L_{1\omega}^{(\lambda)}$	=	Distance travelled as treated waste from originator ω (m),
$L_{t\omega}^{(\lambda)}$	=	Total distance travelled for originator ω and location option λ (m),
Φ_{23}	=	TRUPACT-II's source shape function,
K_0	=	Dose-Rate Conversion factor for point source ($Sv\ s^{-1}\ Bq^{-1}\ m^2$),

v_i = Transport speed in area i (m s^{-1}),
$f_{0i\omega}^{(\lambda)}$ = Fraction of travel as untreated waste from originator ω in area i,
$f_{1i\omega}^{(\lambda)}$ = Fraction of travel as treated waste from originator ω in area i,
d_i = Population density in area i (m^{-2}),
$r_{i,min}$ = Minimum distance to TRUPACT-II centerline (m),
$r_{i,max}$ = Maximum distance to TRUPACT-II centerline (m),
a_1 = Cancer risk factor (Sv^{-1}),
C_j = Constant parts of equations,
$R_{23p\kappa\lambda}$ = Annual cancer risk for transportation for treatment/location option k (yr^{-1}), with
Index for rural areas i = 1,
Index for suburban areas i = 2,
Index for urban areas i = 3,

and the expression for this risk component is

$$R_{23p\kappa\lambda} = \left\{ q_2^{(0)}\, n_d^{(0)}\, n_t^{(0)} \right\} K_0\, \Phi_{23}\, a_1 \sum_{\omega=1}^{\Omega} f_{21\omega} \sum_{i=1}^{3} \frac{d_i}{v_i}\, ln\left(\frac{r_{i,max}}{r_{i,min}}\right)\left[f_{0i\omega}^{(\lambda)} L_{0\omega}^{(\lambda)} + f_{1i\omega}^{(\lambda)} L_{1\omega}^{(\lambda)} \right]. \tag{E.6.5}$$

Note that the source term is independent of treatment due to Equation (E.6.4) and appears, therefore, in front of the sums. Thus, the risk scales according to

$$R_{23p\kappa\lambda} = C_1 \sum_{\omega=1}^{\Omega} f_{21\omega} \sum_{i=1}^{3} \frac{d_i}{v_i}\, ln\left(\frac{r_{i,max}}{r_{i,min}}\right)\left[f_{0i\omega}^{(\lambda)} L_{0\omega}^{(\lambda)} + f_{1i\omega}^{(\lambda)} L_{1\omega}^{(\lambda)} \right], \tag{E.6.6}$$

and with the relationship

$$L_{0\omega}^{(\lambda)} + L_{1\omega}^{(\lambda)} = L_{t\omega}^{(\lambda)}, \tag{E.6.7}$$

arising from the definitions of the quantities, as well as the fact that for the baseline case all travel is done with untreated waste, the risk reduction factors are

$$\rho_{23p\kappa\lambda} = \frac{\sum_{\omega=1}^{\Omega} f_{21\omega} L_{t\omega}^{(0)} \sum_{i=1}^{3} \frac{d_i}{v_i}\, ln\left(\frac{r_{i,max}}{r_{i,min}}\right) f_{0i\omega}^{(0)}}{\sum_{\omega=1}^{\Omega} f_{21\omega} \sum_{i=1}^{3} \frac{d_i}{v_i}\, ln\left(\frac{r_{i,max}}{r_{i,min}}\right)\left[f_{0i\omega}^{(\lambda)} L_{0\omega}^{(\lambda)} + f_{1i\omega}^{(\lambda)} L_{1\omega}^{(\lambda)} \right]}. \tag{E.6.8}$$

These risk reduction factors are independent of the treatment option κ, but do depend explicitly on the location parameters λ.

The uncertainty of the risk reduction factor arises mostly from the population densities d_i and the speeds v_i in the various areas i. The rest of the parameters are geometrical or based on waste statistics and have much smaller standard errors. The uncertainties of the quantities d_i and v_i enter both in numerator and denominator and thus tend to cancel in part. As the resulting uncertainty in these risk reduction factors is much smaller than those in others, they will not be evaluated in detail but set at a few percent. The errors are then estimated to be

$$\left(\frac{\Delta \rho_{23p\kappa\lambda}}{\rho_{23p\kappa\lambda}} \right) = 0.03 \ . \qquad \text{(E.6.9)}$$

The risk reduction factors have to be assembled from the values for the ten originators ω. They are given in Table E.6-3, with the values for the baseline risks from Table D.3.14 of the FSEIS (DOE, 1990a).

The numerical values for the risk reduction factors are about unity for all treatments. This is understandable, considering the fact that the same amount of radioactivity is being transported over slightly different routes, except for $\lambda = 1$ and 4, where the same routes result in a reduction factor of 1. The baseline risk of about 1 in three million for the public along the route is very small.

E.6.3.3 Cancer Risk To Public During Stops

During stops along the highway, the members of the public using the same facility as the TRUPACT-II transport, are exposed to the penetrating part of the total activity. Their cancer risk is Risk Component 24, and with the definitions:

$q_2^{(\kappa)}$	=	Total activity per drum (Bq),
$n_d^{(\kappa)}$	=	Number of drums per TRUPACT-II transport,
$n_t^{(\kappa)}$	=	Number of shipments per year (yr^{-1}),
Ω	=	Number of originators,
$f_{21\omega}$	=	Fraction of waste generated by originator ω,
$L_{0\omega}^{(\lambda)}$	=	Distance travelled as untreated waste from originator ω (m),
$L_{1\omega}^{(\lambda)}$	=	Distance travelled as treated waste from originator ω (m),
$L_{t\omega}^{(\lambda)}$	=	Total distance travelled for originator ω and location option λ (m),
L_s	=	Average distance between stops (m),
K_0	=	Dose-Rate Conversion factor for point source ($Sv\ s^{-1}\ Bq^{-1}\ m^2$),
Φ_{241}	=	Dosimetry function of rms of inverse distance (m^{-2}),
N_{p1}	=	Average number of persons exposed at rest stops,
Δt_s	=	Average time spent at rest stops (s),

TABLE E.6-3

RISK REDUCTION FACTORS FOR ROUTINE TRANSPORTATION EXPOSURES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{23\ p\kappa 1}$	1.00 ± 0.03	
$\rho_{23\ p\kappa 2}$	0.94 ± 0.03	
$\rho_{23\ p\kappa 3}$	0.99 ± 0.03	
$\rho_{23\ p\kappa 4}$	1.00 ± 0.03	
Annual Baseline Risks:		
$R_{23\ p00}$	$3.6 \cdot 10^{-7}$	FSEIS (DOE, 1990a), Table D.3.14

a_1 = Cancer risk factor (Sv^{-1}),
C_i = Constant parts of equations, and
$R_{24\,p\,\kappa\,\lambda}$ = Cancer risk for exposures at rest stops for option $k = (\kappa,\lambda)$ per year of operation (yr^{-1}),

the cancer risk component is

$$R_{24\,p\,\kappa\lambda} = \left\{ q_2^{(0)}\, n_d^{(0)}\, n_t^{(0)} \right\} \frac{K_0}{L_s}\, \Phi_{24\,1}\, N_{p1}\, \Delta t_s\, a_1 \sum_{\omega=1}^{\Omega} f_{21\,\omega} \left(L_{0\omega}^{(\lambda)}\, L_{1\omega}^{(\lambda)} \right) . \tag{E.6.10}$$

As the terms in the first row are all independent of the treatment/location options and using Equation (E.6.7) the risk can be scaled as

$$R_{24\,p\,\kappa\lambda} = C_1 \sum_{\omega=1}^{\Omega} f_{21\,\omega}\, L_{t\omega}^{(\lambda)} . \tag{E.6.11}$$

The risk reduction coefficients are then again independent of treatment

$$\rho_{24\,p\,\kappa\lambda} = \frac{\sum_{\omega=1}^{\Omega} f_{21\,\omega}\, L_{t\omega}^{(0)}}{\sum_{\omega=1}^{\Omega} f_{21\,\omega}\, L_{t\omega}^{(\lambda)}} , \tag{E.6.12}$$

with the standard error

$$\left(\frac{\Delta \rho_{24\,p\,\kappa\lambda}}{\rho_{24\,p\,\kappa\lambda}} \right) = 0.01 , \tag{E.6.13}$$

estimated again under the assumption that well known data on road and waste are used in a way in which the uncertainties largely cancel. The numerical values of the parameters have been taken from the RADTRAN III code (Madsen et al., 1986) and are tabulated in Table E.6-1. Use of these parameters leads to the numerical values given in Table E.6-4. They lie very closely to 1 as in Component 23, reflecting small changes in total route lengths. The baseline risk is relatively small.

TABLE E.6-4

RISK REDUCTION FACTORS FOR PUBLIC RISKS AT STOPS AND FOR SOME ACCIDENTS

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{24\,p\kappa 1}$	1.00 ± 0.01	$\rho_{30\,p\kappa\lambda} = \rho_{24\,p\kappa\lambda}$
$\rho_{24\,p\kappa 2}$	0.98 ± 0.01	$\rho_{31\,p\kappa\lambda} = \rho_{24\,p\kappa\lambda}$
$\rho_{24\,p\kappa 3}$	0.99 ± 0.01	$\rho_{32\,p\kappa\lambda} = \rho_{24\,p\kappa\lambda}$
$\rho_{24\,p\kappa 4}$	1.00 ± 0.01	
Annual Baseline Risks:		
$R_{24\,p\,00}$	$1.3 \cdot 10^{-4}$	FSEIS (DOE, 1990a), Table D.3.14
$R_{30\,p\,00}$	---	Not available in FSEIS
$R_{31\,p\,00}$	---	Not available in FSEIS
$R_{32\,p\,00}$	---	Not available in FSEIS

E.6.3.4 Cancer Risk To Public Due To Traveling In The Opposite Direction

Drivers proceeding in the opposite direction of the TRUPACT-II transport are exposed only shortly. This risk is Component 25, with the definitions,

$q_2^{(\kappa)}$ = Total activity per drum (Bq),
$n_d^{(\kappa)}$ = Number of drums per TRUPACT-II transport,
$n_t^{(\kappa)}$ = Number of shipments per year (yr^{-1}),
$f_{21\omega}$ = Fraction of waste generated by originator ω,
Ω = Number of originators,
$L_{0\omega}^{(\lambda)}$ = Distance travelled as untreated waste from originator ω (m),
$L_{1\omega}^{(\lambda)}$ = Distance travelled as treated waste from originator ω (m),
$L_{t\omega}^{(\lambda)}$ = Total distance travelled for originator ω and location option λ (m),
K_0 = Dose-Rate Conversion factor for point source ($Sv\ s^{-1}\ Bq^{-1}\ m^2$),
Φ_{21} = TRUPACT-II shape function,
v_i = Transport speed in area i ($m\ s^{-1}$),
$f_{0i\omega}^{(\lambda)}$ = Fraction of travel as untreated waste from originator ω in area i,
$f_{1i\omega}^{(\lambda)}$ = Fraction of travel as treated waste from originator ω in area i,
$f_{25i\omega}$ = Fraction of freeway travel, area i, originator ω,
$g_{25i\omega}$ = Fraction of rush hour travel, area i, originator ω,
$h_{25i\omega}$ = Fraction of city street travel, originator ω,
x_i = Minimum exposure distance (m),
N_{p2} = Average number of persons in vehicle on TRUPACT-II routes,
N_{25i} = One way traffic count of vehicles in area i (s^{-1}),
a_1 = Cancer risk factor (Sv^{-1}),
C_j = Constant parts of equations, and
$R_{25p\kappa\lambda}$ = Annual cancer risk for transportation for treatment/location option k (yr^{-1}), with
Index for rural areas i = 1,
Index for suburban areas i = 2,
Index for urban areas i = 3,

it can be written as

$$R_{25p\kappa\lambda} = \left\{ q_2^{(0)}\ n_d^{(0)}\ n_t^{(0)} \right\} \Phi_{21}\ K_0\ N_{p2}\ a_1\ \frac{\pi}{2} \sum_{\omega=1}^{\Omega} f_{21\omega} \sum_{i=1}^{3} N_{25i} \left[f_{0i\omega}^{(\lambda)}\ L_{0\omega}^{(\lambda)} + f_{1i\omega}^{(\lambda)}\ L_{1\omega}^{(\lambda)} \right] H_{25i\omega}\ , \tag{E.6.14}$$

with the definitions of auxiliary functions

$$H_{251\omega} = \frac{f_{251\omega}\,\dfrac{1}{x_1} + \left(1 - f_{251\omega}\right)\dfrac{1}{x_2}}{v_1^{\,2}}\,, \tag{E.6.15}$$

and

$$\begin{aligned} H_{252\omega} &= \frac{1}{x_1}\, f_{252\omega}\left[\frac{8\,g_{252\omega}}{v_2^{\,2}} + \frac{1 - g_{252\omega}}{v_1^{\,2}}\right] \\ &\quad + \frac{1}{x_2}\left(1 - g_{252\omega}\right)\left[\frac{7\,g_{252\omega} + 1}{v_2^{\,2}}\right], \end{aligned} \tag{E.6.16}$$

and

$$\begin{aligned} H_{253\omega} &= \frac{1}{x_2}\left(1 - h_{253\omega}\right)\left[\frac{8\,g_{253\omega}}{v_2^{\,2}} + \frac{1 - g_{253\omega}}{v_1^{\,2}}\right] \\ &\quad + \frac{1}{x_3}\, h_{253\omega}\left[\frac{7\,g_{253\omega} + 1}{v_3^{\,2}}\right]. \end{aligned} \tag{E.6.17}$$

These three auxiliary functions have the dimension ($s^2\ m^{-3}$). Note that the source term is independent of treatment due to Equation (E.6.4) and so are the other factors on the first line of Equation (E.6.14). Thus the scaling property on this component is

$$R_{25p\kappa\lambda} = C_1 \sum_{\omega=1}^{\Omega} f_{21\omega} \sum_{i=1}^{3} N_{25i}\left[\, f_{0i\omega}^{(\lambda)}\, L_{0\omega}^{(\lambda)} + f_{1i\omega}^{(\lambda)}\, L_{1\omega}^{(\lambda)}\,\right] H_{25i\omega}\,, \tag{E.6.18}$$

and the risk reduction factors are given by

$$\rho_{25p\kappa\lambda} = \frac{\sum_{\omega=1}^{\Omega} f_{21\omega} \sum_{i=1}^{3} N_{25i} f_{0i\omega}^{(0)} L_{t\omega}^{(0)} H_{25i\omega}}{\sum_{\omega=1}^{\Omega} f_{21\omega} \sum_{i=1}^{3} N_{25i} \left[f_{0i\omega}^{(\lambda)} L_{0\omega}^{(\lambda)} + f_{1i\omega}^{(\lambda)} L_{1\omega}^{(\lambda)} \right] H_{25i\omega}} , \qquad \text{(E.6.19)}$$

with standard errors of a few percent,

$$\left(\frac{\Delta \rho_{25p\kappa\lambda}}{\rho_{25p\kappa\lambda}} \right) = 0.03 , \qquad \text{(E.6.20)}$$

estimated again by assuming the partial compensation of the small uncertainties in road and vehicle density data.

The risk reduction factors are independent of treatment, and have to be assembled from the parameter values for the ten originators ω in Table E.6-1. They are given in Table E.6-5, together with their errors and the values for the baseline risks. Again, all values lie close to 1, reflecting the fact that the same activity is transported every year, regardless of treatment.

E.6.3.5 Cancer Risk To Public Driving In Same Direction As TRUPACT-II Transport

Longer exposure times occur for vehicles driving in the same direction as a TRUPACT-II transport. This leads to Risk Component 26. Using the symbols

$q_2^{(\kappa)}$ = Total activity per drum (Bq),
$n_d^{(\kappa)}$ = Number of drums per TRUPACT-II transport,
$n_t^{(\kappa)}$ = Number of shipments per year (yr^{-1}),
$f_{21\omega}$ = Fraction of waste generated by originator ω,
$L_{0\omega}^{(\lambda)}$ = Distance travelled as untreated waste from originator ω (m),
$L_{1\omega}^{(\lambda)}$ = Distance travelled as treated waste from originator ω (m),
$L_{t\omega}^{(\lambda)}$ = Total distance travelled for originator ω and location option λ (m),
Φ_{23} = TRUPACT-II shape function,
K_0 = Dose-Rate Conversion factor for point source ($Sv\ s^{-1}\ Bq^{-1}\ m^2$),
v_i = Transport speed in area i ($m\ s^{-1}$),
$f_{0i\omega}^{(\lambda)}$ = Fraction of travel as untreated waste from originator ω in area i,
$f_{1i\omega}^{(\lambda)}$ = Fraction of travel as treated waste from originator ω in area i,
$f_{25i\omega}$ = Fraction of freeway travel, area i, originator ω,
$g_{25i\omega}$ = Fraction of rush hour travel, area i, originator ω,
$h_{25i\omega}$ = Fraction of city street travel, originator ω,
x_i = Minimum exposure distance (m),

TABLE E.6-5

RISK REDUCTION FACTORS FOR PUBLIC RISKS DUE TO CARS TRAVELING IN THE OPPOSITE DIRECTION

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{25\ p\kappa 1}$	1.00 ± 0.03	
$\rho_{25\ p\kappa 2}$	0.97 ± 0.03	
$\rho_{25\ p\kappa 3}$	0.99 ± 0.03	
$\rho_{25\ p\kappa 4}$	1.00 ± 0.03	
Annual Baseline Risks:		
$R_{25\ p\ 00}$	--	Not available in FSEIS

a_1 = Cancer risk factor (Sv^{-1}),
τ = Average time (2 sec) needed for vehicle to close the distance to TRUPACT-II transport (s),
N_{p2} = Average number of persons in vehicle on the road,
N_{25i} = One-way vehicle count in area i (s^{-1}),
C_j = Constant parts of equations, and
$R_{26p\kappa\lambda\omega}$ = Cancer risk for transportation for treatment/location option k and originator ω per year of operation (yr^{-1}), with
Index for rural areas i = 1,
Index for suburban areas i = 2,
Index for urban areas i = 3,

it can be written as

$$R_{26p\kappa\lambda\omega} = \left\{ q_2^{(0)}\, n_d^{(0)}\, n_t^{(0)}\, f_{21\omega} \right\} K_0\, \Phi_{23}\, N_{p2}\, a_1$$

$$\sum_{i=1}^{3} \left[f_{0i\omega}^{(\lambda)}\, L_{0\omega}^{(\lambda)} + f_{1i\omega}^{(\lambda)}\, L_{1\omega}^{(\lambda)} \right] \left(H_{26i\omega} + G_{26i\omega} \right), \tag{E.6.21}$$

with the auxiliary functions defined by

$$H_{261\omega} = \frac{N_{251}}{v_1^3\, \tau}, \tag{E.6.22}$$

and

$$H_{262\omega} = N_{252} \left[f_{252\omega} \left(\frac{16\, g_{252\omega}}{\tau\, v_2^3} + \frac{1 - g_{252\omega}}{\tau\, v_1^3} \right) + \left(1 - f_{252\omega} \right) \frac{15\, g_{252\omega} + 1}{\tau\, v_2^3} \right], \tag{E.6.23}$$

and

$$H_{263\omega} = N_{253}\left[(1 - h_{253\omega})\left(\frac{16\,g_{253\omega}}{\tau\,v_2^{\,3}} + \frac{1 - g_{253\omega}}{\tau\,v_1^{\,3}}\right) + (h_{253\omega})\,\frac{15\,g_{253\omega} + 1}{\tau\,v_3^{\,3}}\right]. \tag{E.6.24}$$

Both auxiliary functions H and G have the dimension [s m^{-3}]

$$G_{261\omega} = \frac{N_{251}}{2v_1^{\,2}}\left(\frac{1}{x_1} - \frac{1}{\tau\,v_1}\right), \tag{E.6.25}$$

and

$$G_{262\omega} = N_{252}\left\{f_{252\omega}\left[\frac{4\,g_{252\omega}}{v_2^{\,2}}\left(\frac{1}{x_2} - \frac{2}{v_2\tau}\right) + \frac{1 - g_{252\omega}}{2\,v_1^{\,2}}\left(\frac{1}{x_2} - \frac{1}{v_1\tau}\right)\right]\right.$$
$$\left. + (1 - f_{252\omega})\left[\frac{4\,g_{252\omega}}{v_2^{\,2}}\left(\frac{1}{x_2} - \frac{2}{v_2\tau}\right) + \frac{1 - g_{252\omega}}{2\,v_2^{\,2}}\left(\frac{1}{x_2} - \frac{1}{v_2\tau}\right)\right]\right\}, \tag{E.6.26}$$

and

$$G_{263\omega} = N_{253}\left\{(1 - h_{253\omega})\left[\frac{4\,g_{253\omega}}{v_2^{\,2}}\left(\frac{1}{x_3} - \frac{2}{v_2\tau}\right) + \frac{1 - g_{253\omega}}{2\,v_1^{2}} - \left(\frac{1}{x_3} - \frac{1}{v_1\tau}\right)\right]\right.$$
$$\left. + h_{253\omega}\left[\frac{4\,g_{253\omega}}{v_3^{\,2}}\left(\frac{1}{x_3} - \frac{2}{v_3\tau}\right) + \frac{1 - g_{253\omega}}{2\,v_3^{\,2}}\left(\frac{1}{x_3} - \frac{1}{v_3\tau}\right)\right]\right\}. \tag{E.6.27}$$

Note that the source term is independent of treatment due to Equation (E.6.16) and so are the other factors on the first line of Equation (E.6.23). Thus this risk scales as

$$R_{26\,p\kappa\lambda} = C_1 \sum_{\omega=1}^{\Omega} f_{21\omega} \sum_{i=1}^{3} \left[f_{0i\omega}^{(\lambda)} L_{0\omega}^{(\lambda)} + f_{1i\omega}^{(\lambda)} L_{1\omega}^{(\lambda)} \right] \left(H_{26\,i\omega} + G_{26\,i\omega} \right) , \tag{E.6.28}$$

and the risk reduction factors are again independent of treatment

$$\rho_{26\,p\kappa\lambda} = \frac{\sum_{\omega=1}^{\Omega} f_{21\omega} \sum_{i=1}^{3} f_{0i\omega}^{(0)} L_{i\omega}^{(0)} \left(H_{26\,i\omega} + G_{26\,i\omega} \right)}{\sum_{\omega=1}^{\Omega} f_{21\omega} \sum_{i=1}^{3} \left[f_{0i\omega}^{(\lambda)} L_{0\omega}^{(\lambda)} + f_{1i\omega}^{(\lambda)} L_{1\omega}^{(\lambda)} \right] \left(H_{26\,i\omega} + G_{26\,i\omega} \right)} , \tag{E.6.29}$$

with the standard errors estimated to be a few percent

$$\left(\frac{\Delta \rho_{26\,p\kappa\lambda\omega}}{\rho_{26\,p\kappa\lambda\omega}} \right) = 0.04 , \tag{E.6.30}$$

based on the same assumptions as those in the preceding sections. The risk reduction factors which have to be assembled from the parameter values for the 10 originators ω are given in Table E.6-6, together with the value for the baseline risks. All factors cluster around unity, as expected, and are applied to a very small baseline risk.

E.6.3.6 Cancer Risk To Crew During Transport

The persons constantly in the radiation field of the TRUPACT-II containers are the members of the transport crew. Their exposure leads to Risk Component 27 with two subcomponents, cancer and genetic effects. Using the symbols:

$q_2^{(\kappa)}$	=	Total activity per drum (Bq),
$n_d^{(\kappa)}$	=	Number of drums per TRUPACT-II transport,
$n_t^{(\kappa)}$	=	Number of shipments per year (yr^{-1}),
Ω	=	Number of originators,
$f_{21\omega}$	=	Fraction of waste generated by originator ω,
$f_{0i\omega}^{(\lambda)}$	=	Fraction of travel as untreated waste from originator ω in area i,
$f_{i1\omega}^{(\lambda)}$	=	Fraction of travel as treated waste from originator ω in area i,
$L_{0\omega}^{(\lambda)}$	=	Distance travelled as untreated waste from originator ω (m),
$L_{1\omega}^{(\lambda)}$	=	Distance travelled as treated waste from originator ω (m),

TABLE E.6-6

RISK REDUCTION FACTORS FOR PUBLIC DRIVING IN SAME DIRECTION AS TRUPACT-II

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{26\ p\kappa 1}$	1.00 ± 0.04	
$\rho_{26\ p\kappa 2}$	0.96 ± 0.04	
$\rho_{26\ p\kappa 3}$	0.99 ± 0.04	
$\rho_{26\ p\kappa 4}$	1.00 ± 0.04	
Annual Baseline Risks:		
$R_{26\ p\ 00}$	$3.6 \cdot 10^{-7}$	FSEIS (DOE, 1990a), Table D.3.14

$L_{t\omega}^{(\lambda)}$ = Total distance travelled for originator ω and location option λ (m),
Φ_{23} = TRUPACT-II shape function,
K_0 = Dose-Rate Conversion factor (Sv s^{-1} Bq^{-1} m^2),
v_i = Transport speed in area i (m s^{-1}),
Φ_{271} = Dosimetry function (rms inverse distance, i.e., m^{-2}),
N_{o3} = Average number of crewmen aboard TRUPACT-II transport, .
a_1 = Cancer risk factor (Sv^{-1}),
C_j = Constant parts of equations, and
$R_{27o\kappa\lambda}$ = Cancer risk for crew exposures during transport for option k per year of operation (yr^{-1}), with

Index for rural areas i = 1,
Index for suburban areas i = 2,
Index for urban areas i = 3,

the formula for this risk component is

$$R_{27o\kappa\lambda} = \left\{ q_2^{(0)}\, n_d^{(0)}\, n_t^{(0)} \right\} K_0\, \Phi_{23} \Phi_{271}\, N_{o3}\, a_1 \left[\sum_{\omega=1}^{\Omega} f_{21\omega} \left(L_{0\omega}^{(\lambda)} \sum_{i=1}^{3} \frac{f_{0i\omega}^{(\lambda)}}{v_i} + L_{1\omega}^{(\lambda)} \sum_{i=1}^{3} \frac{f_{1i\omega}^{(\lambda)}}{v_i} \right) \right]. \tag{E.6.31}$$

As the factors in the first row are all independent of the treatment/location options, the risk can be rewritten to scale according to

$$R_{27o\kappa\lambda} = C_1 \left[\sum_{\omega=1}^{\Omega} f_{21\omega} \left(L_{0\omega}^{(\lambda)} \sum_{i=1}^{3} \frac{f_{0i\omega}^{(\lambda)}}{v_i} + L_{1\omega}^{(\lambda)} \sum_{i=1}^{3} \frac{f_{1i\omega}^{(\lambda)}}{v_i} \right) \right]. \tag{E.6.32}$$

The risk reduction coefficient is then again independent of the treatment option selected

$$\rho_{27o\kappa\lambda} = \frac{\sum_{\omega=1}^{\Omega} f_{21\omega}\, L_{t\omega}^{(0)} \sum_{i=1}^{3} \frac{f_{0i\omega}^{(0)}}{v_i}}{\sum_{\omega=1}^{\Omega} f_{21\omega} \left(L_{0\omega}^{(\lambda)} \sum_{i=1}^{3} \frac{f_{0i\omega}^{(\lambda)}}{v_i} + L_{1\omega}^{(\lambda)} \sum_{i=1}^{3} \frac{f_{1i\omega}^{(\lambda)}}{v_i} \right)}. \tag{E.6.33}$$

The standard error is estimated to be

$$\left(\frac{\Delta \rho_{27 o \kappa \lambda}}{\rho_{27 o \kappa \lambda}} \right) = 0.03 \ , \tag{E.6.34}$$

again under the assumptions made in the preceding sections.

The numerical values of the risk reduction factors are given in Table E.6-7, together with baseline risks. They cluster around one, being applied to a rather small baseline risk.

E.6.3.7 Cancer Risk To Waste Handlers

In loading the TRUPACT-II transport, the work crew will be exposed in various drum geometries according to a particular time-motion profile. The exposure of handlers during the unloading at the WIPP is accounted for in Component 4 for external radiation and Components 1 and 2 for internal exposure. Putting the treatment facility at the site of the originator or at the WIPP does not affect the total dose to the loaders of the TRUPACT-II transport. Putting the facility somewhere in between, however, results in an additional loading and unloading operation. For the calculation of Risk Component 28, the symbols are:

$q_2^{(\kappa)}$ = Total activity per drum (Bq),
$n_d^{(\kappa)}$ = Number of drums per TRUPACT-II transport,
$n_t^{(\kappa)}$ = Number of shipments per year (yr^{-1}),
n_h = Number of handling operations per shipment,
$f_{21\omega}$ = Fraction of waste generated by originator ω,
K_0 = Dose-Rate Conversion factor for point source ($Sv\ s^{-1}\ Bq^{-1}\ m^2$),
$\Phi_{28\,1}$ = Dosimetry function (rms inverse distance, i.e., m^{-2}),
$\Phi_{28\,2}$ = Time-averaged shape function of drum assemblies,
$\Phi_{28\,3\,\omega}^{(\kappa\lambda)}$ = Location factor for Treatment Plant
$N_{o\,4}$ = Average number of crewmen for the loading of TRUPACT-II,
Δt_h = Average handling time (s),
a_1 = Cancer risk factor (Sv^{-1}),
C_i = Constant parts of equations, and
$R_{28\,o\,\kappa\lambda}$ = Annual cancer risk for exposures during handling for option k (yr^{-1}),

TABLE E.6-7

RISK REDUCTION FACTORS FOR CREW DURING TRANSPORT

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{27\,p\kappa 1}$	1.00 ± 0.03	
$\rho_{27\,p\kappa 2}$	0.98 ± 0.03	
$\rho_{27\,p\kappa 3}$	0.99 ± 0.03	
$\rho_{27\,p\kappa 4}$	1.00 ± 0.03	
Annual Baseline Risks:		
$R_{27\,p\,00}$	$7.8 \cdot 10^{-5}$	FSEIS (DOE 1990a), Table D.3.14

the cancer risk per year of operation is

$$R_{28o\kappa\lambda} = \left\{ q_2^{(0)}\, n_d^{(0)}\, n_t^{(0)} \right\} K_0\, \Phi_{281}\, \Phi_{282} \left[\sum_{\omega=1}^{\Omega} f_{21\omega}\, \Phi_{283\omega}^{(\kappa\lambda)} \right] n_h\, \Delta t_h\, N_{04}\, a_1 \quad .$$

(E.6.35)

The product of all factors in the source term is independent of the measurement/location option due to Equation (E.6.4). Of the rest of the factors, only the sum is location dependent. Thus the scaling properties of the risk are

$$R_{28o\kappa\lambda} = C_1 \sum_{\omega=1}^{\Omega} f_{21\omega}\, \Phi_{283\omega}^{(\kappa\lambda)} \; .$$

(E.6.36)

The values and standard errors for the function $\Phi_{283\omega}^{(\kappa\lambda)}$ are given in Tables D.3-9 and D.3-10.

The risk reduction factor is then both location and treatment dependent and is given by

$$\rho_{28o\kappa\lambda} = \frac{\sum_{\omega=1}^{\Omega} f_{21\omega}\, \Phi_{283\omega}^{(00)}}{\sum_{\omega=1}^{\Omega} f_{21\omega}\, \Phi_{283\omega}^{(\kappa\lambda)}}$$

$$= \frac{1}{\sum_{\omega=1}^{\Omega} f_{21\omega}\, \Phi_{283\omega}^{(\kappa\lambda)}} \equiv \frac{1}{V_{28o\kappa\lambda}} \; .$$

(E.6.37)

The simplification in the numerator arises from the fact that all $\Phi_{283\omega}^{(00)}$ are equal to 1, and that the sum of the fraction of the total waste is also equal to 1. Because $\Phi_{283\omega}^{(\kappa\lambda)} \geq 1$, the risk reduction factors are smaller than 1, $\rho_{28o\kappa\lambda} \leq 1$, i.e., there is an increase in risk. Also, the standard error is small, arising only from the standard errors of the fractions $\Phi_{283}^{(\kappa\lambda)}$

$$\left(\frac{\Delta \rho_{28o\kappa\lambda}}{\rho_{28o\kappa\lambda}} \right)^2 = \sum_{\omega=1}^{\Omega} \left(\frac{f_{21\omega}\, \Delta \Phi_{283\omega}^{(\kappa\lambda)}}{V_{28o\kappa\lambda}} \right)^2 \; .$$

(E.6.38)

The risk reduction factors, calculated using data from Tables D.3-9 and D.3-10, are listed in Table E.6-8. Their values range from a risk increase by 50 percent to a risk reduction by a factor of almost 4. The relative standard errors are small, ranging from 2 to 8 percent.

E.6.3.8 Cancer Risk To Warehouse Personnel

The amount of time the warehouse crew is exposed is assumed to be a constant. During storage, a large number of drums at larger distances than during handling irradiate the warehouse crew. This leads to Risk Component 29, with one subcomponent. Using the notation

$q_2^{(\kappa)}$ = Total activity per drum (Bq),
$n_d^{(\kappa)}$ = Number of barrels per TRUPACT-II container,
$n_t^{(\kappa)}$ = Number of shipments per year (yr^{-1}),
$f_{21\omega}$ = Fraction of waste generated by originator ω,
Ω = Number of waste originators,
Δt_s = Total storage time per shipment in baseline case (s),
K_o = Dose-Rate Conversion factor ($Sv\ s^{-1}\ Bq^{-1}\ m^2$),
Φ_{291} = Geometry-dosimetry function (m^{-2}),
$\Phi_{292\omega}^{(\kappa\lambda)}$ = Time extension function due to location and treatment,
$N_{o5}^{(\kappa)}$ = Average number of personnel in warehouse,
a_1 = Annual cancer risk factor (Sv^{-1}),
C_i = Constant parts of equations, and
$R_{29o\kappa\lambda}$ = Annual cancer risk for exposures during storage (yr^{-1}),

the cancer risk per year of operation is

$$R_{29o\kappa\lambda} = \left\{ q_2^{(0)}\ n_d^{(0)}\ n_t^{(0)} \right\} K_0\ \Phi_{291} \left(\sum_{\omega=1}^{\Omega} f_{21\omega}\ \Phi_{292\omega}^{(\kappa\lambda)} \right) \Delta t_s\ N_{o5}^{(\kappa)}\ a_1\ . \tag{E.6.39}$$

The source term is independent of treatment due to Equation (E.6.4). For different location/treatment options, only the quantities in the rounded brackets change. The risk can, therefore, be scaled as

$$R_{29o\kappa\lambda} = C_1 \left(\sum_{\omega=1}^{\Omega} f_{21\omega}\ \Phi_{292\omega}^{(\kappa\lambda)} \right). \tag{E.6.40}$$

TABLE E.6-8

RISK REDUCTION FACTORS FOR WASTE HANDLERS

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{28\ o\ 11}$	1	Identical risk component
$\rho_{28\ o\ 12}$	0.689 ± 0.025	
$\rho_{28\ o\ 13}$	0.726 ± 0.029	
$\rho_{28\ o\ 14}$	0.712 ± 0.029	
$\rho_{28\ o\ 21}$	1	Identical risk component
$\rho_{28\ o\ 22}$	0.654 ± 0.022	
$\rho_{28\ o\ 24}$	0.680 ± 0.025	
$\rho_{28\ o\ 24}$	0.663 ± 0.024	
$\rho_{28\ o\ 31}$	1	Identical risk component
$\rho_{28\ o\ 32}$	0.970 ± 0.086	
$\rho_{28\ o\ 33}$	1.14 ± 0.12	
$\rho_{28\ o\ 34}$	1.19 ± 0.14	
$\rho_{28\ o\ 41}$	1	Identical risk component
$\rho_{28\ o\ 42}$	1.65 ± 0.03	
$\rho_{28\ o\ 43}$	2.51 ± 0.06	
$\rho_{28\ o\ 44}$	3.61 ± 0.13	
Annual Baseline Risks:		
$R_{28\ o\ 00}$	---	Not given in FSEIS

The risk reduction factor can now be written as

$$\rho_{29\,o\,\kappa\lambda} = \frac{1}{\sum_{\omega=1}^{\Omega} f_{21\,\omega}\,\Phi_{29\,2\,\omega}^{(\kappa\lambda)}} \equiv \frac{1}{V_{29\,o\,\kappa\lambda}}\,, \tag{E.6.41}$$

with a standard error

$$\left(\frac{\Delta\rho_{29\,o\,\kappa\lambda}}{\rho_{29\,o\,\kappa\lambda}}\right)^2 = \sum_{\omega=1}^{\Omega}\left(\frac{f_{21\,\omega}}{V_{29\,o\,\kappa\lambda}}\,\Delta\Phi_{29\,2\,\omega}^{(\kappa\lambda)}\right)^2 . \tag{E.6.42}$$

The function $\Phi_{29\,2\,\omega}^{(\kappa\,\lambda)}$ is modeled in Appendix I, Section D.3.11 and its numerical values are given in Tables D.3-11 and D.3-12. They range from unity up to risk reduction factors of 1.5, and down to values corresponding to risk increases by a factor of 4. The numerical values for the risk reduction factors are given in Table E.6-9.

E.6.4 Cancer Risks Due To Transportation Accident Exposures

E.6.4.1 Basic Considerations

The accidents discussed here are those considered in RADTRAN III. The amount of radioactive material released in an accident depends on the severity of the accident, the properties of the waste, and the characteristics of the shipping containment. The overall accident rate and the accident severity category are used to evaluate the risk. Accidents range in severity from categories one through eight (U.S. NRC, 1977b), defined by the crush force and fire duration of the accident. Nondispersal accidents are considered by using the source strength of penetrating external radiation only. External radiation is not assumed to attenuate in any structures between the center of the source and the exposed individual or population. Dispersal accident risks incorporate the resuspension and dissolution in addition to the source term's contribution to the risk. In this report, the probability of an accident is based on systemwide averages; the dispersal function is assumed to be a constant based on a systemwide average.

E.6.4.2 Risks Due To Nondispersal Accidents

E.6.4.2.1 Early Fatalities Due To Nondispersal Accidents

Nondispersal accidents are assumed to produce a closely distributed source of penetrating radiation at the accident site. For persons close by, this may lead to sizeable exposures to gammas and neutrons and in rare cases a potential for early health effects, such as radiation

TABLE E.6-9

RISK REDUCTION FACTORS FOR RISK TO WAREHOUSE PERSONNEL

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{29\,o\,11}$	1	Identical to baseline
$\rho_{29\,o\,12}$	1.04 ± 0.03	
$\rho_{29\,o\,13}$	1.31 ± 0.05	
$\rho_{29\,o\,14}$	1.39 ± 0.05	
$\rho_{29\,o\,21}$	1	Identical to baseline
$\rho_{29\,o\,22}$	1.078 ± 0.024	
$\rho_{29\,o\,24}$	1.381 ± 0.044	
$\rho_{29\,o\,24}$	1.492 ± 0.052	
$\rho_{29\,o\,31}$	1	Identical to baseline
$\rho_{29\,o\,32}$	0.784 ± 0.077	
$\rho_{29\,o\,33}$	0.842 ± 0.097	
$\rho_{29\,o\,34}$	0.841 ± 0.099	
$\rho_{29\,o\,41}$	1	Identical to baseline
$\rho_{29\,o\,42}$	0.309 ± 0.016	
$\rho_{29\,o\,43}$	0.263 ± 0.013	
$\rho_{29\,o\,44}$	0.243 ± 0.011	
Annual Baseline Risks:		
$R_{29\,o\,00}$	---	Not available in FSEIS

sickness (bone marrow syndrome). The dose-effect function for fatalities is sigmoidal and can be described by a Weibull function (Scott et al., 1988). Due to the high doses required, the probabilities of these effects occurring are very low, resulting in a very small risk. This is Risk Component 30 with one subcomponent, and with the symbols:

p_{nd}	=	Linear probability density of a nondispersive accident (m^{-1}),
$q_2^{(\kappa)}$	=	Total activity per drum (Bq),
$n_d^{(\kappa)}$	=	Number of drums per TRUPACT-II transport,
$n_t^{(\kappa)}$	=	Number of shipments per year (yr^{-1}),
$L_{0\omega}^{(\lambda)}$	=	Distance traveled with untreated waste from originator ω (m),
$L_{1\omega}^{(\lambda)}$	=	Distance traveled with treated waste from originator ω (m),
$L_{t\omega}^{(\lambda)}$	=	Total distance travelled by waste from originator ω (m),
Ω	=	Number of originators ω,
$f_{21\omega}$	=	Fraction of total waste from originator ω,
Φ_{301}	=	Average geometry function due to released and enclosed activity,
Φ_{302}	=	Dosimetry-effect function (nonlinear) for all exposed persons (Bq^{-1}),
C_1	=	Constant parts of equations, and
$R_{30p\kappa\lambda}$	=	Risk of bone-marrow lethality for exposures during accidents per year of operation (yr^{-1}),

and applying Equation (E.1.5), it can be estimated from the expression

$$R_{30p\kappa\lambda} = \left\{ q_2^{(0)}\, n_d^{(0)}\, n_t^{(0)} \right\} p_{nd} \left(\sum_{\omega=1}^{\Omega} f_{21\omega} \left(L_{0\omega}^{(\lambda)} + L_{1\omega}^{(\lambda)} \right) \right) \Phi_{301}\, \Phi_{302} \,. \tag{E.6.43}$$

With regard to a dependence on the alternative k = (κ,λ), the top row of Equation (E.6.43) is constant and so are the last two factors. The risk scales as

$$R_{30p\kappa\lambda} = C_1 \sum_{\omega=1}^{\Omega} f_{21\omega}\, L_{t\omega}^{(\lambda)} \,. \tag{E.6.44}$$

The reduction factors are then the same as those for Component 24,

$$\rho_{30\,p\kappa\lambda} = \frac{\sum_{\omega=1}^{\Omega} f_{21\,\omega}\, L_{t\omega}^{(0)}}{\sum_{\omega=1}^{\Omega} f_{21\,\omega}\, L_{t\omega}^{(\lambda)}} = \rho_{24\,p\kappa\lambda}\,, \tag{E.6.45}$$

with the same standard errors

$$\Delta\rho_{30\,p\kappa\lambda} = \Delta\rho_{24\,p\kappa\lambda}\,. \tag{E.6.46}$$

Thus the numerical values have already been assembled in Table E.6-4, together with the baseline risk.

E.6.4.2.2 Early Morbidity Due To Nondispersal Accidents

Another early effect of a high dose exposure is radiation sickness with a nonfatal outcome. Other effects of this type are radiation pneumonitis, damage to the gastrointestinal tract, hair loss, sterility in males, and the appearance of nodules in the thyroids in the intermediate term. Clearly, the same calculation can be made, except that the dose-effect function used is different. As dose increases, it rises, peaks, and decreases again. That decrease is due to the increase in fatalities at higher doses. Again, the doses required are high and the risks, therefore, very low. This nonfatal outcome results in Risk Component 31 with one subcomponent, and with the symbols:

p_{nd} = Linear probability density of a nondispersive accident (m^{-1}),
$q_2^{(\kappa)}$ = Total activity per drum (Bq),
$n_d^{(\kappa)}$ = Number of drums per TRUPACT-II transport,
$n_t^{(\kappa)}$ = Number of shipments per year (yr^{-1}),
$L_{0\omega}^{(\lambda)}$ = Distance traveled with untreated waste from originator ω (m),
$L_{1\omega}^{(\lambda)}$ = Distance traveled with treated waste from originator ω (m),
$L_{t\omega}^{(\lambda)}$ = Total distance traveled by waste from originator ω (m),
Ω = Number of originators ω,
$f_{21\,\omega}$ = Fraction of total waste from originator ω,
$\Phi_{30\,1}$ = Average geometry function for activity after accident,
$\Phi_{31\,1}$ = Dosimetry-effect function (nonlinear) for all exposed persons (Bq^{-1}),
C_i = Constant parts of equations, and
$R_{31\,p\kappa\lambda}$ = Risk of bone-marrow lethality for exposures during accidents per year of operation (yr^{-1}),

and again applying Equation (E.6.4), the risk component is

$$R_{31\,p\kappa\lambda} = \left\{ q_2^{(0)}\, n_d^{(0)}\, n_t^{(0)} \right\} p_{nd} \left(\sum_{\omega=1}^{\Omega} f_{21\,\omega} \left[L_{0\,\omega}^{(\lambda)} + L_{1\,\omega}^{(\lambda)} \right] \right) \Phi_{301}\, \Phi_{311} \,. \tag{E.6.47}$$

With regard to a dependence on the alternative k = (κ,λ), the risk can be scaled as

$$R_{31\,p\kappa\lambda} = C_1 \sum_{\omega=1}^{\Omega} f_{21\,\omega}\, L_{t\omega}^{(\lambda)} \,, \tag{E.6.48}$$

which is the same as the risks for Component 24. The reduction factors are then also the same

$$\rho_{31\,p\kappa\lambda} = \frac{\sum_{\omega=1}^{\Omega} f_{21\,\omega}\, L_{t\omega}^{(0)}}{\sum_{\omega=1}^{\Omega} f_{21\,\omega}\, L_{t\omega}^{(\lambda)}} = \rho_{24\,p\kappa\lambda} \,, \tag{E.6.49}$$

with the same standard errors

$$\Delta\, \rho_{31\,p\kappa\lambda} = \Delta\, \rho_{24\,p\kappa\lambda} \,. \tag{E.6.50}$$

Thus the values given in Table E.6-4 apply here as well.

E.6.4.2.3 <u>Delayed Health Effects Due To Nondispersal Accidents</u>

The delayed effects of radiation exposure are mainly cancer and genetic damage. Again, the same calculation is made, except that the dose-effect calculation is made differently in that the conservative, no-threshold linear model is used for both effects. The Risk Component 32 thus has two sub-components, and with the symbols:

ρ_{nd}	=	Linear probability density of a nondispersive accident (m^{-1}),
$L_{0\,\omega}^{(\lambda)}$	=	Distance traveled with untreated waste from originator ω (m),
$L_{1\,\omega}^{(\lambda)}$	=	Distance traveled with treated waste from originator ω (m),
$L_{t\,\omega}^{(\lambda)}$	=	Total distance travelled by waste from originator ω (m),
Ω	=	Number of originators ω,
$q_2^{(\kappa)}$	=	Total activity per drum (Bq),
$n_d^{(\kappa)}$	=	Number of drums per TRUPACT-II transport,
$n_t^{(\kappa)}$	=	Number of shipments per year (yr^{-1}),

$f_{21\omega}$ = Fraction of total waste from originator ω,
Φ_{301} = Average geometry function for activity after accident,
Φ_{321} = Dosimetry-effect function for all exposed persons (Sv Bq^{-1}),
a_1 = Cancer risk coefficient (Sv^{-1}),
C_i = Constant parts of equations, and
$R_{32p\kappa\lambda}$ = Annual cancer risk for exposures during nondispersal accidents (yr^{-1}),

and still using Equation (E.6.4), the risk component is

$$R_{32p\kappa\lambda} = \left\{ q_2^{(\kappa)}\, n_d^{(\kappa)}\, n_t^{(\kappa)} \right\} p_{nd} \left(\sum_{\omega=1}^{\Omega} f_{21\omega} \left[L_{0\omega}^{(\lambda)} + L_{1\omega}^{(\lambda)} \right] \right) \Phi_{301}\, \Phi_{321}\, a_1 \,. \tag{E.6.51}$$

Again, this risk scales as

$$R_{32p\kappa\lambda} = C_1 \sum_{\omega=1}^{\Omega} f_{21\omega}\, L_{t\omega}^{(\lambda)} \,, \tag{E.6.52}$$

which is the same as Equations (E.6.44) and (E.6.48). The reduction factors are then again

$$\rho_{32p\kappa\lambda} = \rho_{24p\kappa\lambda} \,, \tag{E.6.53}$$

with the same standard errors

$$\Delta\, \rho_{32p\kappa\lambda} = \Delta\, \rho_{24p\kappa\lambda} \,. \tag{E.6.54}$$

These values are tabulated in Table E.6-4 together with the baseline risk.

E.6.4.3 Risks Due To Dispersal Accidents

E.6.4.3.1 Risk Of Early Fatalities Due To Inhalation

The FSEIS (DOE, 1990a) considers accidents with a breach of containment, suspension, and atmospheric dispersion of a mixture of radioisotopes, leading to inhalation exposures. This puts mainly the lung, but also other organs at risk. Again, the calculations made are similar to those in the preceding sections. The Risk Component 33 for early fatalities has one subcomponent,

using the symbols:

p_d = Linear probability density of a dispersive accident (m^{-1}),
$q_2^{(\kappa)}$ = Total activity per drum (Bq),
$n_d^{(\kappa)}$ = Number of drums per TRUPACT-II transport,
$n_t^{(\kappa)}$ = Number of shipments per year (yr^{-1}),
$L_{0\omega}^{(\lambda)}$ = Distance traveled with untreated waste from originator ω (m),
$L_{1\omega}^{(\lambda)}$ = Distance traveled with treated waste from originator ω (m),
$L_{t\omega}^{(\lambda)}$ = Total distance travelled by waste from originator ω (m),
Ω = Number of originators ω,
$f_{21\omega}$ = Fraction of total waste from originator ω,
$f_{331}^{(\kappa)}$ = Fraction of activity suspended in average (systemwide) accident,
$f_{332}^{(\kappa)}$ = Fraction of airborne particles in inhalable form,
$S_{33\kappa}$ = Reduction factor for suspension in inhalable form due to treatment κ,
f_{333} = Fraction of airborne particles deposited in lung,
Φ_{331} = Dosimetry-effect function for fatal effects in exposed persons (Bq^{-1}),
a_1 = Cancer risk coefficient (Sv^{-1}),
C_i = Constant parts of equations, and
$R_{33p\kappa\lambda}$ = Risk of early fatalities for exposures during dispersal accidents per year of operation (yr^{-1}),

and again applying Equation (E.6.4), is given by

$$R_{33p\kappa\lambda} = \left\{ q_2^{(0)}\, n_d^{(0)}\, n_t^{(0)} \right\} p_d \left(\sum_{\omega=1}^{\Omega} f_{21\omega} \left[L_{0\omega}^{(\lambda)} f_{331}^{(0)} f_{332}^{(0)} + L_{1\omega}^{(\lambda)} f_{331}^{(\kappa)} f_{332}^{(\kappa)} \right] \right) f_{333}\, \Phi_{331}\, a_1 \,. \tag{E.6.55}$$

With regard to a dependence on the alternative $k = (\kappa,\lambda)$, the risk can be split into a constant and a variable part. The constant part consists of the first row and the last three factors. This risk component thus has the scaling property

$$R_{33p\kappa\lambda} = C_1 \sum_{\omega=1}^{\Omega} f_{21\omega} \left[L_{0\omega}^{(\lambda)} \phi_{33}^{(0)} + L_{1\omega}^{(\lambda)} \phi_{33}^{(\kappa)} \right], \tag{E.6.56}$$

with the suspendability factor

$$\phi_{33}^{(\kappa)} \equiv f_{331}^{(\kappa)} f_{332}^{(\kappa)} \,. \tag{E.6.57}$$

Using the definition of the reduction factor

$$S_{33\kappa} \equiv \frac{\phi_{33}^{(0)}}{\phi_{33}^{(\kappa)}} , \tag{E.6.58}$$

for the reduction in suspendability of waste in inhalable form in the average TRUPACT-II accident with breach of containment, the reduction factors are given by

$$\rho_{33p\kappa\lambda} = \frac{\sum_{\omega=1}^{\Omega} f_{21\omega} L_{t\omega}^{(0)}}{\sum_{\omega=1}^{\Omega} f_{21\omega} \left[L_{0\omega}^{(\lambda)} + \frac{L_{1\omega}^{(\lambda)}}{S_{33\kappa}} \right]} \equiv \frac{V_{3300}}{V_{33\kappa\lambda}} . \tag{E.6.59}$$

The standard errors are given by the relatively large errors of the factors $S_{33\kappa}$ and the relatively small errors of the road lengths and waste fractions; the latter are estimated at about two percent. Thus the errors are

$$\left(\frac{\Delta \rho_{33p\kappa\lambda}}{\rho_{33p\kappa\lambda}} \right)^2 = \left(\frac{\sum_{\omega=1}^{\Omega} f_{21\omega} L_{1\omega}^{(\lambda)}}{V_{33\kappa\lambda} S_{33\kappa}} \right)^2 \left(\frac{\Delta S_{33\kappa}}{S_{33\kappa}} \right)^2 + (0.02)^2 . \tag{E.6.60}$$

The first term with the large factor $S_{33\kappa}$ in the denominator will usually be smaller than the second, even for large relative errors of $S_{33\kappa}$. The risk reduction factors do depend on κ and λ and their values are given in Table E.6-10. Inspection shows that the variability of the factors with the treatment alternative κ is minute. Table E.6-10, therefore, shows only the variability with location, which goes from 1 to about 15 with relative errors of 2 percent.

E.6.4.3.2 Risk Of Early Morbidity Due To Inhalation

All individuals that are exposed to a dose higher than the effect threshold but exhibit and survive the acute syndrome fall into the class of nonfatal early health effects. For this risk, the calculations are similar to those in the preceding section. Risk Component 34 for early nonfatal health effects has one subcomponent, using the symbols:

p_d = Linear probability density of a dispersive accident (m^{-1}),
$q_2^{(\kappa)}$ = Total activity per drum (Bq),
$n_d^{(\kappa)}$ = Number of drums per TRUPACT-II transport,
$n_t^{(\kappa)}$ = Number of shipments per year (yr^{-1}),
$L_{0\omega}^{(\lambda)}$ = Distance traveled with untreated waste from originator ω (m),
$L_{1\omega}^{(\lambda)}$ = Distance traveled with treated waste from originator ω (m),

TABLE E.6-10

RISK REDUCTION FACTORS AND BASELINE RISKS FOR COMPONENTS

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{33\,p\kappa 1}$	1	$\rho_{34\,p\kappa\lambda} = \rho_{33\,p\kappa\lambda}$
$\rho_{33\,p\kappa 2}$	2.94	$\rho_{35\,p\kappa\lambda} = \rho_{33\,p\kappa\lambda}$
$\rho_{33\,p\kappa 3}$	10.8	$\rho_{36\,p\kappa\lambda} = \rho_{33\,p\kappa\lambda}$
$\rho_{33\,p\kappa 4}$	14.7	$\rho_{37\,p\kappa\lambda} = \rho_{33\,p\kappa\lambda}$
		$\rho_{39\,p\kappa\lambda} = \rho_{33\,p\kappa\lambda}$
Annual Baseline Risks:		
$R_{33\,p\,00}$	--	Not available in FSEIS
$R_{34\,p\,00}$	--	(DOE, 1990a)
$R_{35\,p\,00}$	--	"
$R_{36\,p\,00}$	--	"
$R_{37\,p\,00}$	--	"
$R_{39\,p\,00}$	--	"

Ω = Number of originators ω,
$f_{21\omega}$ = Fraction of total waste from originator ω,
$f_{331}^{(\kappa)}$ = Fraction of activity released in average accident (systemwide),
$f_{332}^{(\kappa)}$ = Fraction of airborne particles in inhalable form,
Φ_{341} = Dosimetry-effect function (nonfatal effects for exposed persons) (Bq^{-1}),
a_1 = Cancer risk coefficient (Sv^{-1}),
C_i = Constant parts of equations, and
$R_{34p\kappa\lambda}$ = Annual risk of early fatalities for exposures during dispersal accidents (yr^{-1}),

and again applying Equations (E.6.4) and definition (E.6.57), is given by

$$R_{34p\kappa\lambda} = \left\{ q_2^{(0)}\, n_d^{(0)}\, n_t^{(0)} \right\} p_d \left(\sum_{\omega=1}^{\Omega} f_{21\omega} \left[L_{0\omega}^{(\lambda)} f_{331}^{(0)} f_{332}^{(0)} + L_{1\omega}^{(\lambda)} f_{331}^{(\kappa)} f_{332}^{(\kappa)} \right] \right) \Phi_{341}\, a_1 \,. \tag{E.6.61}$$

With regard to a dependence on the alternative $k = (\kappa,\lambda)$, the risk can be split into a constant and a variable part, yielding the scaling law

$$R_{34p\kappa\lambda} = C_1 \sum_{\omega=1}^{\Omega} f_{21\omega} \left[L_{0\omega}^{(\lambda)} \phi_{33}^{(0)(0)} + L_{1\omega}^{(\lambda)} \phi_{33}^{(\kappa)} \right], \tag{E.6.62}$$

which is the same as the equations in the preceding section for $R_{33p\kappa\lambda}$. The reduction factors are thus given in Table E.6-10, together with the baseline risk.

E.6.4.3.3 Risk Of Delayed Health Effects Due To Inhalation

The inhalation of both the directly transmitted and the resuspended airborne particles contribute to the long-term exposure. With cancer and genetic effects as delayed action endpoints, Risk Component 35 has two subcomponents. The risks of incurring these consequences, using the symbols:

p_d = Linear probability density of a dispersive accident (m^{-1}),
$L_{0\omega}^{(\lambda)}$ = Distance traveled with untreated waste from originator ω (m),
$L_{1\omega}^{(\lambda)}$ = Distance traveled with treated waste from originator ω (m),
Ω = Number of originators ω,
$q_2^{(\kappa)}$ = Total activity per drum (Bq),
$n_d^{(\kappa)}$ = Number of drums per TRUPACT-II transport,
$n_t^{(\kappa)}$ = Number of shipments per year (yr^{-1}),
$f_{21\omega}$ = Fraction of total waste from originator ω,
$f_{331}^{(\kappa)}$ = Fraction of activity released in average accident (systemwide),

$f_{332}^{(\kappa)}$ = Fraction of airborne particles in inhalable form,
Φ_{351} = Dosimetry function for all exposed persons (Sv Bq^{-1}),
a_1 = Cancer risk coefficient (Sv^{-1}),
$R_{35p\kappa\lambda}$ = Annual cancer risk for inhalation exposures during dispersal accidents (yr^{-1}),

and again applying Equation (E.6.4), is given by

$$R_{35p\kappa\lambda} = \left\{ q_2^{(0)}\ n_d^{(0)}\ n_t^{(0)} \right\} p_d \left(\sum_{\omega=1}^{\Omega} f_{21\omega} \left[L_{0\omega}^{(\lambda)}\ f_{331}^{(0)}\ f_{332}^{(0)} + L_{1\omega}^{(\lambda)}\ f_{331}^{(\kappa)}\ f_{332}^{(\kappa)} \right] \right) \Phi_{351}\ a_1 , \tag{E.6.63}$$

which again leads to cancer risk reduction factors and errors given in Table E.6-10.

E.6.4.3.4 Risks Of Delayed Health Effects Due To Cloudshine

This is a direct external exposure from a passing cloud of radioactive suspended particles. With cancer and genetic effects as delayed action endpoints, Risk Component 36 has two sub-components. The risks of these consequences, using the symbols:

p_d = Linear probability density of a dispersive accident (m^{-1}),
$q_2^{(\kappa)}$ = Total activity per drum (Bq),
$n_d^{(\kappa)}$ = Number of drums per TRUPACT-II transport,
$n_t^{(\kappa)}$ = Number of shipments per year (yr^{-1}),
$L_{0\omega}^{(\lambda)}$ = Distance traveled with untreated waste from originator ω (m),
$L_{1\omega}^{(\lambda)}$ = Distance traveled with treated waste from originator ω (m),
Ω = Number of originators ω,
$f_{21\omega}$ = Fraction of total waste from originator ω,
$f_{331}^{(\kappa)}$ = Fraction of activity released in average accident (systemwide),
$f_{332}^{(\kappa)}$ = Fraction of airborne particles in inhalable form,
Φ_{361} = Cloudshine dosimetry function for all exposed persons (Sv Bq^{-1}),
a_1 = Cancer risk coefficient (Sv^{-1}),
$R_{36p\kappa\lambda}$ = Cancer risk for exposures during dispersal accidents per year of operation (yr^{-1}),

and again applying Equation (E.6.4), is given by

$$R_{36p\kappa\lambda} = \left\{ q_2^{(0)}\ n_d^{(0)}\ n_t^{(0)} \right\} p_d \left(\sum_{\omega=1}^{\Omega} f_{21\omega} \left[L_{0\omega}^{(\lambda)}\ f_{331}^{(0)} + L_{1\omega}^{(\lambda)}\ f_{331}^{(\kappa)} \right] \right) \Phi_{361}\ a_1 \ . \tag{E.6.64}$$

This equation has the same basic structure as Equation (E.6.63), except for the factors $f_{332}^{(0)}$ and $f_{332}^{(\kappa)}$, respectively. The fraction of the suspended particles which is in inhalable form is assumed to be independent of the treatment κ. Thus the terms in the sum in Equation (E.6.64) can be multiplied by $f_{332}^{(0)}$ and $f_{332}^{(\kappa)}$, respectively, and this again leads to the same cancer risk reduction factors as in the last section and errors given in Table E.6-10.

E.6.4.3.5 Risks Of Delayed Health Effects Due To Groundshine

Eventually, all the activity suspended in the accident is again deposited, leading to a surface contamination of the ground. The assumption is made here that this surface contamination level is proportional to the released radioactivity, i.e., the source term. The direct exposure to penetrating radiation from the fallout leads to Risk Component 37 with two sub-components. Using the symbols:

p_d	=	Linear probability density of a dispersive accident (m^{-1}),
$L_{0\omega}^{(\lambda)}$	=	Distance traveled with untreated waste from originator ω (m),
$L_{1\omega}^{(\lambda)}$	=	Distance traveled with treated waste from originator ω (m),
$L_{t\omega}^{(\lambda)}$	=	Total distance travelled by waste from originator ω (m),
Ω	=	Number of originators ω,
$q_2^{(\kappa)}$	=	Total activity per drum (Bq),
$n_d^{(\kappa)}$	=	Number of drums per TRUPACT-II transport,
$n_t^{(\kappa)}$	=	Number of shipments per year (yr^{-1}),
$f_{21\omega}$	=	Fraction of total waste from originator ω,
$f_{331}^{(\kappa)}$	=	Fraction of activity released in average accident (systemwide),
$f_{332}^{(\kappa)}$	=	Fraction of activity released and suspended in inhalable form,
Φ_{371}	=	Deposition function over exposure area (m^{-2}),
Φ_{372}	=	Groundshine dosimetry function for all exposed persons ($Sv\ Bq^{-1}\ m^2$),
a_1	=	Cancer risk coefficient (Sv^{-1}),
$R_{37p\kappa\lambda}$	=	Annual cancer risk for exposures during dispersal accidents (yr^{-1}),

and again applying Equation (E.6.4), the risk is is given by

$$R_{37p\kappa\lambda} = \left\{ q_2^{(0)}\, n_d^{(0)}\, n_t^{(0)} \right\} p_d \left(\sum_{\omega=1}^{\Omega} f_{21\omega} \left[L_{0\omega}^{(\lambda)} f_{331}^{(0)} + L_{1\omega}^{(\lambda)} f_{331}^{(\kappa)} \right] \right) \Phi_{371}\, \Phi_{372}\, a_1 \,. \tag{E.6.65}$$

With the general assumption that the particle size spectrum does not change with treatment, the quantity $f_{331}^{(\kappa)}$ can be multiplied with the spectrum dependent factor $f_{332}^{(\kappa)}$ for the calculation of the risk reduction factors. According to Equation (E.6.57) this is equal to $\phi_{33}^{(\kappa)}$. This brings Equation (E.6.65) into line with all the other risk equations for dispersal accidents, and the risk reduction factors and their errors are given in Table E.6-10.

E.6.5 Risk Of Monetary Losses Due To Decontamination Procedures

The largest potential financial losses treated in the RADTRAN-III code, but not in the FSEIS, are decontamination costs incurred in a dispersal accident. The assumption is made here that the only quantities sensitive to the treatment/location option are the accident probability and the source term. The risk is assumed to be linearly dependent on these parameters. While, for the general assumptions used here this is evident for the accident probability, it does not necessarily hold for the source term and the contamination caused by the accident. Assuming that the areas and number of people requiring a particular action scale with the quantity released, the financial Risk Component 39, with the symbols:

p_d = Linear probability density of a dispersive accident (m^{-1}),
$L_{0\omega}^{(\lambda)}$ = Distance traveled with untreated waste from originator ω (m),
$L_{1\omega}^{(\lambda)}$ = Distance traveled with treated waste from originator ω (m),
$L_{1\omega}^{(\lambda)}$ = Total distance travelled by waste from originator ω (m),
Ω = Number of originators ω,
$q_2^{(\kappa)}$ = Total activity per drum (Bq),
$n_d^{(\kappa)}$ = Number of drums per TRUPACT-II transport,
$n_t^{(\kappa)}$ = Number of shipments per year (yr^{-1}),
$f_{21\omega}$ = Fraction of total waste from originator ω,
$f_{331}^{(\kappa)}$ = Fraction of activity suspended in average accident (systemwide),
Φ_{371} = Deposition function over exposure area (m^{-2}),
Φ_{392} = Cost function for all persons and areas contaminated ($\$\ Bq^{-1}\ m^2$),
$R_{39p\kappa\lambda}$ = Cost of decontamination incurred in dispersal accidents ($\$\ yr^{-1}$),

and again applying Equation (E.6.4), is given by

$$R_{39p\kappa\lambda} = \left\{ q_2^{(0)} \; n_d^{(0)} \; n_t^{(0)} \right\} p_d \left(\sum_{\omega=1}^{\Omega} f_{21\omega} \left[L_{0\omega}^{(\lambda)} \; f_{331}^{(0)} + L_{1\omega}^{(\lambda)} \; f_{331}^{(\kappa)} \right] \right) \Phi_{371} \; \Phi_{392} \; . \tag{E.6.66}$$

The variability of factors with alternative allows the risk component to be written as

$$R_{39p\kappa\lambda} = C_1 \left(\sum_{\omega=1}^{\Omega} f_{23\omega} \left[L_{0\omega}^{(\lambda)} \; f_{331}^{(0)} + L_{1\omega}^{(\lambda)} \; f_{331}^{(\kappa)} \right] \right), \tag{E.6.67}$$

with the general assumption that the particle size spectrum does not change with treatment, the quantity $f_{331}^{(\kappa)}$ can again be multiplied with the spectrum dependent factor $f_{332}^{(\kappa)}$ for the calculation of the risk reduction factors, making Equation (E.6.67), the risk reduction factors and their errors, the same as those in the preceding sections which are listed in Table E.6-10.

E.7 LATE OCCURRING RISKS

E.7.1 Basic Considerations

For post-closure effects due to the presence of the repository, transportation options are irrelevant and the options are distinguished only by the treatment, i.e., $k = (\kappa, \lambda_0)$. For the risk calculations, it is assumed that the total activity in the repository is independent of the waste treatment. The activity concentration in the repository is then given by

$$d_0^{(\kappa)} = \frac{Q_0}{A_0^{(\kappa)} \; h_0} \; , \tag{E.7.1}$$

where the four quantities are

$d_0^{(\kappa)}$ = Activity concentration in repository (Bq m^{-3}),
Q_0 = Total activity in repository (Bq),
$A_0^{(\kappa)}$ = Footprint of wastes in repository (m^2),
h_0 = Height of wastes in repository panel (m).

In addition, the ratio of the footprints for different treatment options is related to the volume reduction factor $F_{v\kappa}$ due to the treatment of the wastes by

$$F_{v\kappa} = \frac{A_0^{(0)}}{A_0^{(\kappa)}} . \tag{E.7.2}$$

With the symbols

$P_{1i}^{(\kappa)}$ = Probability of a drill hole i through the wastes in scenario i, and
σ_i = Probability density of type i drill hole in region of WIPP (m^{-2}),

the probability of drilling a borehole through the wastes is

$$P_{1i}^{(\kappa)} = \sigma_i \, A_0^{(\kappa)} , \tag{E.7.3}$$

and the product

$$d_0^{(\kappa)} \, P_{1i}^{(\kappa)} = \frac{\sigma_i \, Q_0}{h_0} = const , \tag{E.7.4}$$

is a constant, assuming that the height h_0 of the waste in the repository does not change due to treatment, i.e., remains at a stack height of three drums.

In drilling operations according to scenario i, the activity $\{Q_i^{(\kappa)}\}$ is brought to the surface. With its gamma component, it irradiates the drilling crew over the short term. The corresponding risk is, in the general terms of Equation (E.7.1), only treatment option-dependent through the source term $Q_i^{(\kappa)}$. In this evaluation, it will be assumed that, for treated wastes, the mobilization is restricted to the drill hole, and is not changed thereafter until the hole is plugged. The activity brought to the surface is the same for each drill hole in each of the three intrusion scenarios.

Similarly, after the pond for the drilling mud has dried out, wind erosion will lead to a very low public inhalation risk, which is again only treatment option-dependent through the same source term according to Equation (E.7.2). Thus the public inhalation risk is subject to reduction factors which are identical to those of the occupational risks.

In the risk through the contamination of stock well water and, therefore, beef, the mobilization of the activity in the repository and its transport to the Culebra must be accounted for. From there to the stockwell, the activity transport is assumed to be linear in the source term at the drill hole. In the combined human intrusion Scenario E1E2, contaminations in groundwater and air can arise from different source locations. It is assumed here, that these effects superpose linearly. This

is particularly important in the groundwater contamination in the Culebra, as the water that carries the contamination also may carry salt at elevated concentrations.

E.7.2 Post-Closure Occupational Radiation Risks From Drilling Operations

E.7.2.1 Risk Of Drilling Operations In Scenario E1

In this scenario, a hole is drilled through the wastes and continued down into a portion of the Castile Formation containing a pressurized brine reservoir. The risk arises from direct external exposure to activity brought up in the drilling mud and the brine flowing to the surface. In addition to the waste in the borehole, the drilling mud and the brine will dissolve some of the waste around the borehole.

The mobilized material thus consists not only of drill cuttings but also includes material adjacent to the hole that becomes available for transport through processes such as dissolution or entrainment. The amount of the material in addition to drill cuttings depends upon the waste form and fluid flow environment. Cemented or vitrified waste will contribute less additional material than will a loose and unconsolidated waste form.

A two-step process is considered in this analysis: (1) a quantity of waste is "mobilized" in the vicinity of the hole penetrating the waste horizon, and (2) the mobilized quantity is transported to the surface. At any moment, the accumulated activity brought to the surface serves as source term for direct irradiation of the crew by penetrating gamma radiation. The assumption made here is that the increase in activity, and thus in the dose rate, is linear with time. The average surface activity and dose rate over the time interval of changing dose rate is, therefore, equal to the ultimately accumulated value for half the time it takes to drill through the waste. Afterward, the entire activity mobilized contributes to the dose to the drill crew. Any members of the public are assumed to be far enough away to incur only exposures that lie far below cosmic and terrestrial background.

Risk Component 40 then has two subcomponents, and with the symbols

$P_{11}^{(\kappa)}$ = Probability of a drill hole through the waste and into the Castile Formation,
P_{13} = Probability of hitting a brine reservoir in Castile Formation in area of WIPP,
$\Phi_{40\,1}^{(\kappa)}$ = Time average of total activity mobilized in scenario E1 (Bq),
$\Phi_{40\,2}^{(\kappa)}$ = Transport function to surface,
$\Phi_{40\,3}^{(\kappa)}$ = Global exposure function for drilling crew (Sv Bq^{-1}),
a_1 = Cancer risk coefficient (Sv^{-1}),
C_i = Constant parts of equations, and
$R_{40\,o\,\kappa\,\lambda}$ = Cancer risk of an E1 drilling operation,

the occupational cancer risk of an E1 drilling scenario is

$$R_{40o\kappa\lambda} = [P_{11}^{(\kappa)} P_{13}] \left\{ \Phi_{401}^{(\kappa)} \Phi_{402}^{(\kappa)} \right\} \Phi_{403}^{(\kappa)} a_1 . \tag{E.7.5}$$

With no factor outside the source term and the probability being treatment option-dependent, only the footprint $A_o^{(\kappa)}$ in $P_{11}^{(\kappa)}$ [see equation (E.7.3)] and $\Phi_{401}^{(\kappa)}$ change with treatment options, because the transport function to the surface is assumed to be treatment independent. The scaling of the risk can then be written as

$$R_{40o\kappa\lambda} = C_1 A_0^{(\kappa)} \Phi_{401}^{(\kappa)} , \tag{E.7.6}$$

and the risk reduction factors are

$$\rho_{40o\kappa\lambda} = \frac{A_0^{(0)} \Phi_{401}^{(0)}}{A_0^{(\kappa)} \Phi_{401}^{(\kappa)}} = F_{v\kappa} F_{a\kappa} , \tag{E.7.7}$$

where the ratio of total mobilized activities is defined by

$$F_{a\kappa} \equiv \frac{\Phi_{401}^{(0)}}{\Phi_{401}^{(\kappa)}} . \tag{E.7.8}$$

Numerical values and errors estimated for the reduction factor for mobilized activities are given in Table D.5-1 of Attachment D. The standard errors of the risk reduction factors are

$$\left(\frac{\Delta \rho_{40o\kappa\lambda}}{\rho_{40o\kappa\lambda}} \right)^2 = \left(\frac{\Delta F_{v\kappa}}{F_{v\kappa}} \right)^2 + \left(\frac{\Delta F_{a\kappa}}{F_{a\kappa}} \right)^2 . \tag{E.7.9}$$

The risk reduction factors for an E1 scenario are listed in Table E.7-1. They are grouped around a value of 5 but are applied to an exceedingly small baseline risk.

E.7.2.2 Risk Of Drilling Operations In Scenario E2

In this scenario, a borehole is drilled into or through the waste without also penetrating a pressurized brine reservoir. Waste from the hole itself and dissolution of waste in regions adjacent to the hole again leads to a mobilized activity brought to the surface. Using the same

TABLE E.7-1

RISK REDUCTION FACTORS FOR HUMAN INTRUSION SCENARIO E1

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{40\,o1\lambda}$	4.7 ± 0.7	$\rho_{41\,o\kappa\lambda} = \rho_{40\,o\kappa\lambda}$
$\rho_{40\,o2\lambda}$	4.8 ± 0.7	$\rho_{43\,p\kappa\lambda} = \rho_{40\,o\kappa\lambda}$
$\rho_{40\,o3\lambda}$	5.3 ± 1.4	$\rho_{44\,p\kappa\lambda} = \rho_{40\,o\kappa\lambda}$
$\rho_{40\,o4\lambda}$	4.5 ± 0.7	
Annual Baseline Risks:		
$R_{40\,o\,o\,o}$	$3 \cdot 10^{-8}$	FSEIS (DOE 1990a), Table 5.61
$R_{41\,o\,o\,o}$	--	Not available in FSEIS
$R_{43\,o\,o\,o}$	--	Not available in FSEIS
$R_{44\,o\,o\,o}$	--	Not available in FSEIS

assumptions as in the preceding section, this leads to a model for Risk Component 41 with two subcomponents. With the symbols:

$P_{12}^{(\kappa)}$ = Probability of drill hole into or through repository, no brine,
$\Phi_{41\,1}^{(\kappa)}$ = Time average of total activity mobilized in scenario E2 (Bq),
$\Phi_{41\,2}^{(\kappa)}$ = Transport function to surface in scenario E2,
$\Phi_{41\,3}^{(\kappa)}$ = Global exposure function for crew in E2 scenario (Sv Bq $^{-1}$),
a_1 = Cancer risk coefficient (Sv^{-1}),
C_l = Constant parts of equations, and
$R_{41\,o\kappa\lambda}$ = Cancer risk from direct exposure in an E2 drilling operation,

this risk component is

$$R_{41\,o\kappa\lambda} = [\,P_{12}^{(\kappa)}\,]\left\{\Phi_{41\,1}^{(\kappa)}\;\Phi_{41\,2}^{(\kappa)}\right\}\Phi_{41\,3}^{(\kappa)}\;a_1\;. \tag{E.7.10}$$

With Equation (E.7.3) and the fact that $\Phi_{41\,2}^{(\kappa)}$ is assumed to be constant and the factors outside the source term and probability (in brackets) do not depend on the alternative, the risk can again be scaled as

$$R_{41\,o\kappa\lambda} = C_1\;A_0^{(\kappa)}\;\Phi_{41\,1}^{(\kappa)}\;. \tag{E.7.11}$$

Again, reduction ratios can be defined for the mobilized activities which are the same as those in Scenario E1, due to the assumptions made in Sections D.5.1 and E.7.1,

$$\frac{\Phi_{41\,1}^{(0)}}{\Phi_{41\,1}^{(\kappa)}} = F_{a\kappa}\;. \tag{E.7.12}$$

Numerical values for these reduction ratios are listed in Attachment D, Table D.5-1, together with their standard errors. The risk reduction factors are then given by

$$\rho_{41\,o\kappa\lambda} = \frac{A_0^{(0)}\;\Phi_{41\,1}^{(0)}}{A_0^{(\kappa)}\;\Phi_{41\,1}^{(\kappa)}} = F_{v\kappa}\;F_{a\kappa}\;, \tag{E.7.13}$$

with the standard error

$$\left(\frac{\Delta\rho_{41\,o\kappa\lambda}}{\rho_{41\,o\kappa\lambda}}\right)^2 = \left(\frac{\Delta F_{v\kappa}}{F_{v\kappa}}\right)^2 + \left(\frac{\Delta F_{a\kappa}}{F_{a\kappa}}\right)^2\;. \tag{E.7.14}$$

The numerical values are thus the same as those given in Table E.7-1.

E.7.2.3 Risk Of Drilling Operations In Scenario E1E2

Scenario E1E2 consists of a sequence of an E1 and an E2 scenario. The first drilling leads to an E1 contribution to the risk which is equal to the component $R_{40\,o\,\kappa\,\lambda}$ discussed in Section E.7.2.1 and thus leads to the risk reduction factors given in Table E.7-2. In addition, this scenario implies drilling into a pressurized repository in the E2 part, and results in the additional Risk Component 42. The respository consists of eight panels and a central zone, each of which is sealed. Therefore, Scenario E1E2 requires the E1 and E2 events to occur at least in the same sealed waste zone. Further, the consequence of Scenario E1E2 depends upon the time proximity and distance proximity of the two holes. E1E2 can involve a pressure gradient that causes collection and entrainment of larger quantities of material than does E1. Thus, the scenario depends not only upon the drilling of two holes, but also depends upon an interaction function between the two holes. Using the symbols

$P_{11}^{(\kappa)}$	=	Probability of first drill hole into repository and into the Castile Formation,
P_{13}	=	Probability of drilling into a brine reservoir in the Castile Formation,
$P_{12}^{(\kappa)}$	=	Probability of drill hole into or through repository,
$\Phi_{421}^{(\kappa)}$	=	Time average of total activity mobilized in E2 part of scenario (Bq),
$\Phi_{422}^{(\kappa)}$	=	Interaction function between the two drill holes,
$\Phi_{423}^{(\kappa)}$	=	Transport function to surface in E2 part of scenario,
$\Phi_{424}^{(\kappa)}$	=	Global exposure function for crew in E2 part of the scenario (Sv Bq^{-1}),
a_1	=	Cancer risk coefficient (Sv^{-1}),
C_i	=	Constant parts of equations, and
$R_{42\,o\,\kappa\,\lambda}$	=	Cancer risk from direct irradiation in the E2 part of an E1E2 drilling scenario,

The risk component for that part is

$$R_{42\,o\,\kappa\,\lambda} = [\, P_{11}^{(\kappa)}\, P_{13}\, P_{12}^{(\kappa)} \,] \left\{ \Phi_{421}^{(\kappa)}\, \Phi_{422}^{(\kappa)}\, \Phi_{423}^{(\kappa)} \right\} \Phi_{424}^{(\kappa)}\, a_1 \,. \tag{E.7.15}$$

Using Equation (E.7.3) this risk contribution can be rewritten as scaling according to

$$R_{42\,o\,\kappa\,\lambda} = C_1 \left(A_0^{(\kappa)} \right)^2 \Phi_{421}^{(\kappa)}\, \Phi_{422}^{(\kappa)} \,. \tag{E.7.16}$$

With the definition of the reduction factors

$$\frac{\Phi_{421}^{(0)}}{\Phi_{421}^{(\kappa)}} = F_{a\kappa} \,, \tag{E.7.17}$$

TABLE E.7-2

RISK REDUCTION FACTORS FOR DRILLING CREWS IN SCENARIO E1E2

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{42\,o1\lambda}$	5.6 ± 1.2	$\rho_{45\,p\kappa\lambda} = \rho_{42\,o\kappa\lambda}$
$\rho_{42\,o2\lambda}$	5.7 ± 1.2	
$\rho_{42\,o3\lambda}$	11.6 ± 5.4	
$\rho_{42\,o4\lambda}$	41.5 ± 9.5	
Annual Baseline Risks:		
$R_{42\,o00}$	$3 \cdot 10^{-8}$	FSEIS (DOE 1990a), Table 5.61
$R_{45\,o00}$		Not available in FSEIS

given Table E.7-1, this leads to the risk reduction ratio of

$$\rho_{42o\kappa\lambda} = F_{a\kappa} \frac{\left(A_0^{(0)}\right)^2}{\left(A_0^{(\kappa)}\right)^2} = F_{v\kappa}^2 F_{a\kappa} , \qquad \text{(E.7.18)}$$

with standard error of

$$\left(\frac{\Delta \rho_{42o\kappa\lambda}}{\rho_{42o\kappa\lambda}}\right)^2 = 4\left(\frac{\Delta F_{v\kappa}}{F_{v\kappa}}\right)^2 + \left(\frac{\Delta F_{a\kappa}}{F_{a\kappa}}\right)^2 . \qquad \text{(E.7.19)}$$

The numerical values for the risk reduction factors are calculated using the values for $F_{a\kappa}$ in Table D.5-1 and those for $F_{v\kappa}$ in Table D.3-2, both in Attachment D. The aggregation of the contributions form the E1 and the E2 part of the E1E2 scenario is not carried out explicitly, because the E1 scenario is already included in the evaluation. The risk reduction factors are tabulated in Table E.7-2, ranging from a risk reduction factor of almost 6 for Level II treatments to risk reduction factors of 12 and 42 for Treatment Options 3 and 4, respectively.

E.7.3 Post-Closure Public Radiation Risks From Drilling Operations

E.7.3.1 Basic Considerations

Whereas the direct public exposure from the drilling mud is negligible, the dried out pond may through wind erosion give rise to an inhalation hazard. As stated before, the superposition of exposures from two different drill sites is assumed to be linear. Another source of radiation exposure arises from the transport of the mobilized radioactive salt brine through the Culebra aquifer to a stock well, leading to a radioactive contamination of the beef produced on the surrounding land. Ingestion by man causes an internal exposure and a risk of cancer or genetic damage.

E.7.3.2 Inhalation Risks From Dried Up Ponds Of Drilling Mud

E.7.3.2.1 Public Inhalation Risk Due To Drilling In Scenario E1

The assumptions for this scenario are the same as those in Section E.7.2.1. After the drilling stops, the mud pond contains the total activity mobilized and brought to the surface in the E1 scenario. It is assumed to be eroded at a constant rate, leading to a constant time-averaged source term and activity concentrations in the air. Risk Component 43 then has two sub-components, and with the symbols

$P_{11}^{(\kappa)}$ = Probability of a drill hole through the waste and into the Castile Formation,
P_{13} = Probability of hitting a brine reservoir in Castile Formation in area of WIPP,

$\Phi_{431}^{(\kappa)}$ = Total activity brought to surface in Scenario E1 (Bq),
$\Phi_{432}^{(\kappa)}$ = Suspension and transport function from pond to receptors (m^{-3}),
$\Phi_{433}^{(\kappa)}$ = Global dosimetry function for exposed persons ($Sv\ m^3\ Bq^{-1}$),
C_l = Constant parts of equations,
a_1 = Cancer risk coefficient (Sv^{-1}), and
$R_{43p\kappa\lambda}$ = Public cancer risk by inhalation caused by an E1 drilling operation,

the inhalation pathway leads to a public cancer risk of an E1 drilling scenario of

$$R_{43p\kappa\lambda} = [P_{11}^{(\kappa)}\ P_{13}]\left\{\Phi_{431}^{(\kappa)}\ \Phi_{432}^{(\kappa)}\right\}\Phi_{433}^{(\kappa)}\ a_1\ . \tag{E.7.20}$$

With no factor outside the source term and the probability treatment option-dependent, only the footprint $A_0^{(\kappa)}$ in $P_{11}^{(\kappa)}$ [see Equation (E.7.3)] and $\Phi_{431}^{(\kappa)}$ change with treatment options, because the suspension and transport function to the receptors is assumed to be independent. The risk can then be scaled as

$$R_{43p\kappa\lambda} = C_1\ A_0^{(\kappa)}\ \Phi_{431}^{(\kappa)}\ , \tag{E.7.21}$$

and the risk reduction factors are the same for the cancer and genetic risks,

$$\rho_{43p\kappa\lambda} = \frac{A_0^{(0)}\ \Phi_{431}^{(0)}}{A_0^{(\kappa)}\ \Phi_{431}^{(\kappa)}} = F_{v\kappa}\ F_{a\kappa}\ . \tag{E.7.22}$$

The standard errors of the reduction factors are given by

$$\left(\frac{\Delta\rho_{43o\kappa\lambda}}{\rho_{43o\kappa\lambda}}\right)^2 = \left(\frac{\Delta F_{v\kappa}}{F_{v\kappa}}\right)^2 + \left(\frac{\Delta F_{a\kappa}}{F_{a\kappa}}\right)^2\ . \tag{E.7.23}$$

The numerical values of the reduction factors and thus also of their errors are the same as those given for $\rho_{40o\kappa\lambda}$ in Section E.7.2.1 and Table E.7-1.

E.7.3.2.2 Public Inhalation Risk Due To Drilling In Scenario E2

This scenario is discussed in Section E.7.2.2 but also entails the suspension of the dried and eroded mud by wind. Using the same assumptions as in that section leads to a model for Risk Component 44 with two subcomponents. Defining the symbols

$P_{12}^{(\kappa)}$ = Probability of drill hole into or through repository, no brine,
$\Phi_{441}^{(\kappa)}$ = Total activity brought to surface for Scenario E2 (Bq),

$\Phi_{442}^{(\kappa)}$ = Suspension and transport function to receptor in Scenario E2 (m^{-3}),
Φ_{443} = Global dosimetry function for public in Scenario E2 ($Sv\ m^3\ Bq^{-1}$),
C_1 = Constant part of equations,
a_1 = Cancer risk coefficient (Sv^{-1}), and
$R_{44p\kappa\lambda}$ = Cancer risk from direct irradiation in E2 drilling operation,

this risk component is

$$R_{44p\kappa\lambda} = [\,P_{12}^{(\kappa)}\,]\left\{\Phi_{441}^{(\kappa)}\ \Phi_{442}^{(\kappa)}\right\}\Phi_{443}\ a_1\ . \qquad \text{(E.7.24)}$$

This expression has the same properties as Equation (E.7.10) in Section E.7.2.2 . Thus, the risk is again scaled according to

$$R_{44p\kappa\lambda} = C_1\ A_0^{(\kappa)}\ \Phi_{441}^{(\kappa)}\ . \qquad \text{(E.7.25)}$$

Assuming again that the mobilized activity reduction factors $F_{a\kappa}$ are the same as those in E2, the risk reduction factors are

$$\rho_{44p\kappa\lambda} = \frac{A_0^{(0)}\ \Phi_{441}^{(0)}}{A_0^{(\kappa)}\ \Phi_{441}^{(\kappa)}} = F_{v\kappa}\ F_{a\kappa}\ , \qquad \text{(E.7.26)}$$

and, therefore, the same standard errors as those of $\rho_{41o\kappa\lambda}$ and thus $\rho_{40o\kappa\lambda}$. Numerical values for these risk reduction factors have, therefore, already been given in Table E.7-1.

E.7.3.2.3 <u>Public Inhalation Risks Due To Drilling In Scenario E1E2</u>

The assumptions about Scenario E1E2 are the same as those for the calculation of the risk reductions factors $\rho_{42o\kappa\lambda}$ in Section E.7.2.3. The first drilling leads to an E1 contribution to the public inhalation risk which is equal to the component $R_{40o\kappa\lambda}$ discussed in Section E.7.2.1 and thus leads to the risk reduction factors given in Table E.7-2. In addition, it means a second source of activity in the air from the E2 part of the scenario, and the addition of Risk Component 45. Using the symbols

$P_{11}^{(\kappa)}$ = Probability of first drill hole into repository and into the Castile Formation,
P_{13} = Probability of hitting a brine reservoir in the Castile Formation,
$P_{12}^{(\kappa)}$ = Probability of drill hole into or through repository,
$\Phi_{451}^{(\kappa)}$ = Time average of total activity mobilized and brought to surface in E2 part of scenario (Bq),
$\Phi_{452}^{(\kappa)}$ = Interaction function between the two holes,
$\Phi_{453}^{(\kappa)}$ = Suspension and transport function to receptor in E2 part of scenario (m^{-3}) ,

$\Phi_{454}^{(\kappa)}$ = Global exposure function for public in E2 scenario (Sv m^3 Bq^{-1}),
a_1 = Cancer risk coefficient (Sv^{-1}),
C_i = Constant parts of equations, and
$R_{45p\kappa\lambda}$ = Cancer risk from inhalation in E2 part of E1E2 drilling operation,

the risk component for that part is

$$R_{45p\kappa\lambda} = [\, P_{11}^{(\kappa)}\, P_{13}\, P_{12}^{(\kappa)} \,] \left\{ \Phi_{451}^{(\kappa)}\, \Phi_{452}^{(\kappa)}\, \Phi_{453}^{(\kappa)} \right\} \Phi_{454}^{(\kappa)}\, a_1 \,. \tag{E.7.27}$$

Using Equation (E.7.3) the risk can be scaled as

$$R_{45p\kappa\lambda} = C_1 \left(A_0^{(\kappa)} \right)^2 \Phi_{451}^{(\kappa)} \,. \tag{E.7.28}$$

As in Section E.7.2.3, this leads to a risk reduction ratio of

$$\rho_{45p\kappa\lambda} = \frac{\Phi_{451}^{(0)} \left(A_0^{(0)} \right)^2}{\Phi_{451}^{(\kappa)} \left(A_0^{(\kappa)} \right)^2} = F_{v\kappa}^2\, F_{a\kappa} = \rho_{42o\kappa\lambda} \,, \tag{E.7.29}$$

with the same standard error as $\rho_{42o\kappa\lambda}$. These values are thus the same as those in Section E.7.2.3 and are listed in Table E.7.2.

E.7.3.3 Public Ingestion Risks Due To Drilling Operations

E.7.3.3.1 Public Ingestion Risks Due To Beef Contaminated By Stock Well Water In Scenario E1

The assumptions for the E1 model are the same as before. Here, however, the pathway goes from the repository to an aquifer in the Culebra and from there to a stock well. This transport is assumed to be linear in the source term as are the subsequent transfer functions into beef and man. The activity concentrations in the water, in the beef, and, therefore, in the intake by man are assumed to be at an equilibrium value. This ingestion risk constitutes Risk Component 46 with two subcomponents for cancer and genetic risk. With the symbols

$P_{11}^{(\kappa)}$ = Probability of a borehole through the repository and into the Castile Formation,
P_{13} = Probability of hitting a brine reservoir in Castile Formation in area of WIPP,
$\Phi_{461}^{(\kappa)}$ = Long-term rate of activity mobilization and transport to the Culebra aquifer for Scenario E1 (Bq s^{-1}),
$\Phi_{462}^{(\kappa)}$ = Transport function to stock well via Culebra (s L^{-1}),
$\Phi_{463}^{(\kappa)}$ = Transfer-dosimetry function for water to beef to man (Sv L Bq^{-1}),
C_i = Constant parts of equations,

a_1 = Cancer risk coefficient (Sv^{-1}),
$R_{46p\kappa\lambda}$ = Public cancer risk of an E1 drilling operation,

the expression for this component is

$$R_{46p\kappa\lambda} = \left[P_{11}^{(\kappa)} \; P_{13} \right] \left\{ \Phi_{461}^{(\kappa)} \; \Phi_{462}^{(\kappa)} \right\} \Phi_{463}^{(\kappa)} \; a_1 \; . \tag{E.7.30}$$

With only the product of the long-term rate of activity mobilization and the footprint in $P_{11}^{(\kappa)}$ changing with treatment options, the risk has the scaling property

$$R_{46p\kappa\lambda} = C_1 \; A_0^{(\kappa)} \; \Phi_{461}^{(\kappa)} \; , \tag{E.7.31}$$

the risk reduction factors are

$$\rho_{46p\kappa\lambda} = \frac{A_0^{(0)} \; \Phi_{461}^{(0)}}{A_0^{(\kappa)} \; \Phi_{461}^{(\kappa)}} = F_{v\kappa} \; F_{b\kappa} \; , \tag{E.7.32}$$

where

$$F_{b\kappa} \equiv \frac{\Phi_{461}^{(0)}}{\Phi_{461}^{(\kappa)}} \; , \tag{E.7.33}$$

with values given in Table D.5-2 of Attachment D and with the assumption that the long-term rate of activity mobilization achieves equilibrium concentrations at the stock well by the time of the sampling. The errors of the model calculation of $F_{b\kappa}$ are large, and lognormally distributed quantities are involved. The geometric standard deviations (see Section C.1.5) are

$$\sigma_g \; (\rho_{46p\kappa\lambda}) = \sigma_g \; (F_{b\kappa}) \; , \tag{E.7.34}$$

calculated in a simplified version made possible by the large difference in the geometrical standard deviations of the two factors. Numerical values for the risk reduction factors are listed in Table E.7-3. The means range from 10,000 to 100,000 with geometric standard errors of factors of 20 up and down from these values. The range of values, however, leads to risk reductions exclusively, applied to extremely low baseline risks.

TABLE E.7-3

RISK REDUCTION FACTORS FOR PUBLIC INGESTION IN SCENARIO E1

QUANTITY	VALUE	(GSD) *	COMMENTS/REFERENCES
Risk Reduction Factors:			
$\rho_{46\,p1\lambda}$	$1.14 \cdot 10^{4}$	(20)	$\rho_{50\,p\kappa\lambda} = \rho_{46\,p\kappa\lambda}$
$\rho_{46\,p2\lambda}$	$1.14 \cdot 10^{4}$	(20)	
$\rho_{46\,p3\lambda}$	$2.12 \cdot 10^{4}$	(20)	
$\rho_{46\,p4\lambda}$	$9.95 \cdot 10^{4}$	(20)	
Annual Baseline Risks:			
$R_{46\,p00}$	$2.2 \cdot 10^{-13}$		FSEIS (DOE, 1990a), Table 5.70
$R_{50\,p00}$	--		Not available in FSEIS

* GSD = Geometric standard deviation of a lognormal distribution.

E.7.3.3.2 Public Ingestion Risks Due To Beef Contaminated By Stock Well Water In Scenario E2

Risk Component 47 with two subcomponents is calculated using the same assumptions for this scenario as before. Using the symbols

$P_{12}^{(\kappa)}$ = Probability of drill hole into or through repository, no brine,
$\Phi_{471}^{(\kappa)}$ = Long-term rate of activity mobilization and transport to the Culebra (Bq s^{-1}),
$\Phi_{472}^{(\kappa)}$ = Transport function to stock well via Culebra in Scenario E2 (L^{-1} s),
$\Phi_{473}^{(\kappa)}$ = Transfer-dosimetry function for contaminated beef (Sv Bq^{-1} L),
C_i = Constant parts of equations,
a_1 = Cancer risk coefficient (Sv^{-1}), and
$R_{47p\kappa\lambda}$ = Public risk due to an E2 drilling scenario,

the expression for the public ingestion risk is

$$R_{47p\kappa\lambda} = \left[P_{12}^{(\kappa)} \right] \left\{ \Phi_{471}^{(\kappa)} \, \Phi_{472}^{(\kappa)} \right\} \Phi_{473}^{(\kappa)} \, a_1 \, . \tag{E.7.35}$$

With the constant parts eliminated, the scaling of risks is given by

$$R_{47p\kappa\lambda} = C_1 \, A_0^{(\kappa)} \, \Phi_{471}^{(\kappa)} \, , \tag{E.7.36}$$

and the risk reduction factors are

$$\rho_{47p\kappa\lambda} = F_{v\kappa} \, F_{c\kappa} \, , \tag{E.7.37}$$

with the definition of the factor $F_{c\kappa}$ as

$$F_{c\kappa} \equiv \frac{\Phi_{471}^{(0)}}{\Phi_{471}^{(\kappa)}} \, . \tag{E.7.38}$$

$F_{c\kappa}$ is the reduction factor for the activity mobilized to be transported to the stock well. Numerical values are listed in Table D.5-2 in Attachment D. The errors are calculated under the assumption that the standard errors of $F_{c\kappa}$ are much larger than those of all other contributions. Thus the geometric standard deviations are

$$\sigma_g \, (\rho_{47p\kappa\lambda}) = \sigma_g \, (F_{c\kappa}) \, . \tag{E.7.39}$$

Numerical values for the risk reduction factors are given in Table E.7-4, grouped closely to 1 for Treatments 1 and 2, with geometrical standard deviations corresponding to a factor of 3 up and down for Level II treatments, rising to a factor of 1.8 for Treatment 3 and 64 for Treatment 4. This

TABLE E.7-4

RISK REDUCTION FACTORS FOR PUBLIC INGESTION IN SCENARIO E2

QUANTITY	VALUE	(GSD) *	COMMENTS/REFERENCES
Risk Reduction Factors:			
$\rho_{47\,p1\lambda}$	1.2	(3)	$\rho_{51\,p\kappa\lambda} = \rho_{47\,p\kappa\lambda}$
$\rho_{47\,p2\lambda}$	1.3	(3)	
$\rho_{47\,p3\lambda}$	1.8	(5)	
$\rho_{47\,p4\lambda}$	64	(50)	
Annual Baseline Risks:			
$R_{47\,p00}$	$5.9 \cdot 10^{-11}$		FSEIS (DOE 1990a), Table 5.70
$R_{51\,p00}$	--		Not available in FSEIS

* GSD = Geometric standard deviation of a lognormal distribution.

may result in either considerable risk reductions. These reduction factors are applied to an exceedingly small baseline risk.

E.7.3.3.3 Public Ingestion Risks Due To Beef Contaminated By Stock Well Water in Scenario E1E2

Using the same model assumptions as in Section E.7.2.3, the ingestion of contaminated beef leads to a risk contribution which is the same as that of Scenario E1, so that the risk reduction factors, errors, and numerical values for the E1 part of the operation apply [Equations (E.7.32) and (E.7.34)]. In addition, there is the Risk Component 48 for the E2 part of Scenario E1E2. With the symbols

$P_{11}^{(\kappa)}$ = Probability of first drill hole into repository and into Castile Formation,
P_{13} = Probability of hitting a brine reservoir in the Castile Formation,
$P_{12}^{(\kappa)}$ = Probability of drill hole into or through repository,
$\Phi_{48\,1}^{(\kappa)}$ = Long-term rate of activity mobilization and transport to the Culebra for E2 part of Scenario E1E2 (Bq s^{-1}),
$\Phi_{48\,2}^{(\kappa)}$ = Interaction function between the two drill holes,
$\Phi_{48\,3}^{(\kappa)}$ = Transport function to surface via Culebra in E2 part of Scenario E1E2 (s L^{-1}),
$\Phi_{48\,4}^{(\kappa)}$ = Transfer-dosimetry function for residents eating beef (Sv Bq^{-1} L),
C_i = Constant parts of all equations,
a_1 = Cancer risk coefficient (Sv^{-1}),
$R_{48\,p\,\kappa\,\lambda}$ = Public cancer risk due to an E1E2 scenario,

this risk component is

$$R_{48\,p\kappa\lambda} = \left[P_{11}^{(\kappa)}\ P_{13}\ P_{12}^{(\kappa)} \right] \left\{ \Phi_{48\,1}^{(\kappa)}\ \Phi_{48\,2}^{(\kappa)}\ \Phi_{48\,3}^{(\kappa)} \right\} \Phi_{48\,4}^{(\kappa)}\ a_1 \ . \tag{E.7.40}$$

As in Section E.7.2.3, the component is proportional to the product of the square of the footprint and the rate of activity mobilization

$$F_{d\kappa} \equiv \frac{\Phi_{48\,1}^{(0)}\ \Phi_{48\,2}^{(0)}\ \Phi_{48\,4}^{(0)}}{\Phi_{48\,1}^{(\kappa)}\ \Phi_{48\,2}^{(\kappa)}\ \Phi_{48\,4}^{(\kappa)}} \ . \tag{E.7.41}$$

The risk reduction is, therefore,

$$\rho_{48\,p\kappa\lambda} = F_{d\kappa} \frac{\left(A_0^{(0)}\right)^2}{\left(A_0^{(\kappa)}\right)^2} = F_{d\kappa}\ F_{v\kappa}^2 \ . \tag{E.7.42}$$

Under the assumption that the last three factors in the numerator and denominator of Equation (E.7.41) do not depend on the waste treatment and, therefore, cancel, the ratio of activity mobilization factors reduces to

$$F_{d\kappa} \equiv \frac{\Phi_{481}^{(0)}}{\Phi_{481}^{(\kappa)}} . \tag{E.7.43}$$

The ratio of activities F_{dk}, mobilized for each waste treatment are listed in Table D-5.2 of Attachment D. Despite the factor $F_{v\kappa}{}^2$, the geometrical standard deviations remain at

$$\sigma_g \left(\rho_{48p\kappa\lambda} \right) = \sigma_g \left(F_{d\kappa} \right) , \tag{E.7.44}$$

because the uncertainties in $F_{v\kappa}$ are much smaller than those of $F_{d\kappa}$. The numerical values for the risk reduction factors given in Table E.7-5 show considerable variation from about one million to 10 billion. The geometric standard deviations range from 40 to 80, adding one to two orders of magnitude to the range of risk reduction factors. Note that these factors are applied to a very small baseline risk.

E.7.4 Post-Closure Public Risks Due To Chemical Agents

E.7.4.1 Basic Considerations

The FSEIS (DOE, 1990a) calculates one post-closure chemical risk. It is due to the presence of lead, and it is assumed for the risk calculations that the total amount of lead in the repository is independent of the waste treatment, except in Treatment Option 4 in which metals are largely decontaminated and removed. The lead concentration in the repository is then given by

$$d_1^{(\kappa)} = \frac{M_0}{A_0^{(\kappa)} \, h_0} , \tag{E.7.45}$$

for $1 \leq \kappa \leq 3$, where the quantities

$d_1{}^{(\kappa)}$ = Lead concentration in repository (kg m^{-3}),
M_0 = Total mass of lead in repository (kg),
$A_0{}^{(\kappa)}$ = Footprint of wastes in repository (m^2),
h_0 = Height of wastes in repository panel (m).

For Treatment Option 4 the melting process leads to a reduction in the total lead mass by a factor f_{red}. This factor is assumed to be one here. In the groundwater, lead is assumed to be attached to colloidal matter and to move with the water. In combined human intrusion scenarios, the contaminations in groundwater can arise from different sources. It is again assumed here that

TABLE E.7-5

RISK REDUCTION FACTORS FOR PUBLIC INGESTION IN AN E1E2 SCENARIO

QUANTITY	VALUE	(GSD) *	COMMENTS/REFERENCES
Risk Reduction Factors:			
$\rho_{48\,p1\lambda}$	$8.3 \cdot 10^{5}$	(80)	$\rho_{52\,p\kappa\lambda} = \rho_{48\,p\kappa\lambda}$
$\rho_{48\,p2\lambda}$	$1.2 \cdot 10^{6}$	(60)	
$\rho_{48\,p3\lambda}$	$9.5 \cdot 10^{6}$	(80)	
$\rho_{48\,p4\lambda}$	$1.3 \cdot 10^{10}$	(40)	
Annual Baseline Risks:			
$\rho_{48\,p00}$	$7.8 \cdot 10^{-6}$		FSEIS (DOE, 1990a), Table 5.70
$\rho_{52\,p00}$	--		Not available in FSEIS

* GSD = Geometric standard deviation of a lognormal distribution.

these effects superpose linearly, implying in particular that the salt content in the Culebra does not saturate.

E.7.4.2 Ingestion Risk Caused By Lead In Contaminated Beef

E.7.4.2.1 Risks Due To Beef Contaminated By Stock Well Water In Scenario E1

The assumptions for the E1 model are the same as before, and the transport is assumed to be linear in the source term as are the subsequent transfer functions into beef and man. The lead concentrations in the water, in the beef, and, therefore, in the intake by man are assumed to be at an equilibrium value. This ingestion risk constitutes Risk Component 50. With the symbols

$P_{11}^{(\kappa)}$ = Probability of a borehole through the repository into the Castile Formation,
P_{13} = Probability of hitting a brine reservoir in the Castile Formation,
$\Phi_{501}^{(\kappa)}$ = Long-term lead mobilization and transport rate to the Culebra (mg s^{-1}),
$\Phi_{502}^{(\kappa)}$ = Transport function to stock well via Culebra (s L^{-1}),
Φ_{503} = Transfer/daily-intake function for contaminated beef (L day^{-1}),
N_{p4} = Number of persons exposed by ingestion,
$L_{Pb}^{(ref)}$ = Reference level for lead (mg Pb kg^{-1} day^{-1}),
M_1 = Mass of reference man (kg),
f_t = Exposure time correction factor for one year (yr^{-1}),
C_i = Constant parts of equations,
r_o = Risk associated with reference level,
$R_{50p\kappa\lambda}$ = Morbidity risk due to lead ingestion (yr^{-1}),

the lead ingestion risk from an E1 event is

$$R_{50p\kappa\lambda} = \left[P_{11}^{(\kappa)} P_{13} \right] \left\{ \Phi_{501}^{(\kappa)} \Phi_{502}^{(\kappa)} \right\} \Phi_{503}^{(\kappa)} \frac{N_{p4} r_o f_t}{M_1 L_{Pb}^{(ref)}} . \qquad \text{(E.7.46)}$$

With only the product of the long-term rate of lead mobilization and the footprint in $P_1^{(\kappa)}$ changing with treatment options, the risk is found to scale according to

$$R_{50p\kappa\lambda} = C_1 A_0^{(\kappa)} \Phi_{501}^{(\kappa)} . \qquad \text{(E.7.47)}$$

The risk reduction factors for this scenario are

$$\rho_{50p\kappa\lambda} = \frac{A_0^{(0)} \Phi_{501}^{(0)}}{A_0^{(\kappa)} \Phi_{501}^{(\kappa)}} = F_{v\kappa} F_{Pbb\kappa} , \qquad \text{(E.7.48)}$$

with the definition,

$$F_{Pb\,b\,\kappa} \equiv \frac{\Phi_{50\,1}^{(0)}}{\Phi_{50\,1}^{(\kappa)}} , \tag{E.7.49}$$

for the reduction factor in the long-term rate of lead mobilization. The geometrical standard deviations of the risk reduction factors are the determining contribution,

$$\sigma_g \left(\rho_{50\,p\,\kappa\,\lambda} \right) = \sigma_g \left(F_{Pb\,b\,\kappa\,\lambda} \right) . \tag{E.7.50}$$

If it is assumed that the dissolution of radioisotopes and lead is impeded by treatment in the same way, then $F_{Pb\,b\,\kappa} = F_{b\,\kappa}$ and the last two equations are the same as those calculated for Scenario E1 as $\rho_{46\,p\,\kappa\,\lambda}$. The numerical values for the risk reduction factors are given in Table E.7-3.

E.7.4.2.2 Risks Due To Beef Contaminated By Stock Well Water In Scenario E2

Risk Component 51 is calculated using the same assumptions for this scenario as before. With the symbols

$P_{12}^{(\kappa)}$	=	Probability of a borehole into or through the repository, no brine,
$\Phi_{51\,1}^{(\kappa)}$	=	Long-term lead mobilization and transport rate to the Culebra (mg s^{-1}),
$\Phi_{51\,2}^{(\kappa)}$	=	Transport function to stock well via Culebra (s L^{-1}),
$\Phi_{51\,3}^{(\kappa)}$	=	Transfer/daily-intake function for contaminated beef (L day^{-1}),
N_{p4}	=	Number of persons exposed by ingestion,
$L_{Pb}^{(ref)}$	=	Reference level for lead (mg Pb kg^{-1} day^{-1}),
M_1	=	Mass of reference man (kg),
r_o	=	Risk associated with reference level,
f_t	=	Exposure time correction factor for one year (yr^{-1}),
C_i	=	Constant parts of equations,
$R_{51\,p\,\kappa\,\lambda}$	=	Morbidity risk due to lead ingestion (yr^{-1}),

the lead ingestion risk from an E2 event is

$$R_{51\,p\,\kappa\,\lambda} = \left[P_{12}^{(\kappa)} \right] \left\{ \Phi_{51\,1}^{(\kappa)} \; \Phi_{51\,2}^{(\kappa)} \right\} \Phi_{51\,3}^{(\kappa)} \; \frac{N_{p4} \; r_o \; f_t}{M_1 \; L_{Pb}^{(ref)}} . \tag{E.7.51}$$

With only the product of the long-term rate of lead mobilization and the footprint in $P_1^{(k)}$ changing with treatment options, the risk scales as

$$R_{51\,p\kappa\lambda} = C_1\, A_0^{(\kappa)}\, \Phi_{51\,1}^{(\kappa)}\,, \tag{E.7.52}$$

and the risk reduction factors are

$$\rho_{51\,p\kappa\lambda} = \frac{A_0^{(0)}\, \Phi_{51\,1}^{(0)}}{A_0^{(\kappa)}\, \Phi_{51\,1}^{(\kappa)}} = F_{v\kappa}\, F_{Pb\,c\,\kappa} = F_{v\kappa}\, F_{c\kappa}\,, \tag{E.7.53}$$

where

$$F_{Pb\,c\,\kappa} \equiv \frac{\Phi_{51\,1}^{(0)}}{\Phi_{51\,1}^{(\kappa)}}\,. \tag{E.7.54}$$

This assumes just as in the case of radioactivity that while the mobilization rates for lead and radioisotopes may differ, the reduction ratios due to treatment are the same. The geometrical standard deviations of the risk reduction factors are again assumed to be

$$\sigma_g\left(\rho_{51\,p\kappa\lambda}\right) = \sigma_g\left(F_{Pb\,c\,\kappa}\right) = \sigma_g\left(F_{c\kappa}\right)\,. \tag{E.7.55}$$

This is the same result as that for the component $\rho_{47\,p\,\kappa\,\lambda}$ and the values are again those of Table E.7-4.

E.7.4.2.3 Risks Due To Beef Contaminated By Stock Well Water In Scenario E1E2

The use of the same model assumptions as in Section E.7.2.3 leads to a risk contribution which is the same as that of the E1 scenario, so that the risk reduction factors, errors, and numerical values for the E1 part of the operation apply, as described by Equations (E.7.48) and (E.7.50). In addition, there is Risk Component 52 for the E2 part of the drilling scenario E1E2. With the symbols

$P_{11}^{(\kappa)}$ = Probability of first drill hole into repository and into the Castile Formation,
P_{13} = Probability of drilling into a brine reservoir in the Castile Formation,
$P_{12}^{(\kappa)}$ = Probability of drill hole into or through repository,
$\Phi_{52\,1}^{(\kappa)}$ = Long-term rate of lead mobilization and transport to the Culebra (mg s^{-1}),
$\Phi_{52\,2}^{(\kappa)}$ = Interaction term between drills holes,
$\Phi_{52\,3}^{(\kappa)}$ = Transport function to stock well via Culebra (s L^{-1}),
$\Phi_{52\,4}^{(\kappa)}$ = Transfer/daily-intake function for contaminated beef (L day^{-1}),
$N_{p\,4}$ = Number of persons exposed by ingestion,
$L_{Pb}^{(ref)}$ = Reference level for lead (mg Pb kg^{-1} day^{-1}),
M_1 = Mass of reference man (kg),

f_t = Exposure time correction factor for one year (yr^{-1}),
C_i = Constant parts of equations,
r_o = Risk associated with reference level,
$R_{52p\kappa\lambda}$ = Morbidity risk due to lead ingestion (yr^{-1}),

this risk component is given by

$$R_{52p\kappa\lambda} = \left[P_{11}^{(\kappa)} \; P_{13} \; P_{12}^{(\kappa)} \right] \left\{ \Phi_{521}^{(\kappa)} \; \Phi_{522}^{(\kappa)} \; \Phi_{523}^{(\kappa)} \right\} \Phi_{524}^{(\kappa)} \; \frac{N_{p4} \; r_o \; f_t}{M_1 \; L_{Pb}^{(ref)}} \; . \qquad \text{(E.7.56)}$$

As in Section E.7.2.3, the component is proportional to the product of the square of the footprint and the rate of lead mobilization, assuming all functions $\Phi_{j\nu}^{(\kappa)}$ independent of treatment except $\Phi_{521}^{(\kappa)}$. The risk reduction is, therefore,

$$\rho_{52p\kappa\lambda} = \frac{\Phi_{521}^{(0)} \left(A_0^{(0)} \right)^2}{\Phi_{521}^{(\kappa)} \left(A_0^{(\kappa)} \right)^2} = F_{Pbd\kappa} \; F_{v\kappa}^2 \; , \qquad \text{(E.7.57)}$$

with the definition

$$F_{Pbd\kappa} \equiv \frac{\Phi_{521}^{(0)}}{\Phi_{521}^{(\kappa)}} \; . \qquad \text{(E.7.58)}$$

With the assumption that the ratio of lead mobilization $F_{Pbd\kappa}$ is the same as that for the radioactivity,

$$\rho_{52p\kappa\lambda} = F_{v\kappa}^2 \; F_{d\kappa} = \rho_{48p\kappa\lambda} \; . \qquad \text{(E.7.59)}$$

The geometrical standard deviation is again

$$\sigma_g \left(\rho_{52p\kappa\lambda} \right) = \sigma_g \left(F_{d\kappa} \right) \; . \qquad \text{(E.7.60)}$$

The numerical values have already been given in Table E.7-5.

ATTACHMENT F

RISKS OF TREATMENT OPTIONS

F.1 BASIC CONSIDERATIONS

F.1.1 Scope for Assessment of Treatment Risks

Scope and limitations of the model for the Treatment Facility have already been described in Appendix I and in more detail in Attachment D. The description here will be limited to aspects which are important to the approach to risk assessment.

The simplifying assumptions of the modular form without taking credit for economies of scale for larger units makes most evaluations location-independent. Each module is assumed to contain all two, four, or six devices, or multiples thereof, according to the treatment level chosen. There are seven modules with the appropriate capabilities that are moved along the path from the WIPP to the originators of the waste according to the location scenario selected.

The risks chosen as baseline risks are those of the assay and certification process in the WHB in the currently proposed sequence of activities. An exception is the general occupational risks for fatalities and injuries. These are not considered in the FSEIS but play a more important role in a risk comparison. For these risk components, the occupational risks of the assay and certification process are calculated and used as baseline. Apart from these general accidents, no accidents particular to the treatment of radioactive waste are considered, in order to limit the scope of this study. Only routine exposures to radioactivity and to volatile organic chemicals (VOCs) are taken into account.

All treatment devices are assumed to be operating in airtight enclosures with access through air locks until the treated wastes are enclosed in drums again. Shielding is used to lower penetrating radiation to levels compatible with the ALARA concept and DOE's health and safety goals.

In both routine and maintenance operations, internal exposures to radioisotopes occur. In this assessment, only inhalation exposures are evaluated. Ingestion, wound, and skin exposures are not considered because in routine and maintenance scenarios they tend to be much lower than inhalation exposures and the corresponding doses.

F.1.2 Treatment of the Engineered Waste Forms

F.1.2.1 Treatment Options 1 and 2

In Treatment Option 1, after the assay and certify operation, the solidified sludges are left as they are. Without sorting, combustibles, metals, glasses, and the drum are shredded and then cemented. This Level II treatment is the least work-intensive treatment option considered here. As discussed in Attachment D, this process leads to a decrease of void space and an increase in the weight of the drum. In Treatment Option 2, the only change is that the sludges are cemented as well.

F.1.2.2 Treatment Option 3

Treatment Option 3 is a Level III treatment. After assay and certification, the sludges are cemented and the rest of the waste is sorted. Shredding is done separately for combustibles and for metals and glasses. Combustibles are then incinerated and the ashes transported to the cementing area for inclusion in the process. Metals and glass, on the other hand, are cemented directly.

F.1.2.3 Treatment Option 4

This is the most ambitious Level III treatment considered here. After the assay and certify procedure, the sludges are vitrified, possibly in a microwave oven. Separate shredding is used for combustibles and for metals and glasses. Combustibles are incinerated and their ashes vitrified. Shredded metals and glasses are melted with frit, taking advantage of the disproportionation of radioisotopes between slag and metal. The metals are disposed of as low level waste and only the slag is emplaced in the WIPP.

F.2 GENERAL OCCUPATIONAL ACCIDENTS

Normal occupational accidents are not addressed in the FSEIS. Here they are needed because they increase as the complexity of the treatment increases. Directly relevant incidence data are not available, but data for similar industries were used in Attachment D, Section D.4.1, to estimate the relevant risk coefficients.

F.2.1 Industrywide Occupational Accidents

F.2.1.1 Fatal Occupational Accidents

Fatal occupational accidents are addressed here, excluding forklift accidents with fatal outcome. Those are evaluated separately. This class of accidents leads to Risk Component 53. Using the symbols:

$N_{o1}^{(\kappa)}$ = Number of persons in WHB and TF,
P_{14} = Annual occupational fatality rate per worker in accidents not involving forklifts (yr^{-1}),
C_i = Constant parts of equations,
P_{of} = Annual probability rate for occupational accidents with fatal outcome,
f_{531} = Fraction of forklift accidents in all occupational accidents, and
$R_{53o\kappa\lambda}$ = Risk of occupational fatality per year (yr^{-1}),

the general expression for this risk is given by

$$R_{53o\kappa\lambda} = N_{o1}^{(\kappa)} P_{14} . \tag{F.2.1}$$

The data given in Attachment D, Section D.4.1, gives the probability rate P_{14} in terms of the annual probability rate P_{of}

$$P_{14} = P_{of}\left(1 - f_{531}\right) , \tag{F.2.2}$$

where $f_{531} = 10^{-2}$. Thus the baseline risk is $R_{53000} = (1.6 \pm 0.4) \cdot 10^{-3}$, and the risk is

$$R_{53o\kappa\lambda} = N_{o1}^{(\kappa)} P_{of} (1 - f_{531}) . \tag{F.2.3}$$

The risk equation has the scaling property

$$R_{53o\kappa\lambda} = C_1 N_{o1}^{(\kappa)} . \tag{F.2.4}$$

The risk reduction ratios are, therefore

$$\rho_{53o\kappa\lambda} = \frac{N_{o1}^{(0)}}{N_{o1}^{(\kappa)}} = F_{m\kappa} , \tag{F.2.5}$$

with the standard errors of

$$\Delta\rho_{53o\kappa\lambda} = \Delta F_{m\kappa} . \tag{F.2.6}$$

The numerical values are given in Table F.2-1 with values for the factor $F_{m\kappa}$ and its errors taken from Table D.3-2. The risk reduction factors decrease with more treatment, indicating an increase in risk due to an increasing crew in the Treatment Facility. The baseline risks are derived from the risk coefficients in D.4.1 for a crew of 12.

TABLE F.2-1

RISK REDUCTION FACTORS FOR GENERAL OCCUPATIONAL ACCIDENT FATALITIES AND INJURIES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{53o1\lambda}$	0.276 ± 0.016	$\rho_{54o\kappa\lambda} = \rho_{53o\kappa\lambda}$
$\rho_{53o2\lambda}$	0.260 ± 0.015	
$\rho_{53o3\lambda}$	0.170 ± 0.010	
$\rho_{53o4\lambda}$	0.076 ± 0.004	
Annual Baseline Risk:		
R_{53o00}	$(1.6 \pm 0.4) \cdot 10^{-3}$	U.S. Dept. of Labor,
R_{54o00}	0.70 ± 0.03	Bulletin 2366, 1990

F.2.1.2 Nonfatal Injuries

The model for general occupational injuries in Attachment D, Section D.4.1, derives an estimate for nonfatal accidents with workdays lost. One percent of those are the forklift accidents not considered in this section. These accidents form Risk Component 54. Using the symbols

$N_{o1}^{(\kappa)}$	=	Number of persons in WHB and TF,
P_{15}	=	Annual occupational injury rate per worker in accidents not involving forklifts (yr^{-1}),
C_1	=	Constant parts of equations,
P_{oi}	=	Annual probability of general occupational injury,
f_{541}	=	Fraction of injuries caused by forklift in all occupations, and
$R_{54o\kappa\lambda}$	=	Risk of occupational injuries per year of operation (yr^{-1}),

the general risk expression is for every year of operation is

$$R_{54o\kappa\lambda} = N_{o1}^{(\kappa)} P_{15} . \tag{F.2.7}$$

In Section D.4.1, Attachment D, the value for P_{oi} is given. It is related to P_{15} by

$$P_{15} = P_{oi} (1 - f_{541}) , \tag{F.2.8}$$

where $f_{541} = 0.01$. For a crew of 12, the baseline risk is $R_{54o00} = 0.70 \pm 0.03$. Thus the risk can be written as

$$R_{54o\kappa\lambda} = N_{o1}^{(\kappa)} P_{oi} (1 - f_{541}) , \tag{F.2.9}$$

and hence the scaling property of this risk component depends only on the numbers of persons handling the waste, not including forklift operations,

$$R_{54o\kappa\lambda} = C_1 N_{o1}^{(\kappa)} . \tag{F.2.10}$$

The risk reduction ratios are again

$$\rho_{54o\kappa\lambda} = \frac{N_{o1}^{(o)}}{N_{o1}^{(\kappa)}} = F_{m\kappa} , \tag{F.2.11}$$

which is the same as for the fatalities with the same standard errors

$$\Delta\rho_{54o\kappa\lambda} = \Delta F_{m\kappa} . \tag{F.2.12}$$

The values for both risk reduction factors are given in Table F.2-1.

F.2.2 Forklift Accidents

F.2.2.1 Fatal Forklift Accidents

This scenario is a subset of the occupational accidents considered in Section F.2.1. However, it is an important component and will be considered separately. It is assumed that the number of forklift accidents is independent of drum weight, although accidents involving heavier vehicles may lead to increased severity of consequences. Fatal forklift accidents form Risk Component 55. Using the symbols

$n_r^{(\kappa)}$ = Number of drums handled per year (yr^{-1}),
$n_f^{(\kappa)}$ = Number of forklift operations per drum handled,
P_{of} = General annual occupational fatality rate,
C_i = Constant parts of equations,
f_{531} = Fraction of fatal forklift accidents in all fatal occupational accidents,
Φ_{551} = Conversion function to baseline risk per forklift operation,
P_{16} = Probability of a fatal accident per forklift operation, and
$R_{550\kappa\lambda}$ = Risk of a fatal forklift accident per year of operation (yr^{-1}),

the risk of a fatal forklift accident per year of operation can be stated as

$$R_{55o\kappa\lambda} = n_r^{(\kappa)}\, n_f^{(\kappa)}\, P_{16} \,. \tag{F.2.13}$$

The probability of a forklift fatality per forklift operation P_{16} derives from the total probability rate of occupational fatalities by the expression

$$P_{16} = P_{of}\, f_{531}\, \Phi_{551} \,. \tag{F.2.14}$$

Thus the risk can be rewritten as

$$R_{55o\kappa\lambda} = n_r^{(\kappa)}\, n_f^{(\kappa)}\, P_{of}\, f_{531}\, \Phi_{551} \,, \tag{F.2.15}$$

and the baseline risk is given by 10 percent of the total occupational fatalities according to Section D.4.1. The baseline risk is thus $R_{55000} = 0.00016 \pm 0.00006$.

The scaling property of Risk Component 55 is derived from the fact that only the product of the number of drums handled per year and the number of forklift operations per drum handled is treatment dependent,

$$R_{55o\kappa\lambda} = C_1\, n_r^{(\kappa)}\, n_f^{(\kappa)} \,. \tag{F.2.16}$$

The risk reduction ratios are thus

$$\rho_{55o\kappa\lambda} = \frac{n_r^{(0)}\, n_f^{(0)}}{n_r^{(\kappa)}\, n_f^{(\kappa)}} = F_{v\kappa}\, F_{f\kappa}\,, \tag{F.2.17}$$

with standard errors

$$\left(\frac{\Delta\,\rho_{55o\kappa\lambda}}{\rho_{55o\kappa\lambda}}\right)^2 = \left(\frac{\Delta\,F_{v\kappa}}{F_{v\kappa}}\right)^2 + \left(\frac{F_{f\kappa}}{F_{f\kappa}}\right)^2 . \tag{F.2.18}$$

The risk reduction factors for the forklift fatalities and the standard errors are given in Table F.2-2. The risk reduction factors correspond to increases in risk that vary from about 4 to about 14. The relative errors lie near 5 percent.

F.2.2.2 Nonfatal Forklift Injuries

This component is again a subset of occupational injuries. It is important because 1 percent of the industrial accidents cause 10 percent of the workdays lost. Again, it is assumed that the frequency of forklift accidents does not depend on the drum weight. This is achieved by utilizing forklifts appropriate to the weight. These accidents comprise Risk Component 56. Using the symbols

$n_r^{(\kappa)}$ = Number of drums handled per year (yr^{-1}),
$n_f^{(\kappa)}$ = Number of forklift operations per drum handled,
P_{oi} = General annual occupational injury rate,
f_{541} = Fraction of all occupational injuries caused in forklift accidents,
Φ_{561} = Conversion function to baseline risk per forklift operation,
C_i = Constant parts of the equations,
P_{17} = Probability of an injury per forklift operation, and
$R_{56o\kappa\lambda}$ = Risk of a forklift injury per year of operation (yr^{-1}),

the risk of nonfatal forklift injury per year of operation can be stated as

$$R_{56o\kappa\lambda} = n_r^{(\kappa)}\, n_f^{(\kappa)}\, P_{17}\,. \tag{F.2.19}$$

Again, there is a relationship between probabilities analogous to those in the previous sections,

$$P_{17} = P_{oi}\, f_{541}\, \Phi_{561}\,. \tag{F.2.20}$$

TABLE F.2-2

RISK REDUCTION FACTORS FOR FORKLIFT ACCIDENT FATALITIES AND INJURIES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{55o1\lambda}$	0.276 ± 0.016	$\rho_{56o\kappa\lambda} = \rho_{55o\kappa\lambda}$
$\rho_{55o2\lambda}$	0.260 ± 0.015	
$\rho_{55o3\lambda}$	0.170 ± 0.010	
$\rho_{55o4\lambda}$	0.076 ± 0.004	
Annual Baseline Risk:		
R_{55o00}	$(1.6 \pm 0.6) \cdot 10^{-4}$	U.S. Dept. of Labor,
R_{56o00}	0.070 ± 0.003	Bulletin 2257, 1986

The risk of a nonfatal forklift injury is then

$$R_{56\,o\kappa\lambda} = n_r^{(\kappa)}\, n_f^{(\kappa)}\, P_{oi}\, f_{541}\, \Phi_{561}\,, \tag{F.2.21}$$

and the baseline risk is one tenth of the general injury risk $R_{56\,o\,0\,0} = 0.070 \pm 0.003$. Thus, as in the previous scenario, the scaling property of Risk Component 56 is dependent only on the product of the number of drums handled per year and the number of forklift operations per drum handled

$$R_{56\,o\kappa\lambda} = C_1\, n_r^{(\kappa)}\, n_f^{(\kappa)}\,. \tag{F.2.22}$$

The risk reduction ratios are the same as those for $\rho_{55\,o\kappa\lambda}$ with the same standard errors listed in Table F.2-2.

F.3 RISK OF RADIATION EXPOSURES

F.3.1 External Exposures

External exposures are the result of irradiation by penetrating radiations, both gammas and neutrons. For routine operations, shielding is provided and for maintenance operations little or only partial shielding is available. Because waste handling facilities are at large distances from the public, public exposures are much smaller than the background levels and can, therefore, be ignored.

F.3.1.1 Routine Operations: External Exposure

External exposure of the work crew depends on the shielding, which is dictated by health and safety concerns as well as the ALARA concept. It is also dependent on the type of waste and on the time-motion parameters and the time spent at each particular choice. This leads to Risk Component 57 with two subcomponents, cancer and genetic. With the symbols

$q_2^{(\kappa)}$ = Total activity per drum (Bq),
$n_r^{(\kappa)}$ = Number of drums handled annually (yr^{-1}),
η_w = Fraction of waste in form w.
$N_{o\,6}^{(\nu)}$ = Number of persons needed for treatment ν,
$\Phi_{57\,1}^{(w\,\nu)}$ = Shielding-geometry function of facility ν to treat waste w,
$\Phi_{57\,2}^{(w\,\nu)}$ = Dosimetry function of average exposed person ($Sv\ s^{-1}\ Bq^{-1}$),
$t_{57}^{(\nu)}$ = Exposure time for treatment ν of one drum of waste form w (s),
a_1 = Lifetime cancer risk coefficient (Sv^{-1}),
C_i = Constant parts of equation, and
$R_{57\,o\,\kappa\lambda}^{(w\,\nu)}$ = Occupational risk of cancer due to treatment ν of waste form w in alternative κ per year of operation (yr^{-1}),

the general occupational risk equation used is

$$R_{57o\kappa\lambda}^{(w\nu)} = \left\{ q_2^{(\kappa)} \; n_r^{(\kappa)} \; \eta_w \right\} N_{o6}^{(\nu)} \; \Phi_{571}^{(w\nu)} \; \Phi_{572}^{(w\nu)} \; t_{57}^{(\nu)} \; a_1 \; . \tag{F.3.1}$$

The dependence on alternative κ is simplified by the assumption of a constant amount of activity treated annually [Equation (E.1.5)] which eliminates the variability of the first two factors, and the assumption that operational health and safety standards will provide at least the same level of shielding protection at every plant. The second condition leads to the requirement that for the drum being processed in different devices ν the residual radiation level outside the containment is the same

$$q_2^{(0)} \; \Phi_{571}^{(w\nu)} = C_1 \; . \tag{F.3.2}$$

In addition, in the absence of time-motion studies in the type of treatment plants needed here, it will be assumed that the dosimetry function $\Phi_{572}^{(w\nu)}$ is the same for all devices. Under these conditions, the risk can be rewritten as

$$R_{57o\kappa\lambda}^{(w\nu)} = C_2 \; \eta_w \; N_{o6}^{(\nu)} \; t_{57}^{(\nu)} = C_2 \; \phi_{57\kappa}^{(w\nu)} \; , \tag{F.3.3}$$

where the quantity $\phi_{57\kappa}^{(w\nu)}$ is the effort (in man-hours) expended for the treatment of one drum of waste form w in device ν,

$$\phi_{57\kappa}^{(w\nu)} \equiv \eta_w \; N_{o6}^{(\nu)} \; t_{57}^{(\nu)} \; . \tag{F.3.4}$$

Assuming that the device ν can accommodate all types of wastes sent to it, the total risk of alternative κ is

$$R_{57o\kappa\lambda} = C_2 \sum_{w=1}^{W} \sum_{\nu=1}^{T} \phi_{57\kappa}^{(w\nu)} \; , \tag{F.3.5}$$

where W is the number of waste forms (three), and T the number of different treatment devices in the treatment facility (two, four, or six). The summation over ν starts with $\nu = 1$ because the term with $\nu = 0$ is already included in a component of the baseline risk which consists of that term only. The risk reduction factors are then

$$\rho_{57o\kappa\lambda} = \frac{\sum_{w=1}^{W} \phi_{570}^{(w0)}}{\sum_{w=1}^{W} \sum_{\nu=1}^{T} \phi_{57\kappa}^{(w\nu)}} \equiv \frac{V_{57o0}}{V_{57o\kappa}} \; , \tag{F.3.6}$$

with standard errors calculated under the assumption that no appreciable contributions come from the abundances η_w

$$\left(\frac{\Delta\rho_{57o\kappa\lambda}}{\rho_{57o\kappa\lambda}}\right)^2 = \sum_{w=1}^{W}\left[\left(\frac{\Delta\phi_{57o}^{(w0)}}{V_{57o0}}\right)^2 + \sum_{v=1}^{T}\left(\frac{\Delta\phi_{57\kappa}^{(wv)}}{V_{57o\kappa}}\right)^2\right], \qquad \text{(F.3.7)}$$

with the error given by the approximation

$$\frac{\Delta\phi_{57\kappa}^{(wv)}}{\phi_{57\kappa}^{(wv)}} \approx \frac{\Delta t_{57}^{(v)}}{t_{57}^{(v)}} . \qquad \text{(F.3.8)}$$

The numerical values for the effort factors $\phi_{57\kappa}^{(wv)}$ needed here are given in Table D.4-1. The numerical values of the risk reduction factors $\rho_{57o\kappa\lambda}$ and their errors are given in Table F.3-1. They are smaller than 1, indicating risk increases of factors between 2 and about 10, increasing with more complex treatment. The baseline risk data in the FSEIS for the assay and certify process are not detailed enough to provide a value.

F.3.1.2 Routine Maintenance: External Exposure

External exposure to penetrating radiation during maintenance operations is particularly important. Depending on the type of waste and the device, different times must be spent in the contaminated area. This leads to Risk Component 58 with two subcomponents. With the symbols

$q_2^{(\kappa)}$	=	Total activity per drum (Bq),
$n_r^{(\kappa)}$	=	Number of drums handled annually (yr^{-1}),
η_w	=	Fraction of waste in form w,
$f_{582}^{(wv)}$	=	Fraction of waste in form w released into containment of device v,
$N_{o7}^{(v)}$	=	Number of persons needed for maintenance of device v,
Φ_{581}	=	Dosimetry function of average exposed person ($Sv\ s^{-1}\ Bq^{-1}$),
$\Phi_{58\kappa}^{(v)}$	=	Maintenance function (annual number of operations) for device v,
$t_{58}^{(v)}$	=	Exposure time for maintenance of device v (s),
a_1	=	Lifetime cancer risk coefficient (Sv^{-1}),
C_i	=	Constant parts of equations, and
$R_{58o\kappa\lambda}^{(wv)}$	=	Occupational risk of cancer due to device v treating waste form w in alternative κ,

the general occupational risk equation is

$$R_{58o\kappa\lambda}^{(wv)} = \left\{q_2^{(\kappa)}\ n_r^{(\kappa)}\ \eta_w\ f_{582}^{(wv)}\right\} N_{o7}^{(v)}\ \Phi_{581}\ \Phi_{58\kappa}^{(v)}\ t_{58}^{(v)}\ a_1 . \qquad \text{(F.3.9)}$$

TABLE F.3-1

RISK REDUCTION FACTORS FOR ROUTINE EXTERNAL EXPOSURES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{5701\lambda}$	0.469 ± 0.033	
$\rho_{5702\lambda}$	0.429 ± 0.030	
$\rho_{5703\lambda}$	0.234 ± 0.017	
$\rho_{5704\lambda}$	0.104 ± 0.008	
Annual Baseline Risks:		
R_{57000}	--	Not available in FSEIS

The dependence on alternative κ is simplified by the assumption of a constant amount of activity treated annually [Equation (E.1.5)] which eliminates the product of the first two factors as a variable. Again, because of the lack of time-motion studies, it will be assumed that the dosimetry function $\Phi_{58\,1}$ is the same for all treatment plants. Under these conditions, the risk can be rewritten as scaling according to

$$\begin{aligned} R^{(wv)}_{58\,o\kappa\lambda} &= C_1 \;\; \eta_w \, f^{(wv)}_{58\,2} \, N^{(v)}_{o7} \, \Phi^{(v)}_{58\,\kappa} \, t^{(v)}_{58} \\ &= C_1 \;\; f^{(wv)}_{58\,2} \, \phi^{(wv)}_{58\,\kappa} \, , \end{aligned} \tag{F.3.10}$$

with the definition of the manpower factor

$$\phi^{(wv)}_{58\,\kappa} \equiv \eta_w \, N^{(v)}_{o7} \, \Phi^{(v)}_{58\,\kappa} \, t^{(v)}_{58} \, . \tag{F.3.11}$$

The total risk of alternative κ is then

$$R_{58\,o\kappa\lambda} = C_1 \sum_{v=1}^{T} \sum_{w=1}^{W} \phi^{(wv)}_{58\,\kappa} \, f^{(wv)}_{58\,2} \, , \tag{F.3.12}$$

where W is the number of waste forms and T the number of treatment devices. The risk reduction factors are then

$$\rho_{58\,o\kappa\lambda} = \frac{\sum_{w=1}^{W} \phi^{(0)}_{58\,0} \, f^{(w0)}_{58\,2}}{\sum_{v=1}^{T} \sum_{w=1}^{W} \phi^{(wv)}_{58\,\kappa} \, f^{(wv)}_{58\,2}} \equiv \frac{V_{58\,o0}}{V_{58\,o\kappa}} \, , \tag{F.3.13}$$

with standard errors derived under the assumption that the errors $\Delta\eta_w$, $\Delta t_{58}^{(v)}$, and $\Delta\Phi_{58\,\kappa}^{(v)}$ are considerably smaller than the errors of the suspension factors $\Delta f_{58\,2}^{(v)}$. The error of $N_{o\,7}^{(v)}$ is included in that of $\Delta t_{58}^{(v)}$. Error propagation is thus calculated for these factors only,

$$\left(\frac{\Delta \rho_{58\,o\kappa\lambda}}{\rho_{58\,o\kappa 11\lambda}} \right)^2 = \sum_{w=1}^{W} \left[\left(\frac{\phi^{(w0)}_{58\,0} \, \Delta f^{(w0)}_{58\,2}}{V_{58\,o0}} \right)^2 + \sum_{v=1}^{T} \left(\frac{\phi^{(wv)}_{58\,\kappa} \, \Delta f^{(wv)}_{58\,2}}{V_{58\,o\kappa}} \right)^2 \right] . \tag{F.3.14}$$

The numerical values for the manpower factor $\phi_{58\,\kappa}^{(wv)}$ are available in Table D.4-2 of Attachment D. Using the values in Tables D.4-3 for $f_{52\,2}^{(wv)}$ leads to the numerical values of the risk reduction factors

in Table F.3-2. They show effective increases in risk by factors between 250 and 1400 with standard errors of about 25 percent.

F.3.2 Internal Exposures

F.3.2.1 Routine Operations: Internal Exposure

F.3.2.1.1 Occupational Risks Due to Internal Routine Exposures

In this routine scenario a certain fraction of waste form w treated in device v escapes from containment and fills the treatment module concerned to equilibrium air concentrations without tripping the alarm setting on continuous air monitors. The crews, therefore, do not leave the area and do not don respirators. These conditions give rise to a chronic inhalation exposure to alpha-, beta-, and gamma-emitters, and thus the two subcomponents of Risk Component 59. Using the symbols

$q_2^{(\kappa)}$	=	Total activity per drum (Bq),
$n_r^{(\kappa)}$	=	Number of drums handled annually (yr^{-1}),
η_w	=	Fraction of waste in form w,
$f_{59\kappa}^{(v)}$	=	Fraction of waste in form w suspended and released from containment in inhalable form due to treatment v in alternative κ,
$N_{o1}^{(\kappa)}$	=	Number of persons in treatment plant,
f_{15}	=	Fraction of personnel exposed,
L_1	=	Annual ventilation volume (m^3),
V_1	=	Annual breathing volume (m^3),
f_{593}	=	Deposited fraction of suspended particles,
Φ_{591}	=	Overall dosimetry function of average exposed person ($Sv\ Bq^{-1}$),
a_1	=	Lifetime cancer risk coefficient (Sv^{-1}),
C_i	=	Constant parts of equations, and
$R_{59o\kappa\lambda}^{(wv)}$	=	Occupational risk of cancer due to treatment v of waste form w in alternative κ (yr^{-1}),

the general risk equation is

$$R_{59o\kappa\lambda}^{(wv)} = \left\{ q_2^{(\kappa)}\ n_r^{(\kappa)}\ \eta_w\ f_{59\kappa}^{(v)} \right\} f_{15}\ N_{o1}^{(\kappa)}\ \frac{V_1}{L_1}\ f_{593}\ \Phi_{591}\ a_1\ . \qquad \text{(F.3.15)}$$

The dependence on alternative κ is simplified by the assumption of a constant amount of activity treated annually [Equation (E.1.5)] which eliminates the variability of the first two factors. Upon elimination of the other constant terms, the risk can be scaled as

$$R_{59o\kappa\lambda}^{(wv)} = C_1\ \eta_w\ f_{59\kappa}^{(v)}\ N_{o1}^{(\kappa)}\ . \qquad \text{(F.3.16)}$$

TABLE F.3-2

RISK REDUCTION FACTORS FOR EXTERNAL EXPOSURE DURING ROUTINE MAINTENANCE

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{58\,o1\lambda}$	$(4.0 \pm 1.0) \cdot 10^{-3}$	
$\rho_{58\,o2\lambda}$	$(3.9 \pm 1.0) \cdot 10^{-3}$	
$\rho_{58\,o3\lambda}$	$(2.9 \pm 0.7) \cdot 10^{-3}$	
$\rho_{58\,o4\lambda}$	$(7.2 \pm 2.1) \cdot 10^{-4}$	
Annual Baseline Risks:		
$R_{58\,o00}$	--	Not available in FSEIS

The total risk of alternative κ is then scaled according to

$$R_{59\,o\kappa\lambda} = C_1 \; N_{o1}^{(\kappa)} \sum_{v=1}^{T} f_{59\kappa}^{(v)} \; . \tag{F.3.17}$$

No sum over w appears, because the sum over v is independent of w, and the sum over the normalized waste fractions η_w leads to a factor of 1. The risk reduction factors are then

$$\rho_{59\,o\kappa\lambda} = F_{m\kappa} \frac{f_{590}^{(0)}}{\sum_{v=1}^{T} f_{59\kappa}^{(v)}} \equiv F_{m\kappa} \frac{V_{59\,o0}}{V_{59\,o\kappa}} \; , \tag{F.3.18}$$

with standard errors

$$\left(\frac{\Delta \rho_{59\,o\kappa\lambda}}{\rho_{59\,o\kappa\lambda}} \right)^2 = \left(\frac{\Delta F_{m\kappa}}{F_{m\kappa}} \right)^2 + \left(\frac{\Delta f_{590}^{(0)}}{V_{59\,o0}} \right)^2 + \sum_{v=1}^{T} \left(\frac{\Delta f_{59\kappa}^{(v)}}{V_{59\,o\kappa}} \right)^2 . \tag{F.3.19}$$

Numerical values for the factors $f_{59\kappa}^{(v)}$ are listed in Table D.4-4 of Attachment D, and values of the risk reduction factors are listed in Table F.3-3. Risk reductions indicate decreases in occupational risk by factors varying from 290 to 1730 with relative errors of about 33 to 40 percent.

F.3.2.1.2 Public Risks Due to Internal Routine Exposures

This scenario employs the same source term as in the previous scenario. It is assumed that there is a release of radioactivity from containment which exits through the HEPA filters and is dispersed on the outside. The actual dispersion function is not dependent on the treatment option, but the number of persons exposed and their location may be. Using the symbols

$q_2^{(\kappa)}$	=	Total activity per drum (Bq),
$n_r^{(\kappa)}$	=	Number of drums handled annually (yr^{-1}),
η_w	=	Fraction of waste in form w,
$f_{59\kappa}^{(v)}$	=	Fraction of waste in form w suspended and released from containment in inhalable form due to treatment v in alternative κ,
$f_{dep}^{(\kappa)}$	=	Fraction of equilibrium concentration not deposited before filters,
$f_{rem}^{(\kappa)}$	=	Fraction of concentration penetrating HEPA filters,
$\Phi_{59\,dd}^{(\kappa)}$	=	Dispersion-dosimetry function ($Sv\ Bq^{-1}$),
a_1	=	Lifetime cancer risk coefficient (Sv^{-1}),

TABLE F.3-3

RISK REDUCTION FACTORS FOR OCCUPATIONAL RISKS DUE TO ROUTINE INTERNAL EXPOSURES DURING WASTE TREATMENT

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{5901\lambda}$	$(1.73 \pm 0.70) \cdot 10^3$	
$\rho_{5902\lambda}$	$(1.44 \pm 0.56) \cdot 10^3$	
$\rho_{5903\lambda}$	$(7.1 \pm 2.5) \cdot 10^2$	
$\rho_{5904\lambda}$	$(2.9 \pm 1.0) \cdot 10^2$	
Annual Baseline Risks:		
R_{59000}	--	Not available in FSEIS

C_i = Constant parts of equation, and
$R_{59p\kappa\lambda}^{(wv)}$ = Public cancer risk due to treatment v of waste w in alternative κ (yr^{-1}),

the general type of risk equation is

$$R_{59p\kappa\lambda}^{(wv)} = \left\{ q_2^{(\kappa)}\, n_r^{(\kappa)}\, \eta_w\, f_{59\kappa}^{(v)} \right\} f_{dep}^{(\kappa)}\, f_{rem}^{(\kappa)}\, \Phi_{59dd}^{(\kappa)}\, a_1 \,. \tag{F.3.20}$$

As always, the dependence on alternative κ is simplified by the assumption of a constant amount of activity treated annually [Equation (E.1.5)]. Upon elimination of the other constant terms, the risk can be rewritten to scale as

$$R_{59p\kappa\lambda}^{(wv)} = C_1\, \Phi_{59dd}^{(\kappa)}\, \eta_w\, f_{59\kappa}^{(v)} \,. \tag{F.3.21}$$

The total risk is, therefore, scaling according to

$$R_{59p\kappa\lambda} = C_1\, \Phi_{59dd}^{(\kappa)} \sum_{v=1}^{T} f_{59\kappa}^{(v)} \,, \tag{F.3.22}$$

which has the same basic structure as the expression for the occupational risk in Equation (F.3.17). Summation over all waste forms and treatment leads to the same risk reduction factors as Equation (F.3.18), except for the number of persons involved. Thus the risk reduction factors are

$$\rho_{59p\kappa\lambda} = F_{e\kappa} \frac{f_{590}^{(0)}}{\sum_{v=1}^{T} f_{59\kappa}^{(v)}} \equiv F_{e\kappa} \frac{V_{59o0}}{V_{59o\kappa}} \,, \tag{F.3.23}$$

with the standard errors

$$\left(\frac{\Delta \rho_{59p\kappa\lambda}}{\rho_{59p\kappa\lambda}} \right)^2 = \left(\frac{\Delta F_{e\kappa}}{F_{e\kappa}} \right)^2 + \left(\frac{\Delta f_{590}^{(0)}}{V_{59o0}} \right)^2 + \sum_{v=1}^{T} \left(\frac{\Delta f_{59\kappa}^{(v)}}{V_{59o\kappa}} \right)^2 \,. \tag{F.3.24}$$

Note that the second and third terms are identical to those in Equation (F.3.19); only the first term is different. Numerical values of the reduction factors ρ and their errors are listed in Table F.3-4. Again, substantial decreases in risk are indicated, with reduction factors ranging from 1900 to 3100 with errors near 40 percent. Baseline risks in the FSEIS are not detailed enough to give the component associated with the assay and certification procedure.

TABLE F.3-4

RISK REDUCTION FACTORS FOR PUBLIC RISKS DUE TO INTERNAL EXPOSURES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{59p1\lambda}$	$(3.1 \pm 1.4) \cdot 10^3$	
$\rho_{59p2\lambda}$	$(2.8 \pm 1.2) \cdot 10^3$	
$\rho_{59p3\lambda}$	$(2.1 \pm 0.8) \cdot 10^3$	
$\rho_{59p4\lambda}$	$(1.9 \pm 0.7) \cdot 10^3$	
Annual Baseline Risks:		
R_{59p00}	--	Not available in FSEIS

F.3.2.2 Routine Maintenance: Internal Exposure

F.3.2.2.1 Occupational Risk Due to Internal Maintenance Exposures

During maintenance, respiratory protection is assumed to be mandatory for the cleanup crew. Protection is not total, however, but depends again on health and safety as well as ALARA concerns. This leads to inhalation exposures and thus a risk of cancer and genetic damage, both in occupational and public settings. There are four subcomponents of Risk Component 60. Using the symbols

$q_2^{(\kappa)}$	=	Total activity per drum (Bq),
$n_r^{(\kappa)}$	=	Number of drums handled annually (yr^{-1}),
η_w	=	Fraction of waste in form w,
$f_{582}^{(wv)}$	=	Fraction of waste in form w released into containment of device v,
$f_{603}^{(wv)}$	=	Fraction of waste resuspended during cleanup of device v,
$\Phi_{601}^{(v)}$	=	Activity concentration function (L^{-1}),
v_6	=	Inhalation rate of workers ($L\ s^{-1}$),
P_{60}	=	Transmission factor of respiratory protection,
$N_{o7}^{(v)}$	=	Number of persons needed for maintenance of device v,
f_{13}	=	Fraction of airborne particles deposited in lung,
Φ_{602}	=	Internal dosimetry function of average exposed person ($Sv\ Bq^{-1}$),
$\Phi_{58\kappa}^{(v)}$	=	Maintenance function (annual maintenance operations for device v),
$t_{58}^{(v)}$	=	Exposure time for maintenance of device v (s),
a_1	=	Lifetime cancer risk coefficient (Sv^{-1}),
C_i	=	Constant parts of equation, and
$R_{60o\kappa\lambda}^{(wv)}$	=	Occupational risk of cancer due to maintenance of device v (yr^{-1}),

the general risk equation is

$$R_{60o\kappa\lambda}^{(wv)} = \left\{ q_2^{(\kappa)}\ n_r^{(\kappa)}\ \eta_w\ f_{58\kappa}^{(wv)}\ f_{603}^{(wv)} \right\} \Phi_{601}^{(v)}\ v_6\ t_{58}^{(v)}\ P_{60}\ f_{13}\ \Phi_{602}\ \Phi_{58\kappa}^{(v)}\ N_{o7}^{(v)}\ a_1\ . \tag{F.3.25}$$

The assumption of a constant amount of activity treated annually [Equation (E.1.5)] is again used to eliminate the product of the first two factors as a variable. The risk can then be determined to scale as

$$\begin{aligned} R_{60o\kappa\lambda}^{(wv)} &= C_1\ \eta_w\ f_{582}^{(wv)}\ f_{603}^{(wv)}\ N_{o7}^{(v)}\ \Phi_{58\kappa}^{(v)}\ t_{58}^{(v)} \\ &= C_1\ \phi_{58\kappa}^{(wv)}\ f_{582}^{(wv)}\ f_{603}^{(wv)}\ , \end{aligned} \tag{F.3.26}$$

where

$$\phi_{58\kappa}^{wv} = \eta_w\ N_{o7}^{(v)}\ \Phi_{58\kappa}^{(v)}\ t_{58}^{(v)}\ . \tag{F.3.27}$$

The total risk of alternative κ is then scaling as

$$R_{60\,o\,\kappa\,\lambda}^{(wv)} = C_1 \sum_{v=1}^{T} \sum_{w=1}^{W} \phi_{58\,\kappa}^{(wv)} f_{582}^{(wv)} f_{603}^{(wv)} . \tag{F.3.28}$$

Consequently the risk reduction factors are

$$\rho_{60\,o\,\kappa\,\lambda} = \frac{\sum_{w=1}^{W} \phi_{580}^{(w0)} f_{582}^{(w0)} f_{603}^{(w0)}}{\sum_{v=1}^{T} \sum_{w=1}^{W} \phi_{58\,\kappa}^{(wv)} f_{582}^{(wv)} f_{603}^{(wv)}} \equiv \frac{V_{60\,o\,0}}{V_{60\,o\,\kappa}} , \tag{F.3.29}$$

with standard errors which are derived under the assumption that the errors $\Delta\phi_{58\,\kappa}^{(wv)}$ are considerably smaller than the others. Error propagation is thus calculated for the remaining two factors only,

$$\left(\frac{\Delta\rho_{60\,o\,\kappa\,\lambda}}{\rho_{60\,o\,\kappa\,\lambda}}\right)^2 = \frac{1}{V_{60\,o\,0}^2} \sum_{w=1}^{W} \left[\left(f_{603}^{(0)} \Delta f_{582}^{(w0)}\right)^2 + \left(f_{582}^{(w0)} \Delta f_{603}^{(w0)}\right)^2 \right] \left(\phi_{580}^{(w0)}\right)^2$$

$$+ \frac{1}{V_{60\,o\,\kappa}^2} \sum_{v=1}^{T} \sum_{w=1}^{W} \left[\left(f_{603}^{(wv)} \Delta f_{582}^{(wv)}\right)^2 + \left(f_{582}^{(wv)} \Delta f_{603}^{(wv)}\right)^2 \right] \left(\phi_{58\,\kappa}^{(wv)}\right)^2 . \tag{F.3.30}$$

The numerical values of the parameters $f_{603}^{(wv)}$ which are needed in the following are given in Table D.4-5 of Attachment D. Using these values and those in Tables D.4-2 and D.4-3 leads to the numerical values for the risk reduction factors listed in Table F.3-5. These factors are rather closely grouped around values that signify large increases in risk by factors of about 20,000 to about 120,000 with relative standard errors of about 40 percent. Information on risk components in WHB operations are not detailed enough in the FSEIS to yield a baseline risk for this scenario.

F.3.2.2.2 Public Risk Due to Internal Exposures Caused by Maintenance

This scenario is similar to the previous one in that the source term is the same, but it differs by considering in addition the transmission of radioactivity to the outside atmosphere. Dispersion is the same for all alternatives but number and location of the exposed population may not be. Inhalation exposure leads to the two public subcomponents of Risk Component 60. The symbols

$q_2^{(\kappa)}$	=	Total activity per drum (Bq),
$n_r^{(\kappa)}$	=	Number of drums handled annually (yr^{-1}),
η_w	=	Fraction of waste in form w,
$f_{582}^{(wv)}$	=	Fraction of waste in form w released into containment of device v,
$f_{603}^{(wv)}$	=	Fraction of waste resuspended during cleanup of device v,
$\Phi_{60\,\kappa}^{(v)}$	=	Fraction of year spent on maintenance of device v,

TABLE F.3-5

RISK REDUCTION FACTORS FOR OCCUPATIONAL RISKS DUE TO INTERNAL EXPOSURE DURING ROUTINE MAINTENANCE

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{6001\lambda}$	$(4.0 \pm 1.5) \cdot 10^{-5}$	
$\rho_{6002\lambda}$	$(3.9 \pm 1.4) \cdot 10^{-5}$	
$\rho_{6003\lambda}$	$(4.2 \pm 1.4) \cdot 10^{-5}$	
$\rho_{6004\lambda}$	$(8.5 \pm 3.8) \cdot 10^{-6}$	
Annual Baseline Risks:		
R_{60000}	--	Not available in FSEIS

$\Phi_{60\,1}$ = Activity-concentration function (L^{-1}),
$f_{dep}^{(\kappa)}$ = Fraction of equilibrium concentration not deposited before filters,
$f_{rem}^{(\kappa)}$ = Fraction of concentration penetrating HEPA filters,
$\Phi_{60\,dd}^{(\kappa)}$ = Dispersion-dosimetry function (Sv Bq^{-1} L),
a_1 = Lifetime cancer risk coefficient (Sv^{-1}),
C_i = Constant parts of equations, and
$R_{60\,p\,\kappa\,\lambda}^{(w\,v)}$ = Occupational risk of cancer due to maintenance of device v (yr^{-1})

are used for the general risk equation

$$R_{60\,p\kappa\lambda}^{(wv)} = \left\{ q_2^{(\kappa)}\, n_r^{(\kappa)}\, \eta_w\, f_{582}^{(wv)}\, f_{603}^{(wv)}\, \Phi_{60\kappa}^{(v)} \right\} \Phi_{601}\, f_{dep}^{(\kappa)}\, f_{rem}^{(\kappa)}\, \Phi_{60\,dd}^{(\kappa)}\, a_1 \,. \qquad \text{(F.3.31)}$$

The study of the dependence on alternative κ is again simplified by the assumption of a constant amount of activity treated annually [Equation (E.1.5)] which eliminates the product of the first two factors as a variable. With all factors outside the source term which are independent of alternative aggregated into a constant, the risk can be written to scale as

$$R_{60\,p\kappa\lambda}^{(wv)} = C_1\, \eta_w\, f_{582}^{(wv)}\, f_{603}^{(wv)}\, \Phi_{60\kappa}^{(v)} \,. \qquad \text{(F.3.32)}$$

The total risk of alternative k = (κ,λ) then has the scaling property

$$R_{60\,p\kappa\lambda} = C_1 \sum_{v=1}^{T} \Phi_{60\kappa}^{(v)} \sum_{w=1}^{W} \eta_w\, f_{582}^{(wv)}\, f_{603}^{(wv)} \,, \qquad \text{(F.3.33)}$$

where W is the number of waste forms and T the number of treatments in the treatment facility

$$\rho_{60\,p\kappa\lambda} = \frac{\Phi_{600}^{(0)} \sum_{w=1}^{W} \eta_w\, f_{582}^{(w0)}\, f_{603}^{(w0)}}{\sum_{v=1}^{T} \Phi_{60\kappa}^{(v)} \sum_{w=1}^{W} \eta_w\, f_{582}^{(wv)}\, f_{603}^{(wv)}} \equiv \frac{V_{60\,p0}}{V_{60\,p\kappa}} \,, \qquad \text{(F.3.34)}$$

with standard errors which are derived under the assumption that the errors $\Delta\eta_w$ and $\Delta\Phi_{60\,\kappa}^{(v)}$ are considerably smaller than those of the other two factors $f_{582}^{(wv)}$ and $f_{603}^{(wv)}$. The error calculation for

the remaining factors then yields

$$\left(\frac{\Delta \rho_{60\rho\kappa\lambda}}{\rho_{60\rho\kappa\lambda}}\right)^2 = \left(\frac{\Phi^{(0)}_{60\,0}}{V_{60\,o\,0}}\right)^2 \sum_{w=1}^{W} \eta_w^2 \left\{ \left(f^{(w0)}_{60\,3}\, \Delta f^{(w0)}_{58\,2} \right)^2 + \left(f^{(w0)}_{58\,2}\, \Delta f^{(w0)}_{60\,3} \right)^2 \right\}$$

$$+ \frac{1}{V^2_{60\,o\kappa}} \sum_{w=1}^{W} \eta_w^2 \sum_{v=1}^{T} \left(\Phi^{(v)}_{60\,\kappa} \right)^2 \qquad \text{(F.3.35)}$$

$$\left\{ \left(f^{(wv)}_{60\,3}\, \Delta f^{(wv)}_{58\,2} \right)^2 + \left(f^{(wv)}_{58\,2}\, \Delta f^{(wv)}_{60\,3} \right)^2 \right\}.$$

The numerical values of the factors $f_{60\,3}^{(wv)}$ have been given in Table D.4-5; those for factors $f_{58\,2}^{(wv)}$ in Table D.4-3; those for $\Phi_{60\,\kappa}^{(v)}$ are given in Table D.2-2 of Attachment D. The risk reduction factors and their errors are listed in Table F.3-6. Again, a large increase in risk is seen with factors ranging from 40,000 to 260,000 with relative standard errors of about 30 percent.

F.4 RISK OF EXPOSURES TO VOLATILE ORGANIC COMPOUNDS

The chemical agents of concern in the waste are VOCs; three of them are carcinogens, two are not. During treatment, some of the VOCs are released. For Level II treatments, the gases are allowed to escape during shredding. For Level III treatments, sorting and shredding leads to the release of VOCs from all void spaces upon opening liners and bags.

Occupational risks are minimized by respiratory protection by the use of bubble suits during sorting or of glove boxes covering conveyor belts. Low-level releases, however, lead to a residual risk. The baseline risk is given by the routine emissions of the drums through their carbon filters during the assay and certify procedure.

F.4.1 Risk of Cancer by Exposure to VOCs

F.4.1.1 Routine Operations: Occupational Exposures

In this scenario, gases escaping from the wastes are absorbed in filters or vented outside the facility. A small fraction will escape and concentrations of agent j build up against the ventilation system until they reach equilibrium value. The released quantity of carcinogenic VOCs is assumed to be the entire void volume from the drums, all of which is released upon opening the liners and bags in the TF. Using the symbols:

$q_{16\,j}^{(0)}$ = Total mass of gas j per "as received" drum (mg),
$n_r^{(0)}$ = Number of "as received" drums handled annually (yr^{-1}),

TABLE F.3-6

RISK REDUCTION FACTORS FOR PUBLIC RISKS DUE TO ROUTINE MAINTENANCE

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{60p1\lambda}$	$(2.53 \pm 0.72) \cdot 10^{-5}$	
$\rho_{60p2\lambda}$	$(2.16 \pm 0.60) \cdot 10^{-5}$	
$\rho_{60p3\lambda}$	$(1.31 \pm 0.34) \cdot 10^{-5}$	
$\rho_{60p4\lambda}$	$(3.91 \pm 1.03) \cdot 10^{-6}$	
Annual Baseline Risk:		
R_{60p00}	--	Not available in FSEIS

$N_{o1}^{(\kappa)}$ = Number of persons in WHB and treatment plant,
f_{15} = Fraction of crew exposed,
$\Phi_{61j}^{(\kappa)}$ = Gas release function for agent j and alternative κ,
L_1 = Annual ventilation volume (m^3),
V_1 = Annual occupational respiratory volume (m^3),
M = Body mass of receptor (kg),
f_{12j} = Probability of absorption into body for chemical j,
f_t = Exposure time correction factor for one year,
c_j = Lifetime cancer risk coefficient for chemical j (mg^{-1} kg day),
C_i = Constant parts of equations, and
$R_{61o\kappa\lambda j}$ = Occupational risk of cancer due to chemical j per year of operation (yr^{-1}),

are used in the general occupational risk equation

$$R_{61o\kappa\lambda j} = \left\{ q_{16j}^{(0)}\, n_r^{(0)}\, \Phi_{61j}^{(\kappa)} \right\} f_{15}\, N_{o1}^{(\kappa)}\, \frac{V_1}{L_1\, M}\, f_{12j}\, f_t\, c_j \,. \tag{F.4.1}$$

Considering the dependence on alternatives, the risk can be scaled as

$$R_{61o\kappa\lambda j} = C_1\ \Phi_{61j}^{(\kappa)}\, N_{o1}^{(\kappa)} \,. \tag{F.4.2}$$

The risk reduction factors are then

$$\rho_{61o\kappa\lambda j} = \frac{\Phi_{61j}^{(0)}\, N_{o1}^{(0)}}{\Phi_{61j}^{(\kappa)}\, N_{o1}^{(\kappa)}} = F_{m\kappa}\, \frac{\Phi_{61j}^{(0)}}{\Phi_{61j}^{(\kappa)}} = F_{m\kappa}\, F_{r\kappa j} \,, \tag{F.4.3}$$

using the definition

$$F_{r\kappa j} \equiv \frac{\Phi_{61j}^{(0)}}{\Phi_{61j}^{(\kappa)}} \,, \tag{F.4.4}$$

and the standard errors

$$\left(\frac{\Delta \rho_{61o\kappa\lambda j}}{\rho_{61o\kappa\lambda j}} \right)^2 = \left(\frac{\Delta F_{m\kappa}}{F_{m\kappa}} \right)^2 + \left(\frac{\Delta F_{r\kappa j}}{F_{r\kappa j}} \right)^2 . \tag{F.4.5}$$

The reduction factors $F_{r\kappa j}$ are listed in Table D.4-7 where it is also shown that the release reduction factors and, thus, the risk reduction factors are independent of the chemical considered. No aggregation is, therefore, needed. The values of the risk reduction factors $\rho_{61o\kappa\lambda j}$ and their errors are given in Table F.4-1. These values show the same large increases as those found for the radiation risks. Increases of risk over baseline values of factors between 50,000 and 200,000 are found with relative errors of about 13 percent.

TABLE F.4-1

REDUCTION OF OCCUPATIONAL RISK DUE TO ROUTINE GAS RELEASES OF CARCINOGENIC CHEMICALS

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{61o1\lambda}$	$(2.21 \pm 0.28) \cdot 10^{-5}$	For all chemicals j,
$\rho_{61o2\lambda}$	$(1.66 \pm 0.21) \cdot 10^{-5}$	$\rho_{62o\kappa\lambda} = \rho_{61o\kappa\lambda}$
$\rho_{61o3\lambda}$	$(1.09 \pm 0.14) \cdot 10^{-5}$	
$\rho_{61o4\lambda}$	$(4.86 \pm 0.60) \cdot 10^{-6}$	
Annual Baseline Risks:		
R_{61o00}	--	Not available in FSEIS
R_{62o00}	--	Not available in FSEIS

F.4.1.2 Routine Operations: Public Exposures to VOCs

This scenario is the same as the previous one, except that cancer risks are calculated for the public when the vapors escape to the outside. The symbols

$q_{16j}^{(0)}$	=	Total mass of gas j per "as received" drum (mg),
$n_r^{(0)}$	=	Number of "as received" drums handled annually (yr^{-1}),
$\Phi_{61j}^{(\kappa)}$	=	Gas release function for alternative κ,
$f_{out}^{(\kappa)}$	=	Penetration to outside of treatment plant,
$\Phi_{61\,dd}^{(\kappa)}$	=	Dispersion-dosimetry function of all exposed persons (day^{-1}),
M	=	Body mass of receptor (kg),
f_{12j}	=	Probability of absorption into body for chemical j,
c_j	=	Lifetime cancer risk coefficient for chemical j (mg^{-1} kg day),
f_t	=	Exposure time correction factor for one year,
C_i	=	Constant parts of equations, and
$R_{61\,p\kappa\lambda j}$	=	Public risk of cancer due to chemical j per year of operation (yr^{-1}),

are used in the general public risk equation

$$R_{61\,p\kappa\lambda j} = \left\{ q_{16j}^{(0)}\, n_r^{(0)}\, \Phi_{61j}^{(\kappa)} \right\} f_{out}^{(\kappa)}\, \Phi_{61\,dd}^{(\kappa)}\, f_{12j}\, \frac{1}{M}\, f_t\, c_j\,. \tag{F.4.6}$$

Considering the dependence on treatment options in the usual manner, the risk can be shown to scale according to

$$R_{61\,p\kappa\lambda j} = C_1\, \Phi_{61j}^{(\kappa)}\,. \tag{F.4.7}$$

The risk reduction factors are then

$$\rho_{61\,p\kappa\lambda j} = \frac{\Phi_{61j}^{(0)}}{\Phi_{61j}^{(\kappa)}} = F_{r\kappa j}\,, \tag{F.4.8}$$

again independent of the chemical agent j. Their standard errors are

$$\Delta\rho_{61\,p\kappa\lambda j} = \Delta F_{r\kappa j}\,. \tag{F.4.9}$$

The values of the risk reduction factors $\rho_{61\,p\kappa\lambda}$ and their errors are given in Table F.4-2. All of them lie near risk increases of factors of about 15,000 to 20,000 with relative standard errors of 11 percent.

TABLE F.4-2

REDUCTION FACTORS FOR PUBLIC RISKS DUE TO ROUTINE RELEASES OF CARCINOGENIC CHEMICALS

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$\rho_{61p1\lambda j}$	$(8.00 \pm 0.90) \cdot 10^{-5}$	$\rho_{62p\kappa j} = \rho_{61p\kappa j}$
$\rho_{61p2\lambda j}$	$(6.40 \pm 0.70) \cdot 10^{-5}$	
$\rho_{61p3\lambda j}$	$(6.40 \pm 0.70) \cdot 10^{-5}$	
$\rho_{61p4\lambda j}$	$(6.40 \pm 0.70) \cdot 10^{-5}$	
Annual Baseline Risk:		
R_{61p00}	--	Not available in FSEIS
R_{62p00}	--	Not available in FSEIS

F.4.2 Risk of Noncancer Health Effects

F.4.2.1 Routine Operations: Occupational Exposures

Again, as in Section F.4.1.1, workers are exposed to concentrations of agent j that build up against the ventilation system to equilibrium value. This time, however, the noncancer health effects risk is calculated. With the symbols

$q_{16j}^{(0)}$ = Total mass of gas j per "as received" drum (mg),
$n_r^{(0)}$ = Number of "as received" drums handled annually (yr^{-1}),
$N_{o1}^{(\kappa)}$ = Number of persons in WHB and Treatment Facility,
$\Phi_{61j}^{(\kappa)}$ = Gas release function for alternative κ,
f_{15} = Fraction of personnel exposed to chemicals,
L_1 = Annual ventilation volume (m^3),
V_2 = Daily occupational respiratory volume ($m^3\ day^{-1}$),
M = Body mass of receptor (kg),
f_{12j} = Probability of absorption into body for chemical j,
$L_j^{(ref)}$ = Reference level for chemical j [mg (kg day)$^{-1}$],
r_{oj} = Risk of reference level $L_j^{(ref)}$,
C_i = Constant parts of equations, and
$R_{62o\kappa\lambda j}$ = Occupational noncancer risk due to chemical j per year of operation (yr^{-1}),

the general occupational risk equation can be written as

$$R_{62o\kappa\lambda j} = \left\{ q_{16j}^{(0)}\, n_r^{(0)}\, \Phi_{61j}^{(\kappa)} \right\} N_{o1}^{(\kappa)}\, f_{15}\, \frac{V_2}{L_1\, M\, L_j^{(ref)}}\, f_{12j}\, r_{oj}\,. \qquad \text{(F.4.10)}$$

Considering the dependence on treatment options as before, the risk can be scaled as

$$R_{62o\kappa\lambda j} = C_1\ N_{o1}^{(\kappa)}\, \Phi_{61j}^{(\kappa)}\,, \qquad \text{(F.4.11)}$$

which is the same result as that for the occupational exposures to carcinogens. The risk reduction factors are then

$$\rho_{62o\kappa\lambda} = \frac{\Phi_{61j}^{(0)}\, N_{o1}^{(0)}}{\Phi_{61j}^{(\kappa)}\, N_{o1}^{(\kappa)}} = F_{m\kappa}\, F_{r\kappa j} = \rho_{61o\kappa\lambda}\,, \qquad \text{(F.4.12)}$$

which is independent of agent j and has standard errors

$$\Delta\rho_{62o\kappa\lambda} = \Delta\rho_{61o\kappa\lambda}\,. \qquad \text{(F.4.13)}$$

The values of the risk reduction factors $\rho_{62o\kappa\lambda}$ and their errors are thus given in Table F.4-1. No aggregation is needed because there is no difference between the different chemical agents.

F.4.2.2 Routine Operations: Public Exposures to VOCs

Again, as in F.4.1.2, the public is exposed to VOCs when concentrations of agent j build up against the ventilation system to equilibrium value and are vented to the outside. Noncancer health effects risks are calculated for this scenario. Using the symbols

$q_{16j}^{(0)}$	=	Total mass of gas j per "as received" drum (mg),
$n_r^{(0)}$	=	Number of "as received" drums handled annually (yr^{-1}),
$\Phi_{61j}^{(\kappa)}$	=	Gas release function for alternative k,
$f_{out}^{(\kappa)}$	=	Penetration to outside of treatment plant,
$\Phi_{62dd}^{(\kappa)}$	=	Dispersion-dosimetry function (day^{-1}),
M	=	Body mass of receptor (kg),
f_{12j}	=	Probability of absorption into body for chemical j,
r_{oj}	=	Risk of reference level $L_j^{(ref)}$,
$L_j^{(ref)}$	=	Reference level for chemical j [mg (kg day)$^{-1}$],
C_i	=	Constant parts of equations, and
$R_{62p\kappa\lambda j}$	=	Public noncancer risk due to chemical j per year of operation (yr^{-1}),

the general public risk expression can be stated as

$$R_{62p\kappa\lambda j} = \left\{ q_{16j}^{(0)}\, n_r^{(0)}\, \Phi_{61j}^{(\kappa)} \right\} f_{out}^{(\kappa)}\, \Phi_{62dd}^{(\kappa)}\, \frac{1}{M\, L_j^{(ref)}}\, f_{12j}\, r_{oj}\,. \qquad \text{(F.4.14)}$$

The dependence on alternatives again leads to a scaling law

$$R_{62p\kappa\lambda j} = C_1\, \Phi_{61j}^{(\kappa)}\,, \qquad \text{(F.4.15)}$$

which is the same result as for the public risk in the last section. The risk reduction factors are then

$$\rho_{62p\kappa\lambda j} = \frac{\Phi_{61j}^{(0)}}{\Phi_{61j}^{(\kappa)}} = \rho_{61p\kappa\lambda j}\,, \qquad \text{(F.4.16)}$$

with the same standard errors

$$\Delta\rho_{62p\kappa\lambda j} = \Delta\rho_{61p\kappa\lambda j}\,. \qquad \text{(F.4.17)}$$

The values of the risk reduction factors $\rho_{62p\kappa\lambda j}$ and their errors are given in Table F.4-2. Again, no aggregation over all chemicals is necessary.

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ATTACHMENT G

RISK COMPARISON

G.1 AGGREGATION OF CONSEQUENCE REDUCTION FACTORS

G.1.1 Set Of Consequence Reduction Factors

The discussion in the preceding sections leads to a total of 124 reduction factors for risk components, including all subcomponents. This is too large a number for the assignment of individual societal weights, even if all baseline risk components and subcomponents were known. One way to reduce the number of subcomponents is to discard risk reduction factors that would not influence the result appreciably and aggregate others into appropriate categories.

Genetic damages are subcomponents with risks that are smaller than the corresponding risks of cancer. (National Research Council, 1980, 1988, 1990). For internal exposures, they are also less well defined. These 45 subcomponents are consequently not included in the aggregation process (National Research Council, 1980, 1988, 1990). Similarly, public noncancer risks due to exposures to chemical toxicants are extremely low (DOE, 1990a) and the health consequences of no great influence. These six subcomponents, too, will be dropped from consideration for aggregation (Table G.1-1).

The rest of the risk reduction factors are sorted into eight supercomponents:

1. Transportation fatalities
2. Transportation injuries
3. Occupational fatalities
4. Occupational injuries
5. Occupational cancers
6. Public cancers
7. Late occupational cancers
8. Late public cancers.

Six of these supercomponents are listed in the FSEIS (DOE, 1990a), but numbers 3 and 4, the occupational accident fatalities and injuries, are not. In a comparison of risks involving waste treatment, however, they are important and have thus been included. These eight supercomponents arise from the aggregation of 73 components and subcomponents.

A problem in the aggregation of these subcomponents arises from the fact that the FSEIS does not give explicit values for a number of component and subcomponent risks, but gives some values for more aggregated risks. These baseline risks will be denoted by the symbol $R_{j\xi 00\tau}$,

TABLE G.1-1

COMPONENTS AND SUBCOMPONENTS FOR THE EIGHT SUPERCOMPONENTS

SUPERCOMPONENT	ALL SUBCOMPONENTS	AGGREGATED IN SUPERCOMPONENTS
1 Transportation fatalities	3	3
2 Transportation injuries	3	3
3 Occupational fatalities	2	2
4 Occupational injuries	11	11
5 Occupational cancers	40	22
6 Public cancers	41	22
7 Late occupational cancers	6	3
8 Late public cancers	12	6
Total classified	118	72
Not classified *	6	
Total	124	

* $\rho_{14\,p\,\kappa\,\lambda}$
$\rho_{15\,p\,\kappa\,\lambda}$
$\rho_{50\,p\,\kappa\,\lambda}$
$\rho_{51\,p\,\kappa\,\lambda}$
$\rho_{52\,p\,\kappa\,\lambda}$
$\rho_{62\,p\,\kappa\,\lambda}$

where the index j denotes the risk component, ξ the receptor type (public or occupational), and τ the index of the subaggregate. This will only be needed for supercomponents 5 and 6, which need subaggregates explicitly. If aggregation proceeds in one step, as for all other supercomponents, then the baseline risks are denoted by $R_{j\chi 00}$, where χ is either 'o' or 'p'.

The aggregation of risk reduction factors that do not have numerical values associated with them, presents a major problem in this evaluation. A large risk reduction factor for a very small risk may bias the aggregation because it cannot be weighted with an appropriately small weight. In this situation, aggregating by means of geometrical average minimizes the bias that may be caused by widely different risk reduction factors. However, there will be a residual bias that cannot be removed unless the baseline risks are known. The related problems and assumptions are discussed in each case.

G.1.2 Aggregation of the Eight Components

G.1.2.1 Supercomponent 1: Fatal Transportation Accidents

In Supercomponent 1, the fatal transportation accidents in the three components listed in Table G.1-2 are aggregated. Direct traffic fatalities are by far the largest risk component, dominating the other two components. The aggregate consequence reduction factor for the first supercomponent is

$$\Gamma_{1\kappa\lambda} = \prod_{\tau=\{n_1\}} \left(\rho_{\tau p\kappa\lambda}\right)^{g_{1\tau}} , \tag{G.1.1}$$

with the set $\{n_1\} = \{21, 30, 33\}$, and the weights

$$g_{1\tau} = \frac{R_{\tau p00}}{\sigma_1} , \tag{G.1.2}$$

with the sum σ_1 given by

$$\sigma_1 = \sum_{\delta=\{n_1\}} R_{\delta p00} . \tag{G.1.3}$$

If the relationship

$$R_{21p00} > 10^5 R_{3\chi p00} , \quad for \ \chi = 0, 3 \tag{G.1.4}$$

TABLE G.1-2

RISK REDUCTION FACTORS AGGREGATED IN SUPERCOMPONENT 1: TRANSPORTATION FATALITIES

COMPONENT	DESCRIPTION	COMMENTS
$\rho_{21 p \kappa \lambda}$	Fatalities caused directly by impact	Large baseline risk
$\rho_{30 p \kappa \lambda}$	Fatalities caused by early radiation effects in nondispersal accidents	Very small baseline risk
$\rho_{33 p \kappa \lambda}$	Fatalities caused by early radiation effects in atmospheric dispersal accidents	Very small baseline risk

holds, then the weights can without significant loss of accuracy be set at

$$g_{30} = g_{33} = 0 , \qquad g_{21} = 1 . \tag{G.1.5}$$

The aggregated risk reduction factor is then simply

$$\Gamma_{1\kappa\lambda} = \rho_{21p\kappa\lambda} , \tag{G.1.6}$$

and its standard error is

$$\Delta\Gamma_{1\kappa\lambda} = \Delta\rho_{21p\kappa\lambda} . \tag{G.1.7}$$

Numerical values for the λ and κ dependent quantities are given in Table G.1-3 for Level II treatments, aggregated consequence reduction factors $\Gamma_{1\kappa\lambda}$ indicate an increase in this supercomponent by factors between 1.0 and 1.5 with a weak dependence on location. The relative errors of these factors 7 to 8 percent. For Treatment Option 3, this component shows no increases within the errors for different locations; for Treatment Option 4, there is a decrease of this risk component by factors of 1 to 3.5 with relative errors of up to 7 percent. Here, a moderate location dependence is found.

The corresponding baseline risk or consequence Γ_{100} is of a significant amount so that even modest risk increases or decreases are of importance. The treatment dependence of these consequence reduction factors is shown in Figure G.1-1 for Location 3. It demonstrates the change from a consequence increase for Level II treatments to a consequence reduction for Level III treatments. For Location 1, the factors are identical to 1; for Treatment Options 1, 2 and 3 and Locations 2, 3 and 4, there are no significant differences from those shown in Figure G.1-1. For Treatment Options 4, however, the value goes from 1 to 3.5, increasing with decentralized location. These reduction factors are applied to a low baseline risk of 0.2 traffic fatalities per year.

G.1.2.2 Supercomponent 2: Transportation Accident Injuries

In Supercomponent 2 injuries in transportation accidents are combined. Three components are aggregated in Table G.1-4. Direct traffic injuries are by far the largest risk component in this aggregate.

$$\Gamma_{2\kappa\lambda} = \prod_{\tau=\{n_2\}} \left(\rho_{\tau p\kappa\lambda}\right)^{g_{2\tau}} , \tag{G.1.8}$$

with the set $\{n_2\} = \{22, 31, 34\}$. With the same argument as in last section, the weights can be set at

$$g_{22} = 1 ; \quad g_{31} = g_{34} = 0 . \tag{G.1.9}$$

TABLE G.1-3

CONSEQUENCE REDUCTION FACTORS $\Gamma_{1\kappa\lambda}$ FOR SUPERCOMPONENT 1: FATALITIES IN TRANSPORTATION ACCIDENTS

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Consequence Reduction Factors:		
Γ_{111}	1	
Γ_{112}	0.760 ± 0.48	
Γ_{113}	0.713 ± 0.57	
Γ_{114}	0.715 ± 0.58	
Γ_{121}	1	
Γ_{122}	0.720 ± 0.42	
Γ_{123}	0.666 ± 0.48	
Γ_{124}	0.666 ± 0.49	
Γ_{131}	1	
Γ_{132}	1.10 ± 0.17	
Γ_{133}	1.17 ± 0.26	
Γ_{134}	1.18 ± 0.27	
Γ_{141}	1	
Γ_{142}	2.00 ± 0.06	
Γ_{143}	3.27 ± 0.21	
Γ_{144}	3.51 ± 0.25	
Annual Baseline Risk or Consequence:		
Γ_{100}	0.2	FSEIS (DOE, 1990a),

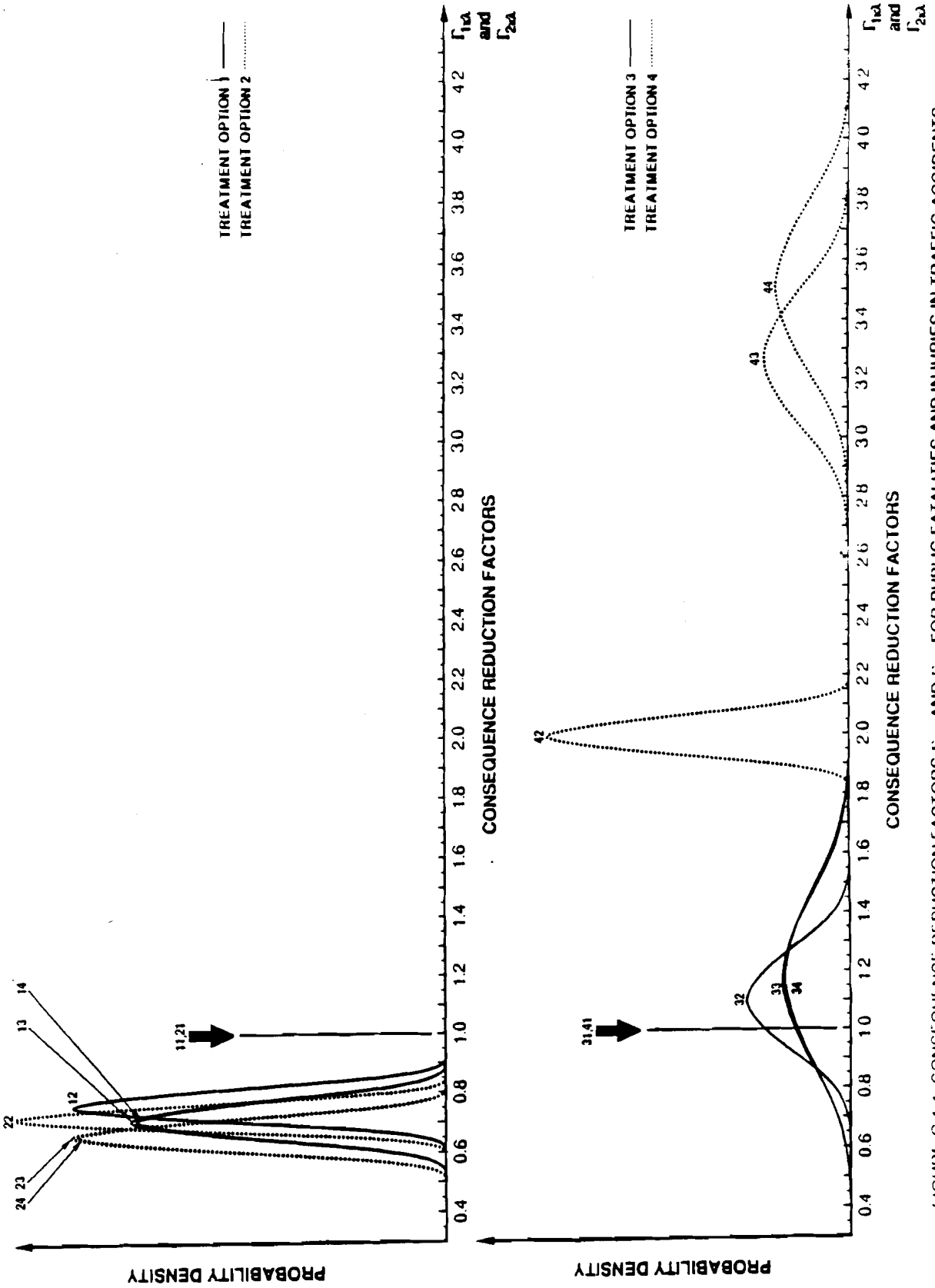

FIGURE G 1-1 CONSEQUENCE REDUCTION FACTORS $\Gamma_{1\lambda}$ AND $\Gamma_{2\lambda}$ FOR PUBLIC FATALITIES AND INJURIES IN TRAFFIC ACCIDENTS. THE LARGER VALUES FOR TREATMENT OPTION 4 ARE DUE TO A DECREASE IN THE NUMBER OF TRANSPORTS.

TABLE G.1-4

RISK REDUCTION FACTORS AGGREGATED IN SUPERCOMPONENT 2: TRANSPORTATION INJURIES

COMPONENT	DESCRIPTION	COMMENTS
$\rho_{22 p \kappa \lambda}$	Injuries caused directly by accident impact	Significant baseline risk
$\rho_{31 p \kappa \lambda}$	Injuries caused by early radiation in nondispersal accidents	Very low baseline risk
$\rho_{34 p \kappa \lambda}$	Injuries caused by early radiation effects in atmospheric dispersal accidents	Very low baseline risk

The aggregated consequence reduction factor is then

$$\Gamma_{2\kappa\lambda} = \rho_{22p\kappa\lambda} , \tag{G.1.10}$$

with a standard error of

$$\Delta\Gamma_{2\kappa\lambda} = \Delta\rho_{22p\kappa\lambda} . \tag{G.1.11}$$

All consequence reduction factors explicitly depend on both the treatment κ and the location λ. Numerical values for the κ and λ quantities are given in Table G.1-5. The values are the same as those in Table G.1-3 due to the assumptions (G.1.5) and (G.1.9). Thus Figure G.1-1 and the corresponding discussion in the last section applies here as well. The consequence reduction factors apply to an acceptable number of about 3 traffic injuries sustained annually.

G.1.2.3 Supercomponent 3: Occupational Fatalities

In Supercomponent 3, two components are aggregated (Table G.1-6).

The aggregation of two components yields

$$\Gamma_{3\kappa\lambda} = \prod_{\tau=\{n_3\}} \left(\rho_{\tau o\kappa\lambda}\right)^{g_{3\tau}} , \tag{G.1.12}$$

with the set $\{n_3\} = \{53, 55\}$. The weights are

$$g_{3\tau} = \frac{R_{\tau o00}}{\sigma_3} , \tag{G.1.13}$$

where

$$\sigma_3 = \sum_{\tau=1}^{2} R_{\tau o00} . \tag{G.1.14}$$

Note that the risks are given in Sections F.2.1.1 and F.2.2.1 by

$$R_{53o\kappa\lambda} = N_{o1}^{(\kappa)} P_{of} (1 - f_{531}) , \tag{G.1.15}$$

TABLE G.1-5

CONSEQUENCE REDUCTION FACTORS $\Gamma_{2\kappa\lambda}$ FOR SUPERCOMPONENT 2: INJURIES IN TRANSPORTATION ACCIDENTS

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Consequence Reduction Factors:		
Γ_{211}	1	
Γ_{212}	0.760 ± 0.048	
Γ_{213}	0.713 ± 0.057	
Γ_{214}	0.715 ± 0.058	
Γ_{221}	1	
Γ_{222}	0.720 ± 0.042	
Γ_{223}	0.666 ± 0.048	
Γ_{224}	0.666 ± 0.049	
Γ_{231}	1	
Γ_{232}	1.10 ± 0.17	
Γ_{233}	1.17 ± 0.26	
Γ_{234}	1.18 ± 0.27	
Γ_{241}	1	
Γ_{242}	2.00 ± 0.06	
Γ_{243}	3.27 ± 0.21	
Γ_{244}	3.51 ± 0.25	
Annual Baseline Risk or Consequence:		
Γ_{200}	3.0	FSEIS (DOE, 1990a), Executive Summary

TABLE G.1-6

RISK REDUCTION FACTORS AGGREGATED IN SUPERCOMPONENT 3: OCCUPATIONAL FATALITIES

COMPONENT	DESCRIPTION	COMMENTS
$\rho_{53 o \kappa \lambda}$	General industrial accidents	
$\rho_{55 o \kappa \lambda}$	Forklift accidents	

and

$$R_{55o\kappa\lambda} = n_r^{(\kappa)} \, n_f^{(\kappa)} \, P_{of} \, f_{531} \, \Phi_{551} \, , \tag{G.1.16}$$

where P_{of} is a mere scale factor and drops out for error calculations; and the relative abundance of forklift accidents f_{531} is contravariant in the two equations. Thus it can be assumed that, in weight calculations, uncertainties are highly correlated. Taking into account that both components have the same risk reduction factor, the standard error of $\Gamma_{3\kappa\lambda}$ is thus

$$\Delta \Gamma_{3\kappa\lambda} = \Delta \rho_{53o\kappa\lambda} \, . \tag{G.1.17}$$

The numerical values are given in Table G.1-7. Although λ is carried as an index, these risk reduction factors all are smaller than 1 and depend only on treatment κ but not on the location parameter λ. They actually indicate an increase in consequence by 3.6 to 13 with relative errors of 5 to 7 percent.

In Figure G.1-2 the inverse of the consequence reduction $\Gamma_{3\kappa\lambda}$ is plotted for the four values κ = 1,4. The data show the increase in risk with more complex treatment, due to the increase in manpower required. These consequence augmentation factors apply to a relatively low baseline risk of 0.0016 occupational fatalities annually.

G.1.2.4 Supercomponent 4: Occupational Injuries

In Supercomponent 4, occupational injuries, the components aggregated are listed in Table G.1-8. Most important in this aggregation are the injuries from general industrial and forklift accidents; morbidity from exposure to chemical agents are very small. Generally, the aggregated risk reduction factor is

$$\Gamma_{4\kappa\lambda} = \left(\rho_{54o\kappa\lambda}\right)^{g_{54}} \left(\rho_{56o\kappa\lambda}\right)^{g_{56}} \left(\prod_{\tau=14}^{20} \rho_{\tau o\kappa\lambda} \, \rho_{15a\kappa\lambda} \, \rho_{62o\kappa\lambda} \right)^{g_{chem}/9} , \tag{G.1.18}$$

where in this particular case

$$g_{54} = \frac{R_{54o00}}{\sigma_4} \quad ; \quad g_{56} = \frac{R_{56o00}}{\sigma_4} \quad ; \quad g_{chem} = 0 \, , \tag{G.1.19}$$

TABLE G.1-7

CONSEQUENCE REDUCTION FACTORS $\Gamma_{3\kappa\lambda}$ FOR SUPERCOMPONENT 3: OCCUPATIONAL FATALITIES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Consequence Reduction Factors:		
$\Gamma_{31\lambda}$	0.276 ± 0.016	
$\Gamma_{32\lambda}$	0.260 ± 0.015	
$\Gamma_{33\lambda}$	0.170 ± 0.010	
$\Gamma_{34\lambda}$	0.076 ± 0.004	
Annual Baseline Risk or Consequence:		
Γ_{300}	$1.6 \cdot 10^{-3}$	U.S. Dept. of Labor, Bulletin 2366, 1990

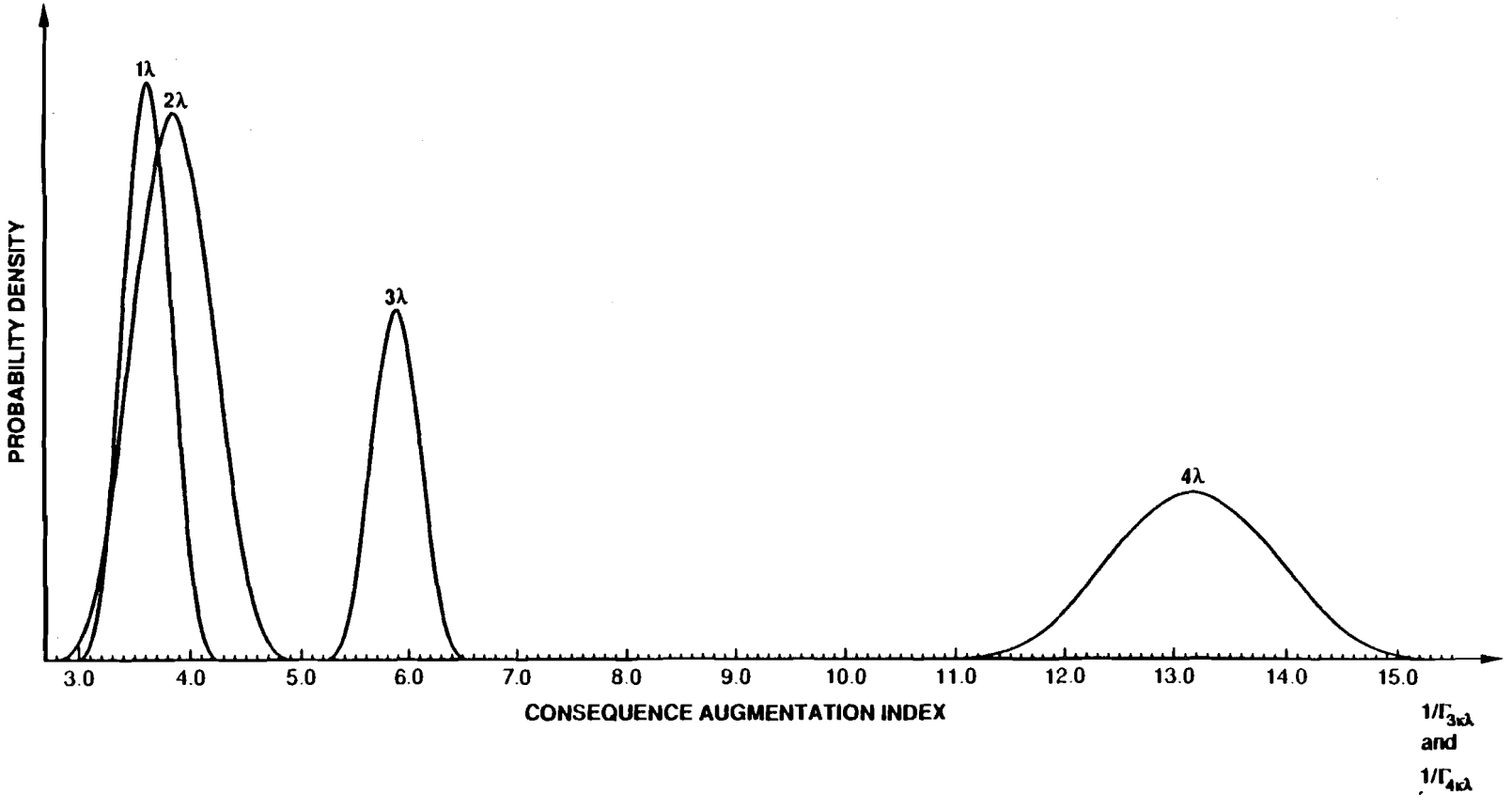

FIGURE G 1-2 CONSEQUENCE AUGMENTATION FACTORS $1/\Gamma_{3k\lambda}$ AND $1/\Gamma_{4k\lambda}$ FOR OCCUPATIONAL FATALITIES AND INJURIES INVOLVING ACCIDENTS. THE INVERSE OF RISK REDUCTION FACTORS, THE CONSEQUENCE AUGMENTATION FACTORS, ARE PLOTTED HERE TO GIVE A BETTER IMPRESSION OF THE INCREASE IN THESE COMPONENTS DUE TO TREATMENT

TABLE G.1-8

RISK REDUCTION FACTORS AGGREGATED IN SUPERCOMPONENT 4: OCCUPATIONAL INJURIES

COMPONENT	DESCRIPTION	COMMENTS
$\rho_{14 o \kappa \lambda}$	Routine, chemical, noncancer effects	Exceedingly small risk
$\rho_{15 o \kappa \lambda}$	Routine, chemical, noncancer effects	Exceedingly small risk
$\rho_{15 a \kappa \lambda}$	Routine, chemical, noncancer effects	Exceedingly small risk
$\rho_{16 o \kappa \lambda}$	Accident, chemical, noncancer effects	Exceedingly small risk
$\rho_{17 o \kappa \lambda}$	Accident, chemical, noncancer effects	Exceedingly small risk
$\rho_{18 o \kappa \lambda}$	Accident, chemical, noncancer effects	Exceedingly small risk
$\rho_{19 o \kappa \lambda}$	Accident, chemical, noncancer effects	Exceedingly small risk
$\rho_{20 o \kappa \lambda}$	Accident, chemical, noncancer effects	Exceedingly small risk
$\rho_{54 o \kappa \lambda}$	General industrial accidents	Sizeable risk
$\rho_{56 o \kappa \lambda}$	Forklift accidents	Small risks
$\rho_{62 o \kappa \lambda}$	VOC, routine, releases, noncancer effects	Exceedingly small risk

and

$$\sigma_4 = R_{54o00} + R_{56o00} \, .$$

(G.1.20)

As no data are available to weight the very small risks of morbidity due to exposure to chemicals, all have to be aggregated in an unweighted geometrical average. As exceedingly small contributions they are neglected here.

In the evaluation of the standard errors, the two components finally aggregated are not independent. In this particular case

$$\Delta \Gamma_{4\kappa\lambda} = \Delta \rho_{54o\kappa\lambda} \, . \tag{G.1.21}$$

Numerical values are given in Table G.1-9; they are the same as those for supercomponent $\Gamma_{3\kappa\lambda}$, varying from an equivalent consequence increase by a factor of 3.6 to a factor of 13. The consequence augmentation factors are given in Figure G.1-2 and are applied to an annual occupational risk of 0.7 injuries with workdays lost.

G.1.2.5 Supercomponent 5: Occupational Cancer

In this supercomponent, the 22 components listed in Table G.1-10 are aggregated. For these components, four aggregated partial risk values are available. The choice made here is to aggregate the appropriate components that make up the partial risk values at equal weight and then, as soon as the partial baseline risks are known, aggregate further with a properly weighted geometric average. This implies the assumption that the components of the partial risks are of about equal risk.

The partial aggregations according to the list in Table G.1-11 are

$$\Xi_{5\kappa\lambda\tau} = \left(\prod_{\chi=\{n_\tau\}} \rho_{\chi o\kappa\lambda} \right)^{\frac{1}{m_\tau}} , \tag{G.1.22}$$

with standard errors

$$\left(\Delta \Xi_{5\kappa\lambda\tau}\right)^2 = \left(\frac{1}{m_\tau} \right)^2 \sum_{\chi=\{n_\tau\}} \left(\frac{\Delta \rho_{\chi o\kappa\lambda}}{\rho_{\chi o\kappa\lambda}} \right)^2 .$$

(G.1.23)

TABLE G.1-9

CONSEQUENCE REDUCTION FACTORS $\Gamma_{4\kappa\lambda}$ FOR SUPERCOMPONENT 4: OCCUPATIONAL INJURIES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Consequence Reduction Factors:		
$\Gamma_{41\lambda}$	0.276 ± 0.016	
$\Gamma_{42\lambda}$	0.260 ± 0.015	
$\Gamma_{43\lambda}$	0.170 ± 0.010	
$\Gamma_{44\lambda}$	0.076 ± 0.004	
Annual Baseline Risk or Consequence:		
Γ_{400}	0.7 ± 0.03	U.S. Dept. of Labor, Bulletin 2366, 1990

TABLE G.1-10

RISK REDUCTION FACTORS AGGREGATED IN SUPERCOMPONENT 5: OCCUPATIONAL CANCER

COMPONENT	DESCRIPTION	COMMENTS
ρ_{1ok}	Routine, internal radiation	
ρ_{2ok}	Routine, internal radiation	
ρ_{3ok}	Routine, internal radiation	
ρ_{4ok}	Routine, external radiation	
ρ_{5ok}	Routine, external radiation	
ρ_{6ok}	Accident, internal radiation	
ρ_{7ok}	Accident, internal radiation	
ρ_{8ok}	Accident, internal radiation	
ρ_{9ok}	Accident, internal radiation	
ρ_{10ok}	Accident, internal radiation	
ρ_{11ok}	Accident, internal radiation	
ρ_{12ok}	Routine, chemical exposure	
ρ_{13ok}	Routine, chemical exposure	
ρ_{13ak}	Routine, chemical exposure	
$\rho_{27ok\lambda}$	Routine transport, external radiation	
$\rho_{28ok\lambda}$	Routine transport, external radiation	
$\rho_{29ok\lambda}$	Routine transport, external radiation	
ρ_{57ok}	Routine, treatment, external radiation	
ρ_{58ak}	Routine, treatment, external radiation	
ρ_{59ok}	Routine, treatment, internal radiation	
ρ_{60ok}	Routine, treatment, internal radiation	
ρ_{61ok}	Routine, treatment, VOC releases	

TABLE G.1-11

SETS FOR PARTIAL AGGREGATIONS Ξ FOR SUPERCOMPONENT 5: OCCUPATIONAL CANCER FATALITIES

τ	m_τ	$\{n_\tau\}$	COMMENTS
1	7	4, 5, 27, 28, 29, 57, 58	Radiation, routine external exposures
2	5	1, 2, 3, 59, 60	Radiation, routine internal exposures
3	6	6, 7, 8, 9, 10 11	Accidents, internal exposures
4	4	12, 13, 13a, 61	Chemicals, routine exposure
Total	22		

In this aggregation, Component 11, the C10 accident, is dropped from consideration. The risk is excessively low and the risk reduction factor very high. This contribution, not listed in the FSEIS (DOE, 1990a), is therefore not allowed to influence the result.

There is an additional obstacle to the weighting of the partial aggregations: for Components 57 to 61, all components of the risks of waste treatment, no baseline risks have been estimated. It is assumed here that the same health and safety concerns that govern all WIPP operations are evident in the Treatment Facility as well, leading essentially to the same risks. Thus it is appropriate to assume that, if the baseline risk is $R_{jo00\tau}$, where j standards for the risk component, 'o' is the index for occupational risk, τ is the index of the partial aggregation applied to a set of m_τ risk reduction factors, the baseline risk for a combined set of $\{ M_\zeta \} = \{ m_\tau \} + \{ n_\tau \}$ factor is given by

$$R_{jo00\zeta} = \frac{M_\zeta}{m_\tau} R_{jo00\tau} \ . \tag{G.1.24}$$

This extension of health and safety practices can be applied to the partial aggregations $\tau = 1, 2,$ and 4 in Table G.1-11.

The final, properly weighted aggregation of occupational cancer then yields a consequence reduction factor

$$\Gamma_{5\kappa\lambda} = \prod_{\tau=1}^{4} \left(\Xi_{5\kappa\lambda\tau} \right)^{g_{5\tau}} , \tag{G.1.25}$$

with the weights

$$g_{5\tau} = \frac{R_{5o00\tau}}{\sum_{\chi=1}^{4} R_{5o00\chi}} , \tag{G.1.26}$$

and standard errors given by

$$\left(\frac{\Delta \Gamma_{5\kappa\lambda}}{\Gamma_{5\kappa\lambda}} \right)^2 = \sum_{\tau=1}^{4} \left(g_{5\tau} \frac{\Delta \Xi_{5\kappa\lambda\tau}}{\Xi_{5\kappa\lambda\tau}} \right)^2 . \tag{G.1.27}$$

Here again the weights have been normalized and are calculated using the aggregated baseline risks in Table G.1-12. Numerical values for the final aggregation are listed in Table G.1-13.

TABLE G.1-12

AGGREGATED BASELINE RISKS FOR THE SETS IN TABLE G.1-11

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Aggregated Baseline Risks $R_{50\,00t}$:		
$R_{50\,001}$	0.025	Compiled from data in FSEIS (DOE, 1990a)
$R_{50\,002}$	0.0012	"
$R_{50\,003}$	0.0011	"
$R_{50\,004}$	$2.9 \cdot 10^{-7}$	"

TABLE G.1-13

CONSEQUENCE REDUCTION FACTORS $\Gamma_{5\kappa\lambda}$ FOR SUPERCOMPONENT 5: OCCUPATIONAL CANCERS

QUANTITY	VALUE ± STANDARD ERROR	COMMENT/REFERENCES
Consequence Reduction Factors:		
Γ_{511}	0.853 ± 0.031	
Γ_{512}	0.814 ± 0.030	
Γ_{513}	0.846 ± 0.031	
Γ_{514}	0.852 ± 0.032	
Γ_{521}	0.841 ± 0.030	
Γ_{522}	0.801 ± 0.029	
Γ_{523}	0.833 ± 0.030	
Γ_{524}	0.840 ± 0.031	
Γ_{531}	0.704 ± 0.023	
Γ_{532}	0.677 ± 0.025	
Γ_{533}	0.699 ± 0.027	
Γ_{534}	0.704 ± 0.028	
Γ_{541}	0.460 ± 0.019	
Γ_{542}	0.420 ± 0.017	
Γ_{543}	0.435 ± 0.018	
Γ_{544}	0.452 ± 0.019	
Annual Baseline Risk or Consequence:		
Γ_{500}	$5 \cdot 10^{-3}$	FSEIS (DOE, 1990a)

Within the error, the consequence reduction factors are independent of the location index λ. For Level II treatments, they range from 7 to 8; for Treatment Option 3, they are grouped around 11; for Treatment Option 4, the consequence reduction factors are down to 8 again. The factors show very little dependence on location, and a mixed influence on Treatment Option. Relative standard errors are about 12 percent.

In Figure G.1-3, the consequence reduction factors $\Gamma_{5\kappa\lambda}$ are shown, demonstrating the grouping around 8 for Level II treatments and the grouping of the Level III treatments around 11 for Treatment Option 3 and around 8 for Treatment Option 4. These risk consequence reduction factors are applied baseline or consequence of 0.005 cancers per year of option.

G.1.2.6 Supercomponent 6: Public Cancers

In Supercomponent 6, public cancers from 22 components are aggregated. They are listed in Table G.1-14. For these 22 contributions, numerical values for only four subaggregates are available. Again the choice is made to aggregate by unweighted geometrical averaging, before final properly weighted aggregation.

The partial aggregations according to Table G.1-15 are

$$\Xi_{6\kappa\lambda\tau} = \left(\prod_{\chi=\{n_\tau\}} \rho_{\chi p \kappa \lambda} \right)^{\frac{1}{m_\tau}} , \qquad \text{(G.1.28)}$$

with standard errors

$$\left(\frac{\Delta \Xi_{6\kappa\lambda}}{\Xi_{6\kappa\lambda}} \right)^2 = \left(\frac{1}{m_\tau} \right)^2 \sum_{\chi=\{n_\tau\}} \left(\frac{\Delta \rho_{\chi p \kappa \lambda}}{\rho_{\chi p \kappa \lambda}} \right)^2 . \qquad \text{(G.1.29)}$$

In this aggregation, the C10 accident in Component 11 is not used because the risk is excessively low and the risk reduction factor very high. Even though the risk is considered in the FSEIS, it will not be allowed to dominate the averaging.

The situation with new treatment risks is the same as that in the last supercomponent: for Components 59, 60, and 61, no baseline risks are available. Again, the assumption of the same health and safety standards, this time for the public, leads to the formulation

$$R_{jp00\zeta} = \frac{M_\zeta}{m_\tau} R_{jp00\tau} , \qquad \text{(G.1.30)}$$

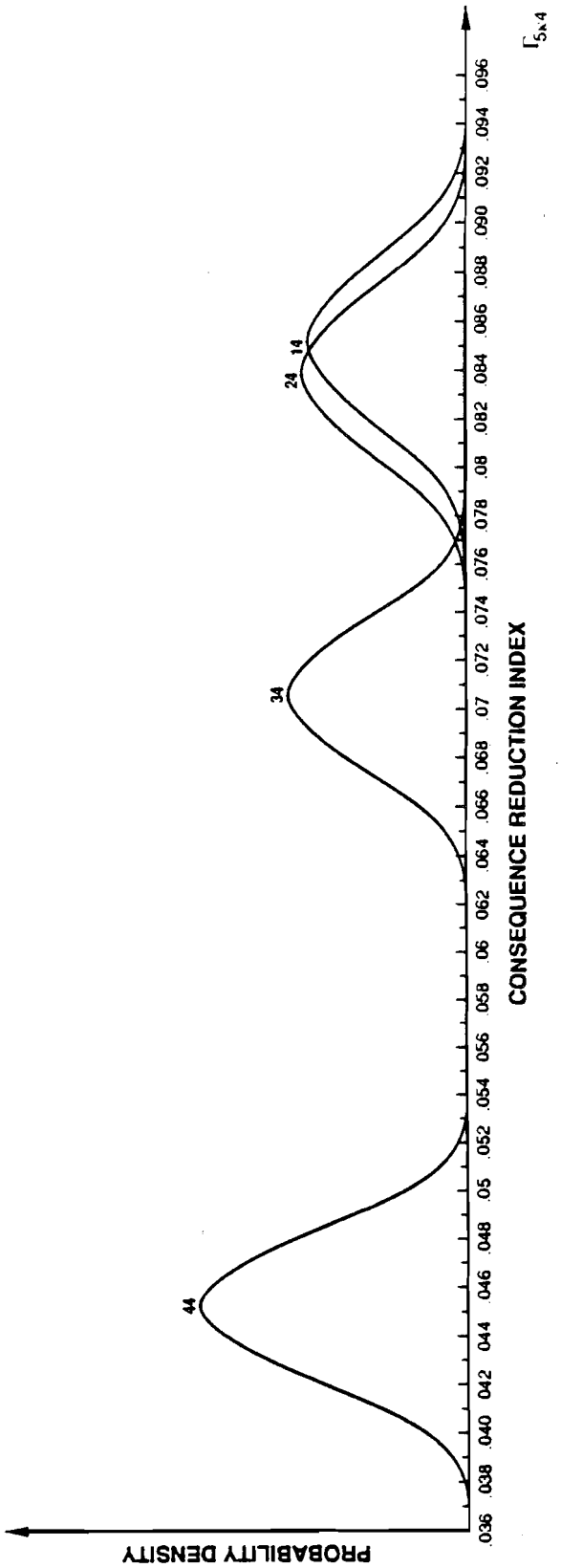

FIGURE G.1-3 CONSEQUENCE REDUCTION INDICES Γ_{5x4} FOR OCCUPATIONAL CANCERS DUE TO RADIATION AND CHEMICAL AGENTS. BECAUSE OF THE NEAR INDEPENDENCE FROM LOCATION, ONLY THE CURVES FOR LOCATION $\lambda = 4$ ARE SHOWN.

TABLE G.1-14

RISK REDUCTION FACTORS AGGREGATED IN SUPERCOMPONENT 6: PUBLIC CANCERS

COMPONENT	DESCRIPTION	COMMENTS
ρ_{1pk}	Routine internal	
ρ_{2pk}	Routine internal	
ρ_{3pk}	Routine internal	
ρ_{6pk}	Internal accident	
ρ_{7pk}	Internal accident	
ρ_{8pk}	Internal accident	
ρ_{9pk}	Internal accident	
ρ_{10pk}	Internal accident	
ρ_{11pk}	Internal accident	
ρ_{12pk}	Routine chemical	
ρ_{13pk}	Routine chemical	
$\rho_{23pk\lambda}$	Routine transportation	
$\rho_{24pk\lambda}$	Routine transportation	
$\rho_{25pk\lambda}$	Routine transportation	
$\rho_{26pk\lambda}$	Routine transportation	
$\rho_{32pk\lambda}$	Transportation accident, nondispersal	
$\rho_{35pk\lambda}$	Transportation accident, dispersal	
$\rho_{36pk\lambda}$	Transportation accident, cloudshine	
$\rho_{37pk\lambda}$	Transportation accident, groundshine	
ρ_{59pk}	Treatment routine internal radiation	
ρ_{60pk}	Treatment routine internal radiation	
ρ_{61pk}	Treatment routine VOC releases	

TABLE G.1-15

SETS FOR PARTIAL AGGREGATIONS Ξ FOR SUPERCOMPONENT 6: PUBLIC CANCER FATALITIES

τ	m_τ	$\{n_\tau\}$	COMMENTS
1	4	23, 24, 25, 26	Radiation, routine external exposures
2	4	32, 35, 36, 37	Radiation, accidental external exposures
3	11	1, 2, 3, 6, 7, 8, 9, 10, 11, 59, 60	Radiation, internal exposures
4	3	12, 13, 61	Chemicals, routine exposure
Total	22		

for the baseline risk of the set $\{M_\zeta\} = \{ m_\tau \} + \{ n_\tau \}$ where the set $\{ m_\tau \}$ forms the subaggregate public risk $R_{1p00\tau}$ and the set $\{ n_\tau \}$ comprises the components for which there are no baseline risk estimates. This extrapolation is needed for the partial aggregations $\tau = 3$ and 4 in Table G.1-15.

The final aggregation of occupational cancer risks then yields consequence reduction factors

$$\Gamma_{6\kappa\lambda} = \prod_{\tau=1}^{4} \left(\Xi_{6\kappa\lambda\tau}\right)^{g_{6\tau}} , \tag{G.1.31}$$

with the normalized weights

$$g_{6\tau} = \frac{R_{6p00\tau}}{\sum_{\chi=1}^{4} R_{6p00\chi}} . \tag{G.1.32}$$

The standard errors are given by

$$\left(\frac{\Delta \Gamma_{6\kappa\lambda}}{\Gamma_{6\kappa\lambda}}\right)^2 = \sum_{\tau=1}^{4} \left(g_{6\tau} \frac{\Delta \Xi_{6\kappa\lambda\tau}}{\Xi_{6\kappa\lambda\tau}}\right)^2 . \tag{G.1.33}$$

Here again the weights have normalized to 1. The aggregated baseline risks $R_{60\,00\tau}$ needed for the final aggregation are listed in Table G.1-16. The resulting numerical values for the consequence reduction factors are given in Table G.1-17. They range from about 1 to about 10, almost independent of the Treatment Option. The location dependence is illustrated in Figure G.1-4 for Treatment Option 3, showing widely separated narrow probability distributions.

G.1.2.7 Supercomponent 7: Occupational Cancer (Late Effects)

In supercomponent 7, the three components listed in Table G.1-18 are aggregated. In this aggregation it is assumed that for all of them the event probability is 1 and that the risk is evaluated for the one year during which the event occurs. As the baseline risks are not known, the risk reductions are geometrically averaged with equal weight.

The consequence reduction factors are then

$$\Gamma_{7\kappa\lambda} = \prod_{\tau=40}^{42} \left(\rho_{\tau o\kappa\lambda}\right)^{1/3} , \tag{G.1.34}$$

TABLE G.1-16

AGGREGATED BASELINE RISKS FOR THE SETS IN TABLE G.1-15

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Aggregated Baseline Risks $R_{60\,00\tau}$:		
$R_{60\,001}$	$7.5 \cdot 10^{-8}$	Compiled from data in the FSEIS (DOE, 1990a)
$R_{60\,002}$	$3.8 \cdot 10^{-2}$	"
$R_{60\,003}$	$9.0 \cdot 10^{-5}$	"
$R_{60\,004}$	$6.9 \cdot 10^{-12}$	"

TABLE G.1-17

CONSEQUENCE REDUCTION FACTORS $\Gamma_{6\kappa\lambda}$ FOR SUPERCOMPONENT 6: PUBLIC CANCERS

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Consequence Reduction Factors:		
Γ_{611}	1.13 ± 0.00	
Γ_{612}	2.64 ± 0.01	
Γ_{613}	7.44 ± 0.02	
Γ_{614}	9.47 ± 0.02	
Γ_{621}	1.13 ± 0.00	
Γ_{622}	2.65 ± 0.01	
Γ_{623}	7.46 ± 0.02	
Γ_{624}	9.49 ± 0.02	
Γ_{631}	1.13 ± 0.00	
Γ_{632}	2.65 ± 0.01	
Γ_{633}	7.46 ± 0.02	
Γ_{634}	9.49 ± 0.02	
Γ_{641}	1.13 ± 0.00	
Γ_{642}	2.65 ± 0.01	
Γ_{643}	7.47 ± 0.02	
Γ_{644}	9.50 ± 0.02	
Annual Baseline Risk or Consequence:		
Γ_{600}	0.02	FSEIS (DOE, 1990a), Executive Summary

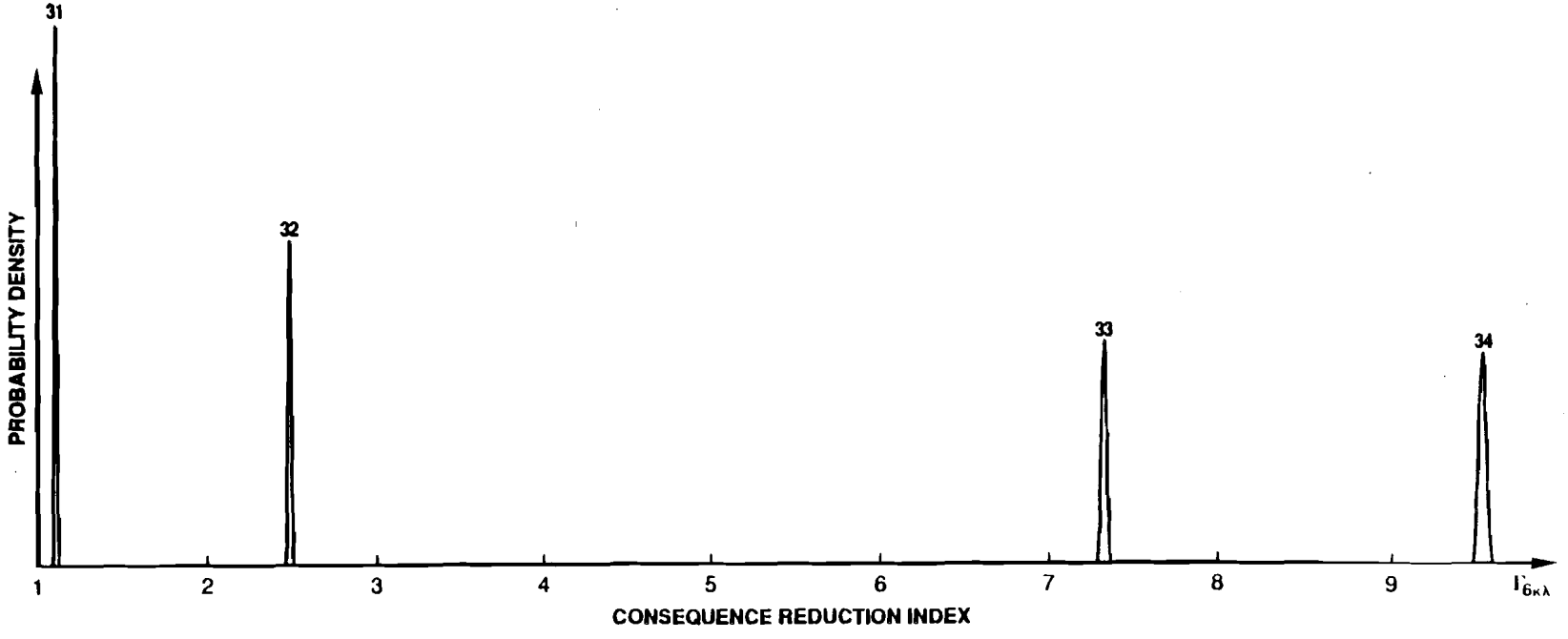

FIGURE G.1-4 CONSEQUENCE REDUCTION INDICES $I'_{6K\lambda}$ FOR PUBLIC CANCERS CAUSED BY EXPOSURE TO RADIATION AND CHEMICAL AGENTS. BECAUSE OF THE NEAR INDEPENDENCE ON TREATMENT, ONLY THE VALUES FOR TREATMENT OPTION 3 ARE SHOWN, VARYING FROM 1 TO ALMOST TEN.

TABLE G.1-18

RISK REDUCTION FACTORS AGGREGATED IN SUPERCOMPONENT 7: POST-CLOSURE OCCUPATIONAL CANCERS

COMPONENT	DESCRIPTION	COMMENTS/REFERENCES
$\rho_{40\,0\,\kappa\,\lambda}$	E1 scenario, direct exposure	Drilling crew
$\rho_{41\,0\,\kappa\,\lambda}$	E2 scenario, direct exposure	Drilling crew
$\rho_{42\,0\,\kappa\,\lambda}$	E1E2 scenario, direct exposure	Drilling crew

with standard errors given by

$$\left(\frac{\Delta\Gamma_{7\kappa\lambda}}{\Gamma_{7\kappa\lambda}}\right)^2 = \left(\frac{1}{9}\right)\sum_{\tau=40}^{42}\left(\frac{\Delta\rho_{\tau o\kappa\lambda}}{\rho_{\tau o\kappa\lambda}}\right)^2 \tag{G.1.35}$$

Numerical values for the consequence reduction factors are given in Table G.1-19. The values are independent of the location parameter λ, as expected for a late post-closure effect. They range from about 5 to 9, with relative standard errors between 10 and 20 percent. Both Level II treatments yield consequence reduction factors close to 5, whereas for Level III treatments the values are 7 and 9, respectively. This is illustrated in Figure G.1-5, showing separate but overlapping values of the consequence reduction factors. They are, however, applied to an exceedingly small consequence in the 10^{-8} range.

G.1.2.8 Supercomponent 8: Public Cancer (Late Effects)

In this supercomponent, the six components in Table G.1-20 are aggregated. Again, no risk values are available for the individual components, and the aggregate is formed by unweighted geometric averaging.

The consequence risk reduction factor is thus given by

$$\Gamma_{8\kappa\lambda} = \prod_{\tau=43}^{48}(\rho_{\tau o\kappa\lambda})^{1/6} , \tag{G.1.36}$$

with geometric standard errors given by Equations (C.1.20) and (C.1.22)

$$\begin{aligned}\left[\log_a \sigma_g(\Gamma_{8\kappa\lambda})\right]^2 &= \left[S(\Gamma_{8\kappa\lambda})\right]^2 \\ &= \sum_{\tau=46}^{48}\left[\log_a \sigma_g(\rho_{\tau o\kappa\lambda})\right]^2 ,\end{aligned} \tag{G.1.37}$$

and thus for the GSD

$$\sigma_g(\Gamma_{8\kappa\lambda}) = a^{S(\Gamma_{8\kappa\lambda})} . \tag{G.1.38}$$

Again, as expected for a late post-closure effect, the factors $\Gamma_{8\kappa\lambda}$ are location independent, with geometric standard errors given by the definitions given in Attachment C, Section C.1.3. The values for the consequence reduction factors range over one order of magnitude from 100 to 2,000 with geometric standard deviations between 2 and 3 (Table G.1-21). This situation is

TABLE G.1-19

CONSEQUENCE REDUCTION FACTORS $\Gamma_{7\kappa\lambda}$ FOR SUPERCOMPONENT 7: OCCUPATIONAL CANCERS, POST-CLOSURE EFFECTS

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Consequence Reduction Factors:		
$\Gamma_{71\lambda}$	5.0 ± 0.48	
$\Gamma_{72\lambda}$	5.0 ± 0.49	
$\Gamma_{73\lambda}$	6.9 ± 1.4	
$\Gamma_{74\lambda}$	9.4 ± 1.0	
Annual Baseline Risk or Consequence:		
Γ_{700}	$3 \cdot 10^{-8}$	FSEIS (DOE, 1990a), Executive Summary

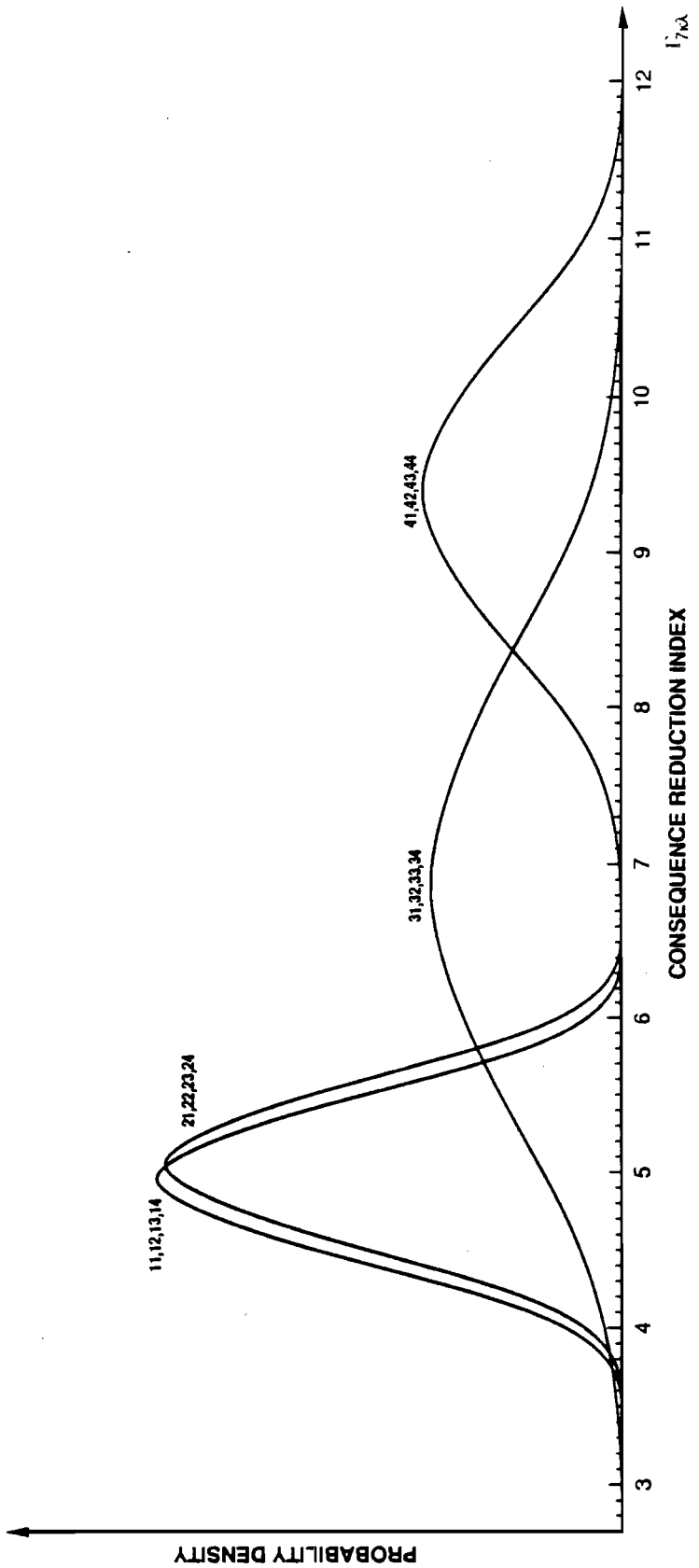

FIGURE G.1-5 CONSEQUENCE REDUCTION INDICES $I_{7\lambda}$ FOR OCCUPATIONAL CANCERS IN THE LATE POST-CLOSURE PERIOD. THE INDICES ARE INDEPENDENT OF LOCATION AND SHOW THE EFFECT OF TREATMENT ONLY.

TABLE G.1-20

RISK REDUCTION FACTORS AGGREGATED IN SUPERCOMPONENT 8: POST-CLOSURE PUBLIC CANCER

COMPONENT	DESCRIPTION	COMMENTS
$\rho_{43pk\lambda}$	Scenario E1 inhalation	Receptors:
$\rho_{44pk\lambda}$	Scenario E2 inhalation	5 persons at ranch
$\rho_{45pk\lambda}$	Scenario E1E2 inhalation	5 km from site
$\rho_{46pk\lambda}$	Scenario E1 ingestion	
$\rho_{47pk\lambda}$	Scenario E2 ingestion	
$\rho_{48pk\lambda}$	Scenario E1E2 ingestion	

TABLE G.1-21

CONSEQUENCE REDUCTION FACTORS $\Gamma_{8\kappa\lambda}$ FOR SUPERCOMPONENT 8: PUBLIC CANCER

QUANTITY	VALUE (GSD)	COMMENTS/REFERENCES
Consequence Reduction Factors:		
$\Gamma_{8 1 \lambda}$	106 (2.3)	
$\Gamma_{8 2 \lambda}$	115 (2.2)	
$\Gamma_{8 3 \lambda}$	221 (2.4)	
$\Gamma_{8 4 \lambda}$	2030 (2.7)	
Annual Baseline Risk or Consequence:		
Γ_{800}	$7 \cdot 10^{-5}$	FSEIS (DOE, 1990a) Executive Summary

GSD = Geometrical Standard Deviation.

illustrated in Figure G.1-6, which shows the factors on a logarithmic scale. There is little difference between the two Level II treatments but a substantial spread between the two Level III treatments. These consequence reduction factors are, in this case, applied to a very small baseline in the range below 10^{-4}.

G.2 CALCULATIONS OF CONSEQUENCE REDUCTION INDICES $\Theta_{\kappa\lambda}$ AND CONSEQUENCE AUGMENTATION INDICES $\Psi_{\kappa\lambda}$

Although the consequence reduction and augmentation indices, $\Theta_{\kappa\lambda}$ and $\Psi_{\kappa\lambda}$, can be calculated directly from Equations (B.3.19 and B.3.20), the indirect route via single and multi-attribute utility indices $\theta_{j\kappa\lambda}$ and $U_{\kappa\lambda}$ and Equations (B.3.13) and (B.3.18) is chosen in order to accommodate quantities with both normal and lognormal distributions. The weighted sum leading to the utility indices $U_{\kappa\lambda}$ provides the vehicle to again apply the Central Limit Theorem and assume a normal distribution for the utility indices and, therefore, a lognormal distribution for the consequence reduction or augmentation indices.

G.2.1 Single Attribute Utility Indices $\theta_{\kappa\lambda}$

G.2.1.1 Consequence Reduction Factors with Assumed Normal Distribution

Assuming a normal distribution by virtue of the Central Limit Theorem discussed before (see Attachment B.4.4), the risk reduction factors $\Gamma_{j\kappa\lambda}$ and their standard errors $\Delta\Gamma_{j\kappa\lambda}$ yield the single attribute utility functions

$$\theta_{j\kappa\lambda} = \log_{10}(\Gamma_{j\kappa\lambda}) , \tag{G.2.1}$$

with standard errors of

$$\Delta\theta_{j\kappa\lambda} = Q\frac{\Delta\Gamma_{j\kappa\lambda}}{\Gamma_{j\kappa\lambda}} \quad \textit{with} \quad Q = \frac{1}{\ln 10} = 0.434294... \ . \tag{G.2.2}$$

The distribution of the stochastic variable $\theta_{j\kappa\lambda}$ with standard error $\Delta\theta_{j\kappa\lambda}$ is no longer normal.

G.2.1.2 Consequence Reduction Factors with Assumed Lognormal Distribution

For quantities with large error intervals such as Supercomponent 8, the assumption of a lognormal distribution is a convenient choice. Given the geometric mean $\Gamma_{j\kappa\lambda}$ and a geometric standard deviation $\sigma_g(\Gamma_{j\kappa\lambda})$, and taking the logarithm of the lognormally distributed argument will result in a normally distributed quantity

$$\theta_{j\kappa\lambda} = \log_{10}(\Gamma_{j\kappa\lambda}) , \tag{G.2.3}$$

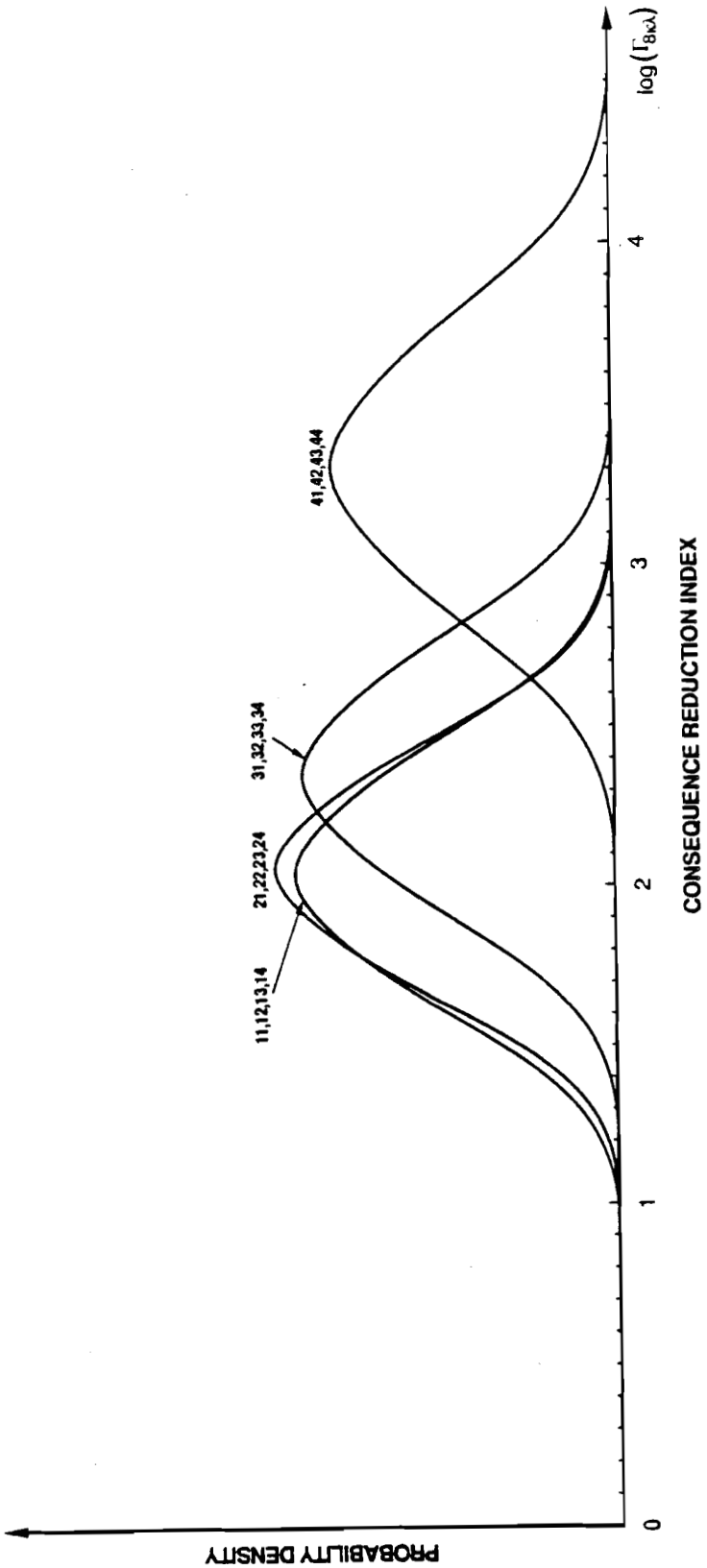

FIGURE G.1-6 CONSEQUENCE REDUCTION INDICES Γ_{8x} FOR PUBLIC CANCERS IN THE LATE POST-CLOSURE PERIOD PLOTTED ON A LOGARITHMIC SCALE. THE INDICES SHOW THE DEPENDENCE ON TREATMENT OPTION, BEING INDEPENDENT OF LOCATION.

with a standard deviation of

$$\Delta \theta_{j\kappa\lambda} = \log_{10} \sigma_g (\Gamma_{j\kappa\lambda}) \ . \qquad \text{(G.2.4)}$$

G.2.2 Calculation of Multiattribute Utility Indices

G.2.2.1 Societal Valuations

The elicitation of the societal weights for various components of the total risk relative to each other is based on premises that are somewhat unusual as compared to those usually elicited in a Multi-Attribute Utility Theory:

- It is not the actual components that are being valuated, but reductions and increases in those components.
- Only relatively small increases and decreases (for the small risks discussed here increases and decreases by a factor of two) are being considered.
- It is recognized that for the small size of these risks, the rough order of magnitude of the risk influences the valuation of a risk reduction or risk enhancement.

The first condition arises from the fact that at issue is a risk comparison, i.e., a risk reduction or a risk augmentation. The second is based on the fact that the law of diminishing marginal utility of economics is applied here to risk comparison. It is taken into account by using the logarithm of a particular risk reduction factor as the utility for that component. It is shown in Attachment B that, in risk assessment, the law of diminishing marginal utility describes the fact that a unit increase in risk reduction is most valuable for a risk reduction of one, less valuable for a risk reduction of 10 and even less for 100, and so on. The third condition accounts for the fact that a risk reduction of 2 is most valuable for a risk of immediate concern, say for $10^{-2} < p < 1$, much less so for a risk of lesser concern with a value of 10^{-3} to 10^{-4}, and almost irrelevant for a risk smaller than 10^{-6}.

The societal valuations or weights needed here, are a measure of the preference for one risk reduction over another by the same factor. Thus, these relative weights have little or nothing to do with the dollar value of a human life. This valuation is squeezed rather tightly into a very narrowly scoped question to every person participating in the valuation procedure:

> "How do I rate an increase or decrease by a factor of two in one component (say occupational fatalities) relative to the same change in another component (say cancer deaths in 10 years)?"

As mentioned above, the absolute magnitude of the components being compared is clearly of some import. A pair-wise comparison, however, should not be influenced by the magnitude of any other component.

In the time schedule of this work, it was not possible to acquaint the necessary number of experts with this new valuation procedure. A more technical viewpoint, represented by one person in the role of a decision maker, but supported by the views of several others, will be presented here.

The considerations that enter the relative weighting of the first four supercomponents is discussed in the main text of this appendix in Section 5.1.1. Consideration of the value of a consequence reduction or augmentation, given the magnitude of the baseline risk, led to the absolute weights 10, 7, 5, and 4 given in Table G.2-1. The absolute weights of the occupational and public cancers relative to all other components are 1 and 3, respectively, taking into account their small size and the fact that for occupational cancers the latency adds 5 to 20 years of useful life after exposure. The last two components finally are set at 0.1 and 0.2, taking into account that in 5,000 years cancer is not likely to be a problem but that these exposures may be indicative of an environmental problem caused by our generation. In order to forestall this, the weights are assumed to be much higher than cancer itself would justify. The resulting societal weights, with a sum normalized to 1, are given in Table G.2-1.

The weights given in Table G.2-1 are based on the opinions of three leading experts in risk assessment and management and three more technically oriented persons. The final selection, however, was made by one person (the project leader) in the role of decision maker. The weights are based on the input received from the six advisors but reflect his own informed valuations.

G.2.2.2 General Considerations

The Multi-Attribute Utility Index, the basic quantity for the risk comparison used here, is given by

$$U_{k\lambda} = \sum_{j=1}^{8} \gamma_j \, \Theta_{j\kappa\lambda} \tag{G.2.5}$$

with the normalized weights defined in the previous section

$$\sum_j \gamma_j = 1 \, . \tag{G.2.6}$$

The standard error of the index is

$$(\Delta U_{\kappa\lambda})^2 = \sum_{j=1}^{8} (\gamma_j \, \Delta\theta_{j\kappa\lambda})^2 + (\theta_{j\kappa\lambda} \, \Delta\gamma_j)^2 \, . \tag{G.2.7}$$

TABLE G.2-1

SOCIETAL VALUATIONS AND WEIGHTS, γ_j

RISK SUPERCOMPONENT	ANNUAL BASELINE RISK	ABSOLUTE WEIGHTS	NORMALIZED WEIGHT γ_j
1 Transportation fatalities	0.2	10	0.33
2 Transportation injuries	3	7	0.23
3 Occupational fatalities	0.002	5	0.17
4 Occupational injuries	0.7	4	0.13
5 Occupational cancers	0.005	1	0.033
6 Public cancers	0.02	3	0.10
7 Late occupational cancers	$3 \cdot 10^{-8}$	0.1	0.003
8 Late public cancers	$7 \cdot 10^{-5}$	0.2	0.007

The single attribute utilities $\theta_{j\kappa\lambda}$ are not normally distributed, except in those cases in which the consequence reduction factors were lognormally distributed. However, with the eight super components in a sum, application of the central limit theorem allows the statement that the multiattribute utility indices should be approximately normally distributed.

The transformation back to linear space yields the two derived quantities of interest, the consequence reduction indices $\Theta_{\kappa\lambda}$ and their inverse quantities, the consequence augmentation indices $\Psi_{\kappa\lambda}$. Due to the use of the Central Limit Theorem, the utility indices $U_{\kappa\lambda}$ can be assumed to be normally distributed, allowing the use of the Gaussian approximation for error propagation. The resulting values of the consequence reduction indices $\Theta_{\kappa\lambda}$ are given in Table G.2-2. Sometimes it is more convenient to discuss the inverse indices, the consequence augmentation indices $\Psi_{\kappa\lambda}$ given in Table 5-2 of the main text and the values are discussed in Section 5.2.1.

Using the definition of the consequence reduction index

$$\Theta_{\kappa\lambda} = 10^{U_{\kappa\lambda}} , \tag{G.2.8}$$

and with $U_{\kappa\lambda}$ being a normally distributed quantity, the risk reduction index is lognormally distributed. As the errors are small, however, a normal distribution is a sufficient approximation with

$$\frac{\Delta \Theta_{\kappa\lambda}}{\Theta_{\kappa\lambda}} = ln\, 10 \cdot \Delta U_{\kappa\lambda} . \tag{G.2.9}$$

For the consequence augmentation index, the definition,

$$\Psi_{\kappa\lambda} = 10^{-U_{\kappa\lambda}} , \tag{G.2.10}$$

results again in a narrow lognormal distribution, approximated by a normal distribution with a standard error given by the same equation,

$$\frac{\Delta \Psi_{\kappa\lambda}}{\Psi_{\kappa\lambda}} = ln\, 10 \cdot \Delta U_{\kappa\lambda} = \frac{\Delta \Theta_{\kappa\lambda}}{\Theta_{\kappa\lambda}} \tag{G.2.11}$$

If a more exact approximation is desired, the geometric standard deviation of the lognormal distribution is given by

$$\sigma_g(\Psi_{\kappa\lambda}) = \sigma_g(\Theta_{\kappa\lambda}) = 10_{\Delta U_{\kappa\lambda}} , \tag{G.2.12}$$

with the mean values given by equations (G.2.8) and (G.2.10).

TABLE G.2-2

CONSEQUENCE REDUCTION INDICES FOR 16 TREATMENT/LOCATION OPTIONS

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Θ_{11}	0.712 ± 0.010	
Θ_{12}	0.663 ± 0.019	
Θ_{13}	0.710 ± 0.025	
Θ_{14}	0.728 ± 0.026	
Θ_{21}	0.700 ± 0.010	
Θ_{22}	0.632 ± 0.017	
Θ_{23}	0.671 ± 0.021	
Θ_{24}	0.688 ± 0.022	
Θ_{31}	0.617 ± 0.008	
Θ_{32}	0.707 ± 0.046	
Θ_{33}	0.811 ± 0.074	
Θ_{34}	0.837 ± 0.078	
Θ_{41}	0.486 ± 0.006	
Θ_{42}	0.779 ± 0.014	
Θ_{43}	1.138 ± 0.033	Actual risk reductions
Θ_{44}	1.213 ± 0.038	Actual risk reductions

The values for the consequence reduction indices in Table G.2-2 lie mostly below 1, indicating increases of the societally weighted geometric average over the eight risk reduction factors. Only the last two treatment/location options show actual decreases in risk. Relative standard errors range from 0 to 10 percent. The values for treatments 1 and 2 (Level II treatment) lie closely together, often little more than a standard error apart. Treatment 3 indices, except for location option 1, decrease with location option λ, beginning to approach the baseline risk. Treatment 4 indices go from the lowest value in the array to the highest (see also Figure 5.1).

G.3 CLASSES OF INDIFFERENCE AND RISK COMPARISON

G.3.1 Approach To Establishing Indifference

For the case of strongly overlapping probability distributions, the criteria of Goodmann (see Section B.4.3) can be used to determine whether two risk reduction or augmentation indices are significantly different or not (Goodmann, 1986). Both criteria are based on comparing the main bodies of two distributions rather than their tails. The first criterion is an information theoretical measure called the divergence between two distributions. It is in essence proportional to the absolute value of the difference between the two distributions [see Equation (B.4.5)]. The second criterion determines for a given confidence level how much of the second distribution lies between the confidence limits of the first one, and vice-versa. From these two numbers, the second criterion is fashioned.

G.3.1.1 Use of the Criteria

Compare two distributions with the means defined as

$$\mu_1 = \Theta_{\kappa_1 \lambda_1} \qquad \text{(G.3.1)}$$

$$\mu_2 = \Theta_{\kappa_2 \lambda_2} ,$$

and with standard errors defined as

$$\sigma_1 = \Delta\Theta_{\kappa_1 \lambda_1} \qquad \text{(G.3.2)}$$

$$\sigma_2 = \Delta\Theta_{\kappa_2 \lambda_2} ,$$

With the additional definitions

$$\sigma_> = max\{\sigma_1 , \sigma_2\} , \qquad \text{(G.3.3)}$$

and

$$\sigma_< = min\{\sigma_1, \sigma_2\}, \tag{G.3.4}$$

and

$$\rho = \frac{\sigma_>}{\sigma_<}, \tag{G.3.5}$$

the test quantity

$$T = \frac{|\mu_1 - \mu_2|}{\sigma_<}, \tag{G.3.6}$$

can be evaluated. For rejection of the hypothesis of different risks, Goodmann's "confidence" criterion derived from Equation (B.4.10) according to Goodmann (1986) is

$$T \leq T_{cr}(\rho, \varepsilon_o) \tag{G.3.7}$$

where

$$T_{cr}(\rho, \varepsilon_o) = 2.306 \sqrt{\varepsilon_o - 0.385(\rho - 1)} . \tag{G.3.8}$$

For acceptance of the hypothesis of different risks, on the other hand, Goodman's "informational" criterion, derived from Equation (B.4.6) can be applied

$$T > T_{ca}(\rho, D_o), \tag{G.3.9}$$

where

$$T_{ca}(\rho, D_o) = \sqrt{\frac{1 + J_o - (\rho^2 + \rho^{-2})}{0.5\,(1 + \rho^{-2})}}\ , \tag{G.3.10}$$

with

$$D_o = 5.318\ \varepsilon_o\ . \tag{G.3.11}$$

The numerical constants are valid for a confidence level of $C_o = 0.9$. For the calculations in this paper, a significance level of $\varepsilon_o = 0.05$ is used.

In the region between the two criteria, i.e., for

$$T_{cr}(\rho, \varepsilon_o) < T \leq T_{ca}(\rho, D_o)\ , \tag{G.3.12}$$

the "informational criterion" rejects the hypothesis of different indices, whereas the 'confidence' criterion does not yet reject it. The assignment of indifference or difference is consequently uncertain. In Figure G.3-1, this situation is shown on a plot of the critical curves, Equations (G.3.8) and (G.3.10), in the (T,ρ) - plane. The two curves divide the plane into three domains: one of different utility indices (D), one of indifferent utility indices (I), and one of questionable status (Q). In the last case, a decision may be reached on the basis of the location of questionable points in this plane relative to the limiting curves.

G.3.1.2 Discussion of Results

The comparison of all pairs (a,b) of the 16 indices is best thought of in terms of a 16 by 16 matrix with 256 elements. Of these, the 16 diagonal pairs (a,a) are irrelevant and all off-diagonal pairs are symmetrical, (a,b) = (b,a). These properties result in (256-16) / 2 = 120 independent pairs. The analysis of all these comparisons yields information on the significance of differences between indices. The results of the analysis in terms of the Goodmann criteria are given in Table G.3-1 and Figure G.3-1, five pairs of indices are indifferent, five are questionable and three lie close enough outside the outer limit to be included due to possible residual systematic errors. This is due to the fact that biases may change the (T,ρ)-combination sufficiently to include them in the difference domain.

The same information is shown graphically in Figure G.3-2. Nine of the 120 combinations of consequence reduction or augmentation indices overlap sufficiently to be shown here. Only one combination clearly lies within the indifference domain and one within the domain of questionable overlap. Three other points lie relatively close to the outer limiting curve. Both limiting curves

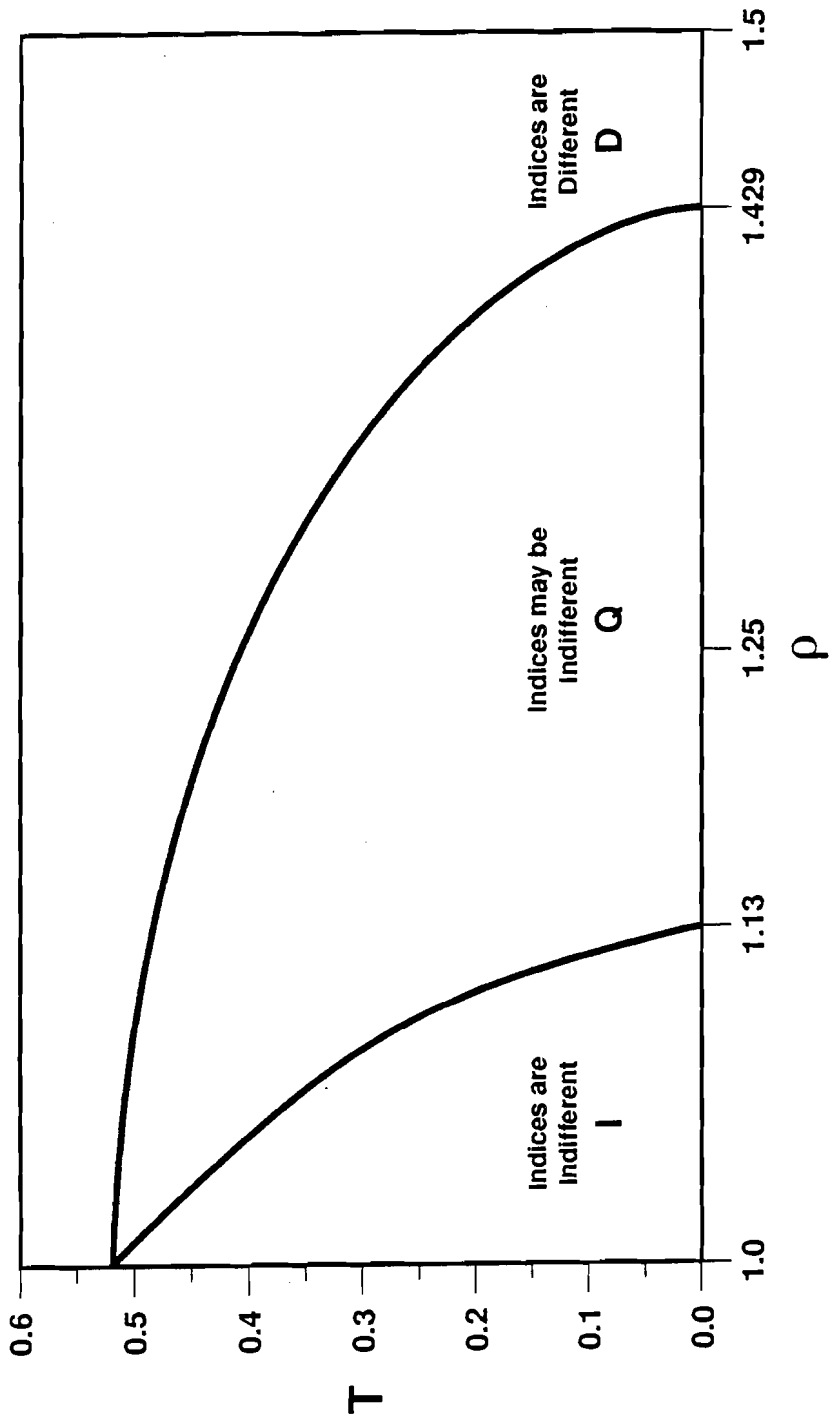

FIGURE G.3-1 DOMAINS OF DIFFERENCE, INDIFFERENCE AND QUESTIONABLE OUTCOME OF A COMPARISON

TABLE G.3-1

DIFFERENCES AND INDIFFERENCES FOR UTILITY INDICES

k			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	κ	λ	11	12	13	14	21	22	23	24	31	32	33	34	41	42	43	44
1	1	1	-	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
2	1	2	-	-	D	D	D	D	Q	D	D	D	D	D	D	D	D	D
3	1	3	-	-	-	C	D	D	D	D	D	C	D	D	D	D	D	D
4	1	4	-	-	-	-	D	D	D	D	D	D	D	D	D	D	D	D
5	2	1	-	-	-	-	-	D	D	D	D	D	D	D	D	D	D	D
6	2	2	-	-	-	-	-	-	D	D	D	D	D	D	D	D	D	D
7	2	3	-	-	-	-	-	-	-	C	D	D	D	D	D	D	D	D
8	2	4	-	-	-	-	-	-	-	-	D	D	D	D	D	D	D	D
9	3	1	-	-	-	-	-	-	-	-	-	D	D	D	D	D	D	D
10	3	2	-	-	-	-	-	-	-	-	-	-	D	D	D	D	D	D
11	3	3	-	-	-	-	-	-	-	-	-	-	-	I	D	D	D	D
12	3	4	-	-	-	-	-	-	-	-	-	-	-	-	D	D	D	D
13	4	1	-	-	-	-	-	-	-	-	-	-	-	-	-	D	D	D
14	4	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	D	D
15	4	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	D
16	4	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

I = Combination of significantly different indices.

D = Combination of different indices.

Q = Combination of questionable status.

C = Combination included due to proximity to limits.

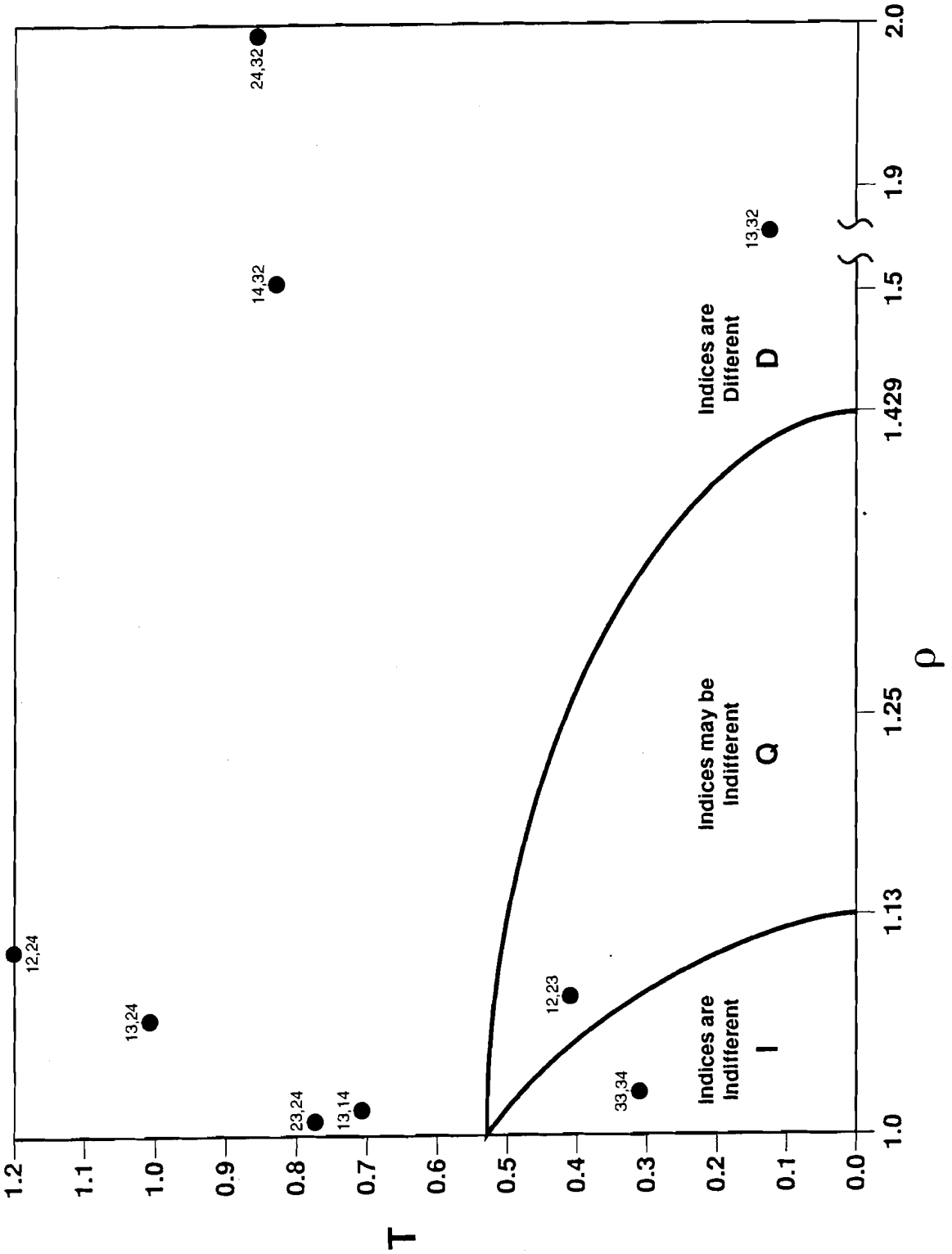

FIGURE G.3-2 CRITICAL COMPARISON FOR RISK REDUCTION INDICES

are functions of quantities defined in Attachment B, Section B.4.3, such as the confidence level $C_0 = 0.9$, the significance level $\varepsilon_0 = 0.05$, and the divergence limit D_0 given by Equation (G.3.11). The selections made here are conventional but otherwise as arbitrary as all such choices. The three points lying closest to the outer limit are included, because changes in the limits could shift the curves so as to engulf these points.

From these discussions, it is obvious that 115 of the 120 possible pairings are clearly different from each other; only 2 show sufficient overlap to be considered indifferent. This is shown clearly in Figure 5-1. There, other groupings are evident, that can be used in the process of reaching conclusions. It is important at this juncture to realize that the errors quoted for the consequence reduction or augmentation indices are generally somewhat too small. As already discussed in Section 3.1.3 of the Introduction, this situation arises both from incomplete information and from the decision not to include the partial effects of systematic errors on the final result. With this fact in mind, the small differences between the indices of the Level II treatments are even less significant, supporting an interpretation as a group.

G.4 ANALYSIS OF THE CONSEQUENCE REDUCTION INDICES

Risk comparisons are usually used in further evaluations of the alternatives being compared. In the present case, the results of this comparison are part of the selection procedure of the Engineered Alternatives for the treatment of wastes to be emplaced at the WIPP. In order to arrive at an appropriate weighting in that process, a detailed analysis of the influence of the different supercomponents on the final values of the consequence reduction indices is needed. It will serve as an additional input for the decision maker at the higher level. Indeed, it is quite likely that the interaction between the two decision makers will result in an iterative process of reweighting at both levels until a consensus is reached. In the present study, this interaction was discussed between the two decision makers, but could not be carried out due to the external constraints of the work.

G.4.1 Contributions of Traditional and Radiological Effects

One of the major concerns about the WIPP is centered on the health effects due to the radioactivity of the wastes. As an inspection of the baseline risk numbers in Table G.2-1 shows, the consequences in supercomponents 5 and 6 are among the smallest expected health effects of the entire operation. Transportation fatalities and injuries, although well within acceptable limits, are much larger. This is a direct consequence of the public and administrative concerns over radiological effects and of the successful efforts by health physicists to keep these effects at low levels.

G.4.1.1 Consequence Reduction Indices Without Transportation Health Effects

Although Supercomponents 1 and 2 contain some radiological risk contributions, their influence was set to zero by the assumptions for Equations (G.1.5) and (G.1.9). The influence of the nonradiological transportation accidents can thus be studied easily by setting their absolute weights in Table G.2-1 to zero. After renormalization, the relative weights listed in the second column of Table G.4-1 are obtained.

An evaluation of the consequence augmentation indices yields the values given in Figure G.4-1. For Level II treatments, the consequences decrease with increasing decentralization of the treatment from indices around 2 down to indices near 1.4. For Level III treatments the indices for Location Option 1 (WIPP) increase to values near 3 for Treatment Option 3 and near 5 for Treatment Option 4. Here too, the indices decrease with decentralization, but only to values near 2 and near 3 for Treatment Options 3 and 4, respectively. The shading of the cells indicates these values, with the lightest shade for the largest increases in the index, i.e., for group 1 with values between 4 and 5, the next darker shade for the group of values near 3, even darker for group 3 with values near 2, and darkest for the lowest consequence augmentation indices near 1.4.

This pattern reflects the increase of the now dominant occupational accident risk with more complex treatment. All treatment/location options show an increase in consequences due to the treatment activities. This trend is overlaid with a decrease in accidental public cancer risk during transportation. In evaluating these data, two facts should be borne in mind: (1) an inspection of the remaining baseline risks in Table G.2-1 shows them to be small and (2) the increases in consequences indicated by the augmentation indices in Figure G.4-1 are not linearly related to these baseline risks. Thus, it would be absolutely false to state that the remaining baseline risks are higher by a factor equal to the consequence augmentation index.

G.4.1.2 Consequence Reduction Indices Without Occupational Health Effects

Supercomponent 4 also has a contribution of a chemical noncancer health risk, whereas supercomponent 3 is a pure consequence of occupational accidents. The chemical health risks are exceedingly small, however, and that contribution was set to zero in Equation (G.1.19). Thus setting the absolute weights of supercomponents 3 and 4 to zero (Table G.2-1) results in the relative weights given in column 3 of Table G.4-1, and shows the consequence reduction indices with the influence of conventional occupational accidents removed.

The consequence reduction indices $\Theta_{\kappa\lambda}$ are mostly larger than 1, so they are listed in Figure G.4-2. For Level II treatments, the values of the indices cluster closely around unity, showing that it is the occupational risk components that are responsible for the increase in the index for all Level II treatments in the fully weighted case. The group of treatment/location options with consequence reduction indices around 1 is shown with the lightest shading of the cells. For Level

TABLE G.4-1

CONTRIBUTIONS OF TRADITIONAL AND RADIOLOGICAL EFFECTS

	NORMALIZED WEIGHTS γ_i		
RISK SUPERCOMPONENT	NO TRAFFIC ACCIDENTS	NO OCCUPATIONAL ACCIDENTS	NO TRAFFIC OR OCCUPATIONAL ACCIDENTS
1 Transportation fatalities	0	0.47	0
2 Transportation injuries	0	0.33	0
3 Occupational fatalities	0.38	0	0
4 Occupational injuries	0.30	0	0
5 Occupational cancers	0.075	0.047	0.23
6 Public cancers	0.23	0.14	0.70
7 Late occupational cancers	0.0075	0.0047	0.023
8 Late public cancers	0.015	0.0094	0.047

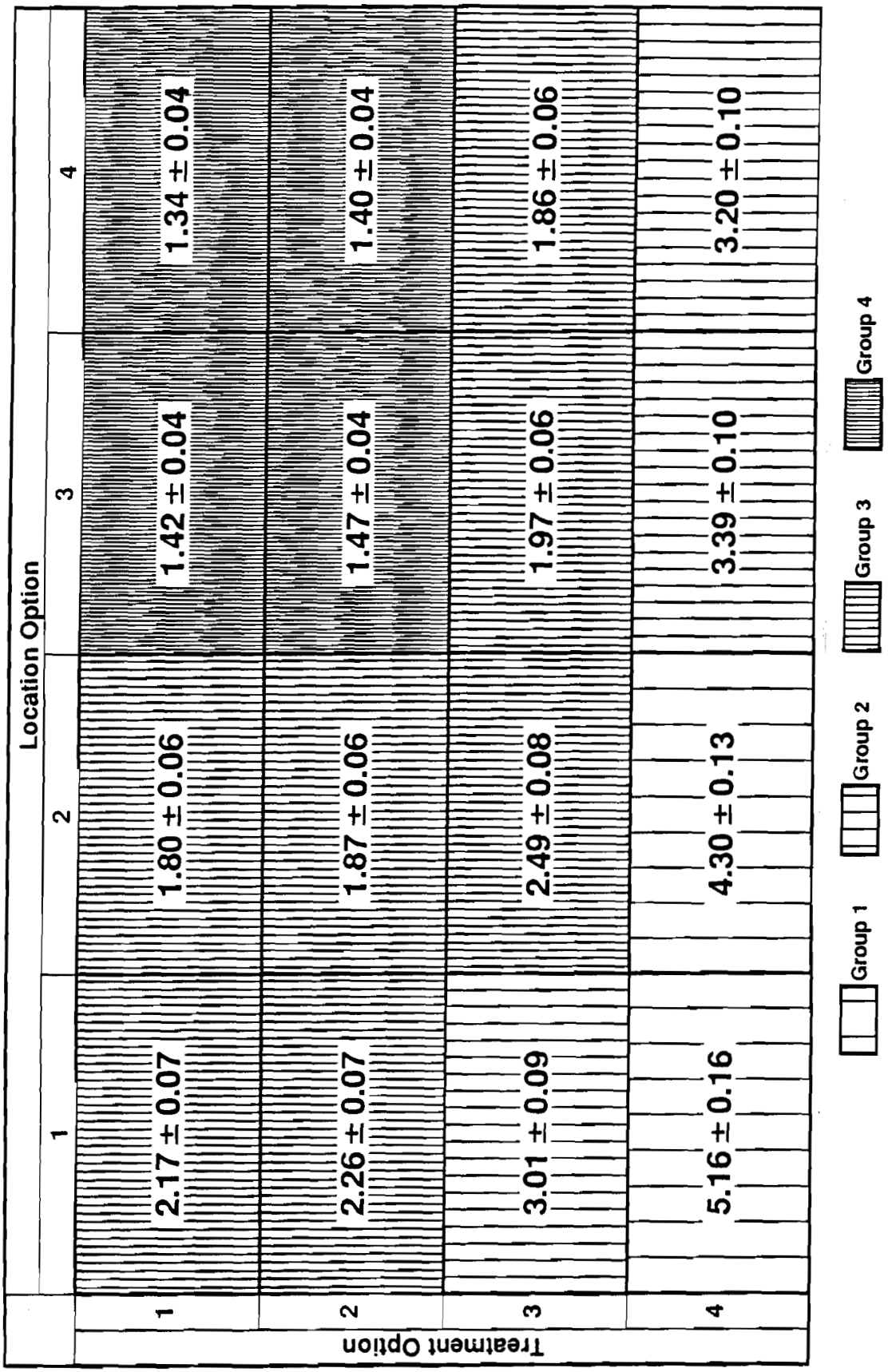

FIGURE G.4-1 CONSEQUENCE AUGMENTATION INDICES FOR ALL TREATMENT AND LOCATION OPTIONS IN THE SENSITIVITY STUDY WITHOUT TRANSPORTATION RISKS. AS ALL CONSEQUENCE REDUCTION FACTORS ARE SMALLER THAN 1, VALUES FOR THEIR INVERSES ARE SHOWN HERE.

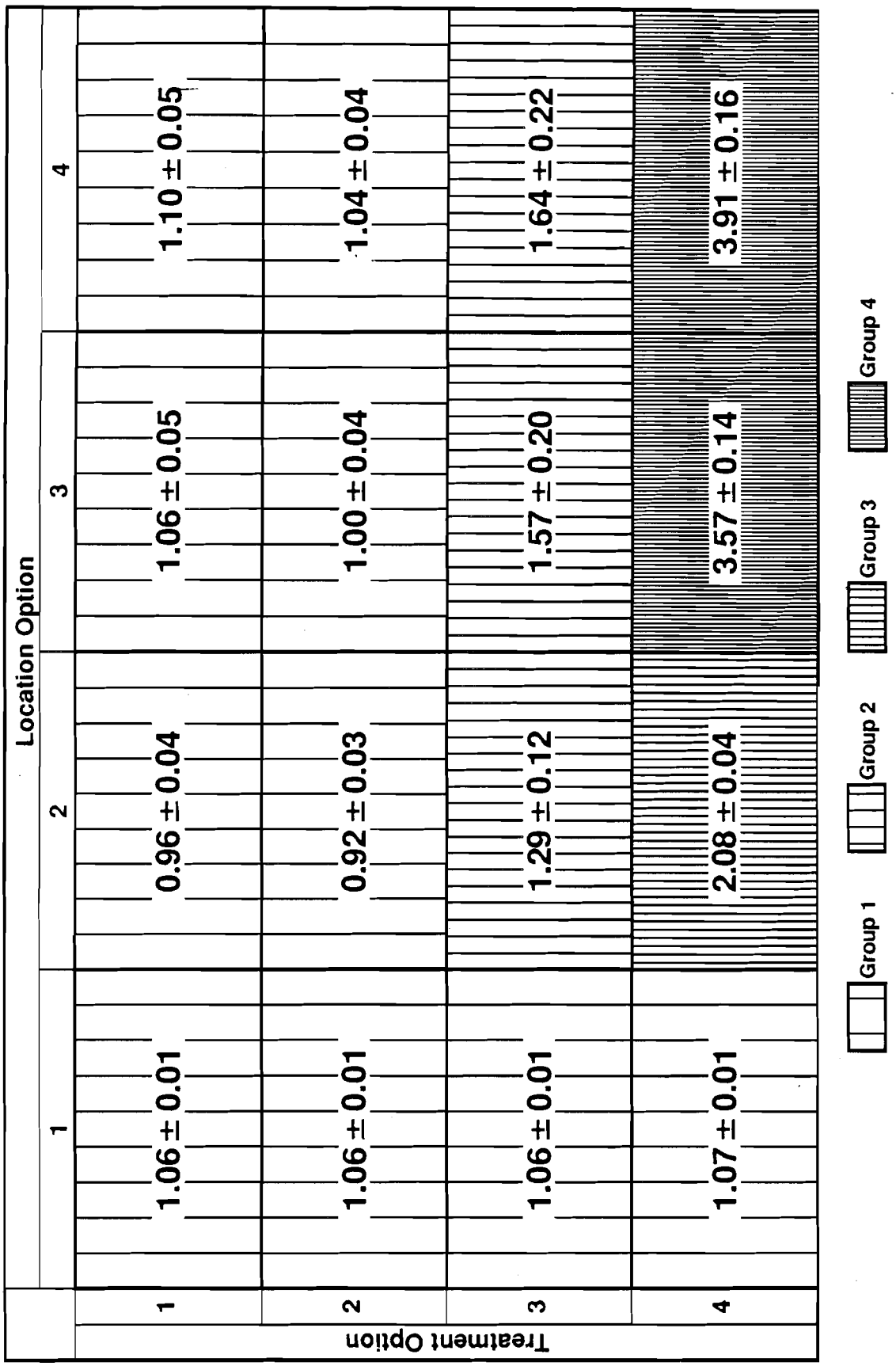

FIGURE G.4-2 CONSEQUENCE AUGMENTATION INDICES FOR ALL TREATMENT AND LOCATION OPTIONS IN THE SENSITIVITY STUDY WITHOUT OCCUPATIONAL ACCIDENT RISKS

III treatments, the reduction indices increase to values near 1.3 to 1.6 (group 2 shading) for Treatment Option 3 carried out in decentralized facilities, and values of 2 (group 3 shading) up to indices near 4 (group 4 with darkest shading) for Treatment Option 4 and treatment near the originators of the waste. This demonstrates the influence of the transportation risk components in the location dependence of Level III treatments in the fully weighted case.

G.4.1.3 Indices Without Transportation or Occupational Health Effects

For the last sensitivity study, both the transportation and the occupational accident risks are weighted with zero. This will remove the influence of the largest baseline risk components and will show the influence of the radiological risk contributions with a small addition for the risks due to the exposure to chemical agents. Using the relative weights given in the last column of Table G.4-1, the consequence reduction indices calculated are all larger than 1, indicating a uniform reduction in consequences (Figure G.4-3). This can be understood from the fact that all direct external radiation doses are essentially independent of treatment because they depend on the total activity transported and handled per year. This quantity is assumed to be constant in this study [see Equation (E.1.5)].

The consequence reduction here is thus almost exclusively due to transportation and handling accidents, which are responsible for relatively small contributions to the baseline risks for supercomponents 5 and 6 in Table G.2-1. This results in large relative decreases for all baseline risks for almost any form of treatment, leading to the nearly treatment-independent consequence reduction indices in Figure G.4-3. The lightest patterns are reserved for cells with indices around 1.35, the group 2 pattern for values around 2.4, the darker group 3 pattern for indices around 5, and the darkest pattern for the highest reduction indices near 6. It should be noted in this context that the accidents contributing to these indices all had to be weighted with equal weights because their baseline risks are not available. A considerable amount of bias may, therefore, be expected. The general location trend is too strong, however, and is probably independent of this bias.

G.4.2 Contribution of Each Supercomponent to the Final Indices

G.4.2.1 Contribution of Each Component to All Indices

The factors defined in Equation (B.3.22) will be given in the 4 x 4 matrices used before for the display of values for the 16 treatment/location options even though the treatment or location dependence does not exist in some cases and is too small to matter in others.

G.4.2.1.1 Supercomponent 1: Fatal Transportation Accidents

By definition, these factors $\Phi_{1\kappa\lambda}$ are equal to 1 for treatment at the WIPP, after all the transportation is done (Figure G.4-4). For Level II treatments, consequence increases of around 10 percent are effected, due to the volume increase in the treated wastes, resulting in an

Treatment Option	Location Option 1	Location Option 2	Location Option 3	Location Option 4
1	1.35 ± 0.06	2.42 ± 0.10	5.03 ± 0.20	5.96 ± 0.24
2	1.36 ± 0.05	2.42 ± 0.10	5.03 ± 0.20	5.97 ± 0.23
3	1.35 ± 0.06	2.42 ± 0.10	5.02 ± 0.21	5.95 ± 0.25
4	1.37 ± 0.06	2.42 ± 0.11	5.03 ± 0.23	6.00 ± 0.28

Group 1 Group 2 Group 3 Group 4

FIGURE G.4-3 CONSEQUENCE AUGMENTATION INDICES FOR ALL TREATMENT AND LOCATION OPTIONS IN THE SENSITIVITY STUDY WITHOUT TRANSPORTATION AND OCCUPATIONAL ACCIDENT RISKS

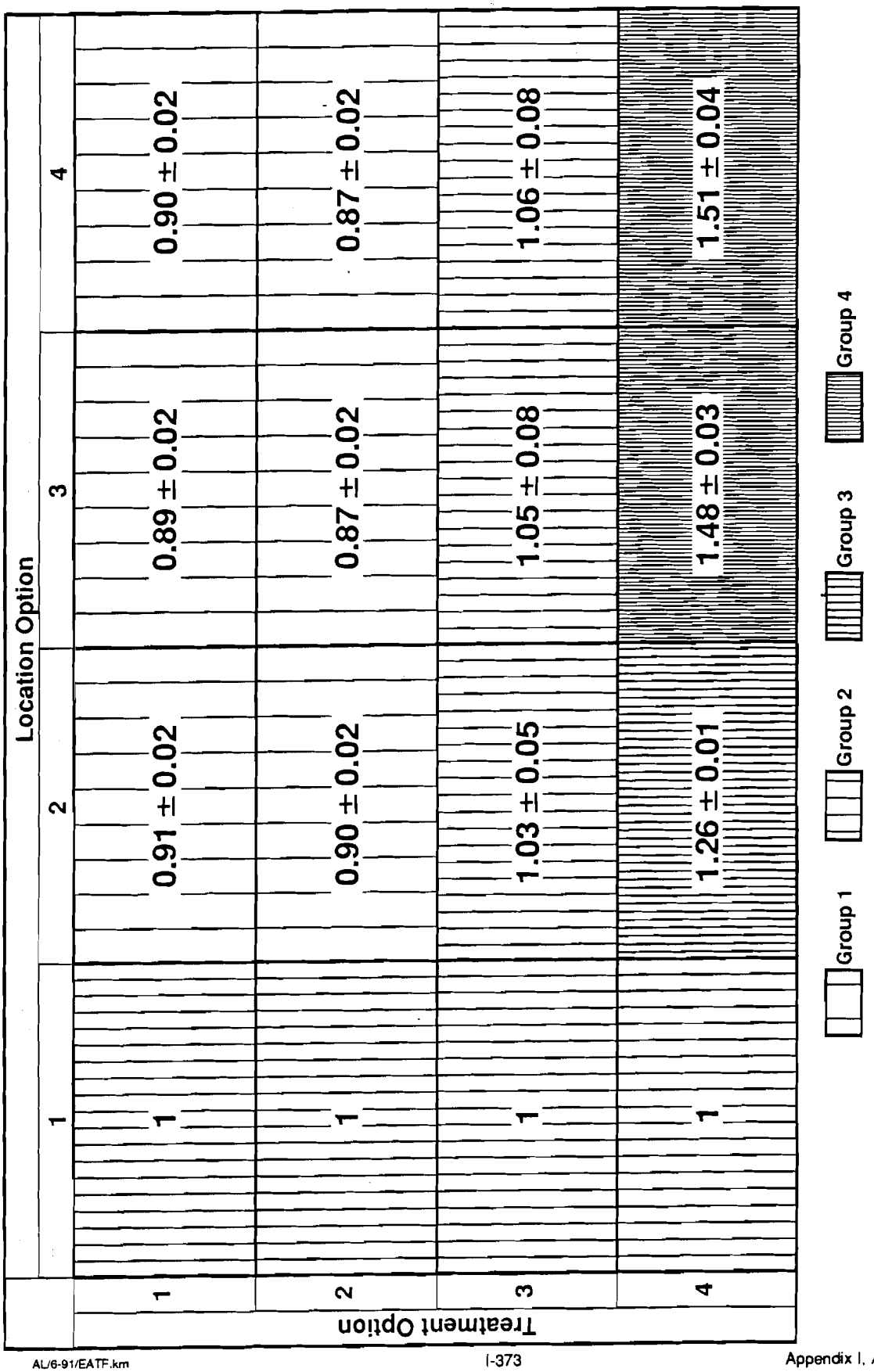

FIGURE G.4-4 CONTRIBUTING FACTORS $\Phi_{1k\lambda}$ FOR SUPERCOMPONENT 1: TRAFFIC ACCIDENT FATALITIES

increased number of transports. For Level III treatments, relative contributions to the consequence reduction indices of a few percent occur for Treatment Option 3, and more substantial relative increases of 20 to 50 percent for option 4. Both Level III treatments show a distinct trend to higher factors for decentralized treatment facilities.

G.4.2.1.2 Supercomponent 2: Injuries in Transportation Accidents

By definition, these factors are also equal to 1 for treatment at the WIPP; again because all the transportation is already done. The corresponding factors $\Phi_{2\kappa\lambda}$ are shown in Figure G.4-5. The situation is essentially the same as that for the factors $\Phi_{1\kappa\lambda}$, but with smaller deviations from 1. For Level II treatments, this component contributes increases of up to 10 percent, again due to the volume increase in the treated wastes and an increase in the number of transports needed. For Level III treatments, contributions of 2 to 4 percent are found for Treatment Option 3, and more substantial relative increases of 20 to 30 percent for Treatment Option 4. Again, both show a trend to higher factors for decentralized treatment facilities.

G.4.2.1.3 Supercomponent 3: Fatalities Due to Occupational Accidents

The factors $\Phi_{3\kappa\lambda}$ for the contribution of the occupational fatalities are listed in Figure G.4-6. Here, due to the assumption of a modular treatment plant, the factors do not depend on location. For Level II treatments, the factors practically all the same, decreasing the index by about 20 percent. For Treatment Option 3, the decrease amounts to about 25 percent, for Treatment Option 4, to about 35 percent. This is the expression of the higher contribution of occupational fatalities for more complex treatments to the index.

G.4.2.1.4 Supercomponent 4: Injuries Due to Occupational Accidents

The factors $\Phi_{4\kappa\lambda}$ for the contribution of the occupational injuries are shown in Figure G.4-7. Again, due to the assumption of a modular treatment plant, the factors do not depend on location, but generally deviate less from 1 than the corresponding factors for the third supercomponent. For Level II treatments, the factors practically all decrease the index by about 16 percent. For Treatment Option 3, the decrease amounts to about 20 percent, and for Treatment Option 4 to nearly 30 percent. Again, this can be interpreted as the expression of the higher contribution of occupational injuries for more complex treatments to the index.

G.4.2.1.5 Supercomponent 5: Cancer Cases Due to Occupational Exposures

The factors $\Phi_{5\kappa\lambda}$ for the contribution of the occupational cancer fatalities are listed in Figure G.4-8. These factors all deviate only by a few percent from 1, contributing little to the index. This is largely due to the fact that the occupational cancer risk is almost exclusively due to routine exposures which are independent of treatment, contributing nothing to the consequence reduction.

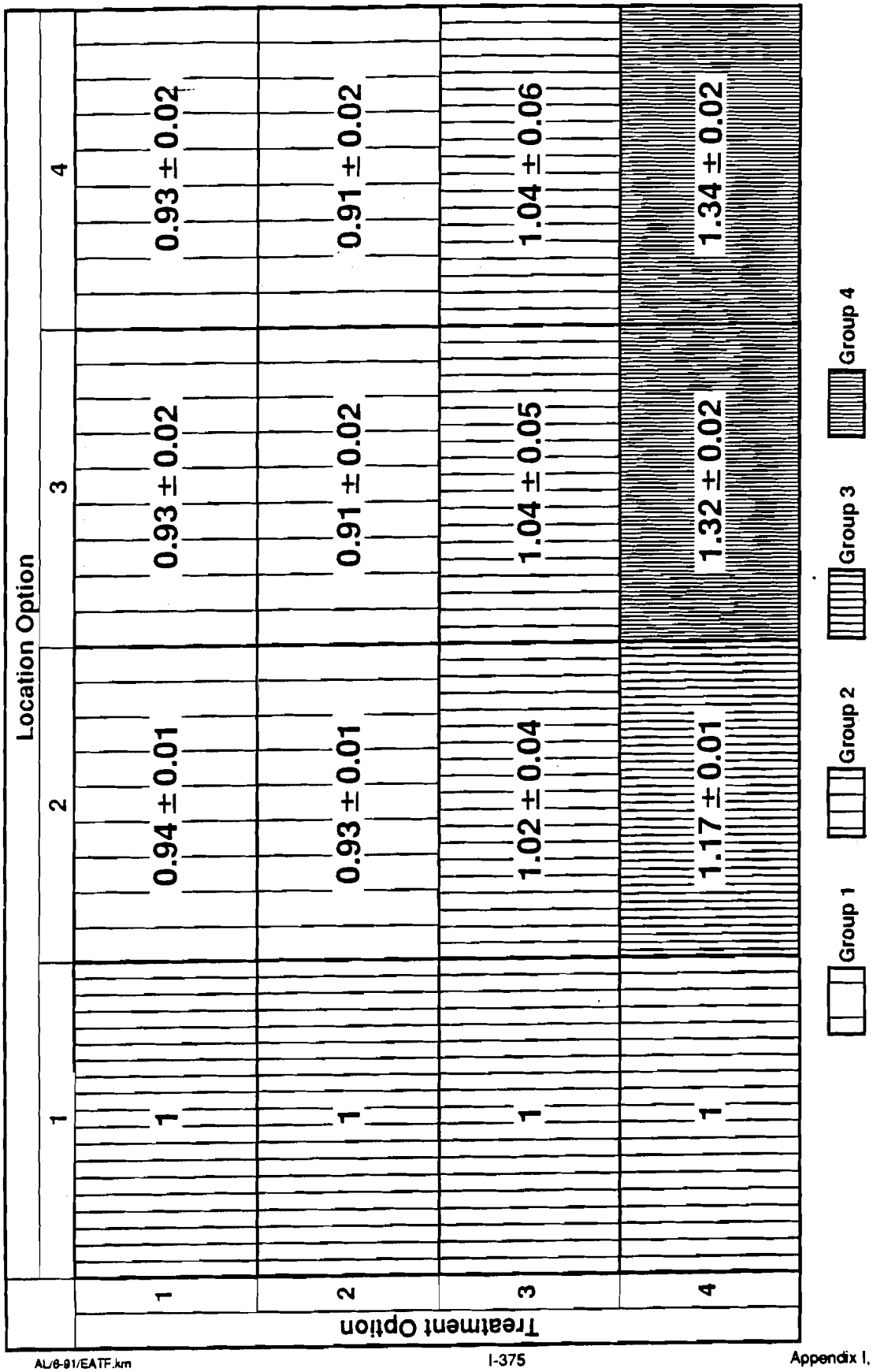

FIGURE G.4-5 CONTRIBUTING FACTORS $\Phi_{2K\lambda}$ FOR SUPERCOMPONENT 2: TRAFFIC ACCIDENT INJURIES

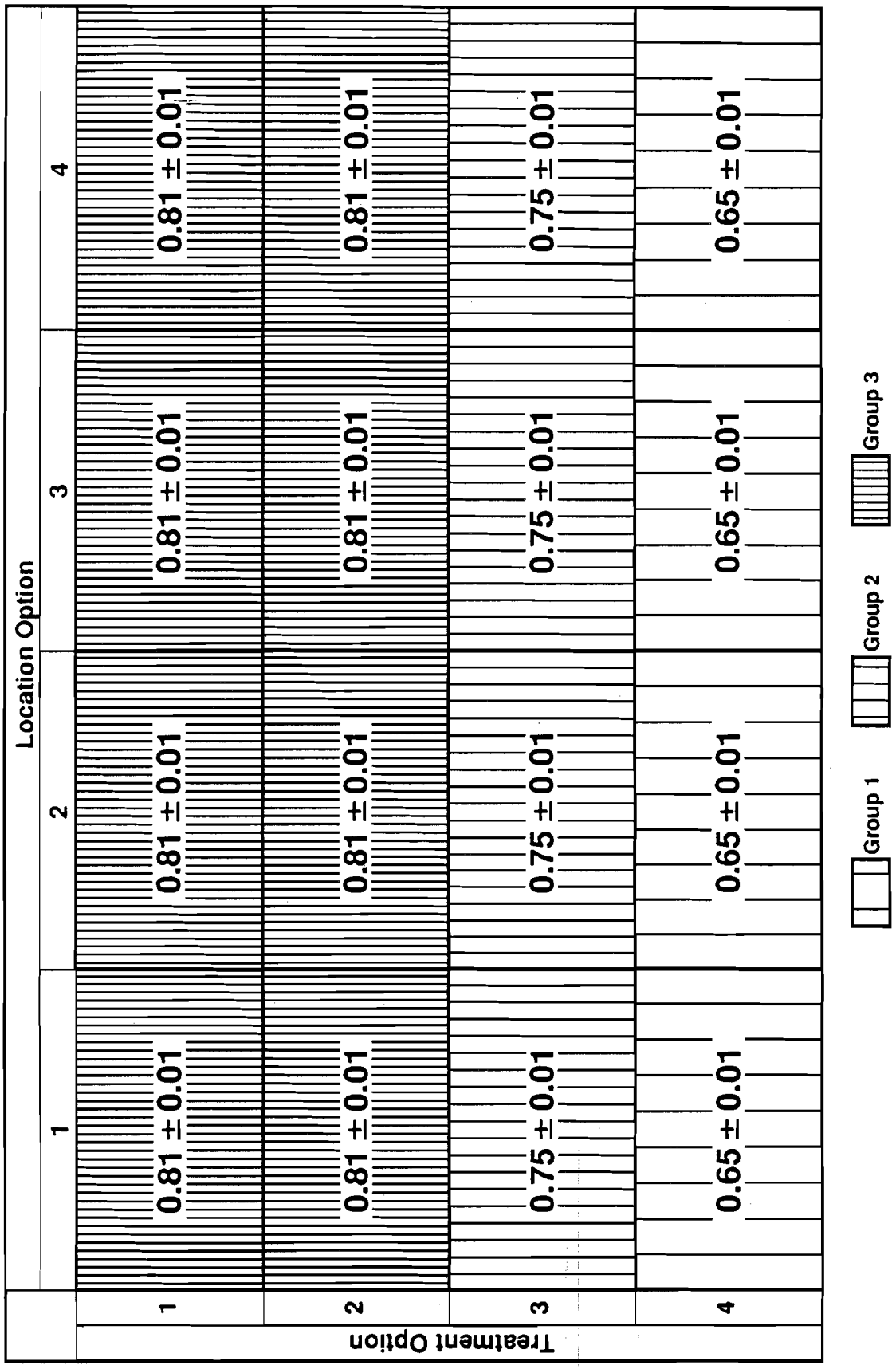

FIGURE G.4-6 CONTRIBUTING FACTORS $\Phi_{3k\lambda}$ FOR SUPERCOMPONENT 3: OCCUPATIONAL ACCIDENT FATALITIES

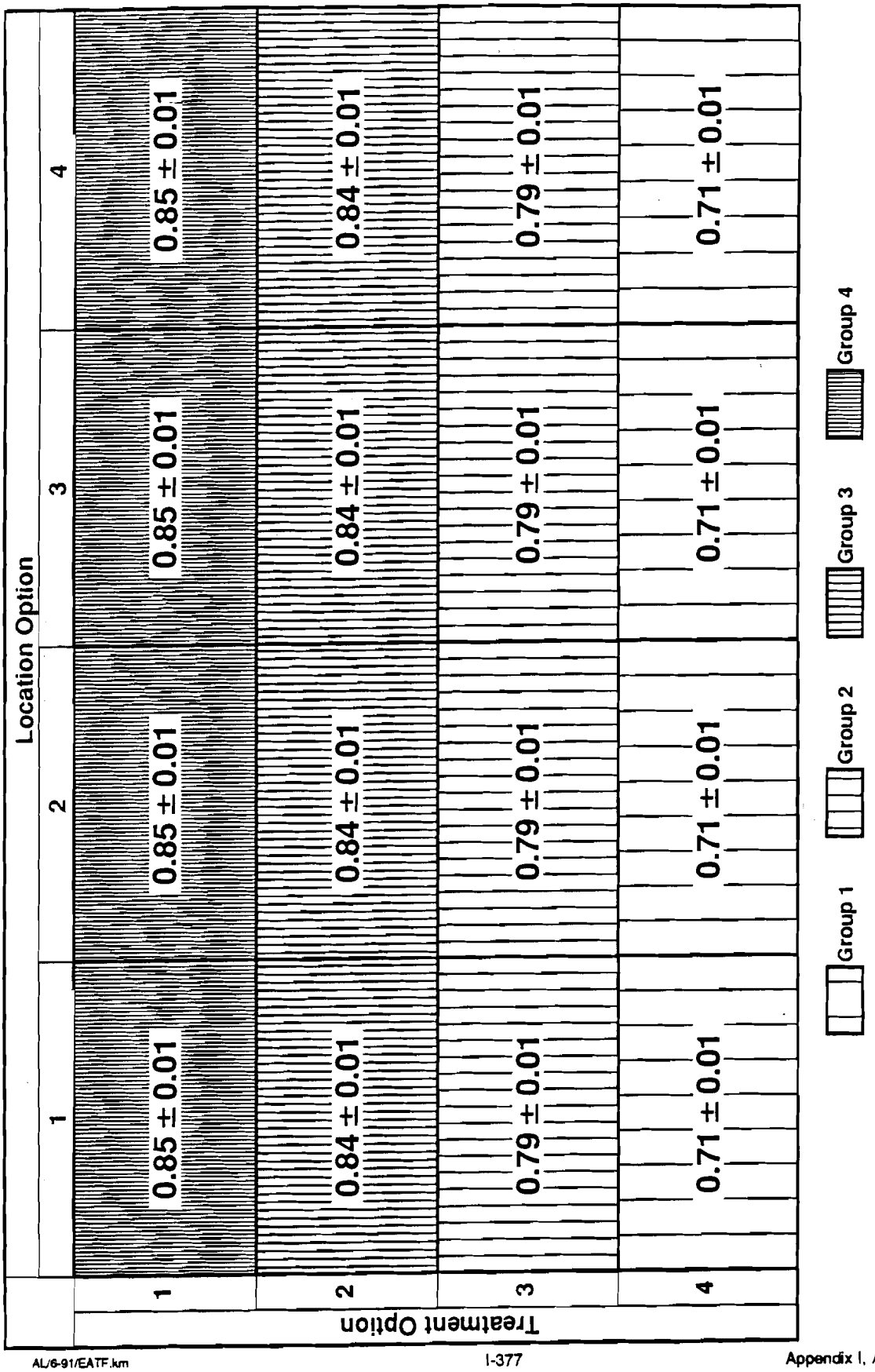

FIGURE G.4-7 CONTRIBUTING FACTORS $\Phi_{4K\lambda}$ FOR SUPERCOMPONENT 4: OCCUPATIONAL ACCIDENT INJURIES

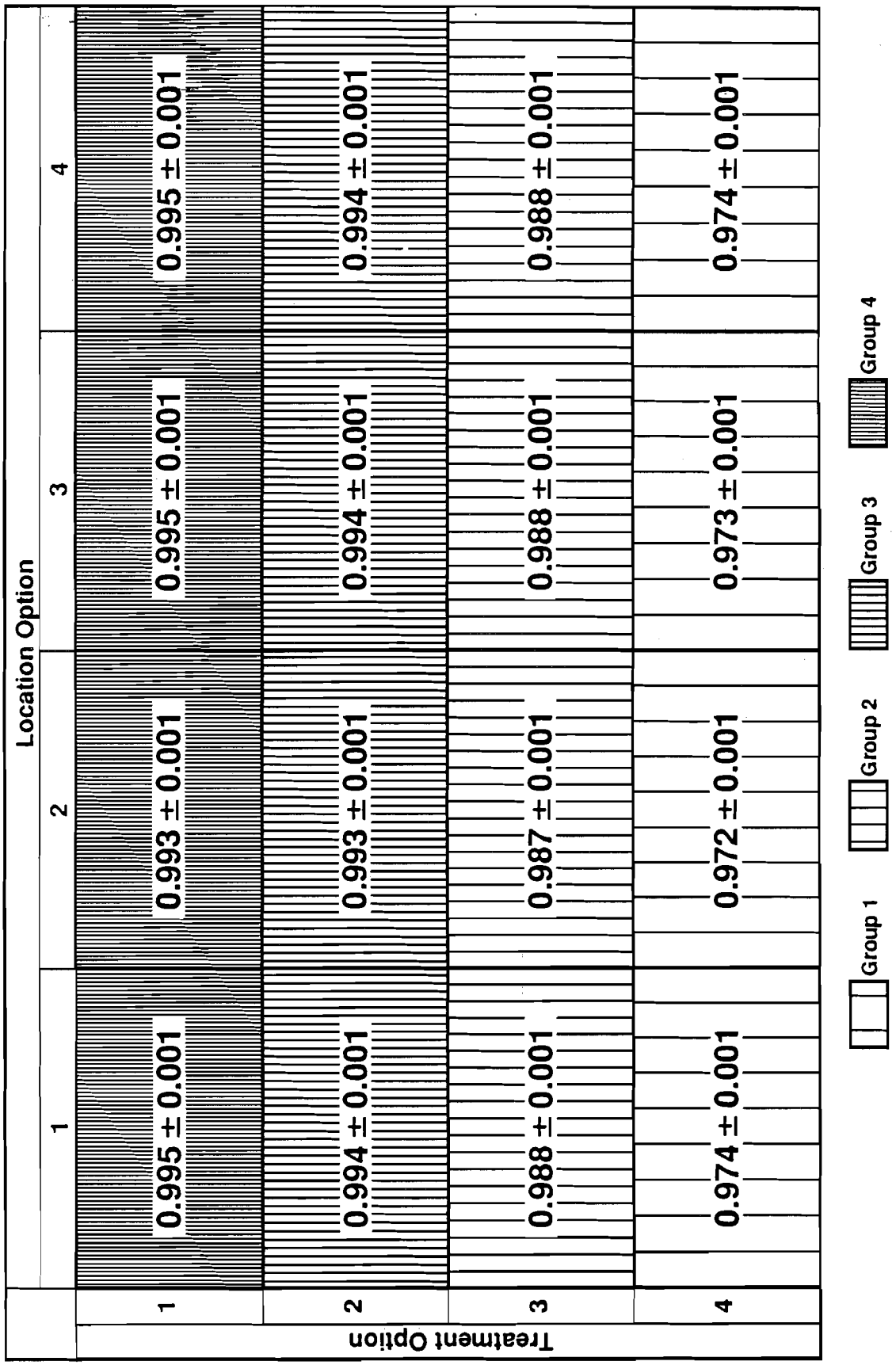

FIGURE G.4-8 CONTRIBUTING FACTORS $\Phi_{5K\lambda}$ FOR SUPERCOMPONENT 5: OCCUPATIONAL CANCERS

G.4.2.1.6 Supercomponent 6: Cancer Cases Due to Public Exposures

The factors $\Phi_{6\kappa\lambda}$ for the contribution of the public cancer fatalities are shown in Figure G.4-9. These factors display a minute dependence on treatment, and practically depend on location only. The deviations from 1 are substantial, ranging from increases of about 1 to 25 percent. These contributions to the index are largely due to the fact that the public cancer risk is almost exclusively due to accidental exposures which are, apart from the fact of treatment, almost independent of the method of treatment.

G.4.2.1.7 Supercomponent 7: Occupational Cancer Cases Due to Post-Closure Exposures

The factors $\Phi_{7\kappa\lambda}$ for the contribution of late occupational cancer fatalities due to human intrusion scenarios are listed in Figure G.4-10. These factors deviate only a fraction of a percent from 1, show as expected no location dependence and only a minute dependence on treatment. These tiny contributions to the index are largely due to the fact that the baseline cancer risk is exceedingly small and thus rank very low in societal valuation.

G.4.2.1.8 Supercomponent 8: Public Cancer Cases Due to Post-Closure Exposures

The factors $\Phi_{8\kappa\lambda}$ for the contribution of late occurring public cancer fatalities due to human intrusion scenarios are listed in Figure G.4-11. These factors also deviate only a few percent from 1, show as expected no location dependence and only a weak dependence on treatment. Again, the small size of the contributions to the index are largely due to the fact that the baseline cancer risk is very small and thus ranks low in societal valuation.

G.4.2.2 Contributions of All Components to Some Indices

Another way to analyze the contributions $\Phi_{j\kappa\lambda}$ to each consequence reduction index is to list all eight factors together as in Table G.4-2 for Level II treatments and G.4-3 for Level III treatments. The small variation in the indices $\Theta_{\kappa\lambda}$ is explained by the fact that most supercomponents do not change with treatment/location options. Only supercomponent 6 shows a moderate increase with location, offset by smaller changes in supercomponents 1 and 2. The overall values of the indices are determined by the small values of the factors for supercomponents 1 to 4. For Level III treatments, however, only supercomponents 3 and 4 yield constant, values below 1. Components 1, 2, and 6 are all increasing considerably with more decentralized treatment while components 5, 7, and 8 are constant, hovering near 1. The driving force in the increase are, therefore, components 1, 2, and 6 for traffic accidents and public cancers, which overcome the low values from the occupational effects and lead to actual consequence reductions.

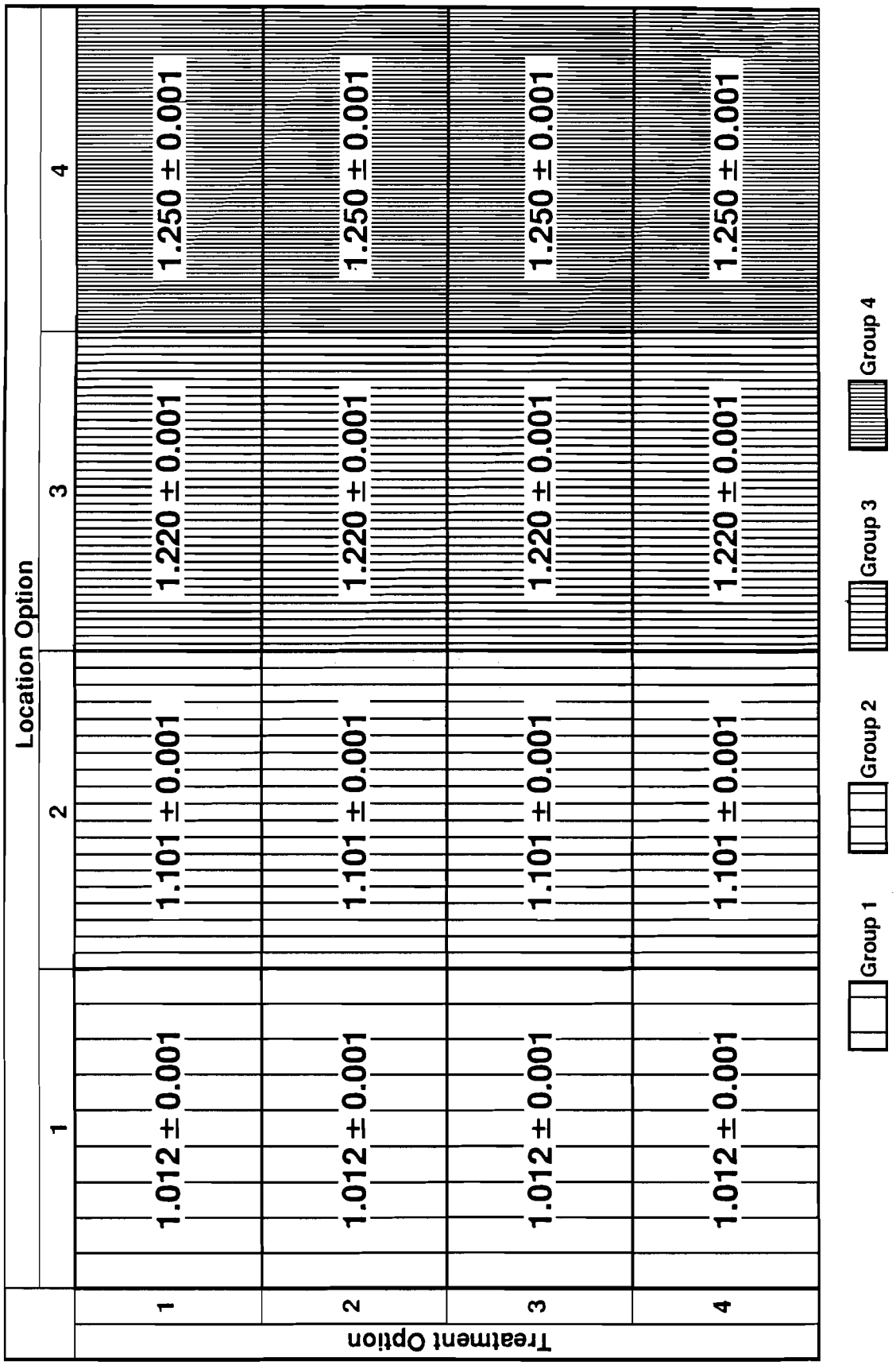

FIGURE G.4-9 CONTRIBUTING FACTORS $\Phi_{6k\lambda}$ FOR SUPERCOMPONENT 6: PUBLIC CANCERS

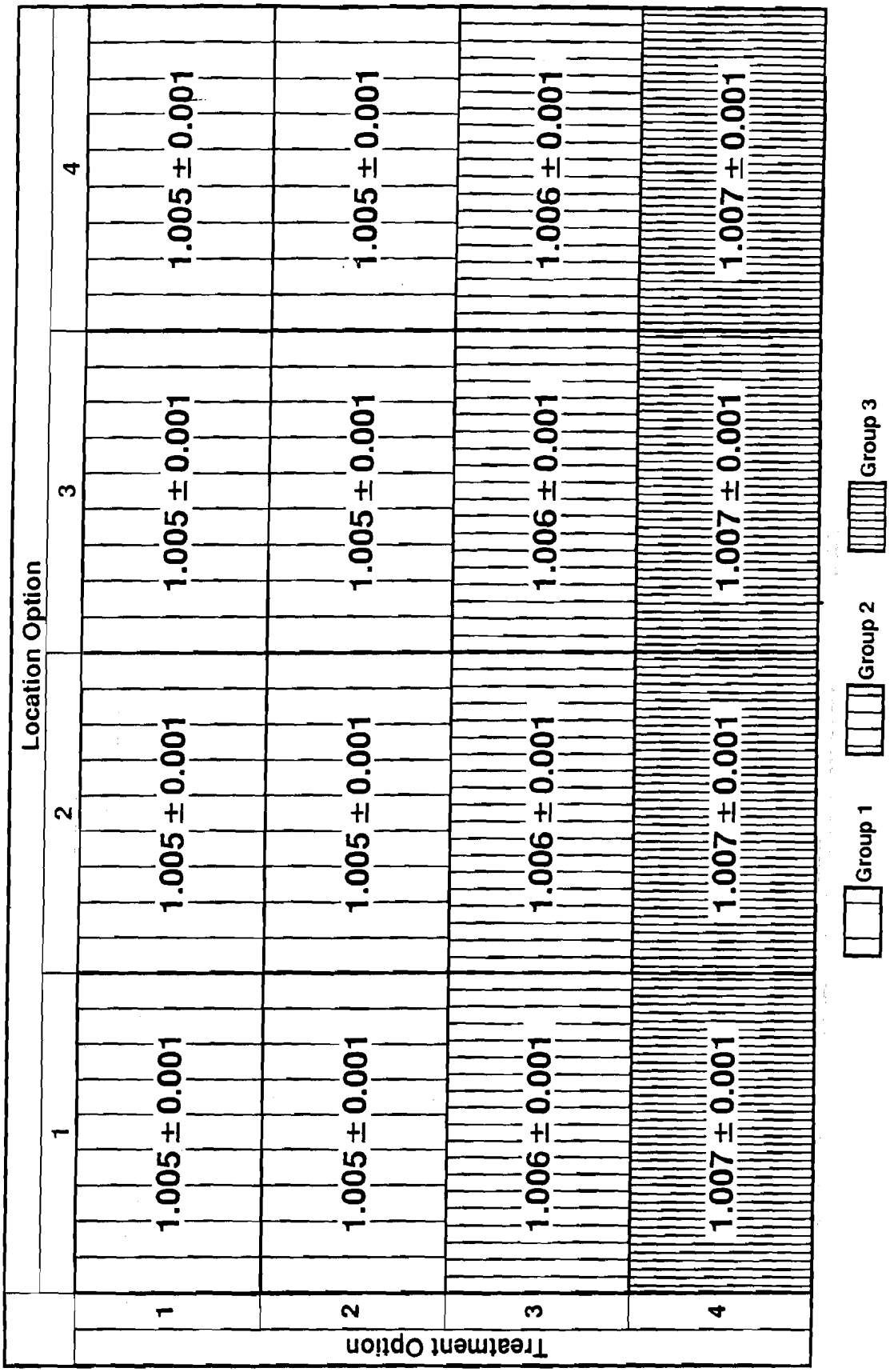

FIGURE G.4-10 CONTRIBUTING FACTORS $\Phi_{7\kappa\lambda}$ FOR SUPERCOMPONENT 7: LATE OCCUPATIONAL CANCERS

Treatment Option	Location Option 1	Location Option 2	Location Option 3	Location Option 4
1	1.031 ± 0.006	1.031 ± 0.006	1.031 ± 0.006	1.031 ± 0.006
2	1.032 ± 0.005	1.032 ± 0.005	1.032 ± 0.005	1.032 ± 0.005
3	1.036 ± 0.006	1.036 ± 0.006	1.036 ± 0.006	1.036 ± 0.006
4	1.052 ± 0.007	1.052 ± 0.007	1.052 ± 0.007	1.052 ± 0.007

Group 1 Group 2

FIGURE G.4-11 CONTRIBUTING FACTORS $\Phi_{8k\lambda}$ FOR SUPERCOMPONENT 8: LATE PUBLIC CANCERS

TABLE G.4-2

FACTORS $\Phi_{j\kappa\lambda}$ FOR THE CONTRIBUTION OF SUPERCOMPONENT j TO THE CONSEQUENCE REDUCTION INDEX $\Theta_{\kappa\lambda}$ OF LEVEL II TREATMENTS

SUPER COMPONENT	1 1	1 2	1 3	1 4	2 1	2 2	2 3	2 4
1	1	0.914	0.895	0.895	1	0.897	0.874	0.874
2	1	0.939	0.925	0.925	1	0.927	0.910	0.910
3	0.809	0.809	0.809	0.809	0.801	0.801	0.801	0.801
4	0.844	0.844	0.844	0.844	0.837	0.837	0.837	0.837
5	0.995	0.993	0.995	0.995	0.994	0.993	0.994	0.994
6	1.012	1.101	1.220	1.249	1.012	1.101	1.220	1.250
7	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005
8	1.031	1.031	1.031	1.031	1.032	1.032	1.032	1.032
$\Phi_{\kappa\lambda}$	0.712	0.663	0.710	0.728	0.700	0.632	0.671	0.688

TABLE G.4-3

FACTORS $\Phi_{j\kappa\lambda}$ FOR THE CONTRIBUTION OF SUPERCOMPONENT j TO THE CONSEQUENCE REDUCTION INDEX $\Theta_{\kappa\lambda}$ OF LEVEL III TREATMENTS

SUPER COMPONENT	3 1	3 2	3 3	3 4	4 1	4 2	4 3	4 4
1	1	1.032	1.053	1.057	1	1.258	1.479	1.513
2	1	1.022	1.037	1.040	1	1.174	1.315	1.337
3	0.746	0.746	0.746	0.746	0.654	0.654	0.654	0.654
4	0.791	0.791	0.791	0.791	0.8	0.8	0.8	0.8
5	0.988	0.987	0.988	0.988	0.975	0.972	0.973	0.974
6	1.012	1.101	1.220	1.250	1.013	1.101	1.220	1.250
7	1.006	1.006	1.006	1.006	1.007	1.007	1.007	1.007
8	1.036	1.036	1.036	1.036	1.051	1.051	1.051	1.051
$\Phi_{\kappa\lambda}$	0.617	0.707	0.811	0.837	0.486	0.779	1.138	1.213

G.4.3 Discussion of the Analysis

The analysis given here reveals the dominant contributions to the consequence reduction factors of the 16 treatment/location options discussed in this study. The main driving force derives from the valuations society puts on the different sources of health effects. It should not come as a surprise that radiological health effects are among the smaller contributions to the total consequences of the entire WIPP operation. After all, there is a type of health and safety professional, the health physicist, whose sole job it is to keep any radiological risks small. Indeed, the entire WIPP effort is dedicated to the purpose of disposing TRU wastes under these conditions. Thus it is only one supercomponent, the public cancer risk in component 6, that influences the consequence reduction indices in an appreciable way. Even that refers to a small, acceptable annual baseline risk (Table G.2-1).

Less weight is given by society to keep non-radiation occupational accidents low, even though occupational health and safety professionals do a creditable job in many industries. However, less time and effort is expended to lower these risks. This leads to the location-independent factors for components 3 and 4 which are lower than 1 and signal progressively increasing consequences with more complex treatment activities.

The dominant influence in the location-dependence of the consequence reduction indices are the traffic accidents in components 1 and 2. They reflect the almost cavalier attitude that our society takes toward the prevention of traffic accidents, with little time and effort expended to curb the number of fatalities on our roads. It, therefore, comes as no surprise that the largest consequences in fatalities and injuries due to the operation of the WIPP are also deemed acceptable (Table G.2-1).

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APPENDIX J

DEVELOPMENT OF COST ESTIMATES FOR WASTE TREATMENT FACILITIES AND FOR TRANSPORTATION

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1.0 METHODOLOGY FOR COST ESTIMATION OF WASTE TREATMENT FACILITIES

1.1 INTRODUCTION

The intent of Appendix J is to provide supporting calculations for cost estimates associated with the waste treatment which is discussed in Section 6.3.4 of Volume I of this report. Specifically, Appendix J presents cost estimation calculations for:

- Capital costs for waste treatment facilities
- Annual operating costs for waste treatment facilities
- Life cycle costs
- Transportation costs (Section 2.0).

1.2 GENERAL ASSUMPTIONS FOR COST ESTIMATION OF FACILITIES

The EATF cost estimation methodology relies on published reports for treatment operation costs. As noted in Section 6.3.4 of Volume I, the scope of EATF work does not permit "bottom-up" cost estimation. If treatment becomes necessary, detailed costs may be estimated for required facilities. Assumptions associated with EATF cost estimates include:

- Treatment operation costs may be scaled and combined with a modified version of the "point six rule" (Baasel, 1990).

- Treatment operation costs may be factored to a common basis year of 1990.

- Life cycle operations costs are calculated based on a cost escalation factor of 3.4 percent (Smedley, 1991) and a discount factor of 10 percent (Bozik, 1991), both on an annual basis.

- Life cycle costs are based on an assumption of waste treatment operations beginning in the year 2000.

- Annual operations costs (labor and materials) may be estimated as a percentage of capital cost (Ross et al., 1982; McKee et al., 1986).

- Batch treatment facilities of a certain minimum size are necessary at sites with small quantities of waste.

- Continuous operation is defined as 24 hours per day, 240 days per year. The remainder of time is used for routine maintenance and periodic down-time.

- Batch operation is defined as 8 hours per day, 240 days per year minimum and will vary up to the definition of continuous operation.

1.3 COST ESTIMATION FOR WASTE TREATMENT FACILITY

1.3.1 Capital Cost Estimation Procedure

Capital cost estimation for waste treatment consists of the following steps:

- Define treatment need by generic waste form (solid organics, solid inorganics, sludges) (Section 1.3.1.1).
- Define treatment operations necessary to meet treatment need. In other words, define the sequence of operations necessary to generate a specified waste form (Section 1.3.1.2).
- Define facility capacity; this is a function of the number of facilities and work-off period (Section 1.3.1.3).
- Calculate capital cost (Section 1.3.1.4).

1.3.1.1 Treatment Need

The various treatment alternatives considered by the EATF are provided in Table 1-2 in Volume I of this report. The combination alternatives defined in Table 1-2 form the basis for determination of the effectiveness and feasibility of engineered alternatives.

1.3.1.2 Treatment Operations

The intent of this section is to define the treatment operations necessary for the combination alternatives of Table 1-2. Prior to defining the sequence of treatment operations required for each waste type and combination alternative, input data specified in Table J-1 presents all the treatment operations used in the fourteen combination alternatives, cost (in a reference year), and cost in 1990 dollars. Cost in 1990 dollars is computed using consumer price indices as follows:

$$Cost_{1990} = \frac{CPI_{1990}}{CPI_n} Cost_n \qquad \text{(J.1-1)}$$

where:

CPI_{1990} = Consumer Price Index for 1990
CPI_n = Consumer Price Index for a reference year, and
$Cost_n$ = Cost of treatment operation in reference year.

TABLE J-1

TREATMENT OPERATION CAPITAL COST ESTIMATES

Treatment Operation	Capital[1] Cost (millions)	Basis Capacity	Basis Year	Reference for Basis	Basis[2] CPI	1990[3] (millions)
Basic Facility	$46.0	18,000 drums/yr	1989	Kaiser, 1989	345.2	$47.6
Cementation	$14.7	367 lb/hr	1981	PNL, 1982[4]	297.0	$18.0
Incineration	$17.6	100 lb/hr	1984	PNL, 1986[5]	322.7	$20.0
Metal Decon.	$19.0	81 lb/hr	1984	PNL, 1986[5]	322.7	$21.6
Metal Melting	$23.0	220 lb/hr	1984	PNL, 1986[5]	322.7	$26.0
Shredding	$4.0	3750 lb/hr	1984	PNL, 1986[5]	322.7	$4.5
Supercompaction	$6.0	3145 lb/hr	1990	Barthel, 1990	366.9	$6.0
Vitrification	$16.1	100 lb/hr	1981	PNL, 1982[4]	297.0	$20.0

(1) Capital costs estimated from references on the basis of applicable equipment.

(2) Cost Price Index (CPI) obtained from Baasel (1990) for Chemical Engineering Plant Cost Indices.

(3) 1990 CPI assumed to be 366.9

(4) Same reference as Ross et al. (1982)

(5) Same reference as McKee et al. (1986)

These base costs are used to estimate capital cost of facilities as described in Section 1.3.1.4.

Table J-2 illustrates how each of the fourteen combination alternatives can actually consist of more than one treatment operation for each generic waste form. This list of treatment operations must be scaled and then cost is estimated based on number of facilities and work-off period. The sum of costs for treatment operations and support facilities (described in Section 6.3, Volume I) represents the rough cost presented in Tables 6-8a, b, and c.

1.3.1.3 Waste Treatment Facility Capacity

Table J-3 presents total waste (sum of retrievably stored and newly generated waste) by waste type in retrievable storage and/or newly generated at each DOE site. The information in Table J-3 is adapted from DOE (1988b). The values in this table indicate the percent of all waste destined for the WIPP.

Table J-4 builds on the information in Table J-3 by first identifying the EATF choices for waste treatment locations for one through seven facilities. It should be noted that other choices can easily be made. The choices made by the EATF place emphasis on selecting sites based on the amount of waste in retrievable storage in addition to the newly generated waste rate at the sites. The WIPP is an EATF choice for waste treatment facility for logistical reasons: current transportation planning can still be used and no further transportation will be required for waste potentially treated at the WIPP.

The second choice presented in Table J-4 involves transportation. The decision of where waste will be shipped for treatment is based on selecting treatment locations in close proximity to waste storage/generators in order to minimize transportation requirements. It should be noted that system capacity is constant. Thus, whether one or multiple facilities are used, processing capacity is always 13,640 cubic meters of waste per year, assuming the work-off period is ten years for treating all waste. The capacity may be adjusted according to the work-off period.

1.3.1.4 Capital Cost Calculation

The information in Tables J-1 through J-4 provide all input parameters necessary for estimation of capital costs. These input parameters are:

- Treatment operation costs and capacity scaled to 1990 dollars
- Capacity required for a given number of facilities
- Sequence of treatment operations required for each waste form for all combination alternatives.

TABLE J-2

TREATMENT OPERATIONS REQUIRED TO PRODUCE FINAL WASTE FORM

Combination[1] Alternative	Unprocessed Waste Form	Sequence of Treatment Operations	Final Waste Form
	Solid Organics	Shred→Cement	Cement Monolith
1	Solid Inorganics	Shred→Cement	Cement Monolith
	Sludges	NA	Unprocessed
	Solid Organics	Shred→Cement	Cement Monolith
2,3	Solid Inorganics	Shred→Cement	Cement Monolith
	Sludges	Cement	Cement Monolith
	Solid Organics	Shred→Incinerate→Cement	Cement Monolith
4,5	Solid Inorganics	Shred→Incinerate→Cement	Cement Monolith
	Sludges	Cement	Cement Monolith
	Solid Organics	Shred→Incinerate→Vitrify	Glass Monolith
6,7	Solid Inorganics	Shred→Incinerate→Melt[2]	Metal Ingot
	Sludges	Vitrify	Glass Monolith
	Solid Organics	Shred→Incinerate→Vitrify	Glass Monolith
8,9,13	Solid Inorganics	Shred→Incinerate→Melt→Vitrify[3]	Glass Monolith
	Sludges	Vitrify	Glass Monolith
	Solid Organics	NA	Unprocessed
10	Solid Inorganics	Decontaminate→Cement	Cement Monolith
	Sludges	NA	Unprocessed
	Solid Organics	Supercompacted	Compacted
11,12,14	Solid Inorganics	Supercompacted	Compacted
	Sludges	NA	Unprocessed

(1) See Table 1-2 in Volume I for complete description of Alternatives.

(2) Metals are melted into TRU waste ingots.

(3) Metals are melted with glass/glass frit; radionuclides partition into slag, and metals are eliminated from the WIPP inventory.

TABLE J-3

TOTAL CH-TRU WASTE STORED/GENERATED[1]

DOE-Site	Solid Organics (m^3)	Solid Inorganics (m^3)	Sludges (m^3)	Site Total (m^3)	Total Inventory (%)
ANL-E	31	19	44	94	0.07
INEL	14859	12990	9672	37521	27.51
LANL	4407	6724	4403	15534	11.39
LLNL	2367	433	87	2887	2.12
Mound	60	120	1017	1197	0.88
NTS	353	254	12	619	0.45
ORNL	927	603	15	1545	1.13
Hanford	8736	11591	1217	21544	15.79
RFP	17017	9828	9550	36395	26.68
SRS	14297	4098	667	19062	13.98
TOTALS	63054	46660	26684	136398	100.00

[1] Values adapted from DOE, 1988b

TABLE J-4

TEN-YEAR WORK-OFF CAPACITIES FOR EATF WASTE TREATMENT FACILITIES

			Required Capacity (10-Year Work-off)				
Number of Facilities	Assumed Treatment Location	Assumed Feed Locations	Solid Organics (lbs/hr)	Solid Inorganics (lbs/hr)	Sludges (lbs/hr)	Total (lbs/hr)	Total (drums/yr)
1	WIPP	All Sites	559	1212	831	2601	60892
2	INEL	Hanford, INEL, LANL, LLNL, NTS, RFP	469	1017	697	2183	51088
	SRS	ANL-E, Mound, ORNL, SRS	90	195	134	419	9804
			559	1212	831	2601	60892
3	INEL	Hanford, INEL	242	525	360	1126	26366
	RFP	RFP	149	324	222	695	16258
	WIPP	All other Sites	168	363	249	780	18268
			559	1212	831	2601	60892
4	INEL	INEL, LANL, LLNL, NTS	232	503	345	1080	25270
	RFP	RFP	149	324	222	695	16258
	SRS	ANL-E, Mound, ORNL, SRS	89	194	133	416	9743
	Hanford	Hanford	88	191	131	410	9621
			559	1212	831	2601	60892
5	INEL	INEL	154	333	229	715	16745
	RFP	RFP	149	324	222	695	16258
	SRS	ANL-E, Mound, ORNL, SRS	89	194	133	416	9743
	Hanford	Hanford	88	191	131	411	9621
	WIPP	LANL, LLNL, NTS	78	170	116	364	8525
			559	1212	831	2601	60892

TABLE J-4, Continued

TEN-YEAR WORK-OFF CAPACITIES FOR EATF WASTE TREATMENT FACILITIES

			Required Capacity (10-Year Work-off)				
Number of Facilities	Assumed Treatment Location	Assumed Feed Locations	Solid Organics (lbs/hr)	Solid Inorganics (lbs/hr)	Sludges (lbs/hr)	Total (lbs/hr)	Total (drums/yr)
6	INEL	INEL	154	133	229	715	16745
	RFP	RFP	149	324	222	695	16258
	SRS	ORNL, SRS	84	183	125	393	9195
	Hanford	Hanford	88	191	131	411	9621
	LANL	LANL	64	138	95	297	6942
	WIPP	ANL-E	20	42	29	91	2131
		LLNL, Mound, NTS					
			559	1212	831	2601	60892
7	INEL	INEL	154	333	229	715	16745
	RFP	RFP	149	324	222	695	16258
	SRS	SRS	78	170	116	364	8525
	Hanford	Hanford	88	191	131	411	9621
	LANL	LANL	64	138	95	297	6942
	ORNL	ORNL	6	13	9	29	670
	WIPP	ANL-E	20	42	29	91	2131
		LLNL, Mound, NTS					
			559	1212	831	2601	60892

The following general expression is used to determine cost, first on a facility basis, and then on a system basis (sum of all facility costs):

$$Capital\ Cost = \sum_{k=1}^{r} \sum_{j=1}^{p} \sum_{i=1}^{n} \left[C_i \left(\frac{Q_{i,j,k} + \mu}{q_i} \right)^m \right] \qquad (J.1\text{-}2)$$

where:

C_i	=	Cost in 1990 dollars of input treatment operation, Table J-1,
q_i	=	Capacity of reference input treatment operation, Table J-1,
$Q_{i,j,k}$	=	Capacity as a function of total waste, for each treatment operation i, given number of facilities j, and generic waste form k,
μ	=	Quantity of secondary waste generated, e.g., incinerator ash which must be vitrified,
m	=	0.88. [It should be noted that Equation J.1-2 in its most basic form is referred to as the point six rule, with point six indicating m = 0.6. The EATF chose a more conservative approach by using m = 0.88 (Baasel, 1990), which predicts higher costs than m = 0.6.]

Equation J.1-2 may be applied to any choice of combination alternative, work-off period, and number of facilities. This expression is easily amenable to application in spreadsheet form.

Table J-5 presents a sample calculation using:

- 1990 treatment operation cost, C_i, and base capacity, q_i, from Table J-1
- Necessary treatment operations (for each unprocessed waste form) from Table J-2
- Waste treatment capacity by waste form for a ten-year work-off period, developed from Table J-3 and presented in Table J-4.

While the applications of costing equations are presented for a particular case of ten-year work-off and Combination Alternatives 2 and 3, minor modifications allow application to all different cases. The data presented in Tables 6-8a, b, and c in Volume I of this report were similarly generated.

TABLE J-5

CAPITAL COST SAMPLE CALCULATIONS: TEN-YEAR WORK-OFF OPTION ALTERNATIVES 2, 3

NUMBER OF FACILITIES	% OF WASTE PROCESSED	TREATMENT: SHRED APPLICABLE WASTE FORMS:		TREATMENT: CEMENTATION APPLICABLE WASTE FORMS:			BASIC FACILITY	FACILITY COST (MILLIONS)	TOTAL (MILLIONS)
		SOLID ORGANICS	SOLID INORGANICS	SOLID ORGANICS	SOLID INORGANICS	SLUDGES			
1(j=1)	100%	$4.5 x $\left(\frac{559 + 1212}{3750}\right)^{0.88}$	+ $18 x $\left(\frac{559 + 1212 + 831}{367}\right)^{0.88}$				+ $47.6 x $\left(\frac{60892}{18000}\right)^{0.88}$	= 241	241
4(j=4)									
1	41.5%	$4.5 x $\left(\frac{232 + 503}{3750}\right)^{0.88}$	+ $18 x $\left(\frac{232 + 503 + 345}{367}\right)^{0.88}$				+ $47.6 x $\left(\frac{25270}{18000}\right)^{0.88}$	= 111	
2	26.7%	$4.5 x $\left(\frac{149 + 324}{3750}\right)^{0.88}$	+ $18 x $\left(\frac{149 + 324 + 222}{367}\right)^{0.88}$				+ $47.6 x $\left(\frac{16258}{18000}\right)^{0.88}$	= 75	
3	16.0%	$4.5 x $\left(\frac{89 + 194}{3750}\right)^{0.88}$	+ $18 x $\left(\frac{89 + 194 + 133}{367}\right)^{0.88}$				+ $47.6 x $\left(\frac{9743}{18000}\right)^{0.88}$	= 48	
4	15.8%	$4.5 x $\left(\frac{88 + 191}{3750}\right)^{0.88}$	+ $18 x $\left(\frac{88 + 191 + 131}{367}\right)^{0.88}$				+ $47.6 x $\left(\frac{9621}{18000}\right)^{0.88}$	= 48	282

NOTE: Equation J.1-2 must be used with caution for small capacity facilities. There is potential for predicting unreasonably low costs. The EATF defined a minimum-size facility for all combination alternatives. This minimum cost is compared to all calculated values. If minimum cost is greater than a facility cost predicted by Equation J.1-2, the minimum facility cost is substituted and becomes part of total capital cost for the particular option.

1.3.2 Operating Costs

1.3.2.1 Costs for Continuous Operation Facilities

Operating costs are estimated based on literature (Ross et al., 1982; McKee et al., 1986) which report operating costs as a function of capital costs. On this basis, the EATF estimates operating costs as 12 percent of capital costs, which represents continuous operation of 24 hours per day and 240 days per year.

1.3.2.2 Batch Facility Operating Costs

As noted in Section 1.3.1.4, care must be taken in estimating cost for small facilities. The same can be said for operating costs of small facilities. In practice, small facilities are operated in batch mode instead of continuous operation. Operating costs for batch facilities are assumed to be a minimum of four percent (1/3 of continuous operation) of capital, which represents a one-shift (eight hours per day) operation for 240 days per year. A sliding scale was developed to account for facilities which may operate between a single shift and 24 hours per day. It should be noted that for the treatment options considered, few facilities required batch operations.

1.3.3 Life Cycle Costs

1.3.3.1 Life Cycle Operating Costs

Operating costs may be computed on a life cycle basis. Application of appropriate factors allows computation of costs on a common basis of 1990 dollars. A number of assumptions are necessary for calculation of life cycle operating costs:

- EATF assumes waste processing begins in 2000 and continues for the duration of the work-off period.
- 1990 costs may be escalated at an average rate of 3.4 percent. This figure is adapted from DOE cost estimation literature (Smedley, 1991).
- Future costs may be discounted to a common basis of 1990 dollars using a discount factor of ten percent (Bozik, 1991).

1.3.3.2 Life Cycle Operating Cost Estimation

Life cycle operation cost estimation is a four-step process, as outlined below:

- 1990 annual operating cost is escalated to year 2000 cost
- A future value of an annuity (for operating cost) is calculated based on the length of the work-off period
- A gradient term is computed to account for the fact that costs rise by 3.4 percent each year. The gradient factor is approximated by annual operating costs in the last year of the work-off period less annual operating cost in the first year (year 2000). This amount is divided by the work-off period n, as illustrated in Equation J.1-3.
- The sum of the annuity and gradient terms are then discounted back to 1990 dollars.

The expression used by the EATF to estimate life cycle operating cost is presented below:

$$LCOC = AOC_{1990} \times (1+i)^{10} \times \left[\frac{(1+i)^n - 1}{i}\right] \times \left[\frac{1}{(1+k)^{(n+10)}}\right] + \frac{G}{i}\left[\frac{(1+i)^n - 1}{i} - n\right] \times \left[\frac{1}{(1+k)^{(n+10)}}\right] \qquad \text{(J.1-3)}$$

where

LCOC	=Life cycle operating cost
AOC_{1990}	=Annual operating cost in 1990 dollars (see Tables 6-8a, b, and c of Volume I)
i	=Escalation factor, 3.4 percent
n	=Work-off period: 5, 10, or 20 years
k	=Discount factor, 10 percent
G	=An approximation of a gradient computed as follows:

$$\frac{(AOC_n - AOC_{2000})}{n}$$

and

$AOC_n = AOC_{1990}\,(1 + i)^{(n+10)}$ operating cost at the end of work-off

$AOC_{2000} = AOC_{1990}\,(1 + i)^{10}$ operating cost in the year 2000

Table J-6 presents life cycle operation cost estimates for combination alternatives 2 and 3, based on a ten-year work-off period (n = 10), and for one through seven facilities.

1.3.3.3 Total Project Cost

The final calculation is a summation of capital costs described in Section 1.3.1.4 and life cycle costs developed in Section 1.3.3.2. This calculation is possible because capital cost and life cycle operating costs are both in 1990 dollars.

TABLE J-6

LIFECYCLE OPERATING COST ESTIMATES[1]

NUMBER OF FACILITIES OPTION	ANNUAL OPERATING COST, (IN MILLIONS)[2]	LIFE CYCLE OPERATING COST (IN MILLIONS)
1	29	82
2	31	87
3	33	93
4	34	96
5	35	99
6	35	100
7	36	102

[1]Computed by applying Equation J.1-3, ten-year work-off period.

[2]Annual operating costs from Table 6-6b for combination alternatives 2 and 3.

[3]As an example, substituting into Equation J.1-3:

$$LCOC = (29) \times (1 + 0.034)^{10} \times \left[\frac{(1 + 0.034)^{10} - 1}{0.034}\right] \times \left[\frac{1}{(1 + 0.10)^{(10+10)}}\right] +$$

$$\left[\frac{29\,(1 + 0.034)^{(10+10)} - 29\,(1 + 0.034)^{10}}{10}\right] \times \left[\frac{1}{0.034}\right] \times$$

$$\left[\frac{(1 + 0.034)^{10} - 1}{0.034} - 10\right] \times \left[\frac{1}{(1 + 0.10^{(10+10)}}\right] = \$82$$

Note: Due to round-off of AOC for example purposes, slightly higher values for LCOC will be produced by hand calculation.

2.0 METHODOLOGY FOR ESTIMATION OF TRANSPORTATION COSTS

2.1 INTRODUCTION

The estimation of costs for transporting waste to the WIPP is based on the following general assumptions:

- TRUPACT-II trailers that originate from a particular shipping site will return to the same shipping site after unloading waste at the processing site.
- TRUPACT-II trailers used for transporting waste from the processing site to the WIPP will return empty to the processing site after unloading treated waste at the WIPP.

In case of options where WIPP itself is selected as the processing site, it is assumed that the TRUPACT-II trailers load waste at the shipping site, transport the waste to the WIPP and unload it there for subsequent treatment, and then return empty to the shipping sites.

Based on the above assumptions, the cost for transportation of waste from the sites to the WIPP consists of the following components:

- Cost of loading TRUPACT-II trailers with untreated waste at the shipping site
- Cost of trucking waste from the shipping site to the waste treatment facility at the processing site, and the cost of trucking empty TRUPACT-II trailers back to the shipping site
- Cost of unloading untreated waste from the TRUPACT-II trailers at the processing site
- Cost of loading TRUPACT-II trailers with treated waste after processing at the waste treatment facility
- Cost of trucking treated waste from the processing site to the WIPP site and the cost of trucking empty TRUPACT-II trailers back to the processing site
- Cost of unloading treated waste from the TRUPACT-II trailers at the WIPP site.

These costs are discussed in Sections 2.2 to 2.7, and a sample calculation is presented later in Section 2.8.

2.2 COST OF LOADING AT THE SHIPPING SITE

The cost of loading untreated waste at the shipping sites has been based on information about operations cost obtained from Westinghouse Electric Corporation (Gregory, 1991). The information provided to the EATF includes estimates of labor hours required for performing the various operations associated with loading one trailer with three TRUPACT-II containers of waste. According to these estimates, it will take 12.8 labor hours per trip for loading waste into a trailer with three TRUPACT-II containers. Thus, the total cost for loading waste at the shipping sites is estimated by the following equation:

Cost of loading = (Labor hours per trip) X (# of trips required) X (Labor cost per hour)

= (12.8) X (# of trips required) X (Labor cost per hour)

The number of trips required for transporting the amount of waste from each site, has been based on the estimate that approximately 10 m^3 of untreated waste is equivalent to the payload for one trailer (Batchelder, 1990). Based on this assumption, the total volume of waste at each site (from Table 6-1 in Volume I) has been divided by 10 to estimate the number of trips required for each site. Finally, a rate of $50 an hour has been assumed for labor costs. Thus, the equation for estimating the loading costs at the shipping sites is then given by:

Cost of loading = (12.8) X (Volume of waste in m^3/10) X (50 dollars)

Once the loading costs for each shipping site are calculated using the above equation, these costs are then added together to arrive at a total loading cost for each option.

2.3 COST OF TRUCKING BETWEEN SHIPPING SITES AND PROCESSING SITES

As mentioned earlier, each TRUPACT-II trailer that transports untreated waste from a particular site to a given shipping site is assumed to return to the same shipping site with empty TRUPACT-II containers. The trucking costs are based on the estimation that the cost for transporting one TRUPACT-II trailer (i.e., three TRUPACT-II containers) through a distance of one mile is approximately $1.70 (Gregory, 1991). This quantity is also referred to as a "TRUPACT-II mile." Thus, the trucking costs are given by the following equation:

Cost of trucking between shipping and processing sites

= (Number of TRUPACT-II miles) X (Cost per TRUPACT-II mile)

= (# of trips) X (2 X distance between shipping and processing sites) X (1.70)

The distance between the shipping and the processing sites is multiplied by two to account for the round trip of a trailer between the two sites. The number of trips required can be estimated using the same procedure that has been outlined earlier in Section 2.2. The total trucking costs are estimated by adding together the cost for each combination of shipping and processing sites considered for a given number of facilities.

2.4 COST OF UNLOADING AT THE PROCESSING SITE

The cost of unloading waste at the processing site has been based on similar estimates of unloading waste at the WIPP site that have been obtained from Gregory (1991). According to these estimates, it takes approximately 11.5 labor hours to unload waste from one TRUPACT-II trailer and to replace the empty TRUPACT-II containers on the trailer after the unloading process has been completed. Therefore, the cost of unloading untreated waste at the processing site is given by the following equation:

Cost of unloading untreated waste at the processing site

= (# of trips) X (Labor hours per trip) X (Cost per labor hour)

= (# of trips) X (11.5 X 50 dollars)

The number of trips can be estimated using the methodology outlined earlier in Section 2.2. The total unloading costs at the processing site are then obtained by adding the costs of unloading waste from each shipping site.

2.5 COST OF LOADING TREATED WASTE AT THE PROCESSING SITE

The cost of loading treated waste can be estimated in a manner similar to the method outlined earlier in Section 2.2. The only exception in this case is that some of the untreated waste will undergo volume reduction due to the waste processing. Consequently, the volume of waste will decrease after treatment, and so will the number of trips required to transport the treated waste to the WIPP. Thus, the number of trips required need to be recalculated using the estimated amount of waste after the volume reduction.

The number of trips required from the processing site to the WIPP site has been estimated using the following methodology:

- Estimation of the volume of waste after treatment, by dividing the untreated waste volumes by the volume reduction factors that were discussed in Section 3.0 of Volume I of this document. This has been done for all three waste forms (i.e., sludges, solid organics, and solid inorganics).

- Estimation of the weight of the processed waste by multiplying the volume of processed waste by the density of processed waste for each option.

- Estimation of the number of trips required based on the information that the maximum allowable waste payload per TRUPACT-II trailer is 13,595 lb. (Gregory, 1991).

Once the required number of trips has been estimated, the loading costs are estimated as follows:

Cost of loading treated waste at the processing site

= (# of trips) X (Labor hours per trip) X (Cost per labor hour)

= (# of trips) X (12.8) X (50 dollars)

The total cost for each option can then be obtained as the sum total of the loading costs for processed waste from all shipping sites.

2.6 COST OF TRUCKING BETWEEN PROCESSING SITES AND THE WIPP SITE

The cost of trucking for carrying treated waste from the processing site to the WIPP site has been calculated using the same methodology outlined earlier in Section 2.3. Therefore, once the number of trips required has been calculated using the methodology described in the previous section, the trucking costs are estimated by the following equation:

Cost of trucking between processing sites and the WIPP site

= (Number of TRUPACT-II miles) X (Cost per TRUPACT-II mile)

= (# of trips) X (2 X distance between processing sites and WIPP) X (1.70)

The distance between the sites is multiplied by a factor of two to account for the round trip required for bringing trailers with empty TRUPACT-II containers back to the processing site.

2.7 COST OF UNLOADING WASTE AT THE WIPP SITE

The cost of unloading waste at the WIPP site has been calculated using the same methodology presented earlier in Section 2.4. Thus, the unloading costs are estimated by the following equation:

Cost of unloading waste at the WIPP site

= (# of trips) X (Labor hours per trip) X (Cost per labor hour)

= (# of trips) X (11.5 X 50 dollars)

The number of trips required from the processing site to the WIPP site is obtained using the same methodology outlined in Section 2.5. Once the unloading costs for waste from each processing site have been calculated, these costs can be added to obtain an estimate for the total unloading costs for each option.

2.8 SAMPLE CALCULATION FOR ESTIMATION OF TRANSPORTATION COSTS

The methodology for estimation of transportation costs is illustrated using the case of two processing facilities from Table J-4 as an example. The following sample calculation uses the example of Hanford as the shipping site and INEL as the processing site, followed by disposal at the WIPP site. It is also assumed that Alternative 2 (or 3) is the selected treatment option.

2.8.1 Cost of Loading Untreated Waste at the Hanford Site

The volume of waste at the Hanford site is given in Table J-3 as follows:

Sludges	1217 m^3
Solid Organic	8736
Solid Inorganics	11591
	21544 m^3

The cost of loading waste at Hanford is then calculated by using the equation provided in Section 2.2 as follows:

Cost of loading untreated waste at the Hanford site

= (12.8) X (Volume of waste in m^3/10) X (50 dollars)

= $ 1,380,000

2.8.2 Cost of Trucking Between Hanford and INEL

The trucking costs are calculated by the equation given in Section 2.3 as follows:

Cost of trucking between Hanford and INEL

= (# of trips) X (2 X distance between Hanford and INEL) X (1.70)

= (Volume of waste in m^3/10) X (2 X 581) X (1.70)

= (21544/10) X (2 X 581) X (1.70)

= $ 4,260,000

2.8.3 Cost of Unloading Waste at INEL

The unloading costs at the INEL site can be calculated using the equation presented in Section 2.4 as follows:

Cost of unloading untreated waste at the INEL site

= (# of trips) X (11.5) X (50 dollars)

= (21544/10) X (11.5) X (50 dollars)

= $ 1,240,000

2.8.4 Cost of Loading Treated Waste at the INEL Site

The costs for loading treated waste at the INEL site is estimated using the step-by-step methodology described in Section 2.5. The volume and weight of the waste after treatment are calculated using volume reduction factors for each of the three waste forms using Alternative 2, and the densities of these processed waste forms. For Alternative 2, these factors are listed on Table J-7. Using these values, the total weight of processed waste can be calculated as follows:

Total volume of sludges after processing

= 1217/1.0

= 1217

Total weight of sludges after processing

= (1217 m^3) X (0.0510 lb/in^3) X (61023.37 in^3/m^3)

= 3,788,000 lb.

TABLE J-7

VOLUME REDUCTION FACTORS AND PROCESSED WASTE DENSITIES FOR ALTERNATIVE 2

WASTE FORM	VOLUME REDUCTION FACTOR	DENSITY (lb/in^3)
Sludges	1:1	.0510
Solid Organics	1.173:1	.0637
Solid Inorganics	1.173:1	.0726

Total volume of solid organics after processing

= 8736/1.173

= 7448 m^3

Total weight of solid organics after processing

= (7448 m^3) X (0.0637 lb/in^3) X (61023.37 in^3/m^3)

= 28,952,000 lb.

Total volume of solid inorganics after processing

= 11591/1.173

= 9881 m^3

Total weight of solid inorganics after processing

= (9881 m^3) X (0.0726 lb/in^3) X (61023.37 in^3/m^3)

= 43,776,000 lb.

Therefore, the total weight of treated waste to be shipped to WIPP is:

= 3,788,000 + 28,952,000 + 43,776,000

= 76,516,000 lb.

Once the total weight to be shipped is known, the number of trips required is calculated as follows:

Number of trips required

= 76,516,000 lb. / 13,595 lb. per trip

= 5628 trips

The loading costs at the processing site for 5628 trips is calculated by the equation given in Section 2.5 as follows:

Cost of loading treated waste at INEL

= (# of trips) X (Labor hours per trip) X (Cost per labor hour)

= (5628) X (12.8) X (50 dollars)

= $ 3,600,000

2.8.5 Cost of Trucking Between INEL and the WIPP Site

The trucking costs are estimated by the equation given Section 2.6 as follows:

Cost of trucking between INEL and the WIPP site

= (# of trips) X (2 X distance between INEL and WIPP) X (1.70)

= (5628) X (2 X 1484) X (1.70)

= $ 28,400,000

2.8.6 Cost of Unloading at the WIPP Site

The cost of unloading waste at the WIPP site is estimated by the equation given in Section 2.7 as follows:

Cost of unloading waste at the WIPP site

= (# of trips) X (11.5) X (50 dollars)

= (5628 X (11.5) X (50 dollars)

= $ 3,240,000

2.8.7 Total Transportation Costs for Two Facilities Using Alternative 2

The estimates presented above can be added together to obtain the total transportation costs for shipping all the waste from the Hanford site to INEL for processing and then transporting the processed waste to the WIPP site. The approach used for Hanford and INEL above can be repeated for all other shipping/processing site combinations and the resulting costs can be added to obtain a total transportation cost using two facilities and Alternative 2 (or 3) as the treatment option.

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