Waste Isolation Pilot Plant

Compliance Certification Application

Reference 187a

DOE (U.S. Department of Energy), 1991.
Evaluation of the Effectiveness and Feasibility of the Waste Isolation Pilot Plant Engineered Alternatives: Final report of the Engineered Alternatives Task Force, DOE/WIPP 91-007, Vol. I., Revision 0, Carlsbad, NM, Westinghouse Electric Corporation.

DOE/WIPP 91-007
Revision 0

Evaluation of the Effectiveness and Feasibility of the Waste Isolation Pilot Plant Engineered Alternatives:

Final Report of the Engineered Alternatives Task Force

Volume I

July 1991

Waste Isolation Pilot Plant

This document is issued by Westinghouse Electric Corporation, Waste Isolation Division, as the Managing and Operating Contractor for the Department of Energy, Waste Isolation Pilot Plant, Carlsbad, New Mexico, 88221 .

DOE CONTRACT NUMBER: DE-ACO4-86AL31950

DOE/WIPP 91-007
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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

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EXECUTIVE SUMMARY

The Engineered Alternatives Task Force (EATF) was established by the United States Department of Energy (DOE) WIPP Project Office (WPO) in September, 1989 (Hunt, A., 1990), to evaluate the relative effectiveness and feasibility of implementation of selected design enhancements (referred to as "engineered alternatives") for the Waste Isolation Pilot Plant (WIPP). These enhancements consist of modifications to existing waste forms and/or the WIPP facility, and other design variations such as passive marker systems. The purpose of this report is to summarize the methodologies and results of evaluation of the effectiveness of selected engineered alternatives relative to the existing repository design, and to discuss the feasibility of implementing these alternatives with respect to availability of technology, cost, schedule, and regulatory concerns.

Preliminary analyses of the long-term performance of the WIPP disposal system performed by Sandia National Laboratories (SNL) (referred to as "performance assessment") have identified two potential problems in demonstrating compliance with the applicable regulation 40 CFR Part 191 (EPA, 1985) that governs the disposal of transuranic radioactive waste. The first potential problem relates to gas generation. Lappin et al. (1989) discuss 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 demonstrate that either excess pressures will not occur, or that excess pressures will not degrade the performance of the disposal system, some type of waste form or facility modification may be required to either eliminate gas generation or reduce the rate of gas generation. For example, if the organics in the waste are incinerated and vitrified, then microbial gas generation can be eliminated.

A second potential problem in demonstrating compliance with 40 CFR Part 191 relates to the consequences predicted from future inadvertent human intrusion events. Preliminary evaluations of compliance with the containment requirement of 40 CFR Part 191 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 storage rooms, radionuclide solubilities, and the availability of brine. Permeability of the storage rooms can be effectively reduced by the use of a grout backfill and/or shredding and cementation of the waste. Solubilities can be reduced by the use of grout backfill or the addition of lime to raise the pH of any brine that may come in contact with the waste.

The primary goal of the EATF is to develop and evaluate engineered alternatives that can mitigate the effects of, or eliminate, potential problems associated with the performance of the WIPP repository. The efforts of the EATF can be subdivided into two activities:

- Design analysis of the relative effectiveness of engineered alternatives
- Evaluation of the feasibility of implementing engineered alternatives.

The ongoing performance assessment studies by SNL involve the development and use of large complex probabilistic computer models. These models predict the cumulative release of radionuclides to the environment over 10,000 years. In contrast, the EATF analyses, which have been performed in parallel with the performance assessment analyses, utilize a model that calculates improvements offered by the engineered alternatives relative to the baseline design. Because performance is calculated relative to the baseline design, less complex codes can be used that do not incorporate all of the detail of the rigorous performance assessment models. With this approach, the EATF can quickly evaluate and screen a large number of alternatives in a relatively short time, that would not be feasible with complex probabilistic models. Alternatives which have been identified as beneficial by the EATF will then be evaluated by SNL using the performance assessment methodology. The EATF design analysis includes engineered alternatives that eliminate any adverse consequences of excess gas pressure in the storage room, and reduce the releases of radionuclides during human intrusion scenarios, should that be necessary.

As a first step in accomplishing the objectives of the EATF, a panel of experts, the Engineered Alternatives Multidisciplinary Panel (EAMP), was assembled. The EAMP identified and qualitatively ranked the effectiveness and feasibility of potential alternatives that address issues related to gas generation and human intrusion (Appendix A). Based on the ranking by the EAMP, the EATF recommended initial waste forms and backfill modifications for inclusion in the WIPP Experimental Test Program (DOE, 1990b).

The EATF has also selected various combinations of alternatives based on nine of the fifteen waste forms and three backfill modifications recommended for the WIPP Experimental Test Program (DOE, 1990b), and analyzed their relative effectiveness for enhancing the performance of the repository by using a design analysis model. In addition to the design analysis of engineered alternatives, the EATF has evaluated the feasibility of implementing these alternatives on the basis of status of development of technology, regulatory issues, cost, schedule, facility locations, and health and safety risks. The EATF also made an appraisal of optimal locations for waste processing facilities based on a comparative risk assessment of engineered alternatives. The discussion presented in this report is limited to Contact Handled-Transuranic (CH-TRU) waste because it constitutes a vast majority (~97 percent) of the overall TRU waste inventory (DOE, 1988c).

DESCRIPTION OF ENGINEERED ALTERNATIVES

Analyses of the baseline design and 14 alternative designs were performed for undisturbed conditions, and for three human intrusion events that are described later. It should be noted that these 14 alternatives were selected to simulate a broad range of improvement in performance by different combinations of treatment of the major waste forms (i.e., sludges, solid organics, and solid inorganics), and by modifications to backfill material or the current facility design at the WIPP. Thus, these 14 combinations are merely a representation of the total spectrum of available alternatives, and do not imply that the final selection of an alternative will be limited to these 14 exact combinations. The baseline design and engineered alternatives that were analyzed are listed in Table ES-1 and described as follows:

Baseline Design: Sludges, solid organics, and solid inorganics are disposed of in their "as-received" (current treatment at the generator sites) state with a crushed salt backfill.

Alternative 1: Sludges are in their as-received state; solid organics and solid inorganics are shredded and cemented, and a crushed salt backfill is used.

Alternative 2: Same as Alternative 1, except the sludges are cemented.

Alternative 3: Sludges are cemented; solid organics and solid inorganics are shredded and cemented. A grout backfill is used.

Alternative 4: Sludges are cemented; solid organics are incinerated and the resulting ash cemented; and solid inorganics are shredded and cemented. A crushed salt backfill is used.

Alternative 5: Same as Alternative 4, but with grout backfill.

Alternative 6: Sludges are vitrified; solid organics are incinerated and vitrified; glasses are melted; and metals are separated out, melted, and disposed of as ingots. A salt backfill is used.

Alternative 7: Same as Alternative 6, but with a grout backfill.

Alternative 8: Same as Alternative 6, except it is assumed that metals are melted, and the radionuclides partition into a slag phase. The molten metal is drawn off from the melter and cast as ingots which are disposed of as low-level waste. Metals are thus removed from the inventory as low-level waste, but the contamination associated with the metals takes the form of a glass slag that is disposed of at the WIPP. Steel drums are replaced with some non-corroding material in Alternatives 8 and 9 so that both anoxic corrosion and microbial gas generation processes are essentially eliminated.

TABLE ES-1

ENGINEERED ALTERNATIVES EVALUATED BY THE EATF RELATIVE TO THE BASELINE CASE

ALTERNATIVE #	SLUDGES	SOLID ORGANICS	SOLID INORGANICS	BACKFILL	WASTE CONTAINER	WASTE MANAGEMENT	FACILITY DESIGN
BASELINE	As received	As received	As received	Salt	As received	As designed	As designed
ALTERNATIVE 1	As received	Shred/Cement	Shred/Cement	Salt	As received	As designed	As designed
ALTERNATIVE 2	Cement	Shred/Cement	Shred/Cement	Salt	As received	As designed	As designed
ALTERNATIVE 3	Cement	Shred/Cement	Shred/Cement	Cement grout	As received	As designed	As designed
ALTERNATIVE 4	Cement	Incin./Cement	Shred/Cement	Salt	As received	As designed	As designed
ALTERNATIVE 5	Cement	Incin./Cement	Shred/Cement	Cement grout	As received	As designed	As designed
ALTERNATIVE 6	Vitrify	Incin./Vitrify	Melt metals*	Salt	As received	As designed	As designed
ALTERNATIVE 7	Vitrify	Incin./Vitrify	Melt metals*	Cement grout	As received	As designed	As designed
ALTERNATIVE 8	Vitrify	Incin./Vitrify	Melt metals**	Salt	Non-ferrous	As designed	As designed
ALTERNATIVE 9	Vitrify	Incin./Vitrify	Melt metals**	Cement grout	Non-ferrous	As designed	As designed
ALTERNATIVE 10	As received	As received: Less Metals	Decontaminate Metals***	None	Non-ferrous/ Rectangular	Minimize space around waste	New dimensions: 10'x31'x188'
ALTERNATIVE 11	As received	Supercompact	Supercompact	Salt	As received	Single layer: 2000 drums	New dimensions: 6'x33'x300'
ALTERNATIVE 12	As received	Supercompact	Supercompact	Cement grout	As received	Single layer: 2000 drums	New dimensions: 6'x33'x300'
ALTERNATIVE 13	Vitrify	Incin./Vitrify	Melt metals**	None	Non-ferrous/ Rectangular	Minimize space around waste	New dimensions: 10'x31'x188'
ALTERNATIVE 14	As received	Supercompact	Supercompact	Salt aggregate Grout	As received	Compartmentalize waste, 2000 drums per room	Salt dikes: Waste Separation

* Metals are melted into TRU waste ingots.
** Metals are melted with glass/glass frit; radionuclides partition into the slag, and metals are eliminated from the WIPP inventory.
*** Metals are decontaminated by vibratory finishing and eliminated from the WIPP inventory.

Alternative 9: Same as Alternative 8, but with grout backfill.

Alternative 10: The waste container material is changed to a noncorroding material, and the shape is changed to rectangular; sludges are in their "as-received" state; solid organics are in "as-received" state less metals (i.e., small amounts of metals present in the solid organic waste, together with the mild steel containers, are separated from the solid organics as a preprocessing step); metals are decontaminated from solid inorganics and removed; the room dimensions are changed to 10'x31'x188' to eliminate backfill.

Alternative 11: Sludges are in their as-received state; solid organics and solid inorganics are supercompacted. The waste is placed in a monolayer. The room dimensions are altered to 6'x33'x300'. A salt backfill is used.

Alternative 12: Same as Alternative 11 but with grout backfill.

Alternative 13: Same as Alternative 8, except it is assumed that a rectangular waste container is used, and the room dimensions are altered to 10'x31'x188' to eliminate backfill.

Alternative 14: Sludges are in their "as-received" state; the solid organics and the solid inorganics are supercompacted. Three seven-packs of drums are placed in each "compartment" which is separated from other compartments by a salt aggregate grout composite. The compartmentalization reduces uncertainties related to the flow of brine through the waste stack and also sets an upper "engineered limit" on the inventory of radionuclides that can be released during any human intrusion event.

These 14 combinations of alternative waste forms and facility designs incorporate nine of the preliminary alternative waste forms recommended by the EATF for incorporation into the SNL bin-scale testing program (DOE, 1990b). Alternatives 1, 2, and 3 involve shredding and cementing of solid organics and solid inorganics, which affects gas generation rates but does not reduce the total gas generation potential. Alternatives 4, 5, 6, 7, 8, 9, and 13 involve thermal treatment (incineration or vitrification) of solid organics to eliminate the source of microbial gas generation. Alternatives 8, 9, and 13 do not have solid organics or metals present in the inventory and thus eliminate both of the sources of gas generation, namely from microbial processes and anoxic corrosion. Alternative 10 eliminates the metals from the inventory and hence the source of gas generation by anoxic corrosion. Alternatives 11, 12, and 14 involve supercompaction of the solid organics and solid inorganics and marginally increase the total gas generation potential based on conservative EATF assumptions.

Engineered alternatives are classified according to the degree of waste processing and its effect on gas generation potential (total number of moles of gas that can be generated) and gas generation rate as (Bertram-Howery and Swift, 1990):

Level I Alternatives - "As received" (unprocessed) waste
Level II Alternatives - Waste is processed to reduce gas generation rates with no effect on potential
Level III Alternatives - Waste is processed to essentially eliminate potential for gas generation.

Examples of engineered alternatives are: waste management or facility design alternatives such as minimizing the space around the waste or changing room configuration, respectively (Level I); shredding and cementation of the waste which may reduce the rate of gas generation, but will not have any effect on total gas generation potential (Level II); and incineration or vitrification of the solid organic waste, which is expected to eliminate the potential for biological gas generation (Level III). The Level II and III classifications provide the framework for evaluating the feasibility of waste treatment alternatives relative to untreated waste (Lappin, 1990).

DESIGN ANALYSES OF ENGINEERED ALTERNATIVES

Design Analysis Model

The Design Analysis Model is a deterministic model which simulates the processes expected to occur following waste emplacement in the WIPP facility. The main program is used to analyze the relative effectiveness of various modifications to the waste forms and facility when compared to the current waste forms and WIPP baseline design.

The Design Analysis Model includes the modeling of the following processes under the isothermal conditions expected in the repository:

- Creep closure of the surrounding host rock
- Gas generation, consumption, and dispersion
- Brine inflow, consumption, and dispersion
- Panel seal leakage
- Consolidation of the shaft/seal system and advection of gas and brine through the shaft seals
- Diffusion and advection of gases into the host formation, and the underlying and overlying anhydrite beds
- Gas compressibility
- Waste compaction and resulting mechanical resistance to closure

- Development of a porous disturbed rock zone surrounding a storage room
- Radionuclide releases caused by three types of inadvertent human intrusion scenarios into the repository

The two main performance parameters that are used to compare the relative merits of each engineered alternative are: (1) the peak index pressure reached in the storage rooms during undisturbed conditions (no human intrusion), and (2) a measure of the cumulative release of radionuclides caused by human intrusion events.

For undisturbed conditions, the program estimates fluid pressure (brine and/or gas) within a typical waste storage room environment as a function of time. Coupling of creep closure, brine inflow and gas generation is incorporated into the model to simulate these interrelated processes over a 10,000-year period following the decommissioning of the repository.

For human intrusion events, three scenarios are considered (Marietta et al., 1989):

- A borehole that penetrates a waste-filled room and continues into or through a pressurized brine pocket assumed to exist in the underlying Castile Formation (E1 scenario)
- A borehole that penetrates the repository and stops (E2 scenario)
- Two boreholes that penetrate storage rooms in the same panel. One of these boreholes also penetrates a pressurized Castile brine pocket (E1E2 scenario).

The studies by Marietta et al. (1989) have determined that the three scenarios listed above constitute a reasonable set of possibilities based on investigation of more than thirty possible scenarios.

For the analysis of human intrusion events, a "Measure of Effectiveness" is calculated for each alternative design based on the cumulative release of twelve radionuclides (Lappin et al., 1989) into an overlying water-bearing strata (the Culebra Dolomite) over a 10,000-year period, plus the activity associated with the direct release of contaminated drill cuttings to the surface. A "Measure of Relative Effectiveness" (MRE) is then calculated for each alternative by dividing the measure of effectiveness for that alternative by the measure of effectiveness for the baseline design. Thus, an MRE greater than one indicates a decrease in performance and an MRE less that one indicates an increase in performance. These measures provide a convenient means of comparing the improvements offered by alternative designs relative to the baseline design, but do not represent absolute measures of repository performance.

<u>Analyses Performed</u>

Specific analyses that were performed for analyzing various effects on room pressurization for undisturbed conditions include:

- Prediction of room pressurization for the baseline design
- Effects of supercompaction of waste, based on a single layer of 2000 drums and a triple layer of 6000 drums per room of supercompacted waste
- Effects of venting the repository for 100 years
- Effects of varying the rate and duration of microbial gas generation
- Effects of varying hydraulic properties of anhydrite beds
- Effects of varying initial brine inflow rate
- Predicted peak index gas pressures for the baseline design and 14 alternative combinations of waste forms and facility designs.

Analyses of human intrusion events include the calculation of MREs for 14 alternative combinations of waste forms and facility designs (listed earlier) including shredded and cemented, incinerated, and vitrified waste.

<u>Results of Design Analyses</u>

Predicted peak index pressures are used as a guide to rank the relative effectiveness of alternative designs in reducing concerns related to excess gas pressure for the undisturbed (no human intrusion) scenario. These peak index pressures are not necessarily the actual pressures that will exist in the storage rooms.

Results of the EATF's design analysis modeling for the undisturbed scenario, using SNL assumptions (Lappin et al., 1989) for gas generation rates, suggest the following:

- Gas pressures in storage rooms will exceed lithostatic pressure for the baseline design.
- Supercompaction of waste results in higher peak index gas pressures than the baseline (uncompacted) waste, based on either a monolayer of 2,000 drums or a triple layer of 6,000 drums of supercompacted waste per room.
- Venting the storage rooms will only be effective in reducing peak index gas pressures if the vent remains open for the entire gas generating period (i.e., an estimated period of approximately 800 years). Venting for only the first 100 years will result in higher peak index gas pressures than the baseline (non-vented) design. Venting will not allow gas pressure to build up, and therefore, will not offer any resistance to creep closure. This will result in lower void volumes in

the repository, and once the vents are closed after 100 years, the generated gas will occupy a smaller volume resulting in higher peak index pressures.

- Predicted peak index pressures are sensitive to the rate and duration of microbial gas generation.

- Predicted peak index pressures are only sensitive to the initial brine inflow rate if that rate exceeds a critical value. This critical value is higher than current estimates of actual brine inflow.

- Factors that affect peak index pressures are the mass of organic materials present in the room and the void volume available for produced gases.

- Alternatives 1, 2, 3, 10, 11, 12, and 14, also generate pressures in excess of lithostatic due to the presence of organic materials. Thus, these alternatives appear to be ineffective in reducing peak index pressures, but they may have application in reducing the consequences if human intrusion occurs.

- Alternatives 4 through 7 involve thermal treatment of organic materials but do not remove metals completely. These alternatives do not exceed lithostatic pressure even though metals are present. This is because once the organic materials are destroyed by thermal treatment, the gas generation from anoxic corrosion is limited by the assumed coupling between anoxic corrosion and brine inflow (i.e., the pressure due to the gas generated by anoxic corrosion reduces the brine inflow, and as a result retards the process of anoxic corrosion).

- Alternatives 8, 9, and 13 that involve both thermal treatment of organic materials and removal of metals, do not exceed lithostatic pressure.

Results of design analysis modeling for the three human intrusion scenarios suggest the following improvements relative to the baseline design:

- Improvements in performance of one order of magnitude in the MRE are predicted for the Castile Brine (E1) scenario for shredded and cemented or supercompacted waste forms and two orders of magnitude for incinerated or vitrified waste forms. Critical parameters for this scenario are waste/backfill permeability, borehole radius and permeability, and radionuclide solubilities.

- Improvements of one to two orders of magnitude in the MRE are predicted for the repository breach (E2) scenario for shredded and cemented, and for incinerated and vitrified waste forms, provided that grout is used as a backfill. Critical parameters for this scenario are waste/backfill permeability, volume of contaminated brine trapped in the repository after repressurization, and radionuclide solubilities.

- Improvements of two to four orders of magnitude in the MRE can be gained for the dual borehole (E1E2) scenario using shredded and cemented, supercompacted, incinerated, vitrified, or melted metal waste forms, provided that grout is used as a backfill. Critical parameters for this scenario are waste/backfill permeability and radionuclide solubilities.

The results presented here are estimates and are subject to change as ongoing laboratory experiments, in situ testing with waste, other site characterization, and modeling activities continue to yield additional data that may alter the current understanding of the complex processes that will occur in the WIPP repository.

FEASIBILITY OF IMPLEMENTING ENGINEERED ALTERNATIVES

The EATF has evaluated the feasibility of implementing selected waste treatment alternatives, and to a more limited extent has evaluated backfill materials and other alternatives such as waste management and WIPP facility design modifications. The results of the EATF provide a preliminary idea of the relative feasibilities of each alternative. The EATF recommends the use of such data only for comparative estimates, and not for arriving at a final decision regarding the choice of an alternative. Detailed assessments of the recommended technology are required before a final decision can be made regarding the feasibility of a particular engineered alternative.

WASTE TREATMENT ALTERNATIVES

The EATF has considered the status of development of waste treatment technologies, and the cost, regulatory issues, schedule, health and safety risks, and potential locations for waste treatment facilities.

Status of Development

The status of development of waste treatment technologies is summarized as follows:

- Vitrification - Viable technology; additional development required before full scale transuranic (TRU) waste vitrification systems can be put into operation
- Incineration - Well developed for hazardous and low-level waste treatment; as of yet not fully developed for TRU waste
- Cementation - Well developed technology; uncertainty regarding long-term effects of the WIPP environment on the stability of cementitious materials

• Compaction, Shredding, Melting Metals	- Commonly used technologies in industry (non-radioactive applications) and for low-level waste
• Removal and Decontamination of metals	- Viable technology. Potential to achieve the effectiveness of a Level III alternative with a Level II alternative
• Addition of pH Buffers to Waste	- Operational consideration with no process development required. Requires selection of effective buffers that will not interact or react with other waste components to either produce gas or increase the radionuclide solubility
• Change Waste Container Material	- Requires evaluation of suitable materials that do not generate gas from anoxic corrosion or biological degradation, and can satisfy safety requirements for handling and transport

Cost of Facilities

The cost and time required to implement Level II waste treatment facilities is less than for Level III facilities. The cost and size of treatment facilities have been estimated on the basis of "work-off periods." The EATF has defined this as the time projected to process all TRU waste generated by the year 2013, based on the volumes of waste estimated in DOE (1988c). Shorter work-off periods increase the facility costs while longer work-off periods reduce the costs. It is important to note that the costs presented in this report are rough cost estimates, and are computed from existing or planned DOE TRU waste treatment facility information that have been appropriately scaled to process all retrievably stored waste in 5, 10, or 20 years. The EATF computed operating cost estimates as a percent of capital cost (on an annualized basis). The EATF has concluded that there is a need for minimum size facilities which will operate in batch mode. Operating cost estimates for waste processing facilities are presented in categories as a means of communicating that estimates are rough and not based on bottom-up estimates (i.e., costs of equipment, material, and services have not been collected in minute detail).

Schedules

Waste treatment implementation schedules also tend to be grouped by level of waste treatment required. For instance, Level II facilities require approximately 5-7 years to permit, construct and start up, whereas Level III facilities require about 8-11 years to implement. The size of the facility required for each level of treatment and the budgetary considerations also influence the schedule.

Health and Safety Risks

The total risk associated with various waste treatments includes evaluation of risks from treating, handling, transporting, and emplacing waste in the WIPP. Within each category, risks components include occupational fatalities and injuries, 5- to 20-year occupational and public cancers, and 5000-year occupational and public cancers. Level II treatments would result in a slight increase in risk relative to the baseline design, and this increase would be independent of the number of facilities. In contrast to Level II treatments, for Level III treatments, the dominance of transportation risks favors treatment of wastes at multiple facilities before transporting the wastes to the WIPP. This is because the Level III treatment of waste before shipment substantially reduces the transportation risks, and this reduction more than compensates for the increase in occupational risks associated with Level III treatment. Long-term or late (5,000-year) risks due to human intrusion of the repository are by far the smallest component of total risk.

Facility Locations

The EATF has evaluated potential waste treatment facility locations (e.g., at the WIPP, at individual waste generator/storage sites, or at centralized facilities). Information has been collected for several factors that should be considered for facility location. These factors are:

- Waste characterization for processing, transportation, and disposal
- Waste volumes and existing location
- Existing and planned facilities
- Transportation issues
- Risk assessment
- Schedule
- Cost
- Institutional and regulatory constraints

A logic diagram developed by the EATF has been used to consider factors that influence a decision between centralized and multiple facilities. The EATF has concluded that additional information such as the type of waste treatment required (based on the performance assessment studies), extent of waste characterization required, and more institutional information, is necessary for a firm decision. The EATF has investigated the pros and cons of a centralized facility versus facilities at multiple locations. The following factors have been found to be influential in choosing between multiple and centralized facilities:

- Cost - If cost is the deciding factor, a single integrated facility would be preferable, because economies of scale can be achieved with a single integrated facility.

- Waste Characterization - If the states receiving the waste mandate extensive characterization as per RCRA requirements, then waste characterization is likely to be expensive. Therefore, the preference would be for waste to be processed at each site before transportation. If transportation only requires limited characterization (i.e., characterization for acceptance of payload), planned and existing capacity at the major storage/generator sites should be adequate.

- Schedule - The time required for simultaneous construction of smaller, multiple processing facilities at different locations is expected to be shorter than the time required to construct a large, single integrated facility having the same total capacity. Therefore, if schedule considerations are the primary deciding factor, then multiple processing sites are favored.

- Risk Assessment - Risks associated with Level II treatments are roughly comparable between multiple and centralized facilities, and are slightly greater than the baseline design. The risks from Level III treatments are dependent on the number of facilities, and show a range of slight increase to a slight decrease in risk as the number of facilities are increased from one to seven, respectively.

BACKFILL ALTERNATIVES

Crushed salt derived from mining the WIPP waste disposal areas was considered as the baseline case for backfilling purposes. The addition of absorbents, or pH buffers (to raise the pH of repository brine) is an operational rather than a technological consideration. Selection of these additives will require further analyses. Grout is also a candidate for use as a backfill, but will require evaluation of longevity under conditions found in the WIPP. The cost of facilities at the WIPP site to prepare the salt additives, or grout, would be small compared to the cost of implementing waste treatment and other alternatives. Such a facility would not be on the overall WIPP schedule critical path, and regulatory impact is expected to be minimal.

OTHER ALTERNATIVES

Alternatives involving waste management, facility design, waste container shape and material, and passive institutional controls are collectively referred to as "other alternatives."

As is the case with backfill, the cost, schedule, and regulatory impact of incorporating other alternatives are expected to be minimal. Two potential exceptions are waste container shape and passive institutional controls. Changing waste container shape and material will require testing for certification purposes for Type A Packaging Tests (DOT, 1989). The passive institutional controls program initiated by Sandia National Laboratories (Bertram-Howery and Swift, 1990) has not matured to the point that schedule, regulatory, and cost impacts can be discussed with any degree of confidence.

Waste management and facility design will require documentation such as National Environmental Policy Act (NEPA) documentation, along with associated cost and schedule requirements. These cost and schedule impacts are not expected to be of the same magnitude as those for waste processing. It may be stated that technology exists for incorporation of all "other" alternatives, with the possible exception of passive institutional controls, for which requirements do not exist at this time. The mining of different repository configurations, minimizing space between waste containers, and repackaging waste into containers of different materials (and shapes) are all feasible from the technological and regulatory standpoints.

OVERALL CONCLUSIONS OF THE EATF

The EATF has concluded that if performance assessment studies by SNL identify a problem in demonstrating compliance using the current waste forms and the baseline design of the WIPP, a number of engineered alternatives could be implemented by DOE to improve the repository performance. The combinations of engineered alternatives evaluated by the EATF include alternatives that have varying degrees of effectiveness for addressing possible gas generation and future inadvertent human intrusion scenarios. These combinations also differ from one another with respect to the availability of technology, cost, regulatory constraints, and schedule. Therefore, the exact choice of an engineered alternative can only be determined after the extent of the problem and the degree of effectiveness required have been identified by the performance assessment studies.

Table ES-2 describes the 14 combinations of alternatives evaluated by the EATF, and summarizes the overall findings of the EATF regarding the effectiveness of these combinations in addressing gas generation issues and human intrusion scenarios. The feasibility of implementing different alternatives with respect to availability of technology, cost, regulatory constraints, schedule, and health and safety risks is also summarized in Table ES-2. It should be noted that the levels of development presented in Table ES-2 are published estimates, and do not take into account various uncertainties that are likely to be encountered. For example, although there might be considerable experience with a particular process for nonradioactive materials, adaptation of the same process for handling radioactive waste is likely to cause unexpected modifications, subsequent delays, and added costs.

The capability of each alternative for addressing gas generation has been summarized in terms of the effect of an alternative on the peak index pressure, and its effect on the gas generation rates by either microbial/radiolytic processes or by anoxic corrosion. If the peak index pressures due to an alternative (as estimated by the Design Analysis Model) do not exceed the lithostatic pressure, then the alternative is considered to be effective, and assigned a blank circle in Table ES-2. On the contrary, if the peak index pressure exceeds the lithostatic pressure, the alternative is considered to be ineffective, and is assigned a dark circle in Table ES-2.

For example, from the results of the Design Analysis Model, the peak index pressures due to Alternative 2 exceed the lithostatic pressure, and therefore this alternative is assigned a dark circle in Table ES-2. Similarly, Alternative 4, which does not exceed the lithostatic pressure, is assigned a blank circle for its effectiveness in addressing peak index pressure.

The effect of an alternative on the gas generation rates has been summarized in Table ES-2 based on the knowledge of processes involved in these alternatives. An alternative is

TABLE ES-2

SUMMARY OF EFFECTIVENESS AND FEASIBILITY OF ENGINEERED ALTERNATIVES

Treatment level[b]	ALTERNATIVE DESCRIPTION						ALTERNATIVE EFFECTIVENESS						ALTERNATIVE FEASIBILITY					
	Number	Sludges	Solid Organics	Solid Inorganics	Backfill	Waste Container	Peak Index Pressure	Gas Generation Rate: Microbial & Radiolytic	Gas Generation Rate: Anoxic Corrosion	Human Intrusion: E1	Human Intrusion: E2	Human Intrusion: E1E2	Level of Develop-ment	Treatment Facility Lifecycle Capital and Operating Cost 10 yr Work-Off Period ($M)	Lifecycle Transportation Costs [a] ($M)	Implem. Schedule (yr)	Regu-latory Requir.	Risk
II	1	AR	S&C	S&C	SLT	AR	●	◓	◓	◓	●	○	H	270-380	71-170	5-7	*	△
II	2	CMT	S&C	S&C	SLT	AR	●	◓	◓	◓	●	○	H	310-420	71-180	5-7	*	△
II	3	CMT	S&C	S&C	CGT	AR	●	◓	◓	◓	○	○	H	310-420	71-180	5-7	*	△
II/III	4	CMT	I&C	S&C	SLT	AR	○	○	◓	●	●	○	H	610-820	71-110	8-11	**	△
II/III	5	CMT	I&C	S&C	CGT	AR	○	○	◓	◓	○	○	H	610-820	71-110	8-11	**	△
III	6	VTR	I&V	MM	SLT	AR	○	○	◓	◓	◓	○	M	830-1100	71-55	8-11	**	NE
III	7	VTR	I&V	MM	CGT	AR	○	○	◓	○	○	○	M	830-1100	71-55	8-11	**	NE
III	8	VTR	I&V	MRM	SLT	NFE	○	○	○	○	◓	○	M	1100-1400	71-27	8-11	**	▧
III	9	VTR	I&V	MRM	CGT	NFE	○	○	○	○	◓	○	M	1100-1400	71-27	8-11	**	▧
III	13	VTR	I&V	MRM	N/A	NFR	○	○	○	○	◓	○	M	1100-1400	71-27	8-11	**	▧
I/III	10	AR	AR	DRM	N/A	NFR	●	●	○	●	●	○	H	510-700	71-60	5-7	*	NE
I	11	AR	SPT	SPT	SLT	AR	●	●	●	●	●	●	H	180-260	71-51	5-7	*	NE
I	12	AR	SPT	SPT	CGT	AR	●	●	●	◓	○	○	H	180-260	71-51	5-7	*	NE
I	14	AR	SPT	SPT	SAG	AR	●	●	●	◓	◓	○	H	180-260	71-51	5-7	*	NE

AR - AS RECEIVED
CMT - CEMENT
VTR - VITRIFY
S&C - SHRED & CEMENT
I&C - INCINERATE & CEMENT
I&V - INCINERATE & VITRIFY
SPT - SUPERCOMPACT
MM - MELT METALS
N/A NOT APPLICABLE

MRM - MELT AND REMOVE METALS
DRM - DECONTAMINATE AND REMOVE METALS
SLT - SALT
CGT - CEMENT GROUT
SAG - SALT AGGREGATE GROUT
NFE - NON FERROUS
NFR - NON FERROUS, RECTANGULAR
● - NO EFFECT
NE - NOT EVALUATED

◓ - PARTIALLY EFFECTIVE
○ - EFFECTIVE
H - HIGH
M - MEDIUM
* - RCRA/HSWA, DOE ORDERS, NEPA, NESHAP
** - RCRA/HSWA, DOE ORDERS, NEPA, NESHAP, CAA, CWA, TSCA, PSD, NAAQS, NSPS
△ SLIGHT RISK INCREASE RELATIVE TO BASELINE
▧ SLIGHT RISK INCREASE FOR SINGLE FACILITY, TO SLIGHT DECREASE FOR 7 FACILITIES

[a] COSTS FOR ONE TO SEVEN PROCESSING FACILITIES

[b] CLASSIFICATION BY TREATMENT LEVELS IS SOMEWHAT GENERALIZED; FOR EXAMPLE, ALTERNATIVE 1 INCLUDES BOTH LEVEL I AND LEVEL II TREATMENTS.

considered to be effective for addressing gas generation from a given mechanism, if it is expected to reduce the generation rates to near zero (i.e., it practically eliminates the potential for gas generation from that mechanism). This is denoted by a blank circle in Table ES-2. Similarly, if an alternative reduces the gas generation rate but does not completely eliminate it, it is considered to be partially effective (denoted by a shaded circle in Table ES-2). An alternative which is not expected to have any effect on the generation rates is termed ineffective, and assigned a dark circle in Table ES-2.

As an example, Alternative 6 which incinerates and vitrifies the solid organics, and vitrifies the sludges, practically eliminates gas generation from microbial/radiolytic processes, and reduces generation rates from this mechanism to zero. Therefore it is assigned a blank circle in Table ES-2 for addressing gas generation rates from microbial/radiolitic processes. However, the melting of metals into ingots (as done in Alternative 6) does not eliminate metals from the inventory, but helps to reduce the rate of gas generation from anoxic corrosion. This is denoted by a shaded circle in Table ES-2. Similarly, although supercompaction of the waste results in a marginal reduction in the total gas generation potential, it has no effect on the gas generation rate, and is therefore assigned a dark circle in Table ES-2.

The discrepancy between predicted peak index pressures and predicted effect on gas generation rates is a function of the simplifying assumptions inherent in model development. The Design Analysis Model includes various assumptions about gas generation rates from waste forms, creep closure rates, brine inflow, coupling of brine inflow and anoxic corrosion, and room response to gas pressure. These assumptions are based on data about the WIPP available at the time of model development, with almost all of the data obtained from SNL publications. Although these assumptions are reasonable at this time, they may change as ongoing experimental and modeling activities continue to provide additional data. If necessary, the Design Analysis Model can be updated to incorporate new assumptions as revised data become available.

Table ES-2 also summarizes the effectiveness of the 14 alternatives in addressing the three hypothetical human intrusion scenarios. The summary is based on the results obtained by the Design Analysis Model for the MRE of an alternative for these scenarios. As explained earlier, the MRE of an alternative needs to be less than 1 to signify an improvement in performance relative to the baseline design. Thereafter, the performance progressively improves as the MRE approaches zero. Although any value of MRE less than 1 signifies an improvement, the EATF has used a conservative upper limit of 0.5 for rating an alternative partially effective (denoted by a shaded circle). If the MRE is greater than 0.5 for a given scenario, the alternative is considered to be ineffective for addressing that particular scenario, and is assigned a dark circle in Table ES-2. Similarly, an MRE of less than 0.05 has been used to classify an alternative to be most effective (denoted by a blank circle in Table ES-2).

As an example, Alternative 7 is effective for all three intrusion scenarios, and is assigned a blank circle under each column. In contrast, Alternative 1 which is partially effective for scenario E1, effective for E1E2, and is ineffective for E2, is assigned a shaded circle, a blank circle, and a dark circle under the respective columns. As with predictions of effectiveness for addressing gas generation, it should be noted that the results of the Design Analysis Model for human intrusion scenarios are also influenced by the assumptions inherent in model development.

Table ES-2 provides a quick reference for comparing the pros and cons of the various alternatives. It can be observed from Table ES-2 that, in general, alternatives that use only Level III processes (e.g., 8, 9, 13) are more effective than alternatives that use only Level II processes (e.g., 1, 2, 3), in addressing both gas generation and human intrusion. It should be noted, however, that the improved effectiveness is not obtained without paying a price. Level III alternatives tend to be more expensive, take longer to implement, and require facilities that are harder to permit than Level II alternatives. Consequently, the greater effectiveness of an alternative does not necessarily make it preferable over others. The selection of an alternative with the optimal effectiveness will depend upon the extent of any problem identified by performance assessment studies.

If a problem is identified by performance assessment, the data developed by the EATF will help to identify a list of candidate alternatives that would be sufficient to alter the performance parameters of concern in order to achieve the required performance. The objective would be to focus the choice of alternatives to a small group of candidate engineered alternatives for further evaluation. For example, if it is determined that merely lowering the gas generation rates will demonstrate compliance, one of Alternatives 1, 2, or 3 from Table ES-2 would be sufficient, and there would not be any need for Level III alternatives. If, on the other hand, it is determined that it is necessary to eliminate gas generation of any kind, then the group of candidate alternatives would be limited to Alternatives 8, 9, and 13. Similarly, based on the results of performance assessment, candidate alternatives can be chosen from Table ES-2 to address the human intrusion scenarios if the current design is predicted to result in noncompliance with any of the three intrusion scenarios.

Once a group of alternatives has been identified that has the effectiveness necessary to address the extent of the problem, Table ES-2 can be used to compare the feasibility of implementing each of them. The second part of Table ES-2 summarizes the feasibility of implementing each alternative design, in terms of availability of technology, cost, likely schedules for implementation, health and safety risks, and regulatory requirements. The availability of technology is summarized in terms of the level of development of technology for the treatment processes. In case of processes like vitrification, where additional development is required for application to TRU waste, the availability of technology has been rated as moderate. The capital costs listed for each alternative design reflect the range of costs estimated by the EATF for one to seven processing facilities. The health and safety risks associated with four alternatives relative to the baseline are summarized in Table ES-2. The risk analysis does not include all 14 alternatives, because the four options analyzed by the EATF represent the total range of treatments involved in the 14 alternatives. The regulatory issues associated with implementing each design are also presented in Table ES-2 in terms of the likely permitting requirements.

The process of narrowing the choice to one alternative from a set of effective alternatives will be primarily decided by the perceived importance of the factors listed under feasibility in Table ES-2. If cost is deemed to be the deciding factor, and the number of facilities is fixed in advance, the logical choice would be to select the least expensive alternative. In contrast, if the decision is constrained by schedule of implementation, then the alternative with the shortest estimated schedule may be chosen. Thus, once a list of effective alternatives are identified by the first part of Table ES-2, the final decision by DOE regarding the choice of a particular alternative can be made only after careful consideration of the different feasibility issues and their relative importance.

1.0 INTRODUCTION

The Engineered Alternatives Task Force (EATF) was formed by the Department of Energy (DOE) WIPP Project Office (WPO) to evaluate the feasibility and relative effectiveness of selected enhancements to the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico (Hunt, A., 1990). These enhancements (referred to as engineered alternatives) include modifications to existing waste forms and/or the WIPP facility and other design variations such as passive marker systems. Recommendations of the EATF will be forwarded by DOE to Sandia National Laboratories (SNL) for input into their experimental and Performance Assessment (PA) programs. Subsequent sections of this report describe the methodology used by the EATF to evaluate the relative effectiveness, the results of this evaluation, and the feasibility of implementing various engineered alternatives. An overview of the WIPP project in reference to the EATF effort and the framework of the EATF are described in this section.

1.1 WIPP CONCEPTUAL MODEL AND FACILITY OPERATIONAL OVERVIEW

The Waste Isolation Pilot Plant is located in southeastern New Mexico as shown in Figure 1-1. The WIPP is a proposed underground repository designed and constructed for the disposal of transuranic (TRU) radioactive wastes. TRU wastes are generated from DOE defense-related activities, including weapons production and research and development. Currently, these wastes are generated and/or stored at ten major DOE sites across the country (DOE, 1988c).

The majority of TRU waste is material that is contaminated with alpha emitting radionuclides (e.g., plutonium-239) with half lives greater than twenty years and concentrations greater than 100 nanocuries per gram (DOE, 1988c). TRU wastes are classified as either Contact-Handled (CH) or Remote-Handled (RH) (DOE, 1988c), depending on the dose rate at the surface of the waste container. CH-TRU waste containers have an external dose rate less than 200 mrem/hr at the surface of the container. The discussion in this report is limited to CH-TRU waste which constitutes a vast majority (~97 volume percent) of the overall TRU waste inventory although the modifications discussed could also be applied to RH-TRU waste. The WIPP repository and the waste to be stored at WIPP are described below.

1.1.1 The WIPP Repository

Detailed descriptions of the geology and hydrology of the WIPP site have been published in numerous documents (DOE, 1990a; Lappin, 1988; Lappin et al., 1989). As shown in Figure 1-2, the WIPP repository is located 2,155 feet below the surface in a bedded salt (halite) formation of Permian age known as the Salado Formation. The basis for the selection of the WIPP site and an analysis of its environmental impacts were initially presented in the WIPP Final Environmental Impact Statement (FEIS) (DOE, 1980) and supplemented according to current understanding in the Final Supplemental Environmental Impact Statement (FSEIS) (DOE, 1990a). Figure 1-3 shows a three-dimensional layout of the repository in relation to the support facilities above the ground. The WIPP rooms and panels are being excavated in the salt beds of the Salado Formation. A panel consists of seven rooms and associated access drifts as shown in Figure 1-3. Figure 1-4 shows the stratigraphy at the repository horizon.

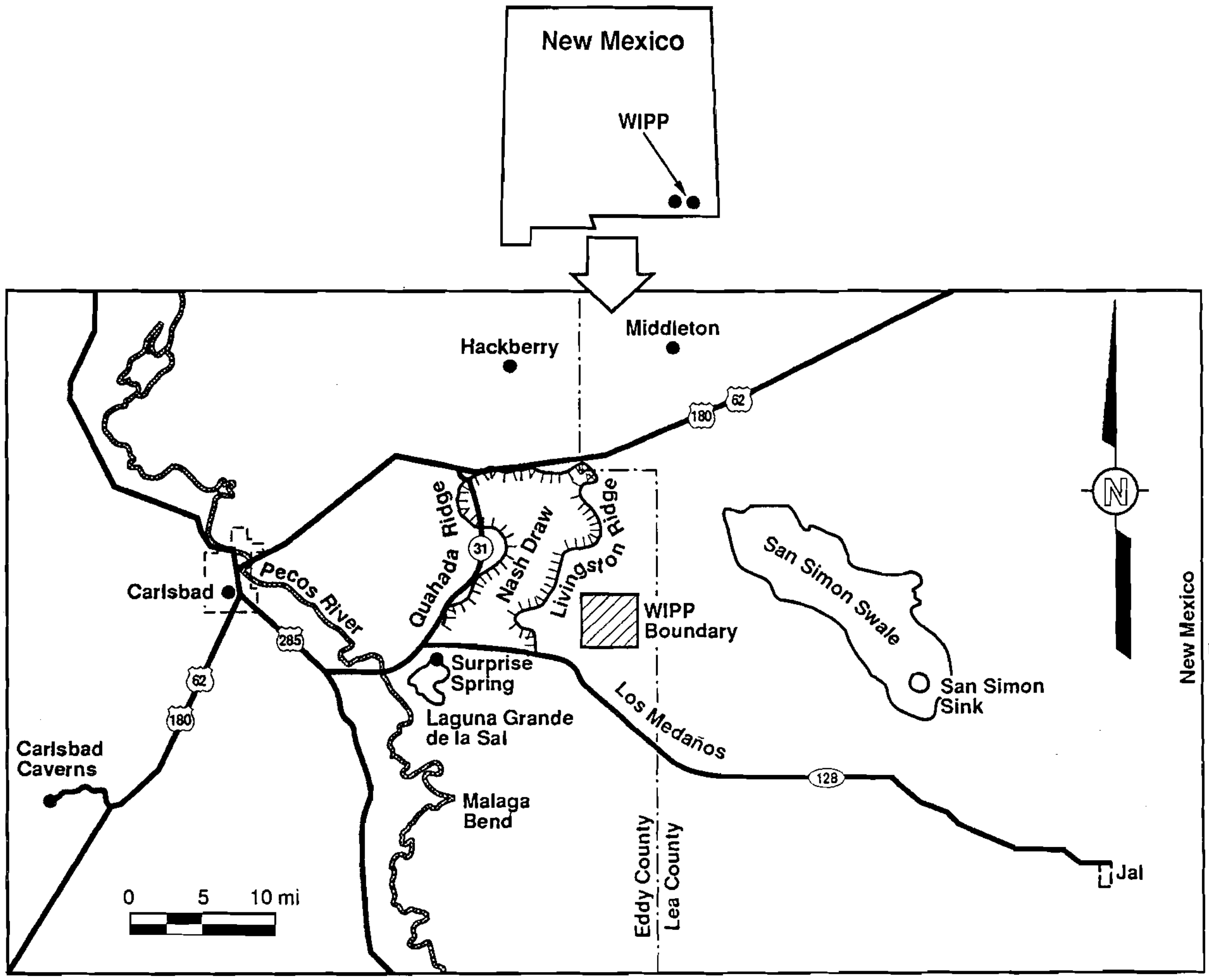

Figure 1-1
WIPP Location in Southeastern New Mexico (Rechard, 1989)

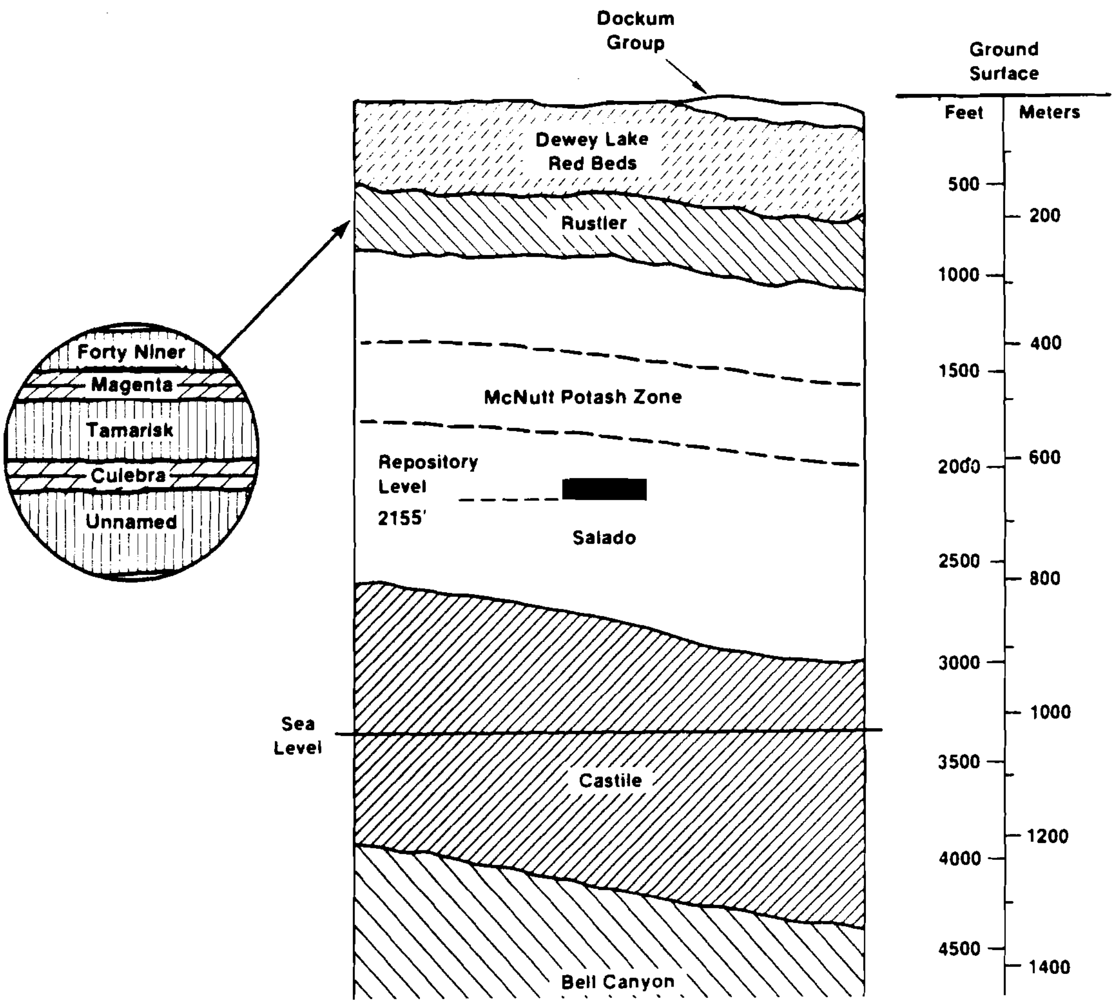

Figure 1-2. Level of WIPP Repository Located in the Salado Formation (Rechard, 1989).

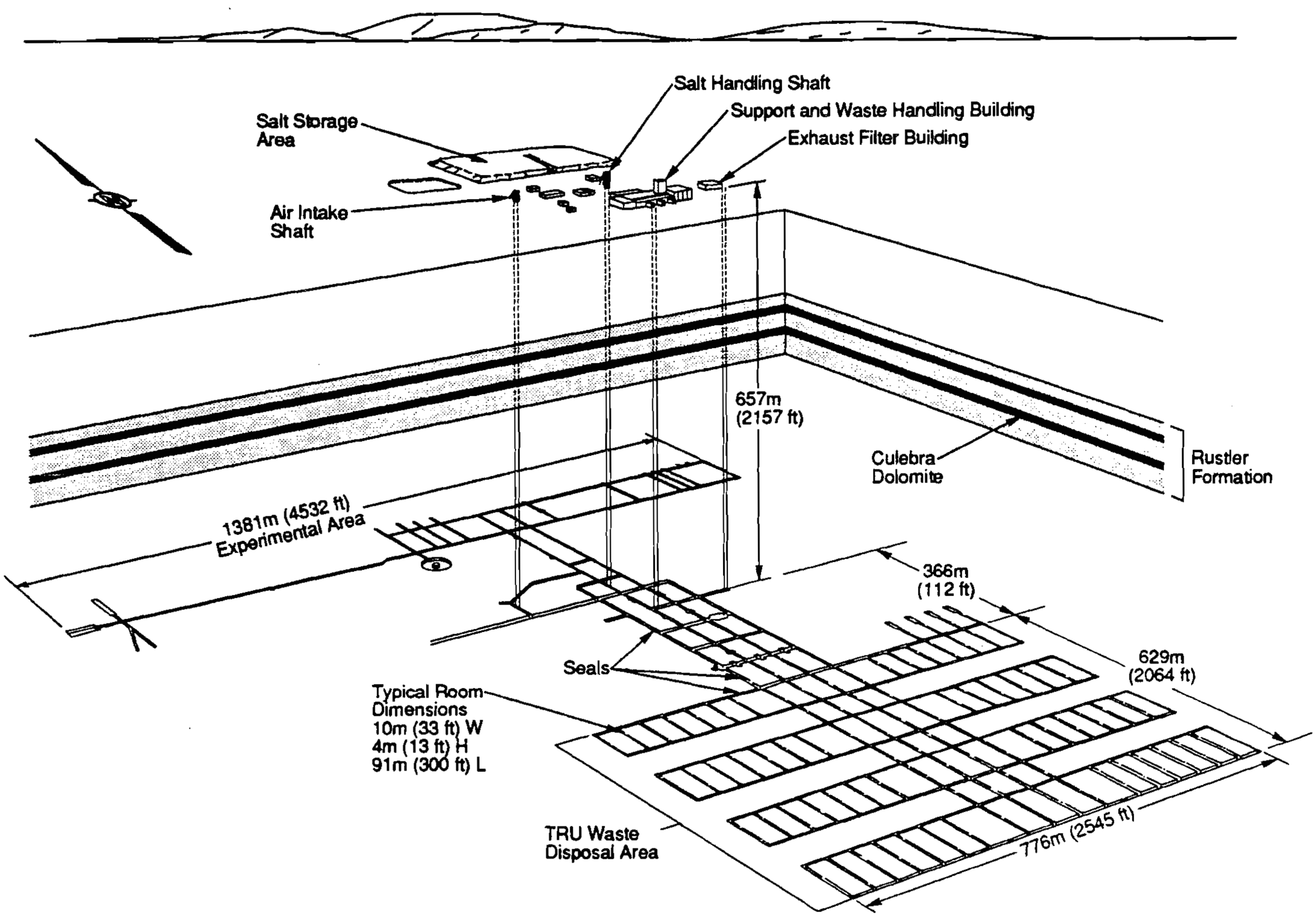

Figure 1-3

Proposed WIPP Repository Showing Both TRU Disposal Areas and Experimental Areas (Nowak et al., 1990)

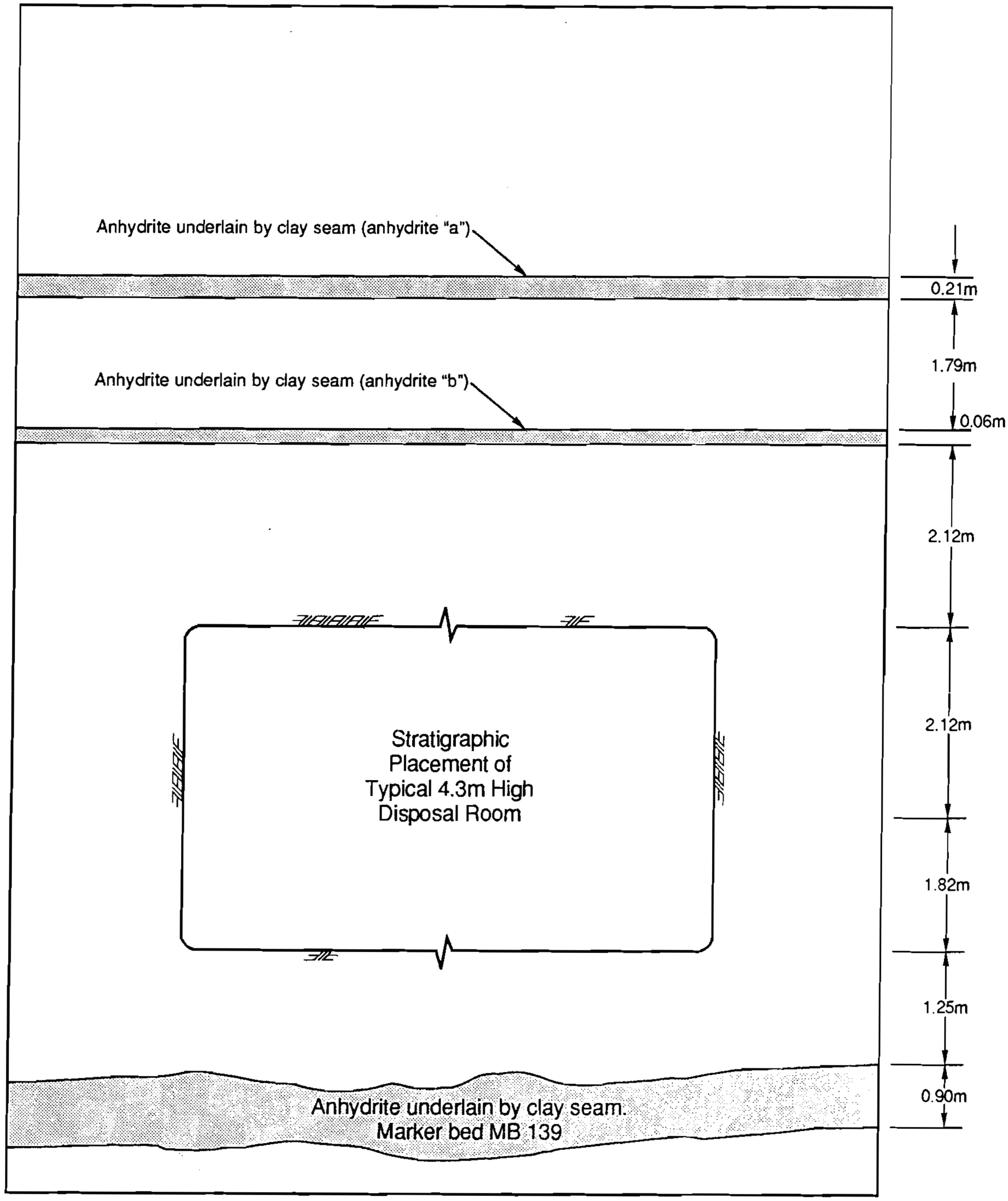

Figure 1-4
Stratigraphy at the Repository Horizon [Modified from Lappin et al. (1989)]

After disposal of the waste in the WIPP storage rooms, closure of the repository occurs due to 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 overlying rock) and the pressure in the repository (which is initially at atmospheric pressure). In a freshly excavated room under atmospheric pressure, this creep is of the order of a few inches per year. Under expected conditions, complete closure of the repository occurs due to creep, and the waste is safely and permanently isolated from the surrounding environment.

1.1.2 Waste Description

Transuranic waste to be disposed of at the WIPP consists of newly generated and/or retrievably stored waste in drums or boxes at major DOE facilities across the United States. Examples of processes that generate the waste are plutonium recovery operations, glove box operations, and the operation of on-site analytical and research and development laboratories. The waste destined for the WIPP site is either solid or solidified material and can be grouped under three major waste forms:

- Sludges
- Solid Organic (Combustible) Waste
- Solid Inorganic (Glass/Metal) Waste

Sludges are predominantly inorganic solidified wastes with some form of solidifying or stabilizing agent, usually a cement-based material. A small percentage of sludges designated as "organic sludges" may contain organic solvents in greater than trace (>1 weight percent) quantities (DOE, 1989e). Solid organic waste consists of organic materials (sometimes referred to as "combustible" waste) such as paper, plastic, tissues, plywood, etc. Solid inorganic waste consists of metals, glass, and a small percentage of other non-combustible material. All of the types of waste are in a chemically stable and non-reactive form (NuPac, 1989) and have been safely stored and handled at the waste generator and storage sites for over four decades. The wastes generated at the different sites are generally comparable, and can all be grouped under the three waste forms listed above (DOE, 1990c), with a few exceptions as noted in Table A-4 in Appendix A.

The waste is generally packaged in plastic bags (polyethylene and/or polyvinyl chloride) that are placed inside the waste containers (55-gallon steel drums or larger metal boxes) (DOE, 1989e). These different layers of confinement serve as barriers for radioactive materials in the waste. The waste containers are fitted with carbon composite filters to allow the diffusion of any hydrogen generated from the waste and to prevent the build-up of gas pressure in the containers, while retaining any particulates inside the containers (NuPac, 1989).

Waste characterization (the constituents and properties) of TRU waste is primarily based on process knowledge and records information, with supporting information from past and current sampling programs in place at the DOE sites. The available waste characterization information has been comprehensively summarized in a number of documents (e.g., DOE, 1989e; DOE, 1990c).

1.2 GOVERNING REGULATIONS

A number of regulations govern the transportation packaging, waste acceptance, storage, and disposal of TRU wastes at the WIPP site. These are summarized in Table 1-1 and addressed in this section. An overview of some of the regulations is presented here, since any modifications recommended by the EATF must comply with these regulations.

1.2.1 Regulations Governing Transportation Packaging and Waste Acceptance

The transportation packaging of radioactive waste is regulated under 10 CFR Part 71 (NRC, 1983). The shipping package to be used for the transportation of CH-TRU waste to the WIPP site is the Transuranic Package Transporter-II (TRUPACT-II) package. The TRUPACT-II is a double-contained, Type B package that can transport up to 14 drums or two metal boxes called Standard Waste Boxes (SWBs) per shipment. A Safety Analysis Report (SAR) for the TRUPACT-II package and its payload was submitted to the U.S. Nuclear Regulatory Commission (NRC) in 1989 (NuPac, 1989). Based on the analysis presented in the SAR, the NRC issued a Certificate of Compliance (C of C) for the TRUPACT-II package in August 1989. The C of C certifies that the TRUPACT-II package meets the requirements of 10 CFR Part 71. Transportation restrictions on the TRUPACT-II package and its payload are defined in the C of C. All waste to be disposed of at WIPP are also required to satisfy the WIPP Waste Acceptance Criteria (WAC), which imposes restrictions on various characteristics (DOE, 1989f).

1.2.2 Regulations Governing the Land Disposal of Mixed Waste

A large portion of the CH-TRU waste to be emplaced at WIPP is mixed, defined as waste that is both radioactive and hazardous. The hazardous component of mixed TRU wastes must comply with the requirements of the Resource Conservation and Recovery Act (EPA, 1990a; 1990b; 1990c; 1990d; 1990e). These include standards for both hazardous waste generators and owners/operators of Treatment, Storage, or Disposal (TSD) facilities.

1.2.2.1 Requirements of Hazardous Waste Generators

40 CFR Part 261 (EPA, 1990a) defines hazardous wastes and provides lists of materials that are considered to be hazardous waste. In addition, Subpart B of 40 CFR Part 261 defines the criteria for identifying the characteristics of hazardous waste.

40 CFR Part 262 (EPA, 1990b) provides guidance for the generators of hazardous waste with regard to characterization. Specifically, 40 CFR Part 262.11 states that a generator must determine if a solid waste is a hazardous waste. This determination can be made based on the list in 40 CFR Part 261, Subpart D, or if it exhibits one of the characteristics discussed in 40 CFR Part 261, Subpart C. The generator can determine if a waste is a characteristic waste by testing [40 CFR Part 262.11(c)(1)] or by applying knowledge of the hazardous characteristics of the waste determined by the materials or the processes used to generate the waste [40 CFR Part 262.11(c)(2)].

TABLE 1-1

REGULATIONS GOVERNING TRU WASTE DISPOSAL AT WIPP

REGULATION	ISSUE	REGULATORY AGENCY
10 CFR Part 71	Transportation	NRC[1]
40 CFR Part 264	Standards for Owners and Operators of Hazardous Waste Treatment, Storage and Disposal Facilities	NM-ED[2]
40 CFR Part 265	Interim Status Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities	NM-ED[2]
40 CFR Part 268	Land Disposal Restrictions	EPA-OSW[3]
40 CFR Part 191 Subpart A	Management and Storage of TRU Waste Prior to Disposal	EPA-ORP[4]
40 CFR Part 191 Subpart B	Disposal of TRU Waste	EPA-ORP[4]
WIPP WAC	Waste Acceptance at WIPP	WACCC[5]

[1] Nuclear Regulatory Commission
[2] New Mexico Environment Department
[3] Environmental Protection Agency Office of Solid Waste
[4] Environmental Protection Agency Office of Radiation Programs
[5] Waste Acceptance Criteria Certification Committee

1.2.2.2 Requirements of Owners/Operators of TSD Facilities

Standards for the owners/operators of TSD facilities are codified in 40 CFR Part 264 (EPA, 1990c) and 40 CFR Part 265 (EPA, 1990d). An owner/operator must obtain a detailed physical and chemical analysis of a representative sample of the waste. The analysis must contain all of the information required to safely manage the waste at the facility; it may include documented or existing published data. Owners/operators of TSD facilities are further required to verify that the waste shipped to the facility is the waste specified on the accompanying manifest. WIPP is currently developing a process for meeting waste analysis/verification requirements.

WIPP has prepared RCRA Permit Applications, Parts A and B (DOE, 1991). The State of New Mexico is reviewing the RCRA Part A and Part B permit applications to determine the status of the WIPP. If the WIPP is determined to be an interim facility, it will be subject to standards contained in 40 CFR Part 265 (EPA, 1990d). If a RCRA Part B permit is issued, the WIPP will be subject to the conditions imposed in the permit, based on those contained in 40 CFR Part 264 (EPA, 1990c).

1.2.2.3 Land Disposal Restrictions

The Hazardous and Solid Waste Amendments (HSWA) of 1984, which amend the RCRA, prohibit the land disposal of hazardous waste, unless the wastes meet treatment standards specified by the EPA. Land disposal of hazardous waste not meeting the treatment standards is permissible if the owner/operator can demonstrate, to a reasonable degree of certainty, that there will be no migration of hazardous constituents from the disposal unit (EPA, 1990e). In response to the No-Migration Variance Petition (NMVP) (DOE, 1990c) submitted by the DOE for WIPP, the EPA has granted a Conditional No-Migration Determination (NMD) (EPA, 1990f) for the test phase of the WIPP facility (a maximum of ten years). The NMD identifies specific waste characterization requirements applicable to waste to be used during the test phase of WIPP.

1.2.3 Regulations Governing the Performance of Nuclear Waste Repositories

The required long-term performance of a nuclear waste repository is governed by 40 CFR Part 191 Subpart B (EPA, 1985), which is currently under revision by the U.S. EPA. An evaluation of compliance with this regulation is referred to as a performance assessment (PA). The PA for the WIPP site is being conducted by Sandia National Laboratories for the U.S. Department of Energy. The methodology being used and the progress made to date appear in Lappin et al. (1989), Marietta et al. (1989), and in Bertram-Howery and Swift (1990). 40 CFR Part 191 Subpart B requires that the cumulative summed, normalized release of specific radionuclides present in the waste should not exceed a value of one over a 10,000-year period using the calculation methodology required by the EPA (EPA, 1985). A range of events and processes have to be considered in evaluating release from the repository. These include human intrusion scenarios that involve the possibility (and probability) of future inadvertent exploratory drilling activities into the repository for a period of 10,000 years after decommissioning. Probabilistic models are generally used in predicting the performance of a disposal system over long time periods. The PA studies being conducted by SNL include lab-scale and full-scale experiments and the acquisition of field information to provide supporting data and input to the PA model (Brush, 1990; Molecke, 1990a; Molecke, 1990b; Molecke and Lappin, 1990). The PA studies are projected to be completed in 1994 (DOE, 1990d).

1.3 THE ENGINEERED ALTERNATIVES TASK FORCE (EATF)

Preliminary analyses (DOE, 1990a) indicated that, given the current baseline design of the WIPP repository and the present waste forms at the sites, PA may not be able to demonstrate compliance with 40 CFR Part 191. In response to this concern, the DOE WPO formed the EATF in September 1989, to evaluate the feasibility of implementation and predict the effectiveness of various engineering modifications to the current waste forms and the WIPP facility design that would improve the long-term performance of the WIPP disposal system (Hunt, A., 1990). In order to maximize the benefits of the EATF evaluations and provide timely integration of EATF activities with the SNL performance assessment, these programs are being conducted in parallel. Program integration between PA and the EATF is described in the Program Plan for Engineered Alternatives (Hunt, A., 1990).

The purpose of the alternatives (or modifications) evaluated by the EATF is to mitigate the effects of, or eliminate, potential problems that might prevent WIPP from demonstrating compliance with the applicable regulations. An example of such a potential problem is gas generation from the waste (e.g., from microbial degradation of organic materials) that may result in overpressurization of the repository after closure. If overpressurization results in fracturing of the host rock, the fractures might become pathways for the migration of contaminated brine beyond the disposal unit boundary and may lead to noncompliance with some of the land disposal restrictions discussed earlier. Similarly, future inadvertent human intrusion into the repository (e.g., for drilling purposes) could potentially result in the release of radionuclides through drill cuttings in amounts exceeding the totals allowed by 40 CFR Part 191 and lead to noncompliance. An example of an engineered alternative to help mitigate the problem of gas generation from microbial degradation would be to incinerate the organics and vitrify them before disposal. The methodology used to evaluate the engineered alternatives that address potential problems, such as gas generation and human intrusion, are described in the following subsections.

1.3.1 EATF Methodology

The overall framework of the evaluation process of engineered alternatives is presented in Figure 1-5. The EATF activities can be subdivided under two headings:

- Design analysis of the effectiveness of engineered alternatives
- Evaluation of the feasibility of implementing engineered alternatives.

Analyses of the long-term performance of the WIPP disposal system performed by SNL have identified two potential problems with demonstrating compliance with applicable regulations.

The first potential problem relates to gas generation. Lappin et al. (1989) discusses the possibility that up to 1,500 moles of gas can be generated per drum of waste from a

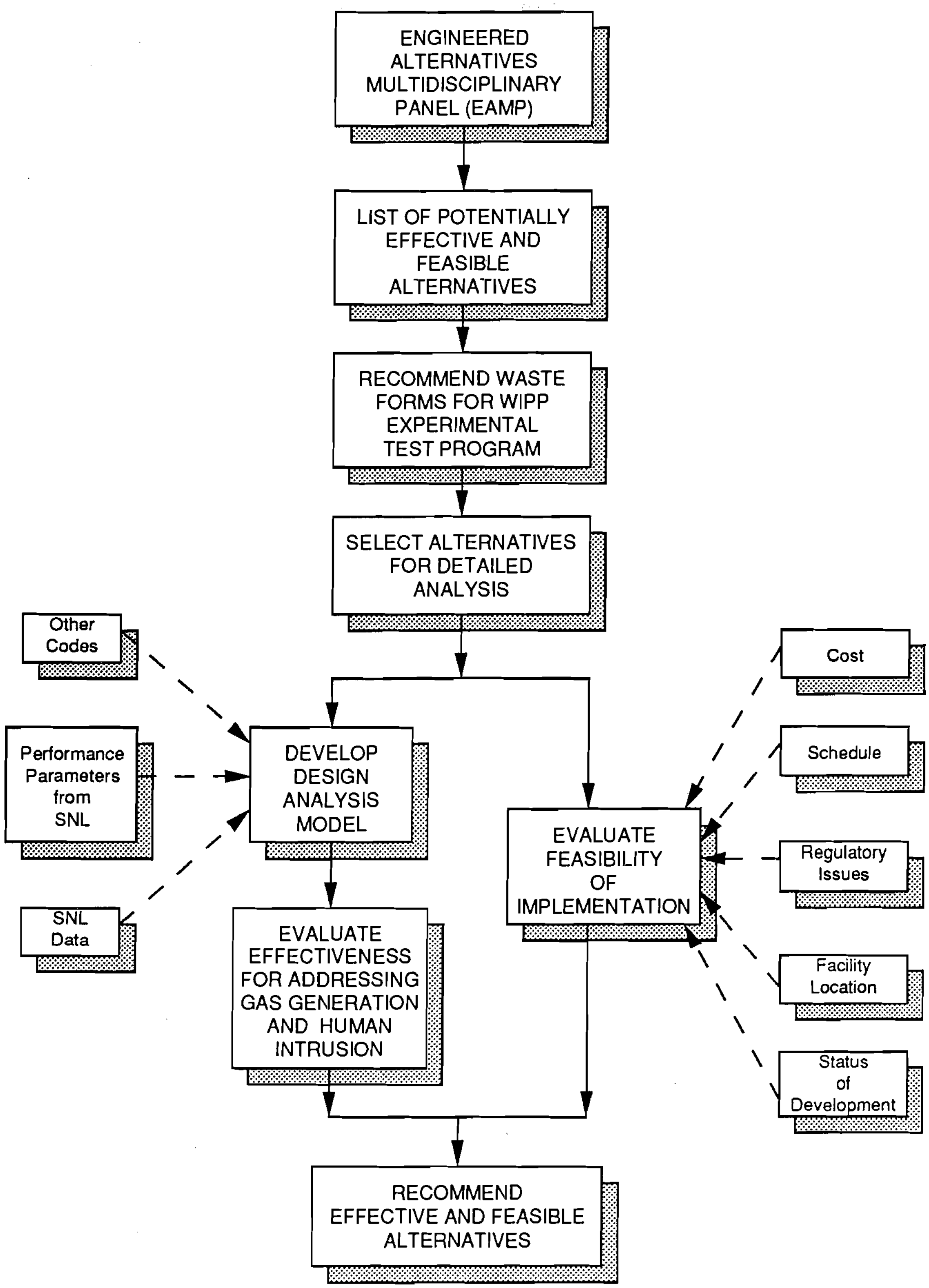

Figure 1-5. Engineered Alternatives Evaluation Process

combination of anoxic corrosion, microbial degradation, and radiolysis, at rates as high as 2.55 moles/drum/year. Anoxic corrosion rates of up to 1.7 moles of hydrogen per drum per year and microbial gas generation rates of 0.85 moles per drum per year are mentioned in the literature (Lappin et al., 1989). However, these gas generation rates can vary over large ranges. The current SNL estimate of 0.85 moles per drum per year of microbial gas generation is based on the arithmetic mean of 0.3 and 1.4 moles per drum per year; the range estimated from an earlier study (Molecke, 1979). Experiments planned in support of the performance assessment studies are expected to yield information on more realistic gas generation rates (Brush, 1990; Molecke, 1990a; Molecke, 1990b; Molecke and Lappin, 1990). As shown later in Section 4.0, existing processes to dissipate excess gas pressure are slow relative to the current estimates of gas generation rates, resulting in gas pressures in storage rooms that may temporarily exceed lithostatic pressure.

The effects of pressure on the gas generation rates is expected to be minimal, because the pressures at which the kinetics are affected are considerably (orders of magnitude) higher than what is expected in the repository. Therefore, pressure effects on gas generation rates have not been considered.

The consequences of exceeding lithostatic pressure are currently being evaluated by SNL (DOE, 1990d). If these evaluations fail to show that either excess pressures will not occur, or that excess pressures will not degrade the performance of the disposal system to the point that 40 CFR Part 191 Subpart B compliance is unachievable, then some type of waste form or facility modification may be required to either eliminate gas generation or reduce the rates of gas generation.

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 performed by SNL suggest that some of the current waste forms may not be acceptable for disposal at the WIPP (Marietta et al., 1989). This may be due to either: (1) conservative assumptions regarding intrusion events, (2) the current large uncertainties in key performance parameters, or (3) actual problems with higher than acceptable waste-form permeability or radionuclide solubility. Key parameters that control the release of waste elements during human intrusion scenarios are permeability of the waste storage rooms and radionuclide solubilities.

The first step in the evaluation of the alternatives was the identification of performance parameters that are critical to the long-term performance of the disposal system. These were determined based on existing PA analyses and the current understanding of the repository system (Marietta et al., 1989). The ten important performance parameters are the following:

- Radiolytic Gas Generation
- Biological Gas Generation
- Corrosion Gas Generation
- Permeability of the Waste and Backfill
- Waste Porosity
- Waste Shear Strength

- Waste Leachability
- Radionuclide Solubility in Brine
- Brine Inflow (seepage)
- Human Intrusion Probability.

1.3.2 Engineered Alternatives Multidisciplinary Panel

Desirable engineered alternatives would be those that mitigate, to some degree, any potential adverse effects on the repository performance. A list of engineered alternatives that address potential problems related to gas generation and human intrusion was compiled, evaluated, and ranked by a multidisciplinary panel of experts [the Engineered Alternatives Multidisciplinary Panel (EAMP)] convened from several fields and disciplines. The panel activities are detailed in a separate report in Appendix A.

The EAMP evaluated engineered alternatives to current waste forms, waste management, backfill materials, facility design, passive marker systems, and several other disposal system features.

Qualitative rankings were assigned to each alternative based initially on three feasibility considerations:

- Regulatory compliance and permitting
- Availability of technology
- Schedule of implementation.

Following initial feasibility screening, each alternative was ranked according to effectiveness in mitigating undesirable effects associated with each of the ten performance parameters described before.

However in the final analysis, the EAMP ranking process was based on the five performance parameters which have been determined by SNL (Anderson, 1990) to be most critical. The condensed set of performance parameters consists of the following:

- Radiolytic Gas Generation

- Biological Gas Generation

- Corrosion Gas Generation

- Permeability of the Waste Stack
  (Waste Stack consists of waste and backfill between drums)

- Radionuclide Solubility in Brine.

To assess the cumulative effects of a particular alternative, the feasibility considerations were evaluated with respect to each of the five performance parameters for each of the three major waste forms:

- Sludges
- Solid Organic (Combustible) Waste
- Solid Inorganic (Glass/metal) Waste.

Within each of the three major waste form categories, the alternatives were ranked for the five performance parameters based on their effectiveness and feasibility (Appendix A). Using this method, the ranking considered the important factors contributing to the applicability of the alternatives: major waste form category, effectiveness relative to the five performance parameters, and the overall feasibility of each alternative. Based on the ranking by the EAMP, the EATF recommended initial waste forms and backfill modifications for inclusion in the WIPP Experimental Test Program (DOE, 1990b).

1.3.3 Selection of Engineered Alternatives

The EATF selected various alternatives based on nine of the fifteen waste forms and three backfill alternatives recommended for the WIPP Experimental Test Program. These alternatives were then analyzed for their relative effectiveness in enhancing the performance of the repository as compared to the current waste forms, by using a design analysis model. The alternatives that have been selected provide a broad range of solutions, if needed, for enhancing the performance of the repository. The basis for the EATF terminology for describing engineered alternatives is discussed in the following sections.

1.3.3.1 Single Alternatives

The individual options recommended for evaluation by the EAMP (Appendix A) are defined by the EATF as "single alternatives". These alternatives include, but are not limited to, waste processing such as incineration (followed by cementation of ash/residue), supercompaction, and shredding (followed by cementation). An example of a single alternative, and a description of the consequences of its application, is the modification of the backfill by adding a sorbent such as bentonite (Butcher, 1990b); this potentially reduces the amount of free brine in the repository. Reduction of free brine inhibits the transport of radionuclides and reduces gas generation by mechanisms such as anoxic corrosion of metals. The complete list of single alternatives considered by the EAMP is presented in Table A-1 in Appendix A. It should be noted that the term "engineered alternative" as used by the EAMP in Table A-1 actually refers to a single alternative as described here.

1.3.3.2 Combination Alternatives

The EATF has defined a "combination alternative" to be the combination of two or more "single alternatives" recommended for evaluation by the EAMP (Appendix A). In other words, single alternatives are the individual components that make up a combination alternative. Many single alternatives are limited in improving repository performance and can only be applied for one type of waste form. For example, incineration followed by solidification is only applicable to solid organic waste forms. In contrast, the appropriate choice of single alternatives can make a combination alternative applicable to all types of waste forms. This also significantly improves the overall effectiveness as compared to the effectiveness of using only one single alternative. An example of a combination alternative is: sludges are cemented, solid organics and solid inorganics are shredded and cemented, and emplaced waste is backfilled with grout.

In later sections, the EATF has often categorized single alternatives according to their purpose. For example, the EATF uses the terms "waste treatment alternatives" and "backfill alternatives" to refer to the single alternatives that deal with the waste treatment component and the backfill component of a combination alternative, respectively.

1.3.3.3 Description of Engineered Alternatives Evaluated by the EATF

All of the engineered alternatives evaluated by the EATF (with the exception of Alternative 1) fall in the category of "combination alternatives". These alternatives and the current baseline design evaluated by the EATF are presented in Table 1-2 and described below:

Baseline Design: Sludges, solid organics, and solid inorganics are disposed of in their "as-received" (current treatment at the generator sites) state with a crushed salt backfill.

Alternative 1: Sludges are in their "as-received" state; solid organics and solid inorganics are shredded and cemented, and a crushed salt backfill is used.

Alternative 2: Same as Alternative 1, except that the sludges are cemented.

Alternative 3: Sludges are cemented; solid organics and solid inorganics are shredded and cemented. A grout backfill is used.

Alternative 4: Sludges are cemented; solid organics are incinerated and the resulting ash cemented; and solid inorganics are shredded and cemented. A crushed salt backfill is used.

Alternative 5: Same as Alternative 4, but with grout backfill.

Alternative 6: Sludges are vitrified; solid organics are incinerated and vitrified; glasses are melted, and metals are separated out, melted, and disposed of as ingots. A salt backfill is used.

Alternative 7: Same as Alternative 6 but with grout backfill.

Alternative 8: Same as Alternative 6, except that it is assumed that metals are melted, and the radionuclides partition into a slag phase. The molten metal is drawn off from the melter and cast as ingots which are then disposed of as low-level waste. Metals are thus removed from the inventory as low-level waste, but the

TABLE 1-2

ENGINEERED ALTERNATIVES EVALUATED BY THE EATF RELATIVE TO THE BASELINE CASE

ALTERNATIVE #	SLUDGES	SOLID ORGANICS	SOLID INORGANICS	BACKFILL	WASTE CONTAINER	WASTE MANAGEMENT	FACILITY DESIGN
BASELINE	As received	As received	As received	Salt	As Received	As designed	As designed
ALTERNATIVE 1	As received	Shred/Cement	Shred/Cement	Salt	As received	As designed	As designed
ALTERNATIVE 2	Cement	Shred/Cement	Shred/Cement	Salt	As received	As designed	As designed
ALTERNATIVE 3	Cement	Shred/Cement	Shred/Cement	Cement grout	As received	As designed	As designed
ALTERNATIVE 4	Cement	Incin./Cement	Shred/Cement	Salt	As received	As designed	As designed
ALTERNATIVE 5	Cement	Incin./Cement	Shred/Cement	Cement grout	As received	As designed	As designed
ALTERNATIVE 6	Vitrify	Incin./Vitrify	Melt metals*	Salt	As received	As designed	As designed
ALTERNATIVE 7	Vitrify	Incin./Vitrify	Melt metals*	Cement grout	As received	As designed	As designed
ALTERNATIVE 8	Vitrify	Incin./Vitrify	Melt metals**	Salt	Non-ferrous	As designed	As designed
ALTERNATIVE 9	Vitrify	Incin./Vitrify	Melt metals**	Cement grout	Non-ferrous	As designed	As designed
ALTERNATIVE 10	As received	As received: Less Metals	Decontaminate Metals***	None	Non-ferrous/ Rectangular	Minimize space around waste	New dimensions: 10'x31'x188'
ALTERNATIVE 11	As received	Supercompact	Supercompact	Salt	As received	Single layer: 2,000 drums	New dimensions: 6'x33'x300'
ALTERNATIVE 12	As received	Supercompact	Supercompact	Cement grout	As received	Single layer: 2,000 drums	New dimensions: 6'x33'x300'
ALTERNATIVE 13	Vitrify	Incin./Vitrify	Melt metals**	None	Non-ferrous/ Rectangular	Minimize space around waste	New dimensions: 10'x31'x188'
ALTERNATIVE 14	As received	Supercompact	Supercompact	Salt aggregate Grout	As received	Compartmentalize waste: 2,000 drums per room	Salt dikes: Waste Separation

* Metals are melted into TRU waste ingots.
** Metals are melted with glass/glass frit; radionuclides partition into the slag, and metals are eliminated from the WIPP inventory.
*** Metals are decontaminated by vibratory finishing and eliminated from the WIPP inventory.

contamination associated with the metal takes the form of a glass slag that is disposed of at the WIPP. Steel drums are replaced with some non-corroding material in Alternatives 8 and 9 so that both anoxic corrosion and microbial gas generation processes are essentially eliminated.

Alternative 9: Same as Alternative 8, but with grout backfill.

Alternative 10: The waste container material is changed to a noncorroding material, and the shape is changed to rectangular; sludges are in their "as-received" state; solid organics are in their "as-received" state less metals (i.e., small amounts of metals that are packaged with the solid organic waste, together with the mild steel container, are separated from the solid organics as a preprocessing step); metals are decontaminated from solid inorganics and removed; the room dimensions are changed to 10'x31'x188' to eliminate backfill.

Alternative 11: Sludges are in their "as-received" state; solid organics and solid inorganics are supercompacted. The waste is placed in a monolayer. The room dimensions are altered to 6'x33'x300'. A salt backfill is used.

Alternative 12: Same as Alternative 11, but with grout backfill.

Alternative 13: Same as Alternative 8, except it is assumed that a rectangular waste container is used, and the room dimensions are altered to 10'x31x188' to eliminate backfill.

Alternative 14: Sludges are in their "as-received" state; the solid organics and the solid inorganics are supercompacted. Three seven-packs of drums are placed in each "compartment" which is separated from other compartments by a salt aggregate grout composite. The compartmentalization reduces uncertainties related to the flow of brine through the waste stack and also sets an upper "engineered limit" on the inventory of radionuclides that can be released during any human intrusion event.

It should be noted that any change of room dimensions (such as in Alternatives 10, 11, 12, and 13) may result in redesigning the equipment for RH-TRU waste emplacement, because the existing room dimensions were based on the size of the equipment.

1.3.4 Classification of Engineered Alternatives

The engineered alternatives are classified according to the degree of waste processing and their effect on gas generation potential (total number of moles of gas that can be generated) and gas generation rate as:

- Level I Alternatives: "As received" (unprocessed) waste

- Level II Alternatives: Waste is processed to reduce gas generation rate with no effect on potential

- Level III Alternatives: Waste is processed to eliminate potential for gas generation.

Level I alternative examples include passive markers, facility design modifications, alternate waste containers, and backfill options. Level II alternatives include cemented sludges, and shredded and cemented solid organics and solid inorganics. Cementation of the waste will limit access of brine to the waste and will also raise the pH of any brine present in the room. High pH conditions should reduce anoxic corrosion and microbial gas generation rates, but will not reduce the total number of moles of gas that may eventually be generated by these processes. Level III alternatives eliminate gas generation potential completely. An example of a Level III alternative is: incineration and cementation of solid organics (this eliminates microbial gas generation potential). It should be noted that the classification is based upon single alternatives. Therefore, a combination alternative (such as Alternatives 1 to 14) is actually made up of single alternatives that belong to different classification levels.

1.3.5 Criteria Used for Evaluation of Engineered Alternatives

Criteria used to compare the alternatives were peak index pressures for undisturbed performance and a "Measure of Relative Effectiveness" for human intrusion. This "Measure of Relative Effectiveness" is based on the predicted 10,000-year cumulative release of radionuclides to the Culebra Dolomite (Figures 1-2 and 1-3) for Alternatives 1 to 14 compared to the baseline design. These peak index pressures and cumulative release estimates are for comparative purposes only, and not meant to be absolute values. The results of the engineered alternative evaluations and the design analyses will be provided as input into performance assessment. Probabilistic modeling by PA will yield absolute release estimates to evaluate compliance with 40 CFR Part 191.

In addition to the design analysis of engineered alternatives, the EATF has also evaluated the feasibility of implementing engineered alternatives on the basis of technical, cost, regulatory, and schedule criteria, and made assessments of various factors (including risk) that need to be considered for potential locations of waste processing facilities (i.e., comparisons of processing at centralized facilities versus individual storage/generator sites).

1.4 LIMITATIONS OF THE EATF EVALUATION OF ENGINEERED ALTERNATIVES

It should be noted that the EATF evaluation of engineered alternatives is based on currently available information. Thus, the design analysis of engineered alternatives reflects the current understanding of the processes that will occur in the repository, and the evaluation of feasibility is based on the current interpretation of applicable regulations. It should be noted that the EATF evaluations are limited by the information available today, and therefore do not include the uncertainties that remain unresolved at the time of this report. Some of these uncertainties and their potential effects are outlined below:

- The potential list of performance parameters that may require engineered alternatives is currently limited to only gas generation and human intrusion issues. Therefore, only these issues were considered in the selection of possible alternatives, and in the development of the Design Analysis Model. If other performance issues are identified later, the list of candidate alternatives may require modification, additional code development may be needed for the Design Analysis Model, and the feasibility of new alternatives may need to be investigated.

- The requirements of the repository, in terms of any performance improvements needed through engineered alternatives, have not been identified at the time of this report. These requirements will be identified from the PA studies. Therefore it is not possible for the EATF to recommend the best (optimal) alternative, because the extent of any improvement that may be needed is not known at this time. This limits the EATF to recommending a group of alternatives that collectively address any potential problem, rather than selecting one "best" alternative. Since the PA and EATF efforts are being conducted in parallel, the choice of an optimal alternative can be formalized only after the potential problems associated with the baseline design are quantified by the performance assessment. This issue is discussed in detail in Section 9.2.

- The design analysis of engineered alternatives is based on various assumptions regarding the different input parameters such as gas generation rate, creep closure rate, brine inflow rate, physical properties of modified waste forms, etc. These assumptions are based on the current information available in SNL studies and elsewhere. As experimental programs (DOE, 1990c) and planned analyses by SNL (DOE, 1990d) continue to provide new data, some of the EATF assumptions could change, and may lead to a need for updating the model in the future. Detailed discussion of this issue can be found in Section 4.

- The feasibility of implementing engineered alternatives is based on different assumptions for various criteria such as cost, schedule, regulatory considerations, and health and safety risk. Although items such as cost estimates developed by the EATF provide a means of rough comparison between alternatives, they should not be interpreted as absolute and precise values. The various assumptions are discussed in detail in Sections 6, 7, and 8.

- The extent of waste characterization required could dictate whether it would be necessary to treat the waste, regardless of the results of performance assessment. For example, if extensive RCRA sampling and analysis is required due to inadequate process knowledge, and if the cost of RCRA sampling is high in comparison to treating the waste, then this might force a decision in favor of treatment even if the performance assessment does not identify any problems with the current waste forms. Unfortunately, the extent of characterization required is currently not well-defined. This issue is discussed in detail later in Section 6.

Thus, given the uncertainties involved, the analysis presented in this report is based on the best available information as of today. The uncertainties are discussed in further detail in appropriate sections of the report.

The subsequent sections of this report present the analysis of the effectiveness of engineered alternatives using the design analysis model, and the feasibility of implementation of engineered alternatives. Sections 2 through 4 deal with the activities related to design analysis and modeling. Sections 5 through 8 discuss the feasibility of implementing engineered alternatives. Section 9 provides a decision methodology that can be used to select an optimal engineered alternative, if one is needed.

2.0 OVERVIEW OF THE DESIGN ANALYSIS MODEL

This section explains the different processes that are expected to occur in the repository after waste emplacement, and also discusses the modeling approach and the various assumptions that have been used in the Design Analysis Model. The criteria used in the Design Analysis Model to evaluate the effectiveness of an engineered alternative for gas generation and human intrusion are also presented in this section.

2.1 GENERAL DESCRIPTION OF THE PROCESSES SIMULATED BY THE DESIGN ANALYSIS MODEL

The Design Analysis Model simulates processes occurring in the repository (rooms, panels, access drifts, and shaft seals) for the 10,000 year regulatory period defined in 40 CFR Part 191 (EPA, 1985). The behavior of the repository can be divided into the following phases:

- Repository under Atmospheric Pressure - Activities during this phase include waste/backfill emplacement followed by sealing of the panels. During this time atmospheric pressure is maintained within the repository.
- Repository Pressurization from Atmospheric to Peak Pressure - This phase is characterized by waste compaction under creep closure, brine inflow, gas generation, possible pressure build-up, and the processes associated with increasing gas pressure and presence of brine.
- Repository after Peak Pressure - This phase is characterized by the long-term processes that continue once peak pressures are reached in the repository, interrupted only by a human intrusion event. For some alternatives this phase may not be reached if, for instance, the pressure in the repository asymptotically approaches lithostatic pressure.

The processes simulated by the Design Analysis Model are discussed below.

2.1.1 Repository under Atmospheric Pressure

The excavation of underground openings at the WIPP horizon results in a predictable disturbance of the equilibrium state of the Salado Formation. This deviation from equilibrium causes creep closure resulting in the formation of a disturbed-rock zone (DRZ). Creep closure is the viscoplastic response towards equilibrium by the rock under a deviatoric stress. Deviatoric stresses are the normal and shear stresses that remain after subtracting a hydrostatic stress, equal to the mean normal stress, from each normal stress component (Goodman, 1980). Closure rates have been measured at thirty locations throughout the WIPP, and are of the order of a few inches per year in a newly excavated room (Nowak et al., 1988).

The DRZ is defined as the zone of rock in which mechanical properties and hydrologic properties have changed in response to the excavation. The term "near-field" is used to describe the zone of rock within the DRZ, and the term "far-field" is used to describe the rock outside the DRZ in which intrinsic parameters such as porosity and permeability are undisturbed from pre-excavation values. The development of a DRZ has been confirmed by geophysical surveys and gas-flow tests, in addition to borehole observations. These three observations have defined a DRZ extending laterally throughout the excavation and varying in thickness from 1 to 5 meters, depending on the size and age of the opening. Visual observations of Marker Bed 139 (MB139) underlying the repository (Figure 1-4) indicate that fractures in this unit are both preexisting and excavation induced. The anhydrites "a" and "b" overlying the repository (Figure 1-4) are probably also fractured. The "disturbed" zone exists above and below the repository, while the "intact" zone is undisturbed, and exists beyond the area affected by the excavations. The halite between the anhydrites above and below the floor of the repository is fractured.

A panel consisting of seven rooms and associated access drifts will be filled with the waste containers (either drums or boxes). In most of the engineered alternatives that were evaluated, a backfill material (e.g. salt) is used to fill the space around and between the waste containers. The waste and backfill material is referred to as "waste/backfill composite" or "composite". The purpose of adding the backfill is to minimize void volume in the room and also reduce the permeability of the composite. This reduction in permeability results in lower release of radionuclides in the case of human intrusion into the repository. A clearance is left between the backfill on top of the waste stack and the roof of a panel as an operational work space for backfilling.

During excavations and waste emplacement, atmospheric pressure is maintained within the repository. Since the atmospheric pressure is substantially lower than the lithostatic pressure in the surrounding rocks, a depressurization of the Salado Formation around the repository will occur. This will be manifested by a gradual decrease in pressure from the far-field pore pressure in the intact Salado to atmospheric pressure in a panel. Naturally occurring gas (nitrogen and methane) is present in brine from the Salado Formation, and has been observed to exsolve from the brine due to depressurization.

Underground experience at the WIPP with the presence and movement of brine within the Salado Formation has yielded an understanding of brine movement in salt. For example, the presence and movement of brine in the Salado Formation adjacent to the underground workings is evidenced by small "weeps" (brine encrustations) that commonly develop on the walls of an excavation shortly after it is mined. These "weeps" are a result of the difference in pressure between the surrounding halite and the atmospheric pressure within the rooms and cease over time. In general, the brine inflow rate is less than the evaporation potential caused by mine ventilation, resulting in humid, but brine free conditions in the repository.

In-situ brine flow experiments are used to measure the permeability of the Salado Formation. The brine flow rates into sealed boreholes are in the range of 5×10^{-8} to 1×10^{-7} liters/s as steady states are approached. These rates have been used to calculate far-field Salado permeabilities that fall within the range of 10^{-21} to 10^{-20} m^2, using a poroelastic Darcy flow model (Lappin et al., 1989). On the basis of preliminary data, the far-field permeability of the anhydrites appears to be one to three orders of magnitude higher than that of the intact host salt.

Emplacement of the waste within a panel is followed by sealing of the access drifts and the shafts with a multicomponent seal system. The goal of the sealing system is to limit ground water from the overlying units from flowing down the shafts, limit brine and/or gas from flowing up the shafts. The panels seals will isolate the contaminants present in the waste from circulating in the air during the operational waste emplacement phase. This objective is accomplished by a combination of short-term and long-term seals as described below.

2.1.2 Repository Pressurization from Atmospheric to Peak Pressure

As long as the generated stress in the rooms is below lithostatic, the Salado will continue to creep due to deviatoric stresses, thereby reducing the room dimensions. As a result, the clearance above the waste composite will be eliminated and the void space within the waste/backfill composite will be reduced.

The creep that continues to compact the waste/backfill composite will be resisted by the combination of two different mechanisms. The first of these is the ability of the particular waste/backfill composite to resist compaction, manifested by its effective stress. The effective stress is the stress that is transferred between the solid particles of the waste/backfill composite. The other is the effect of gas pressure within the void spaces. The increasing gas pressure provides a second component of internal stress resisting creep. As creep ceases, the development of the DRZ ceases and may actually begin to reverse caused by healing of the fractures.

The brine will continue to seep into the panels due to a pressure differential between the panels and the Salado formation. Corrosion of drums and metals in the waste under anoxic conditions will consume large quantities of water in the brine (if present), producing hydrogen. Microbial activity by a potentially broad range of microbes, which may be aerobic, anaerobic, halophilic, or halotolerant, is assumed to consume cellulosic materials and perhaps other organic materials in the waste as well. This activity will produce carbon dioxide and methane, and may also produce nitrogen and hydrogen sulfide. The hydrogen sulfide will probably be removed by reacting with the metals or their corrosion products to form sulfide minerals. Radiolysis of brines, cellulosic materials, plastics, and rubbers, will consume water and degrade the organics to produce limited amounts of carbon monoxide, carbon dioxide, hydrogen, and oxygen. Carbon dioxide may be removed from the gas phase by reacting with cementitious materials present as part of the waste or backfill to form carbonate minerals (calcite, dolomite, magnesite, etc.). The combination of gas generation due to the mechanisms described above, and the decrease in void volume due to creep closure, will result in pressurization of the panel.

Increased gas generation will increase the partial pressures of the gases and their solubility in brine. This will cause additional gas to dissolve in the brine that may be present in the room. The increased concentration of gases in the brine will be the driving force for diffusion of gases into the intact Salado.

In addition to diffusion, advection into the Salado formation could occur as the gas pressure increases within the panel. This process involves the migration of gases under a pressure gradient from the room into the halite and anhydrites that make up the Salado formation. The ability of the Salado to advect gases will depend on: (1) the intrinsic permeability of each bed; (2) the relative brine and gas saturations of these beds; (3) any capillary or threshold-pressure effects involved in gas displacement of brine already present; and (4) the amount of localized depressurization which exists due to the operational phase. Ongoing work suggests the threshold-pressure within the intact Salado halites may be as high as 8 MPa. Therefore, the sum total of the threshold pressure and the in-situ pore pressure may prevent gas advection into the halite. However, if some fractures exist within the DRZ, connecting the panel to the anhydrite beds, gases will be dissipated due to the higher permeability (therefore lower threshold pressure) and lower pore pressure of the anhydrites. Advective processes would allow some gas to escape from the panels, thus lowering the pressure in the disposal rooms.

The proposed short-term seals consisting of concrete plugs and possibly clay materials are designed to function for approximately 100 years after decommissioning. The long-term seals are made of crushed salt that is chemically and mechanically compatible with the host rock formation. Creep closure of the surrounding intact host rock consolidates and densifies the crushed salt to a condition comparable to intact salt.

2.1.3 Repository after Peak Pressure

Gas generation due to microbial degradation of solid organic components of the waste such as paper, cloth, wood etc. would be terminated after peak pressure is reached. Any brine remaining in the panel would have been consumed by anoxic corrosion of the metals. No further brine inflow would take place because the pressures in the panel equal or exceed the far-field pressure of the Salado Formation. Since the water present in the brine would be consumed, reactions of carbon dioxide with cementitious materials would also cease, since these reactions require water.

The mechanical resistance to closure prevents further creep during the late phase, resulting in a cessation of waste/backfill compaction. This mechanical resistance is made up of two components: (1) the stress of compaction and (2) the interstitial fluid pressure. When the sum total of these components becomes greater than the lithostatic pressure, the deviatoric stress is eliminated and creep ceases. At this point, the void volume becomes fixed at a constant value.

Gas advection will continue as long as the pressure within the panel is such that a driving force into the Salado is maintained. Once the pressure in the repository is lithostatic, the driving force is terminated and the system reaches a steady state condition.

2.2 DESIGN ANALYSIS (COUPLED PROCESSES) MODEL

The components of the Design Analysis Model (the ROOM-SCALE model and the SHAFT-SEAL model) are defined according to the physical barriers that will exist following waste emplacement at the WIPP. These barriers and modeling regions (Figure 2-1) are:

- The host rock and panel seals surrounding the rooms and drifts. The seven rooms and the equivalent volume of five and one-half rooms existing in the access drifts within a panel (12.5 room equivalents), are modeled on a collective basis to most accurately approximate the conditions within a storage panel at each time step. The modeling is done using the ROOM-SCALE component of the Design Analysis Model as described in Appendix B.

- The shaft and panel seals. The permeabilities of the seals are obtained as a function of time using the SHAFT-SEAL component of the Design Analysis Model as described in Appendix C.

The Design Analysis Model considers the processes that are essential to predicting changes in performance resulting from the application of alternative repository designs and waste forms. The conceptualization of the repository including the physical orientation and the associated values for the Salado formation is shown in Figure 2-2. The simulation by the Design Analysis Model of the processes described earlier is summarized below.

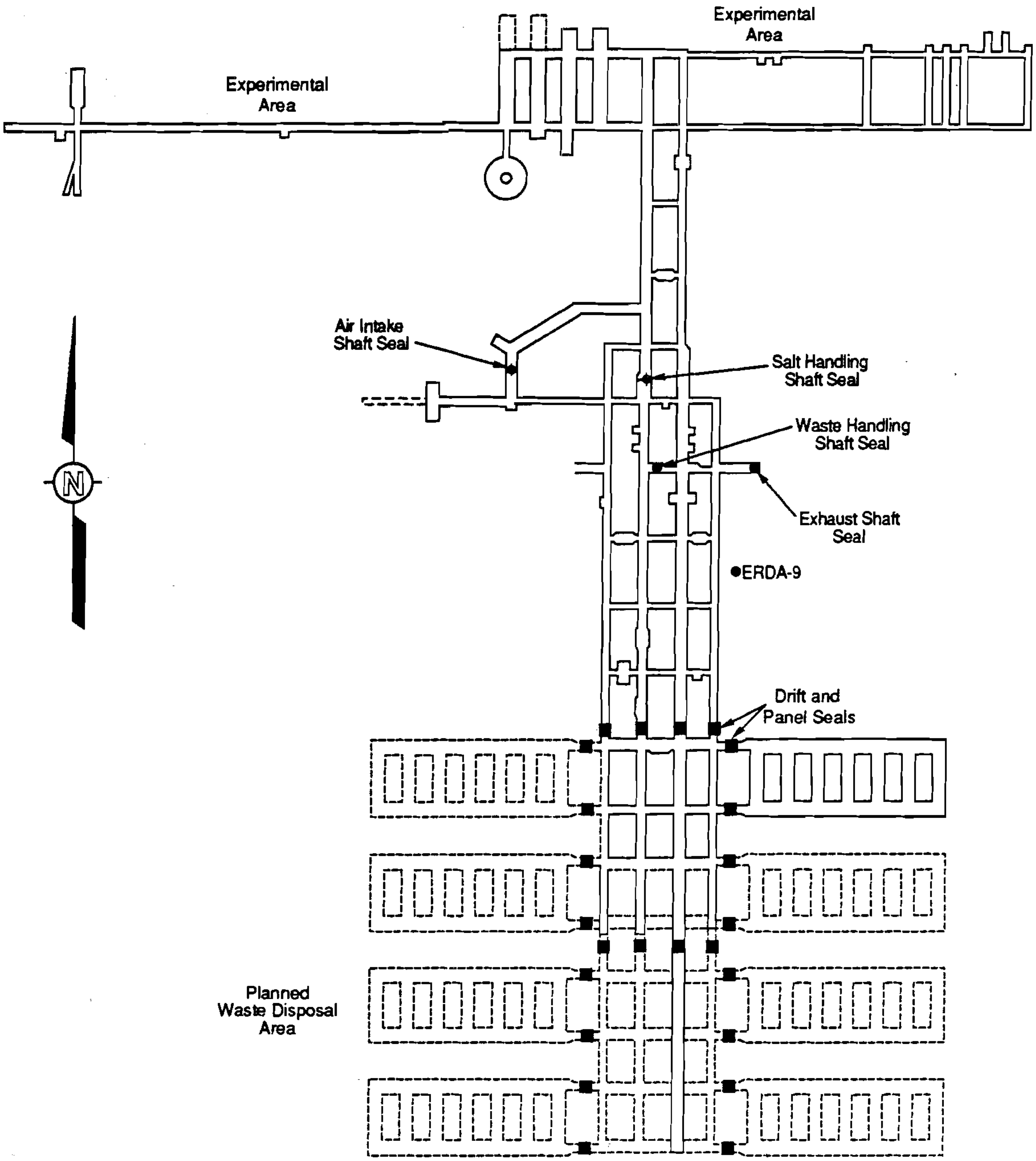

Figure 2-1
Plan View with Proposed Seal Locations
(Marietta et al., 1989)

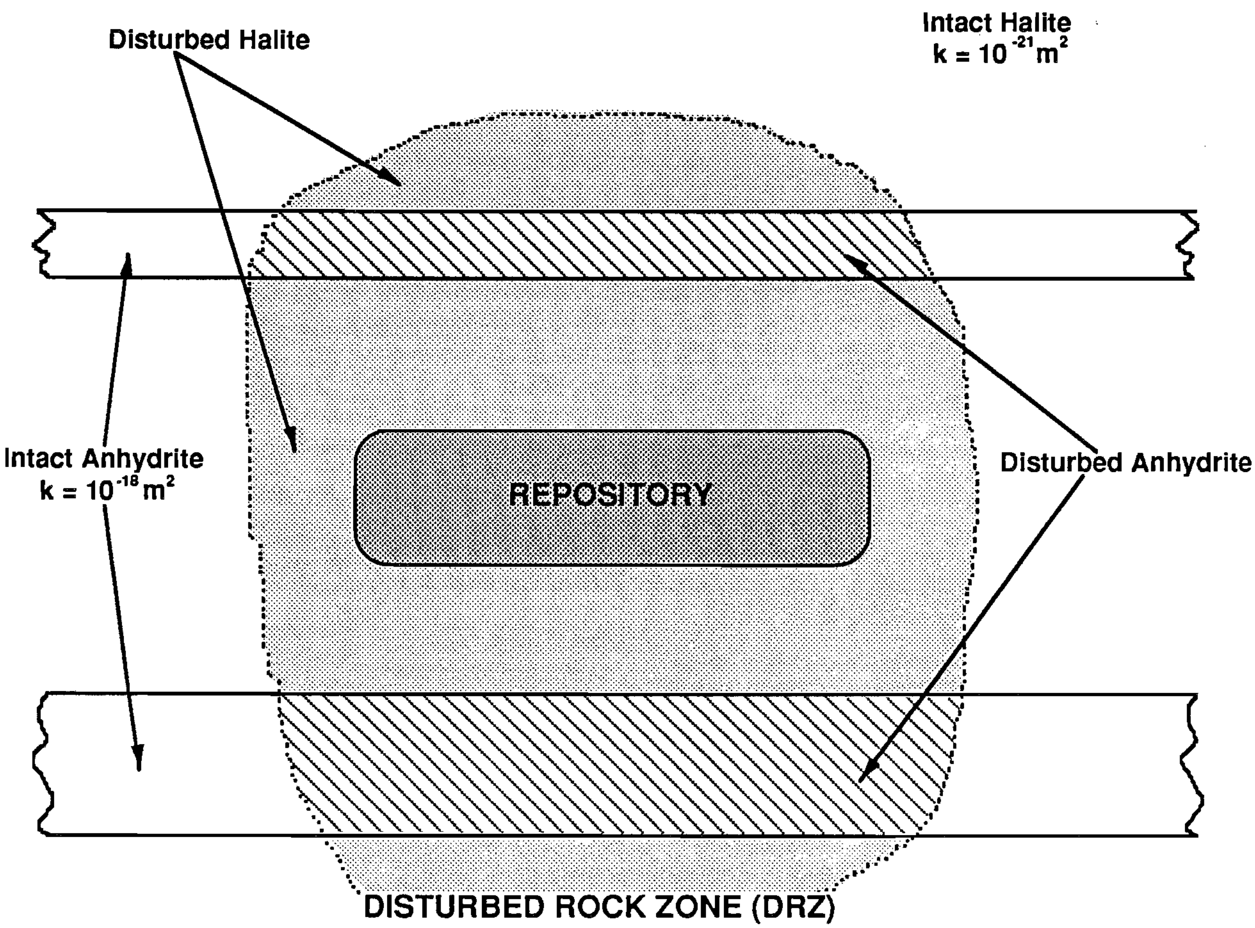

Figure 2-2. Conceptualization of Repository within Salado Formation

- Creep Closure of the Surrounding Host Rock (Appendix B, Section 2.4) - The Chabannes (1982) equation has been combined with a nonlinear regression equation based on several years of measured closure rates at 30 locations in the WIPP to predict creep closure rates of the host rock as a function of time. This equation expresses creep closure rates at each time step as a function of the room height, the room width, and the difference between lithostatic stress (14.8 MPa), and the internal stress in the panel. The internal stress is the sum of the effective stress of the waste/backfill composite and the fluid pressure inside the panel.

- Gas Generation and Consumption - There are four processes related to gas generation and consumption: anoxic corrosion, microbial gas generation, radiolysis, and dissolution of gases in brine. These are described below:

  - Anoxic Corrosion (Appendix B, Section 2.13)

    The dominant corrosion reaction is assumed to be the reaction of iron, usually in the form of mild steel, with water to generate amakanite and hydrogen according to the reaction:

    $$Fe + 2H_2O = Fe(OH)_2 + H_2$$

    This reaction generates one mole of hydrogen for every two moles of water consumed.

    At each time step, brine in a storage room (if available) is assumed to react with iron or steel to generate hydrogen at a maximum rate of 1.7 moles of hydrogen/drum/yr (Lappin et al., 1989). This hydrogen generation rate requires the availability of 5×10^{-5} m^3 of water/drum/yr. If the brine (water) availability is less than the amount required for maximum hydrogen generation, the rate is scaled down based on the amount of water available for corrosion. This corrosion process is thus self-limiting since the hydrogen that is generated contributes to the pressurization of the room, which in turn inhibits brine inflow.

  - Microbial and Radiolytic Gas Generation (Appendix B, Section 2.12) - The total potential for microbial gas generation, along with the rate of generation, have been modeled based on the data of Lappin et al. (1989). Based on the information provided therein, the following assumptions have been incorporated for modeling purposes:

    - Since microbial activity and radiolysis utilize the same organic substrates, the gas generation rate of 0.85 moles/drum/year (Lappin et al., 1989) is assumed to represent both microbial and radiolytic gas generation.

    - Microbial activity is not assumed to be limited by the availability of brine.

    The microbial gas generation assumptions used in modeling the baseline case are explained in detail in Appendix B, Section 2.12, and can be summarized as follows:

- During the first 100 years after decommissioning of the repository, oxygen is completely consumed (aerobic microbial activity) with an equivalent molar production of carbon dioxide. Anaerobic microbial activity is assumed to commence only after this period of 100 years.

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

- Thus, anaerobic microbial activity begins 100 years after the start of the simulation, and lasts for a period of 713 years. The gases generated are assumed to be methane, carbon dioxide, and nitrogen in the ratio of 15:20:12.

- Dissolution of Gases in Brine - The moles of hydrogen, oxygen, and carbon dioxide dissolved in the brine present in a panel are evaluated at each time step (Appendix B, Sections 2.9 and 2.10). The moles of gas dissolved are calculated from phase equilibria relations using Henry's Law constants in brine (Reid et al., 1987). The Henry's Law constants and gas solubilities are evaluated from experimental correlations. The dissolution of nitrogen and methane is not considered since the brine already contains significant amounts of these gases (DOE, 1983).

- Brine Inflow (Appendix B, Section 2.3)

  - An initial brine inflow rate of 0.43 cubic meters/room/year (Nowak et al., 1988) is assumed. This is based on a constant room pressure of 1 atmosphere.

  - The rate of brine inflow is assumed to linearly decrease as fluid (brine and gas) pressure in the room increases, and approaches zero when the pressure in the room reaches lithostatic pressure (14.8 MPa). Lithostatic rather than hydrostatic is used since measurements have been made of pore pressures which exceed hydrostatic (Lappin et al, 1989). This approach couples brine inflow to creep closure and gas generation, because all of these processes affect fluid pressure in the room.

- CO_2/Brine/Cement Interactions (Appendix B, Section 2.14 and Appendix E) - Carbon dioxide generated by microbial or radiolytic processes will partition into any brine present in the room. This dissolved CO_2 will then react with portlandite to produce calcite plus water according to the reaction shown below. Portlandite is a dominant phase in Portland cement and is available in the cementitious materials present in the waste.

  - The pH of any brine in the room is assumed to be buffered by portlandite that is present in the cement waste. CO_2 will react with portlandite to yield calcite and water according to the reaction:

$$CO_2 + Ca(OH)_2 = CaCO_3 + H_2O$$

- The reaction rate is assumed to be proportional to the volume of free brine in the room, and the reaction stops when either all of the portlandite or the brine/water in the room is consumed.

- Water that is generated by the above reaction is added to the total number of moles of water in the room.

- Diffusion of Gases into the Host Formation (Appendix B, Sections 2.2 and 2.11) Since undisturbed Salado brines at lithostatic pressure have significant amounts of dissolved N_2 and CH_4 (DOE, 1983), it is assumed that diffusion of these gases is negligible due to the lack of concentration gradients necessary to drive diffusive transport. Similar data were not available for H_2 and CO_2, and therefore these gases have been considered for their diffusion into the host rock.

- Advection of Gases into the Host Formation, Across Seals, and into the Overlying and Underlying Anhydrite Beds (Appendix B, Section 2.6) - The host formation, panel and shaft seals, and the intact anhydrite beds are modeled as parallel routes for the advection of gases out of the panel. The following assumptions and information are being used for modeling purposes:

  - The permeability of the intact halite ranges from $1 \times 10^{-23} m^2$ to $1 \times 10^{-18} m^2$ with an expected permeability of $3.4 \times 10^{-21} m^2$ (Rechard et al., 1990).

  - The permeability of the intact anhydrite beds is estimated to be 2 to 3 orders of magnitude greater than the halite (10^{-18}), and as such is assumed to be the most probable pathway for gas advection (Lappin et al., 1989).

  Other assumptions include:

  - The halite between each room and the anhydrites is fractured such that there is hydrological communication between the rooms and the disturbed anhydrite.

  - The anhydrite beds above and below the repository are extensively fractured due to excavation of the drifts and panels, and therefore all panels and rooms within each panel are in equilibrium with respect to gas pressure.

  - The disturbed anhydrites above and below the repository are assumed to be saturated with brine at the time of WIPP decommissioning.

  - The intact anhydrites, and the halite layers above and below the repository (outside the DRZ), are assumed to be saturated with brine at pore pressures of 10.36 MPa (70% of lithostatic) and 14.8 MPa (lithostatic), respectively. For the sake of modeling, the pressures in the intact Salado are chosen to provide the largest driving force for brine migration. Since there are measured values of the pore pressure approaching lithostatic, it has been chosen as the value for the far-field pressure of the brine.

  - When the panel fluid pressure exceeds the assumed intact anhydrite pore pressure, the brine in the disturbed anhydrite is assumed to be driven into the undisturbed anhydrite.

- When the panel fluid pressure exceeds the assumed intact halite pore pressure, additional brine is driven from the disturbed anhydrite into the intact halite layer above and below the repository.

- The flow of brine from the disturbed anhydrites to the intact anhydrites and Salado layers, is assumed to be governed by Darcy's equation of flow through porous media.

- The volume from which the brine is expelled is assumed to provide an additional void volume for panel gases to occupy.

A program simulating two-phase flow is used to derive a parametric equation for the advection rate into the intact anhydrites when the panel fluid pressure exceeds 11.3 MPa (brine pore pressure of 10.36 MPa plus a threshold pressure of 0.94 MPa (Davies, 1989)). Concurrently with gas advection into the anhydrites, the advection of panel gases into the four shaft seals (conductance varying with time) is also simulated (Appendix B, Section 2.7). A viscosity correlation which is valid at both low and high pressures is used to estimate the viscosity of the gas mixture for use in the advection calculations.

- <u>Gas Compressibility (Appendix B, Section 2.16)</u> - The Lee-Kessler Equation of State (Reid et al., 1987) is used to estimate the compressibility of the gas mixture in a panel at each time step. The fluid pressure is updated based on the resulting value of compressibility. The fluid pressure is then used to estimate molar advection rates of gases, volume of brine inflow, creep closure rates, and gas solubilities in brine during the next time step.

- <u>Waste/Backfill Composite Compaction and Resulting Mechanical Resistance to Closure (Appendix B, Section 2.15)</u> - Stress/density relationships have been obtained for each waste form and backfill material from literature and experimental data. For each engineered alternative, an average density (based upon the mass fraction and density of each component) is calculated at various stress levels of compaction. The density of the waste/backfill composite is evaluated at each time step. The effective stress corresponding to this density is evaluated using the stress/density relationships of the composite. This effective stress is then used as input to the Chabannes equation (see discussion on creep closure above) as the mechanical component of resistance to creep closure.

- <u>Development of a Zone of Enhanced Porosity Surrounding the Panel (Appendix B, Section 2.17)</u> - The creep of the host rock 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 (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.

  - It is assumed that all the pores in this zone are interconnected.

- Future Human Intrusion Into the Repository (Appendix B, Section 2.18) - Three human intrusion events (Figure 2-3) were evaluated to determine the relative effectiveness of each engineered alternative in reducing radionuclide releases. The three scenarios, the modeling procedure for each scenario, and the assumptions behind them are described as follows:

  - The E1 scenario (Marietta et al., 1989) (Figure 2-3a) assumes a borehole penetration through a waste-filled panel and continuing into or through a pressurized brine pocket existing in the underlying Castile Formation (Figure 1-2). In actuality, the E1 scenario begins with the E2 scenario, but the amounts of brine located within the room are extremely small compared to the brine transported from the Castile through the waste, and therefore the E1 scenario neglects any effects from the E2 scenario. This event was modeled using a parametric equation relating flow rate through the waste/backfill composite to the hydraulic conductivity of the composite. This equation was developed by statistically regressing data resulting from a series of computer runs using the flow and transport code SWIFT III (Reeves et al., 1986).

    The modeling associated with the E1 scenario is performed on a room basis, since only the area surrounding the actual borehole allows the brine to come in contact with the waste. In order to verify this, the SWIFT III was used to determine the velocities of the fluid flow through the waste/backfill composite. A bounding brine velocity was chosen such that in 5000 years a fluid particle would not be able to move a distance equal to the height of the room. This velocity defined a radius of influence used to calculate an effective wash-through volume. This volume was simulated as an ellipsoid, with the major axis along the borehole and the other axes into the room. If the conductivity of the waste/backfill composite was such that the effective radius was greater than the width of the room, the width of the room was chosen for one of the axes since the halite was considered to be impermeable. The other axis was allowed to continue to the edge of the room, but in no case did the effective radius exceed half of the length of one room. The assumption of an infinite reservoir of brine in the Castile allows a constant pressure of 16 MPa to be prescribed for the brine pocket.

  - The E2 scenario (Marietta et al., 1989) (Figure 2-3b) assumes a borehole just penetrating into the repository, not passing through. This scenario is modeled using an analytical solution to the radial flow equation through a porous media, simulating the borehole and the panel as concentric circles. The halite is considered to be an impermeable boundary that is located at a sufficient distance to allow the volume of the cylinder to be the volume of a panel. Simplifying assumptions regarding the flow of gas and brine are made. In actuality, the gas phase would be located towards the top of the panel and the brine phase would be located towards the bottom of the panel. In fact, the amount of brine predicted by the model to be present in the panel at 5,000 years would not be enough to fill the borehole to reach the Culebra. The gas being less viscous and towards the top of the panel, would tend to escape preferentially to the brine, thereby reducing the room pressure.

    For the purposes of comparing alternatives, a hypothetical "fluid" with the properties of brine is used. This fluid is comprised of the appropriate

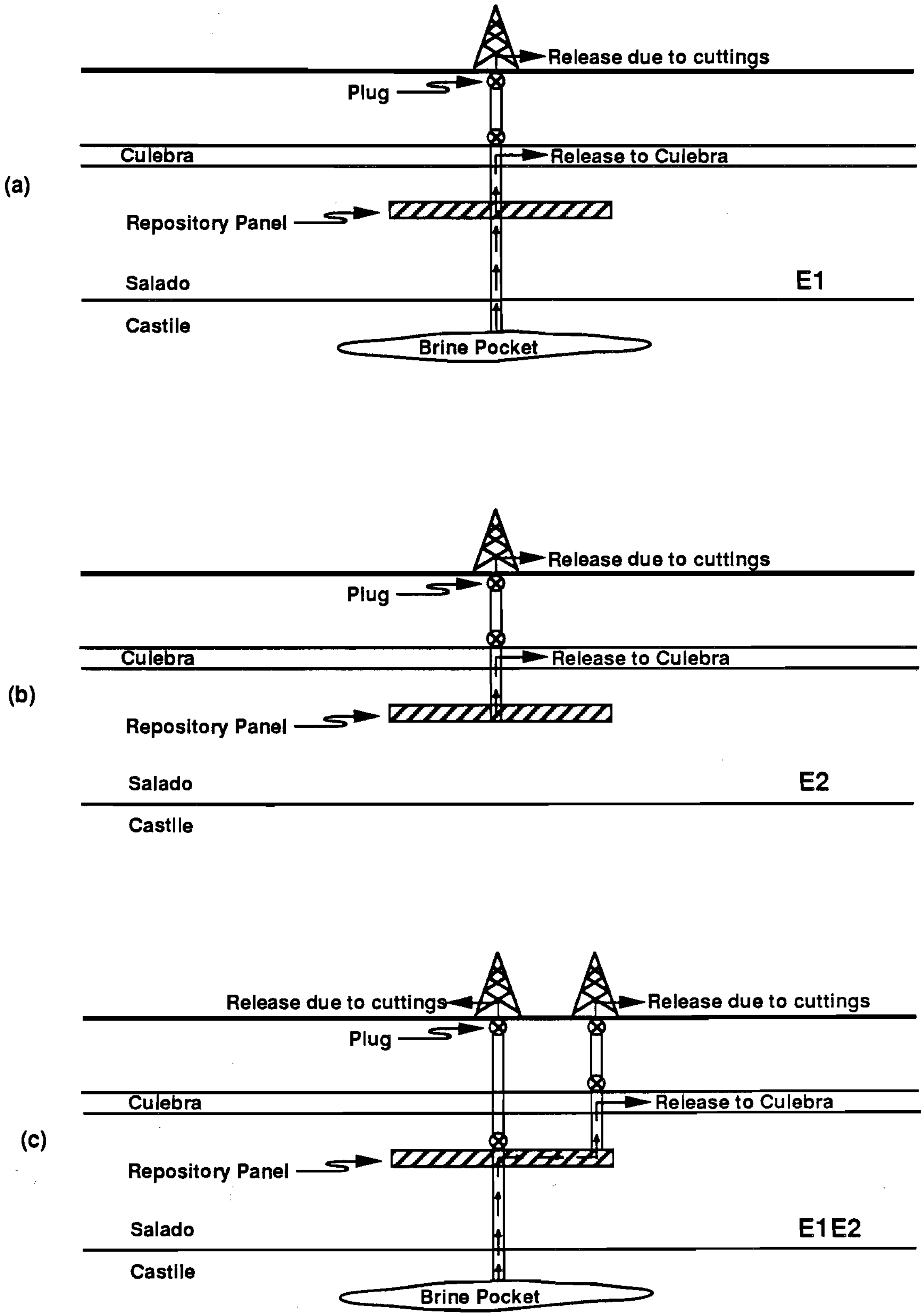

Figure 2-3. Human Intrusion Scenarios

3.0 PHYSICAL AND CHEMICAL PROPERTIES OF THE WASTE/BACKFILL COMPOSITE

3.1 INTRODUCTION

Quantitative estimates of physical and chemical properties for the combination of waste and backfill are required for the Design Analysis Model to determine the relative effectiveness of an engineered alternative. In this section, the term "properties" refers to the physical and chemical properties of a homogeneous composite material consisting of waste and backfill (hereafter referred to as "waste/backfill composite" or "composite"). The properties of a particular engineered alternative are in most cases unique to that alternative; in some cases, similarities occur from one alternative to another. Properties of the composite such as density, porosity, hydraulic conductivity, and effective waste volume are quantified as a function of compaction stress level. The effective waste volume is defined as the volume of the waste/backfill composite minus the volume of the backfill along the sides of the waste stack. This parameter is used in the Design Analysis Model to calculate radionuclide releases to the surface due to removal of drill cuttings (Appendix B, Section 2.22). In addition, gas generation potentials are provided to the Design Analysis Model.

The following sections briefly list the properties developed (Section 3.2), discuss the assumptions made in developing properties for the baseline case and for the different alternatives described earlier in Section 1.3 (Section 3.3), sources of data (Section 3.4), and finally, the quantification of the properties (Section 3.5 and 3.6).

Some of the important properties are coupled; an example is hydraulic conductivity and permeability. Assuming a fixed value for permeability, a mathematical relationship exists to determine hydraulic conductivity. Density and porosity are similarly related.

3.2 COMPOSITE PHYSICAL AND CHEMICAL PROPERTIES

The development of physical and chemical properties for each alternative assumes the waste/backfill composite to be a homogeneous mixture. Five physical and chemical properties of the waste/backfill composite are required as input to the Design Analysis Model:

- Density
- Porosity
- Hydraulic conductivity
- Gas generation potential
- Effective waste volume.

Investigations in radionuclide solubility (Rai et al., 1983; Felmy et al., 1989; Marietta et al., 1989) have shown variabilities of six orders of magnitude. The EATF has therefore assumed a value of 1 x 10^{-6} molar for all radionuclide solubilities.

3.3 WASTE FORM DISTRIBUTION

The effectiveness of Alternatives 1 to 14 (Table 1-2) is evaluated relative to the baseline case. The baseline case is defined as "as received" waste emplaced in the current repository room design and backfilling with crushed salt. "As received" waste composition is assumed to comply with the Butcher (1989) classification of the waste destined for the WIPP, which can be generalized into the three major waste form categories.

The three major waste forms comprise most of the TRU waste inventory. On a volumetric basis, the proportions of the three major waste forms for the baseline case are assumed [based on DOE (1988c)] to be:

- 40 Percent Solid Organics (combustible)
- 40 Percent Solid Inorganics (glass/metal)
- 20 Percent Sludges.

These proportions were developed from the inventory description in Butcher (1989) by grouping waste types with similar physical properties. This proportional distribution for the baseline case is maintained for comparison of each alternative studied, ensuring no calculational bias. Specifying this ratio reduces the number of sensitivity runs necessary to establish the relative effectiveness of the alternatives. In addition to the proportional distribution of waste forms, the initial volume of waste contained in a repository room is assumed constant. Discussion with Westinghouse Engineering (Garcia, 1990) and review of Lappin et al. (1989) indicate variation in the assumed quantity of waste to be placed in WIPP repository rooms and drifts. In this analysis, the current repository design is assumed to contain 6,000 55-gallon drums of TRU waste per room.

The initial conditions for the baseline case waste distribution parameters are listed in Table 3-1. These values, along with the density of each component as a function of stress (from creep closure), are used in computing the composite physical and chemical properties.

3.4 DATA DEVELOPMENT FOR ALTERNATIVES

The raw data necessary for computation of waste/backfill composite properties were obtained from several sources. These sources include:

Required. These three parameters are interrelated based upon the amount of gas pressure within a panel.

The Peak Index Pressure is the maximum pressure in a room predicted by the Design Analysis Model. This is based upon the gas generation properties of the final waste form resulting from a particular alternative, and also upon the resulting void volume in the room. The Peak Index Pressure for a particular alternative is compared with the lithostatic pressure to evaluate the effectiveness of that alternative with respect to gas generation. This is also expressed as a percentage of lithostatic pressure for purposes of comparison.

The Excess Gas Energy is based upon the amount of stored energy, which is represented by the gas which is in excess of lithostatic pressure. This is equal to the pressure in excess of lithostatic multiplied by the void volume which it occupies.

For alternatives in which the Peak Index Pressure does not exceed lithostatic, the Excess Gas Energy is zero. The closer this number is to zero, the better the alternative is in relation to minimizing the amount of excess energy in the system due to gas pressure.

The Additional Volume Required is a measure of the amount of additional volume that would be required for the pressure in a panel to return to lithostatic pressure. A further description of this parameter may be found in Section 4.0.

2.4 CRITERIA FOR EVALUATION OF EFFECTIVENESS OF ALTERNATIVES FOR ADDRESSING HUMAN INTRUSION SCENARIOS

A parameter called the "Measure of Relative Effectiveness" was defined for each alternative in order to quantitatively compare the different alternatives in relation to human intrusion by using the Design Analysis Model. This factor is a measure of the improvement in the performance of the alternative design, compared to the baseline design. The criterion used to measure this improvement is the estimated cumulative release of radionuclides to the Culebra Dolomite in the event of human intrusion. The ratio of the cumulative release of radionuclides for an engineered alternative to the release under baseline conditions is the "Measure of Relative Effectiveness" for that particular alternative. In other words:

$$\text{Measure of Relative Effectiveness} = \frac{\text{Cumulative Release of Radionuclides Using the Alternative Design}}{\text{Cumulative Release of Radionuclides Using the Baseline Design}}$$

For the baseline case, the Measure of Relative Effectiveness is 1. The lower the value of this factor, the more effective the alternative is in improving repository performance relative to the baseline case.

In summary, the Design Analysis Model has been developed by the EATF to simulate the behavior of the repository after waste emplacement. The model analyzes 14 combination alternatives (Table 1-2) relative to the baseline design with respect to their effectiveness for addressing possible gas generation and human intrusion issues. The results of the effectiveness evaluation of the 14 combination alternatives are discussed later in Section 4.0.

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volumetric proportions of gas and brine, which are predicted by the model for each alternative. This fluid is assumed to saturate the room and be transported to the Culebra through the borehole. The amount of radionuclides within the brine portion of the fluid that is released are then compared for each alternative.

- The E1E2 scenario (Marietta et al., 1989) (Figure 2-3c) 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. This borehole is capped above the repository such that no brine can move vertically to the Culebra. The other borehole (occurring later in time) provides a pathway from the repository to the Culebra Dolomite. This pathway consists of a flow path through the panel from the E1 borehole to the E2 borehole. No credit is taken for any processes which may occur or change during the interim between the first and second boreholes. This scheme results in a pressurized flow path directly through the waste/backfill composite.

  The flow rate through the waste is obtained from the analytical solution to the one-dimensional flow equation through porous media, assuming the two boreholes are separated by the length of one room (300 ft., 91.44 m). Any effects of the pressure in the room being greater than the pressure of the Castile brine pocket, are neglected due to the assumption of an infinite brine pocket. It should be noted that the E2 scenario is a part of the E1E2 scenario. This happens when the second borehole breaches the repository potentially releasing any gases and brine initially located there. This is neglected because the amount of brine originally located in the panel would be extremely small in comparison to the volume produced from the Castile brine pocket.

The following assumptions have been applied to all human intrusion scenarios:

- The intrusion occurs 5000 years after decommissioning.

- The diameter of the borehole is 0.14 meter based upon an average borehole area obtained from Marietta et al. (1989, Table 3-10).

- The hydraulic conductivity of the waste/backfill composite is the weighted geometric mean of the waste forms and backfill properties (explained in detail in Section 3.5.3).

- The borehole conductivity is 1×10^{-3} meters/second (clean sand/gravel) obtained from Freeze and Cherry (1979, Table 2-2).

- Waste element solubilities have been assumed to be 1×10^{-6} mol/liter from Marietta et al. (1989, Table 3-10).

The activity of each radionuclide at the time of intrusion is computed using the solutions to differential equations that represent mass balances for each radionuclide (Appendix B, Section 2.20). Based upon the radionuclide solubilities in brine and the volume of brine released, the cumulative activity of each radionuclide released to the Culebra was determined. The objective of these human intrusion simulations is to calculate a number which is similar in functional form to the EPA Summed Normalized Release (EPA, 1985); the difference being that the Design Analysis Model calculates the cumulative release of radionuclides into the Culebra. Alternately, the EPA Summed Normalized Release specifies calculation of the cumulative activity of each radionuclide across the regulatory boundary, and in addition, employs scenario probability weighting to each release (EPA, 1985).

The Design Analysis Model does not consider probabilities of occurrence of scenarios; the scenario is assumed to occur and the effectiveness measure is evaluated. The value generated by the Design Analysis Model is the singular raw score for the effectiveness of each alternative design. Calculation of the measure of relative effectiveness is performed by dividing the effectiveness measure for the alternative by the effectiveness measure for the baseline case (Section 2.4). The baseline case uses "as received" waste with crushed salt backfill. "As received" waste is defined as follows:

- Sludges with some cement added as solidifying agents [i.e., current processes at the Rocky Flats Plant (RFP) for Content Code 111], but not a concreted monolith (DOE, 1989e).
- Solid organics and inorganics are in unshredded form, wrapped in multiple layers of plastic, inside a 90-mil rigid liner in a steel drum [i.e., current packaging at RFP and most other sites (DOE, 1989e)].

The improvement resulting from a waste form modification or a repository design alteration is determined by comparison with the baseline case. For the baseline case, the assumptions are as follows:

- Each room is assumed to be filled to capacity (considered to be 6,000 drums) with "as received" waste and backfilled with crushed salt.
- The initial room dimensions used in the calculations are 13 feet (3.96 m) high by 300 feet (91.44 m) long by 33 feet (10.06 m) wide (Lappin et al., 1989).
- A two-foot high clearance is assumed to be left above the waste/backfill composite in all rooms and drifts in the panel.
- The panel capacity (including the seven storage rooms and the surrounding access drifts as in Figure 2-1) is assumed to be approximately 12.5 times the capacity of one individual room.
- The panel and shaft seals are assumed to be in place.

2.3 CRITERIA FOR EVALUATION OF EFFECTIVENESS OF ALTERNATIVES FOR ADDRESSING GAS GENERATION

Selected alternatives (described earlier in Table 1-2) were quantitatively evaluated using the Design Analysis Model for their effectiveness for addressing gas generation. The criteria of evaluation included Peak Index Pressure, Excess Gas Energy, and Additional Volume

TABLE 3-1

INITIAL CONDITIONS FOR THE BASELINE CASE

WASTE FORM	NUMBER OF 55-GALLON DRUMS PER ROOM[1]	AVERAGE DRUM WEIGHT (kg)[2]
Solid Organics (combustible)	2400	77
Solid Inorganics (glass/metal)	2400	102
Sludges	1200	211
Total Drums	6000	

Backfill Material	Quantity[3] (m^3)	Void Space Between Drums[4] (m^3)
Crushed Salt	1215	402

[1] Number of drums is computed from the distribution of waste forms (pg. 3-2) and the total number of drums per room (pg. 3-2).

[2] Average drum weights are obtained from Butcher (1989).

[3] Volume of backfill is obtained by computing total initial room volume and subtracting the volume of 6000 55-gallon drums, the ventilation space, and the assumed volume resulting from inefficiencies in backfilling (see 4 below).

[4] Void space between drums is the assumed inefficiency in backfilling. For the baseline case it is assumed that half of the volume available for backfilling within the waste stack is not occupied by salt. In other words, backfilling between the drums is assumed to be only 50% efficient. This assumption results from uncertainties in backfill emplacement methodology and the slip sheets between layers of drums. It should be noted that at 100% backfilling efficiency, some void volume will still be present as a result of the porosity of naturally packed salt.

- Information such as mass reduction and volume reduction factors from processing facilities located at Los Alamos National Laboratories (LANL), Idaho National Engineering Laboratory (INEL), Rocky Flats Plant (RFP), Pacific Northwest Laboratory (PNL), and Savannah River Site (SRS)

- SNL (e.g., Molecke, 1979; Butcher, 1990a; Butcher 1990b; Butcher et al., 1990; Stinebaugh, 1979).

The following sections describe various waste treatments, and include data sources used for obtaining the properties of waste forms resulting from these treatments. The waste treatments described here are all single alternatives, and have been used as components of Alternatives 1 to 14, which were listed earlier in Table 1-2.

3.4.1 Incineration

Incineration of the combustible components of TRU waste leads to an overall reduction in waste volume. Since the EAMP evaluated incineration on the basis of the Process Experimental Pilot Plant (PREPP) process, (Appendix A), the volume reduction factors reported in Table 3-2 are also based on the PREPP process (Halford, 1990). It should be noted that the process will not be operational, but the EATF has used the data from the process for the sake of consistency with the EAMP evaluations. The process involves shredding, incineration and cementation of solid organic and solid inorganic waste forms (in the PREPP process both waste and drums would be processed). Application of the PREPP process would result in volume reductions for both solid organic and solid inorganic waste forms.

The mass reduction factor in Table 3-2 applies only to solid organic waste and is based on work done at the Waste Experimental Reduction Facility (WERF). As the solid organic waste is incinerated, organics are oxidized to form combustion product gases consisting primarily of carbon dioxide and water which are removed from the waste stream. Solid inorganic waste, when incinerated, yields no appreciable mass reduction.

3.4.2 Cementation

Cementitious materials in either grout (self-leveling mixtures) or concrete (mixtures containing aggregate which "slump") formulations are used in five applications:

- Cemented sludges
- Shredded and cemented solid organics (combustible)
- Shredded and cemented solid inorganics (glass/metal)
- Incinerated and cemented solid organics
- Grout backfill.

TABLE 3-2

INCINERATED WASTE CHARACTERISTICS

PARAMETER	WASTE FORM	RATIO
Volume Reduction Factors[1]	Solid organics (combustible) Solid inorganics (glass/metal)	3:1 2:1
Mass Reduction Factor[2]	Solid organics (combustible)	20:1

[1] Volume Reduction Factors are based on the PREPP process (Halford, 1990) which would entail shredding, incinerating and cementing solid organics and solid inorganics. In the PREPP process, both waste and containers would have been processed. The EAMP's qualitative assessment of incineration was also based on PREPP methodology.

[2] Mass Reduction Factor applies only to the incineration of solid organics. The mass reduction factor is based on WERF data (Hunt, L., 1990).

NOTE: Waste forms classified as "solid organics" or "solid inorganics" may contain significant amounts of other materials. For example, solid inorganic waste forms such as laboratory glassware may contain amounts of solid organics such as plastic bags containing the glass. Thus, in order to completely destroy all organic material, the "solid inorganics" are processed through the incinerator.

An example of sludge processing involves mixing the sludge with cement (dry powder) which absorbs free water (Petersen et al., 1987). Cementation of sludges (as defined in this report) results in a monolithic form which is assumed to possess physical properties similar to those of an ordinary Portland cement (OPC) monolith. Cementation of incineration residue or shredded waste is significantly different in that the addition of ash and/or shredded metal can alter some of the properties, such as density. For the purpose of this report, a mixture of ash, OPC, and shredded metal waste is assumed to have the same hydraulic conductivity as a mixture of OPC and ash. Physical properties for a salt aggregate grout backfill have been estimated on the basis of recommendations by the Expert Panel on Applications of Cement Materials for Use at the WIPP (Appendix G). For the purpose of this report, the physical properties of grout backfill are the same as those reported for Type 10 grout by Coons et al. (1987). Properties of single alternatives that involve cementation are listed in Table 3-3.

3.4.3 Vitrification

The term "vitrification" is used to refer to any process that results in a vitrified (glass) waste form as described below:

- "Vitrification of sludges" refers to melting the sludge; e.g., addition of energy using a microwave (Petersen et al., 1987) or an induction melter. Depending upon the composition of the sludge, silica may be added prior to melting.
- "Incineration and vitrification process" refers to incineration of solid organics and ash melting or fusing of residue into a glass matrix.
- Melting metals -- under proper conditions radionuclides can be partitioned into a silica-based slag. Partitioning involves reactive conditions for oxidizing radionuclides. Radionuclide oxides then separate from molten metal into the slag phase that can be subsequently vitrified (Heshmatpour et al., 1983).

The Materials Characterization Center at PNL and the Savannah River Site have developed experimental borosilicate glasses for the disposal of high-level nuclear waste (Barkatt et al., 1984). The EATF used the general information concerning borosilicate glasses to develop properties of vitrified waste forms. The density of glass used as a fusing agent is assumed to be that for Type 7740 Borosilicate Glass (McLellan and Shand, 1984). The density of vitrified sludges is assumed from RFP microwave melting studies (Petersen et al., 1987). These densities are given in Table 3-4.

3.4.4 Shredding

Processing waste by shredding is applicable to solid organic (combustible) and solid inorganic (glass/metal) waste forms only. The shredding procedure assumed for alternative evaluations

TABLE 3-3

PROPERTIES OF CEMENTED WASTE FORMS AND BACKFILL

SINGLE ALTERNATIVE	HYDRAULIC CONDUCTIVITY (m/s)	DENSITY[5] (kg/m^3)
Cemented Sludges[1]	4.0×10^{-10}	1410
Shredded and Cemented:[2]		
Solid Organics	1.3×10^{-12}	1760
Solid Inorganics	1.3×10^{-12}	2010
Incinerated and Cemented Solid Organics[3]	6.0×10^{-14}	1980
Grout Backfill[3]	1.3×10^{-12}	1880
Salt Aggregate Grout Backfill[4]	7.37×10^{-14}	2100

(1) This hydraulic conductivity is one order of magnitude less than "as received" sludge reported in Lappin et al., 1989.
(2) Hydraulic conductivities are based on EATF calculations.
(3) Hydraulic conductivity and density: Coons et al., 1987.
(4) Hydraulic conductivity is assumed to be one order of magnitude greater than host salt; density for undisturbed salt from Lappin et al., 1989.
(5) Densities reported are based on EATF calculations unless otherwise noted.

TABLE 3-4

VITRIFICATION PROCESS MATERIAL DENSITIES

MATERIAL	DENSITY (kg/m^3)
Type 7740 Borosilicate Glass (McLellan and Shand, 1984)	2230
Vitrified Simulated Sludge Density (Petersen et al., 1987)	1900

consists of making repeated passes through multiple shredders. This process is assumed to achieve a volume reduction ratio of 1.2 to 1 (Looper, 1990). Waste material is the primary target of the shredding operation, although a fraction of the waste containers may also require this processing technique. Shredded waste materials and containers exhibit:

- Improved compaction capability
- Lower effective hydraulic conductivity (especially after compaction)
- Improved thermal treatment effectiveness.

3.4.5 Supercompaction

Processing waste by supercompaction is applicable to solid organic (combustibles) and solid inorganic (metal/glass) waste forms. The RFP method of supercompaction involves low force precompaction of wastes in 35 gallon drums; the "pucks" are then supercompacted (force in excess of 2200 tons) and packaged for disposal in 55 gallon drums. Calculations by the EATF indicate a slight decrease in total metal (total waste metal is constant, the amount of container metal is reduced) is realized using the proposed RFP method of supercompaction. Physical properties for supercompacted wastes are developed on the basis of information reported from RFP and INEL and a conservative assumption concerning overpacks as outlined in Section 3.6.4. Volume reduction factors of 3:1, for both solid organics and solid inorganics due to supercompaction, were obtained by comparing drum weights before and after processing, and then converting to volumetric units using density data. The processed drum weights for supercompacted TRU waste were communicated to the EATF by Halverson (1988). Density data are obtained from supercompaction tests conducted by the INEL (Larsen and Aldrich, 1986).

3.4.6 Decontamination

Decontamination of metals can be accomplished by thermal methods (refer to Section 3.4.3) or mechanical methods. The EATF has assumed the mechanical method of vibratory finishing as the treatment method for decontaminating metallic waste (see Table 1-2, Alternative 10). Metals can be sufficiently decontaminated by vibratory finishing, to be reclassified as low-level waste (Allen and Hazelton, 1985) and thus removed from the WIPP inventory. The resulting TRU waste form is a contaminated rinsing solution used in the vibratory finisher. The contaminated liquid is concentrated and then solidified by cementation (Allen et al., 1982). Physical properties for this waste form are assumed to be the same as those presented for grout backfill properties listed in Table 3-3.

3.5 PHYSICAL/CHEMICAL PROPERTY CALCULATION METHODOLOGY

Initial calculations supply input values for a spreadsheet designed to compute physical/chemical properties on a per-room or panel basis. Therefore, generating the effective properties resulting from a given combination alternative is reduced to specifying the basic input values for that alternative in the spreadsheet; data files are then generated in the spreadsheet. The default values in the spreadsheet are those corresponding to the baseline case.

Spreadsheet input parameters are listed below:

- The distribution of waste components in an average room. This distribution is dependent on the number of drums of each waste form component (solid organics, sludges, and solid inorganics) present.

- The average weight per drum of each waste form.

- Volume reduction factors are unique to the particular alternative, and to the unprocessed waste form. They allow computation of the equivalent drum count which is the number of unprocessed drums required to produce a processed drum for the particular alternative. Equivalent drum counts for Alternatives 1 to 14 are presented in Table 3-5.

- The total volume of backfill, volume of backfill within the waste stack, and void volume within the waste stack. The void volume within the waste stack is an estimation of the void space within the waste stack resulting from inefficiency in the backfilling process. The void volume is used to estimate an initial waste stack density. The total volume of backfill is utilized in the computation of waste/backfill composite density. The volume of backfill within the waste stack is used in the computation of hydraulic conductivity of the waste/backfill composite.

- The density variations of each component as a function of closure stress, from 0 MPa to lithostatic pressure (approximately 14.8 MPa) in 1.35 MPa increments. The component density values are used in the computation of waste/backfill composite density, porosity, and hydraulic conductivity of the room contents.

The effects of an alternative on the waste/backfill composite properties are calculated with a computer spreadsheet. To compute physical and chemical properties of a single alternative, only those input values which deviate from the baseline case need to be modified in the spreadsheet. The remaining input variables are therefore unaltered from the baseline case. Some alternatives require no computation of various properties (i.e., OPC grout backfill is considered incompressible and therefore has constant density and hydraulic conductivity). The hydraulic conductivity of OPC grout backfill would be considered a fixed input value for all scenarios. Typically, a single alternative will affect properties of one or two waste components, and/or the backfill material. The physical properties of the waste/backfill composite for a particular alternative are computed in a spreadsheet; other parameters may also need to be entered into the spreadsheet (i.e., drum weight and/or distribution of waste forms). This spreadsheet computational methodology is used to evaluate the properties of each single alternative.

TABLE 3-5

UNPROCESSED DRUM EQUIVALENTS PER ROOM

ALTERNATIVES	UNPROCESSED DRUM EQUIVALENTS PER ROOM	PROCESSED DRUMS PER ROOM
BASELINE	6,000	NA
ALTERNATIVE 1	6,803	6,000
ALTERNATIVE 2	6,803	6,000
ALTERNATIVE 3	6,803	6,000
ALTERNATIVE 4	11,250	6,000
ALTERNATIVE 5	11,250	6,000
ALTERNATIVE 6	22,580	6,000
ALTERNATIVE 7	22,580	6,000
ALTERNATIVE 8	56,155	6,000
ALTERNATIVE 9	56,155	6,000
ALTERNATIVE 10	8,395	6,000
ALTERNATIVE 11	4,284	2,000
ALTERNATIVE 12	4,284	2,000
ALTERNATIVE 13	56,155	6,000
ALTERNATIVE 14	4,275	1,995

Combination alternatives are evaluated by simultaneously incorporating input properties developed for two or more single alternatives into the spreadsheet. For example, drum weights of various waste forms may be taken directly from single alternative input, whereas distribution of various waste forms must be computed (and used as input) for each unique combination of alternatives.

3.6 QUANTIFICATION OF PHYSICAL AND CHEMICAL PROPERTIES

The physical and chemical properties used in the Design Analysis Model are evaluated over the range of closure stress expected in the repository. The properties of primary importance are:

- Density
- Porosity
- Hydraulic conductivity
- Gas generation potential
- Effective waste volume.

The waste/backfill composite in the WIPP repository is assumed to contain four components. These components are the backfill material (e.g., crushed salt, grout, etc.) and the three major categories of waste (solid organics, solid inorganics, and sludges) which are processed as described in Table 1-2. The physical and chemical properties of each component will be dependent on the particular single alternative or combination alternative being considered. The methodologies and assumptions used to characterize these properties are detailed in the following sections.

Although material compressibility is not a Design Analysis Model input property, it is a useful parameter upon which to base simplifying assumptions. Material compressibility is used to estimate effects of creep closure on the physical properties of waste/backfill composite. Waste and backfill materials in the WIPP repository will be subjected to triaxial compressive forces. Compressibility of these materials will affect all physical properties. The extent to which different materials consolidate is dependent on the strength of the material. Treated wastes such as grout or glass have compressive strengths in excess of lithostatic pressure (14.8 MPa, Lappin et al., 1989), and are assumed to be incompressible under the stresses expected in the repository.

It is important to note that effects of time on the physical properties of the waste/backfill composite are not considered in this analysis. Long-term (10,000 years) effects such as fatigue and degradation are not well quantified and are therefore considered inappropriate for these generalized calculations (these effects are more suitably considered in the SNL Performance Assessment of the WIPP facility). Therefore, the density, porosity, and hydraulic conductivity of OPC grout used as backfill or sorbent material are assumed to remain constant during the 10,000 year operating life of the WIPP.

3.6.1 Density

Density of the waste/backfill composite at any given stress level can be computed from the density of the individual components at that same stress level. The mass of each waste component is obtained from the mass distribution of the three major waste forms (Butcher, 1989), based on the sampling of RFP TRU wastes stored at INEL (Clements and Kudera, 1985). The quantity of backfill is estimated from current repository room design specifications (Lappin et al., 1989). Total mass for each alternative is assumed constant over the 10,000-year period for the computation of waste/backfill composite densities. This assumption simplifies the density calculations. It is understood that waste/backfill composite mass fluxes resulting from gas production/dissipation, and brine transport will vary the waste/backfill composite mass (e.g., by chemical degradation, physical erosion, and subsequent mass transfer into and out of the waste stack), though the extent to which these processes will occur is not well defined. Initial component volumes are known from the baseline design criteria, thus initial waste/backfill composite density is readily quantified.

The waste/backfill composite density resulting from alternative evaluations may or may not increase during the consolidation process. For the baseline case, waste component densities as a function of stress level were obtained from Butcher et al. (1990); crushed salt compressibility data were obtained from Stinebaugh (1979). The methodology of computing density of a multicomponent system is outlined in Butcher et al. (1990). This method utilizes component densities (or mass and volume) to compute waste/backfill composite density. Implicit in the calculation is the assumption that the components act independently.

The formulation can be summarized as follows; the volume occupied by component i at some stress level x is:

$$V_i(x) = \frac{M_i}{D_i(x)} \qquad (3.6\text{-}1)$$

where,

$V_i(x)$ = *volume of component "i" at stress level x*
M_i = *mass of component "i"*
$D_i(x)$ = *density of component "i" at stress level x.*

The total waste/backfill composite volume at stress level x is the sum of the component volumes:

$$TV(x) = \sum_{i=1}^{n} V_i(x) \qquad (3.6\text{-}2)$$

where,

TV(x) = total waste/backfill composite volume at stress level x.

The total waste/backfill composite mass is the sum of the "n" component masses, or:

$$TM = \sum_{i=1}^{n} M_i \qquad (3.6\text{-}3)$$

where,

TM = the total waste/backfill composite mass.

Therefore, the waste/backfill composite density at stress level x can be computed as follows:

$$RD(x) = \frac{TM}{TV(x)} = \sum_{i=1}^{n} \frac{TM}{(M_i/D_i(x))} \qquad (3.6\text{-}4)$$

where,

RD(x) = density of waste/backfill composite at stress level x.

Equation 3.6-4 can be simplified by introducing a component weight fraction, W_i:

$$W_i = \frac{M_i}{TM} \qquad (3.6\text{-}5)$$

After dividing the numerator and denominator of equation 3.6-4 by TM, the expression for the waste/backfill composite density becomes:

$$RD(x) = \sum_{i=1}^{n} \frac{1.0}{(W_i/D_i(x))} \qquad (3.6\text{-}6)$$

In summary, waste/backfill composite density was computed at a given stress level by:

- Using densities as a function of stress level and weights for each component
- Utilizing the experimental densities of individual components such as metal, glass, sorbents and combustibles (all under pressure) as reported by Butcher et al. (1990)
- Using component mass proportions.

Table 3-6 contains waste/backfill composite densities as a function of stress for the 14 combination alternatives (Table 1-2) analyzed using the Design Analysis Model.

3.6.2 Porosity

Porosity is a measure of void space existing in a material and is defined as the ratio of void volume to total volume of the material (Equation 3.6-7). Within the repository, the waste/backfill composite porosity is dependent on waste characteristics, backfill materials, efficiency of waste emplacement, and the extent to which these materials compact during the consolidation process. Computation of waste/backfill composite porosity (assuming constant mass) can be made on either a volume or density basis (Butcher, 1989), for example:

On volume basis:

$$Porosity = \frac{(V_{total} - V_{solid})}{V_{total}} \quad (3.6\text{-}7)$$

On density basis:

$$Porosity = 1 - \frac{(composite\ density)}{(composite\ solid\ density)} \quad (3.6\text{-}8)$$

where,

V_{total} is the total volume (V_{solid} + V_{void}) of the room components at some stress level and V_{solid} is the total solid volume of all room components. Therefore, the quantity (V_{total} - V_{solid}) represents V_{void}, the room void volume including the waste/backfill composite void volume minus the volume of the overlying air gap. It should be noted that Eqn. 3.6-7 has been developed on a room basis, and should not be confused with similar equations in Appendix B that were developed on a panel basis. Due to greater availability of density data for components, waste/backfill composite porosity is computed on a density basis. Table 3-7 presents the waste/backfill composite porosities as a function of stress for the 14 combination alternatives analyzed using the Design Analysis Model.

TABLE 3-6

COMPOSITE DENSITIES FOR COMBINATION ALTERNATIVES
(kg/m^3)*

STRESS (MPa)*	BASELINE	ALT 1	ALT 2	ALT 3	ALT 4	ALT 5	ALT 6	ALT 7
0	692	1260	1320	1830	1340	1860	1370	1890
0	796	1450	1510	1830	1540	1860	1580	1890
1.4	1300	1710	1700	1830	1730	1860	1990	1890
2.8	1500	1770	1740	1830	1770	1860	2070	1890
4.1	1610	1800	1760	1830	1790	1860	2120	1890
5.5	1700	1830	1780	1830	1810	1860	2170	1890
6.9	1760	1850	1790	1830	1820	1860	2200	1890
8.3	1810	1870	1800	1830	1830	1860	2230	1890
9.7	1860	1880	1810	1830	1850	1860	2250	1890
11.0	1900	1890	1820	1830	1850	1860	2270	1890
12.4	1930	1900	1830	1830	1860	1860	2280	1890
13.8	1970	1910	1830	1830	1870	1860	2300	1890
15.2	1990	1920	1840	1830	1870	1860	2320	1890
Solid	2280	2470	2480	2720	2640	2860	2470	2710

STRESS (MPa)*	BASELINE	ALT 8	ALT 9	ALT 10	ALT 11	ALT 12	ALT 13	ALT 14
0	692	1470	1990	746	1110	1540	2100	1070
0	796	1690	1990	747	1110	1540	2100	1070
1.4	1300	1900	1990	1050	1600	1540	2100	1710
2.8	1500	1940	1990	1310	1780	1540	2100	2070
4.1	1610	1960	1990	1450	1830	1540	2100	2110
5.5	1700	1990	1990	1540	1880	1540	2100	2140
6.9	1760	2000	1990	1610	1920	1540	2100	2160
8.3	1810	2010	1990	1660	1950	1540	2100	2180
9.7	1860	2020	1990	1700	1980	1540	2100	2200
11.0	1900	2030	1990	1740	1990	1540	2100	2210
12.4	1930	2040	1990	1760	2020	1540	2100	2220
13.8	1970	2050	1990	1790	2040	1540	2100	2230
15.2	1990	2050	1990	1810	2050	1540	2100	2250
Solid	2280	2120	2380	2280	2280	2700	2100	2520

*See Glossary for explanation of each abbreviation.

NOTE: In Alternatives 3, 5, 7, and 9, the processed waste forms and grout backfill are assumed incompressible (compressive strengths greater than lithostatic pressure) and, therefore, have constant composite density. The initial zero in the stress column incoporates the void volume due to backfill inefficiency, but it does not include the clearance between the waste/backfill composite and the roof. The second zero in the stress column indicates that the inefficiency is no longer present due to compaction, and the densities are equal to what would be expected from natural packing of the material.

TABLE 3-7

COMPOSITE POROSITIES FOR COMBINATION ALTERNATIVES

STRESS (MPa)*	BASELINE	ALT 1	ALT 2	ALT 3	ALT 4	ALT 5	ALT 6	ALT 7
0	0.697	0.490	0.469	0.326	0.492	0.349	0.446	0.303
0	0.651	0.414	0.390	0.326	0.416	0.349	0.363	0.303
1.4	0.430	0.305	0.314	0.326	0.344	0.349	0.196	0.303
2.8	0.345	0.283	0.300	0.326	0.330	0.349	0.164	0.303
4.1	0.295	0.270	0.291	0.326	0.321	0.349	0.142	0.303
5.5	0.257	0.258	0.283	0.326	0.314	0.349	0.124	0.303
6.9	0.230	0.251	0.278	0.326	0.309	0.349	0.111	0.303
8.3	0.206	0.244	0.273	0.326	0.305	0.349	0.100	0.303
9.7	0.185	0.238	0.269	0.326	0.301	0.349	0.090	0.303
11.0	0.169	0.233	0.266	0.326	0.298	0.349	0.083	0.303
12.4	0.154	0.229	0.263	0.326	0.295	0.349	0.076	0.303
13.8	0.139	0.224	0.260	0.326	0.292	0.349	0.068	0.303
15.2	0.127	0.221	0.258	0.326	0.290	0.349	0.063	0.303

STRESS (MPa)*	BASELINE	ALT 8	ALT 9	ALT 10	ALT 11	ALT 12	ALT 13	ALT 14**
0	0.697	0.307	0.164	0.673	0.513	0.428	0	0.577
0	0.651	0.203	0.164	0.673	0.513	0.428	0	0.577
1.4	0.430	0.105	0.164	0.540	0.299	0.428	0	0.320
2.8	0.345	0.086	0.164	0.428	0.222	0.428	0	0.180
4.1	0.295	0.074	0.164	0.367	0.197	0.428	0	0.164
5.5	0.257	0.064	0.164	0.325	0.175	0.428	0	0.151
6.9	0.230	0.057	0.164	0.295	0.160	0.428	0	0.141
8.3	0.206	0.051	0.164	0.272	0.147	0.428	0	0.134
9.7	0.185	0.046	0.164	0.254	0.134	0.428	0	0.128
11.0	0.169	0.042	0.164	0.239	0.125	0.428	0	0.122
12.4	0.154	0.038	0.164	0.227	0.117	0.428	0	0.117
13.8	0.139	0.034	0.164	0.216	0.108	0.428	0	0.113
15.2	0.127	0.031	0.164	0.206	0.101	0.428	0	0.109

*See Glossary for explanation of abbreviation.
**Porosity computed on a compartment basis (three 7-packs).

NOTE: The initial zero in the stress column incorporates the void volume due to backfilling inefficiency. The second zero in the stress column indicates that this inefficiency is no longer present due to compaction. The resulting porosities are as would be expected due to naturally packed backfill.

3.6.3 Hydraulic Conductivity

Hydraulic conductivity is a measure of the permeability of a porous media. It is dependent on the properties of the media as well as the fluid. The hydraulic conductivity of the waste/backfill composite in an average WIPP repository room is dependent on the waste components, backfill material, and the brine present. In multicomponent systems, an effective hydraulic conductivity can be estimated by averaging the individual component hydraulic conductivities comprising the system. Three different averaging techniques exist:

- Arithmetic mean - applies to flow through a parallel configuration of components
- Harmonic mean - applies to flow through a series configuration of components
- Geometric mean - applies to flow through a randomly distributed configuration of components.

In practice, the effective hydraulic conductivity of randomly distributed components is estimated by using the geometric mean (of components). The geometric mean is preferred over arithmetic and harmonic means (parallel and series flow configurations, respectively), because it results in a better representation of randomly distributed components (Scheidegger, 1974).

In the baseline condition, hydraulic conductivity of solid inorganic and solid organic waste is assumed to vary with porosity and is estimated from a modified version of the Kozeny-Carman Equation (D'Appolonia, 1982). Components such as grout or glass are assumed incompressible under repository conditions (compressive strengths greater than lithostatic pressure) and thus have constant hydraulic conductivities.

It is important to note that fluid movement (hydraulic conductivity) in certain materials, such as glass, is due to diffusion or molecular transport as governed by Fick's Law rather than to Darcy's Law, which governs fluid flow through porous media. For the purposes of this report, vitrified waste forms and metal ingots are considered impermeable. Since fluid flow takes place through the path of least resistance (i.e., higher hydraulic conductivity), these waste forms are assigned a low hydraulic conductivity to limit their relative impact as components in the waste backfill composite. Lappin et al. (1989) reports the permeability of intact repository salt as 10^{-22} m^2 (which is equivalent to a hydraulic conductivity of 7.35×10^{-15} m/s). Based on this and Butcher (1990a), a reference hydraulic conductivity of 7.35×10^{-16} m/s has been assigned to "impermeable" waste forms for calculation purposes. Assigning a hydraulic conductivity one order of magnitude lower than the host rock mimimizes the impact of these almost impermeable waste forms on the overall waste/backfill composite hydraulic conductivity and, in a conservative manner, puts more importance on the conductivity of the rest of the waste.

The components considered in the averaging process are the three primary waste forms and the backfill material within the waste stack. Backfill contained in the volume above the waste stack, and between the waste stack and the side walls in the rooms, is not considered because this region is a physical extension of the host rock.

The values of hydraulic conductivity for each component are estimated on the basis of available data in literature (Coons et al., 1987), personal communication (Butcher, 1990a), and representative equations (Case and Kelsall, 1987). Components with large void space which compact under compressive stresses will typically have hydraulic conductivities that vary with the degree of compaction. This variability can be estimated or computed from the porosity. For example, the hydraulic conductivity of crushed salt is assumed to be a function of porosity and is estimated as a function of compaction with a bilinear system of equations developed by Case and Kelsall (1987). Once the hydraulic conductivity of each component has been estimated, the effective hydraulic conductivity for the composite can be computed. The governing equation employing the geometric mean for averaging hydraulic conductivities is (Scheidegger, 1974):

$$\ln(K_{eff}) = \sum_{i=1}^{n} (F_i \ln(K_i)) \qquad (3.6\text{-}9)$$

where,

K_{eff} = *effective waste/backfill composite hydraulic conductivity at stress level x*
F_i = *volume fraction of component i at stress level x*
K_i = *hydraulic conductivity of component i at stress level x.*

The component volume fraction and the hydraulic conductivity may be functions of stress level or the state of compaction. The component volume fraction is computed as the component volume divided by the waste/backfill composite volume at a particular stress level:

$$F_i(x) = \frac{V_i(x)}{TV(x)} \qquad (3.6\text{-}10)$$

where,

$F_i(x)$ = *volume fraction of component i at stress level x*
$V_i(x)$ = *volume of component i at stress level x (including the void space within the waste/backfill composite)*
$TV(x)$ = *volume of waste/backfill composite at stress level x.*

The component and waste/backfill composite volumes are obtained from estimated values of component masses and densities:

$$V_i(x) = \frac{M_i}{D_i(x)} \tag{3.6-11}$$

$$TV(x) = \sum_{i=1}^{n} V_i(x) \tag{3.6-12}$$

where,

M_i = *mass of commponent "i"*
$D_i(x)$ = *density of component "i" at stress level x.*

The procedure allows computation of an effective hydraulic conductivity for the average contents of a WIPP repository room at various stress levels. Table 3-8 contains the hydraulic conductivities for the 14 combination alternatives.

3.6.4 Gas Generation Potential

Evaluation of design alternatives to the baseline waste disposal system requires estimation of the total potential for gas generation. Gas generation potential is the sum of three processes:

- Radiolytic gas generation
- Biological gas generation
- Corrosion gas generation.

Total potential is dependent on parameters such as brine inflow (for anoxic corrosion), radioactivity per unit volume of waste (for radiolysis), and mass of organic materials per unit volume of waste (for biological degradation). Lappin et al. (1989) report potentials of 894 moles of hydrogen/drum for anoxic corrosion of waste containers and metal waste, and 606 moles of total gas/drum for biological degradation and radiolysis. These constituent potentials are used to compute the total potential. These values are subject to validation by gas generation experiments in the WIPP Experimental Test Program (Molecke, 1990a; Molecke, 1990b).

The gas generation potential for the 14 combination alternatives analyzed by the Design Analysis Model are presented in Table 3-9. It should be noted that alternatives that involve either densification of waste (e.g., supercompaction) or removal of a waste component (e.g., incineration of solid organics), will result in volume reduction. This volume reduction helps to include more drum equivalents of unprocessed waste per room compared to the baseline design (presented earlier in Table 3-5). Since the volume reduction increases the mass of waste that can be stored in a room relative to the baseline, the total gas generation potential per room for some of the alternatives could be more than the baseline. Thus, a comparison of gas generation in terms of

TABLE 3-8

COMPOSITE HYDRAULIC CONDUCTIVITIES FOR COMBINATION ALTERNATIVES
(m/s)*

STRESS (MPa)*	BASELINE	ALT 1	ALT 2	ALT 3	ALT 4	ALT 5	ALT 6	ALT 7
0	4.12E-04	1.10E-09	7.30E-10	3.01E-12	3.15E-10	1.50E-12	7.47E-13	1.04E-14
1.4	1.55E-05	7.62E-11	6.55E-11	3.01E-12	2.70E-11	1.50E-12	9.41E-14	1.04E-14
2.8	3.61E-06	4.57E-11	4.28E-11	3.01E-12	1.74E-11	1.50E-12	5.84E-14	1.04E-14
4.1	1.42E-06	3.30E-11	3.26E-11	3.01E-12	1.32E-11	1.50E-12	4.26E-14	1.04E-14
5.5	6.63E-07	2.52E-11	2.61E-11	3.01E-12	1.05E-11	1.50E-12	3.27E-14	1.04E-14
6.9	3.77E-07	2.10E-11	2.25E-11	3.01E-12	9.09E-12	1.50E-12	2.73E-14	1.04E-14
8.3	2.25E-07	1.79E-11	1.98E-11	3.01E-12	7.96E-12	1.50E-12	2.32E-14	1.04E-14
9.7	1.23E-07	1.46E-11	1.67E-11	3.01E-12	6.71E-12	1.50E-12	1.88E-14	1.04E-14
11.0	4.52E-08	1.03E-11	1.24E-11	3.01E-12	4.96E-12	1.50E-12	1.28E-14	1.04E-14
12.4	1.83E-08	7.63E-12	9.55E-12	3.01E-12	3.82E-12	1.50E-12	9.17E-15	1.04E-14
13.8	6.10E-09	5.23E-12	6.89E-12	3.01E-12	2.75E-12	1.50E-12	6.00E-15	1.04E-14
15.2	2.75E-09	4.07E-12	5.57E-12	3.01E-12	2.22E-12	1.50E-12	4.54E-15	1.04E-14

STRESS (MPa)*	BASELINE	ALT 8	ALT 9	ALT 10	ALT 11	ALT 12	ALT 13	ALT 14**
0	4.12E-04	7.46E-13	1.04E-14	1.80E-07	4.85E-05	7.72E-09	7.35E-16	2.45E-07
1.4	1.55E-05	4.58E-14	1.04E-14	5.48E-08	1.49E-06	7.72E-09	7.35E-16	3.44E-08
2.8	3.61E-06	2.79E-14	1.04E-14	8.91E-09	1.99E-07	7.72E-09	7.35E-16	2.94E-09
4.1	1.42E-06	2.04E-14	1.04E-14	3.44E-09	1.11E-07	7.72E-09	7.35E-16	2.92E-09
5.5	6.63E-07	1.58E-14	1.04E-14	1.83E-09	6.79E-08	7.72E-09	7.35E-16	2.90E-09
6.9	3.77E-07	1.33E-14	1.04E-14	1.14E-09	4.87E-08	7.72E-09	7.35E-16	2.89E-09
8.3	2.25E-07	1.15E-14	1.04E-14	7.81E-10	3.58E-08	7.72E-09	7.35E-16	2.89E-09
9.7	1.23E-07	9.51E-15	1.04E-14	5.67E-10	2.32E-08	7.72E-09	7.35E-16	2.88E-09
11.0	4.52E-08	6.94E-15	1.04E-14	4.28E-10	9.81E-09	7.72E-09	7.35E-16	2.87E-09
12.4	1.83E-08	5.30E-15	1.04E-14	3.31E-10	4.64E-09	7.72E-09	7.35E-16	2.87E-09
13.8	6.10E-09	3.77E-15	1.04E-14	2.58E-10	1.78E-09	7.72E-09	7.35E-16	2.86E-09
15.2	2.75E-09	3.02E-15	1.04E-14	2.03E-10	9.43E-10	7.72E-09	7.35E-16	2.86E-09

*See Glossary for explanation of each abbreviation.
**Hydraulic conductivity computed on a compartment basis (three 7-packs).

TABLE 3-9

GAS GENERATION POTENTIAL FOR EACH COMBINATION ALTERNATIVE
(moles/unprocessed drum equivalent)

	BASELINE	ALT 1	ALT 2	ALT 3	ALT 4	ALT 5	ALT 6	ALT 7
Anoxic Corrosion	894	943	943	943	1093	1093	516	516
Microbial Degradation and Radiolysis	606	606	606	606	0	0	0	0
Total	1500	1548	1548	1548	1093	1093	516	516

	BASELINE	ALT 8	ALT 9	ALT 10	ALT 11	ALT 12	ALT 13	ALT 14
Anoxic Corrosion	894	0	0	53	1053	1053	0	1053
Microbial Degradation and Radiolysis	606	0	0	453	606	606	0	606
Total	1500	0	0	506	1659	1659	0	1659

the total potential is misleading, due to the unequal number of unprocessed drum equivalents for the alternatives and the baseline design.

In order to provide a reasonable comparison between the gas generation potentials for the baseline and the alternatives, the values presented in Table 3-9 are expressed in terms of moles per unprocessed drum. The values for Alternatives 1, 2, and 3 are higher than the baseline because it is assumed that 25 percent of the drums will be damaged, and therefore will also be shredded and cemented in addition to the waste itself. Since the drums are made of mild steel, the shredding and cementing of 25 percent of the drums would result in a net increase in the total metal inventory, thereby increasing the potential for gas generation by anoxic corrosion. Although the potential is higher compared to the baseline, it should be noted that shredding and cementing the waste will decrease the rate of gas generation and will also reduce the permeability of the waste/backfill composite. In alternatives 11, 12, and 14, the EATF has conservatively assumed a supercompaction process in which drums of solid organics and inorganics are supercompacted and overpacked in metal containers. The overpack represents an increase in the quantity of metal in the TRU waste inventory. Consequently, use of an overpack increases the gas generation potential (due to anoxic corrosion) per drum equivalent (see Table 3-9). It should be noted that the process proposed for supercompaction at RFP will employ an in-drum precompaction operation (Barthel, 1988) which results in a reduction of metal per drum equivalent. Thus, in actual practice, the inventory of container metal destined for the WIPP will actually be decreased.

Alternatives which eliminate both metals and solid organics from the inventory (e.g., Alternatives 8, 9, and 13), are not expected to generate any gas, and thus they can accommodate a very large number of unprocessed drum equivalents per room with no effect on the total potential. It should be noted that alternatives which result in densification of waste would also need a smaller number of rooms for waste disposal. Other assumptions used in estimating gas generation potentials are listed in Section 2.0 and Appendix B.

3.6.5 Effective Waste Volume

The effective waste volume is used to determine the radionuclide content in drill cuttings removed from the repository during human intrusion events (Appendix B, Section 2.22). The effective waste volume is the volume of the waste/backfill composite minus the volume of the backfill along the sides of the waste stack. The term "drill cuttings" refers to the waste/backfill composite which would be brought to the surface with circulating drilling fluid during an inadvertent human intrusion event. The effective waste volume evaluation requires determination of the waste/backfill composite density as a function of stress, as per Equation (3.6-6). These calculations differ from each other only in that the waste/backfill composite density calculation neglects backfill on the sides of the waste stack. If penetration through the backfill on the sides of the waste stack occurs, the waste stack is assumed to remain intact and the cuttings are assumed not to contain any radionuclides. The backfill above the waste stack is considered because it would be mixed with extracted waste in the event the waste stack is breached by drilling activities.

3.7 SUMMARY

Input variables required by the Design Analysis Model include the physical and chemical properties of the repository contents following waste and backfill emplacement in the WIPP. The contents are assumed to be a homogeneous waste/backfill composite. This composite consists of four components:

- Sludges
- Solid organics (combustible)
- Solid inorganics (glass/metal)
- Backfill material.

The properties required by the Design Analysis Model for evaluation of the effectiveness of engineered alternatives include:

- Density
- Porosity
- Hydraulic conductivity
- Gas generation potential
- Effective waste volume.

Density of the waste-backfill composite is computed by assigning weights to the individual component densities as illustrated with Equation (3.5-6). The porosity of the composite is a function of the composite density. An estimate of the hydraulic conductivity of the waste/backfill composite is the geometric mean of the component hydraulic conductivities. Gas generation (radiolytic, microbial and corrosion) potentials are computed from the equivalent number of unprocessed drums emplaced in a room, taking into account the effect of waste treatment on components. With the exception of total gas generation potential, the physical properties vary with pressure resulting from creep closure. Properties for the three major waste forms and the backfill materials are obtained from available literature, applicable relationships or equations, and through personal communication with waste process facility personnel. Using the above evaluation process, physical properties of the waste/backfill composite in an average WIPP repository room are computed for use as input to the Design Analysis Model.

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4.0 RESULTS OF DESIGN ANALYSIS

Several analyses of room behavior during undisturbed conditions and human intrusion events have been performed using the Design Analysis Model. These analyses include:

Undisturbed Performance (No Human Intrusion)

- A prediction of peak index gas pressures during undisturbed conditions, using baseline assumptions on gas generation rates and potentials (Section 4.1.1).
- An analysis of the effects of supercompaction of waste on room pressurization (Section 4.1.2).
- An analysis of the effects of venting excess gas pressure from the storage rooms during the first 100 years following repository decommissioning (Section 4.1.3).
- A sensitivity study to determine the effects of varying the microbial gas generation rate on room pressurization (Section 4.1.4).
- A sensitivity study to determine the effects of varying the undisturbed pore pressure and permeability of the anhydrite beds (Marker Bed 139, anhydrites "a" and "b") on room pressurization (Section 4.1.5).
- A sensitivity study to determine the effects of varying the initial brine inflow rates on room pressurization (Section 4.1.6).
- An estimate of the effects of 14 representative combinations of alternative waste forms on the peak storage room gas pressures (Section 4.1.7).

Human Intrusion Scenarios

- A determination of the relative effectiveness of 14 representative combinations of alternative waste forms for reducing the consequences of human intrusion events (Section 4.2).

4.1 ANALYSIS OF DESIGN DURING UNDISTURBED PERFORMANCE

One-dimensional modeling of the performance of the disposal system under normal undisturbed conditions (no human intrusion) is described in Marietta et al. (1989) and Lappin et al. (1989), and two-dimensional modeling of undisturbed performance is described in Rechard et al. (1990). These analyses show that no releases to the accessible environment occur during a 10,000-year period of undisturbed performance.

The generation of large amounts of gas from microbial, chemical, or radiolytic processes may result in some or all of the following phenomena:

- Dissipation of excess gas pressure by advection out into the host rock via the anhydrite beds and clay seams
- Expansion of the storage rooms by reverse creep of the host rock
- Fracturing of the host rock by gas pressures that exceed lithostatic pressure
- Fracturing of the anhydrite beds and clay seams.

It is advantageous to avoid fracturing of the host rock because it may not be possible to accurately predict the direction and magnitude of the fractures which may become pathways for the migration of contaminated brine. The prediction of fracturing, and any subsequent fracture propagation, is being investigated by SNL (DOE, 1990d).

A preliminary analysis of the potential for expansion of the storage rooms by gas generation has been performed by SNL, using a simplified homogeneous isotropic model that predicts the response of the host rock to a room containing fluid pressure in excess of lithostatic pressure. Preliminary results from the model suggest that the room will indeed expand to accommodate any excess moles of gas that are generated by the waste (Lappin et al., 1989, Section 4.10.3). If this analysis proves to be correct, concerns regarding gas generation will be minimal, since the storage room will inflate to accommodate the volume of gas that is generated, as long as the rate of generation was less than the maximum rate of expansion that the host rock will allow. Planned analyses (DOE, 1990d) by SNL that refine the reinflation model to incorporate the actual stratigraphy (including anhydrite beds and clay seams) of the repository horizon may either confirm that the room will expand, or may conclude that fracturing will occur but will be restricted to the anhydrite beds, or that excess gas pressure will generate fractures with unpredictable lengths and directions in the host rock.

An additional concern regarding gas generation is that it may significantly contribute to pressurization of the storage rooms and prop open voids in the waste, thus preventing creep closure from compacting the waste. If this occurs, the permeability of the waste may not significantly decrease from the initial permeability at the time of emplacement.

Definition of a threshold pressure above which the performance of the disposal system is reduced is a complex problem involving the response of a heterogeneous nonisotropic multi-layered system to pressures in excess of the confining stress. This threshold pressure determination is under development by SNL (DOE, 1990d) and has not yet been established. For these reasons, the Design Analysis Model has been used to predict room pressurization as a function of time to evaluate the relative effectiveness of various alternative designs in reducing peak room pressure, should that prove to be necessary.

A common assumption underlying the following design analyses is that the room will not re-expand in response to pressures in excess of lithostatic. This assumption can easily be changed in future simulations when the current uncertainties regarding subsequent room pressurization are resolved.

4.1.1 Prediction of Room Pressurization Using Baseline Assumptions

The Design Analysis Model was used to predict the pressurization of a typical storage room as a function of time for the baseline design, current waste forms and crushed salt backfill, as defined in Table 3-1. The goal of this analysis is to predict the timing and magnitude of peak index gas pressure that will occur. If it is determined that the peak index pressures predicted for the baseline design are in excess of those allowable, engineered alternatives can be selected to avoid potential problems associated with excess pressures. The allowable limits for peak index pressures will be determined from on-going modeling and experimental investigations at SNL (DOE, 1990d). When these limits are established, definitive conclusions regarding the acceptability of the baseline design and/or the need for engineered alternatives can be made.

Index pressure versus time curves for the baseline design are shown in Figure 4-1. The lower of the three curves shows the partial pressure of hydrogen generated by anoxic corrosion. The middle curve shows the sum of the partial pressures of CO_2, N_2, and CH_4, which are the gases generated by both radiolytic and microbial degradation of organic materials (Brush, 1990). The upper curve shows the total pressure, which is the sum of the partial pressures of all gas components.

The partial pressure of hydrogen reaches a peak that coincides with the total pressure reaching lithostatic pressure (Figure 4-1). When lithostatic pressure is reached, brine inflow stops so there is no longer any brine available for anoxic corrosion to proceed. Hydrogen generation is thus self-limiting as a result of the assumed coupling between brine inflow, room pressure, and anoxic corrosion. That is, brine inflow and creep occur at a rate that is proportional to the difference between lithostatic and room pressures. Brine is required, and is also consumed, by anoxic corrosion. Based on these assumptions, when lithostatic pressure is reached, brine inflow and, hence, anoxic corrosion rates approach zero. Although a maximum hydrogen generation limit of 1.7 moles/drum/year is used (Lappin et al., 1989), the corrosion rate is always less than this bounding rate because of limited brine availability. When lithostatic pressure is reached, only about 54 percent of the metals in the inventory is expected to have corroded.

Microbial generation, on the other hand, is assumed to proceed at a constant rate that is independent of brine availability (Lappin et al., 1989). Aerobic conditions are assumed to persist for 100 years after closure, during which oxygen is converted to carbon dioxide via microbial activity with no significant change in pressure. Anaerobic degradation of organic materials occurs from 100 to approximately 815 years after closure at a constant rate of 0.85 moles/drum/year, generating a total of 606 moles/drum (Lappin et al., 1989) of gases composed of CO_2, N_2, and CH_4 at a molar ratio of 20:12:15. At approximately 815 years

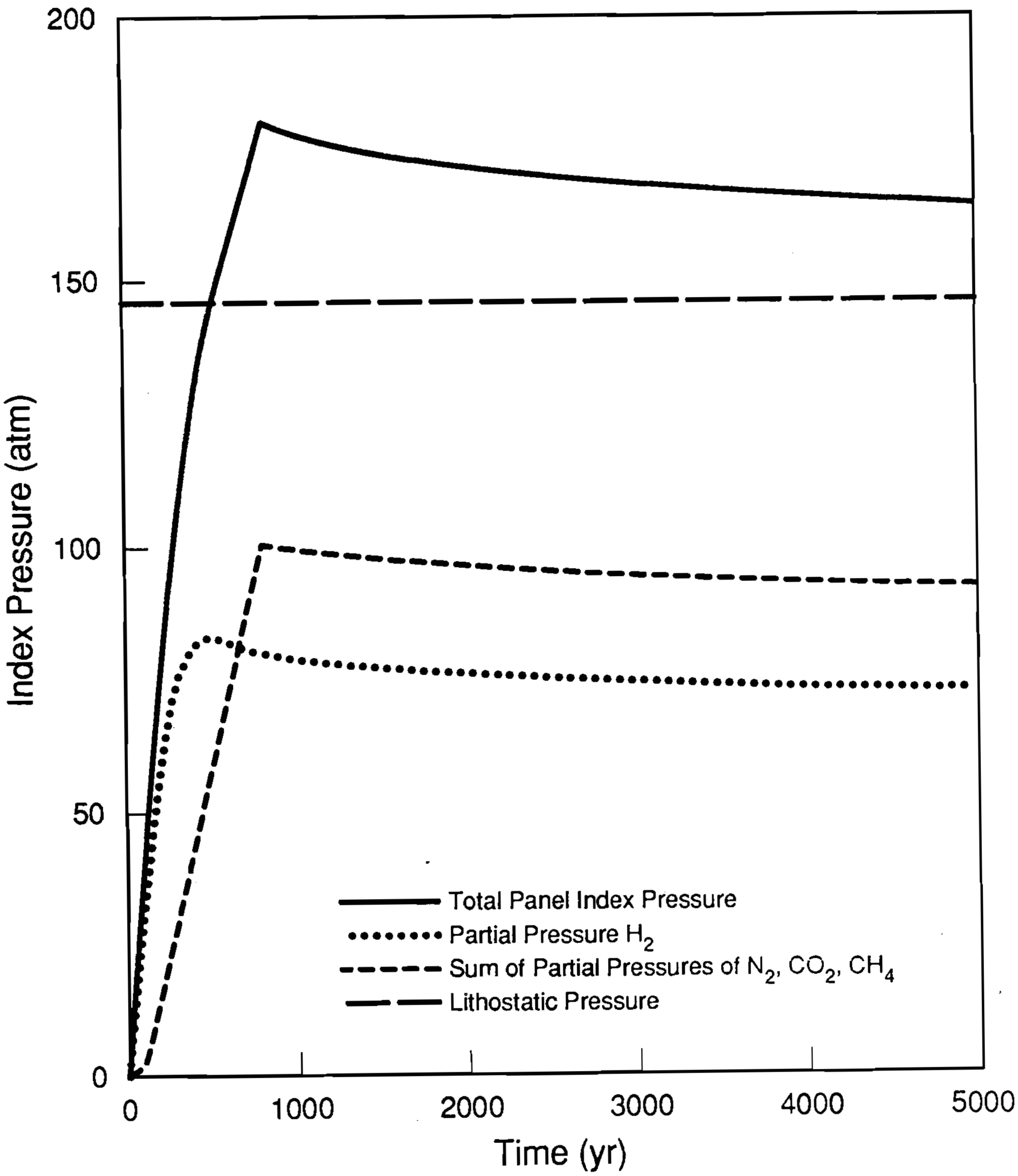

Figure 4-1
Index Pressure Versus Time Curves for the Baseline Case

after closure, the substrate is depleted and microbial gas generation is assumed to stop. These assumptions are reflected in the partial pressure curve for microbial gases in Figure 4-1, which show a small rise during the first 100 years caused by the conversion of oxygen to carbon dioxide, followed by a linear increase in the partial pressures of these gases from 100 years to approximately 815 years.

The upper curve showing total pressure is the sum of the two lower curves. It shows an initial steep slope during the first 300 years, during which brine inflow occurs and hydrogen generation from anoxic corrosion is the dominant gas generation process. When lithostatic pressure (146 atmospheres) is reached at approximately 500 years, brine inflow and anoxic corrosion rates approach zero, which causes a slight decrease in the slope of the total pressure curve. This lower pressurization rate from continued microbial activity prevails until approximately 815 years when organic materials are consumed, and all gas generation ceases. At this point, a peak index pressure of 180 atmospheres (atm) is reached, followed by a gradual decline in pressure caused by continued advection of fluid (gas and brine) into the intact anhydrite beds and diffusion of gases into the intact host rock.

At this point in the discussion, it should be noted that although the Design Analysis Model calculates absolute pressures, these results are very sensitive to assumptions regarding gas generation rates and durations, brine inflow rates, creep closure rates, initial void volume, re-inflation of the rooms, and the degree of coupling between these processes. Thus, the absolute pressures presented here should be viewed as an index by which alternatives can be compared and ranked for effectiveness, rather that a prediction of the actual pressures that will exist in the storage rooms. As experimental programs continue to provide data, and the understanding of these processes increase, some of these assumptions will undoubtedly change, yielding different quantitative results. However, the objective of the EATF design analysis activity is to predict relative changes in performance offered by alternative designs. These relative changes in performance are less subject to modification by increased understanding than are the absolute pressures presented here. For this reason, the term peak index pressure is used to indicate that the absolute values are subject to change, but the relative rankings may not be.

4.1.2 Effects of Supercompaction on Room Pressurization

An analysis was performed to evaluate the effects of supercompaction of waste on room pressurization. For this analysis, two waste emplacement configurations were considered; a single layer of 2,000 drums of supercompacted waste containing the equivalent contents of 4,284 drums of unprocessed waste, and a triple layer of 6,000 drums of supercompacted waste containing the equivalent contents of 12,856 drums of unprocessed waste. Figure 4-2 shows the results in terms of index pressures versus time curves for the monolayer and triple layers of supercompacted waste, along with a similar curve for the baseline configuration of 6,000 drums of uncompacted waste for comparison. These curves show that a room filled with a monolayer of supercompacted waste reaches a peak index pressure that is roughly 24 percent higher than the baseline case, and a triple layer of supercompacted waste reaches a peak index pressure that is greater than twice the baseline case.

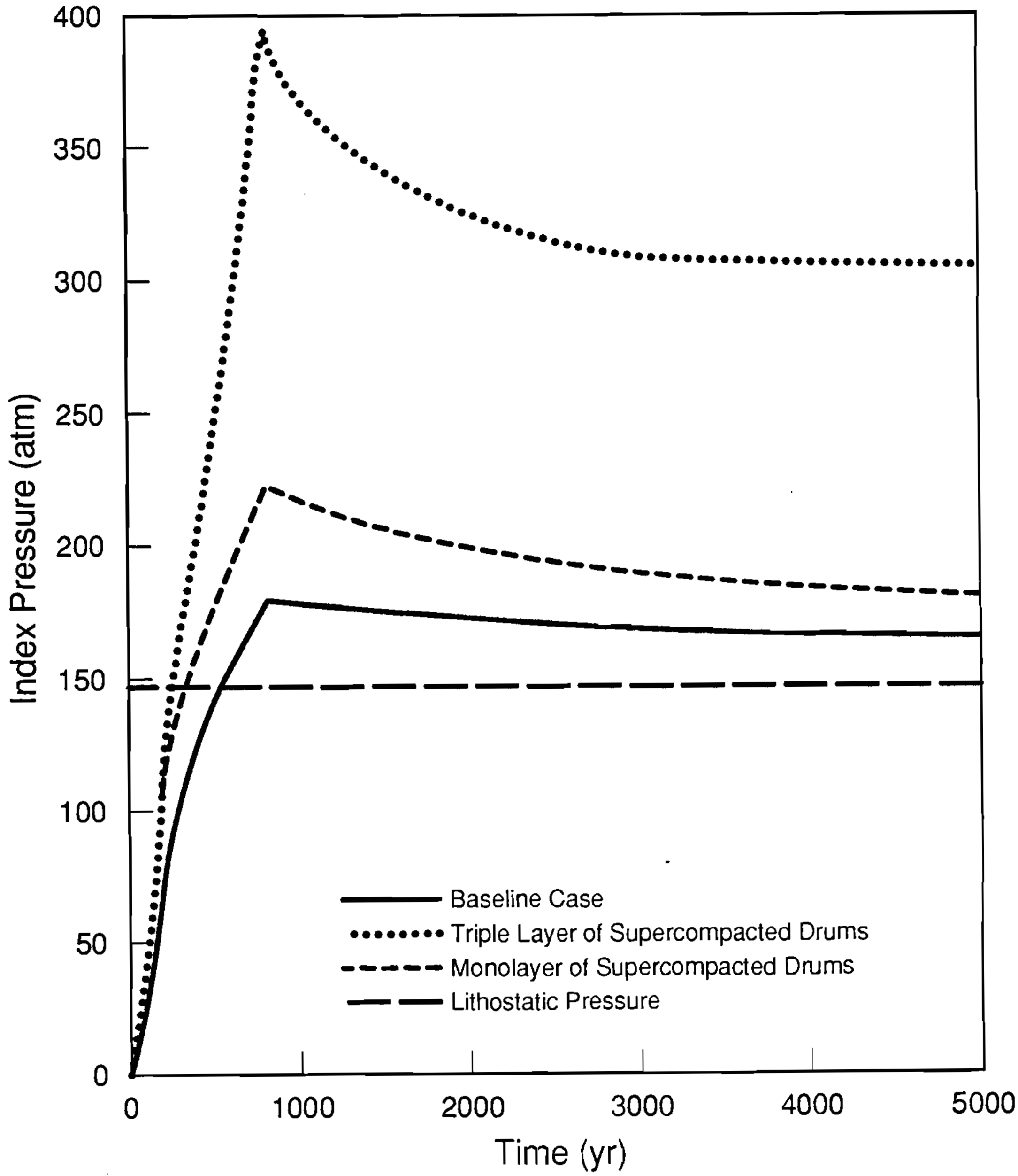

Figure 4-2
Index Pressure Versus Time Curves for Supercompacted and Baseline Waste Forms

The main reason for the higher predicted peak index pressures for supercompacted waste is the decrease in initial void volume. Moles of gas that are generated occupy a smaller void volume, resulting in rapid pressurization. Although this rapid pressurization minimizes brine inflow, thus decreasing in the total moles of hydrogen generated by anoxic corrosion, these fewer moles of hydrogen occupy a smaller void volume. Even though fewer moles of hydrogen are generated, the partial pressure of hydrogen still remains high. In addition, microbial gas generation continues, which is assumed to be independent of brine availability, and is also pressurizing a smaller volume.

An additional factor is present in the case of the triple layer. In this case, there is a greater than two-fold increase in the mass of organic materials on a per-room basis, resulting in an equivalent increase in the microbial gas generation rate and gas generation potential per room.

These results suggest that supercompaction is not effective in reducing peak index pressures. Changing the stack configuration from a triple layer to a monolayer can lower the peak pressure by reducing the mass of organics per room, but the decrease in initial void volume caused by supercompaction still yields higher predicted pressures than the baseline case.

Supercompaction can, however, be effective in lowering the permeability of the waste, which can decrease the consequences of human intrusion scenarios as discussed in Section 4.2.

4.1.3 Effects of Venting the Repository for 100 Years

An analysis was performed to evaluate the effects of venting excess gas pressures from the repository during the first 100 years following decommissioning. A period of 100 years was chosen because it was assumed that some type of active controls would be required to maintain an open vent from the repository to the surface, and 40 CFR Part 191 (EPA, 1985) requires that active institutional controls cannot be assumed for longer that this period of time.

To evaluate the effectiveness of venting the repository, a simulation was performed that maintained a room pressure of one atmosphere during the first 100 years after decommissioning the repository. After 100 years, the storage rooms were allowed to pressurize in accordance with the baseline assumptions regarding gas generation, creep closure, brine inflow, etc. The results of this simulation is shown in Figure 4-3, along with the results of the baseline design. These results show that the peak index pressures that occur at approximately 815 years are 23 percent higher in the vented case than the baseline case. In the vented case, fluid pressure in the room does not build up during the first 100 years, providing no resistance to closure during this period. This results in lower storage room porosity at 100 years. In addition, this permits higher creep closure rates and, thus, results in a smaller void volume compared to an unvented repository. When the vent is closed at 100 years, microbial gas generation continues for approximately 715 years and is pressurizing a smaller void volume, resulting in higher pressures. From this analysis, it can be concluded that venting will be ineffective in reducing peak index gas pressures unless the vent remains open for the entire gas generating period.

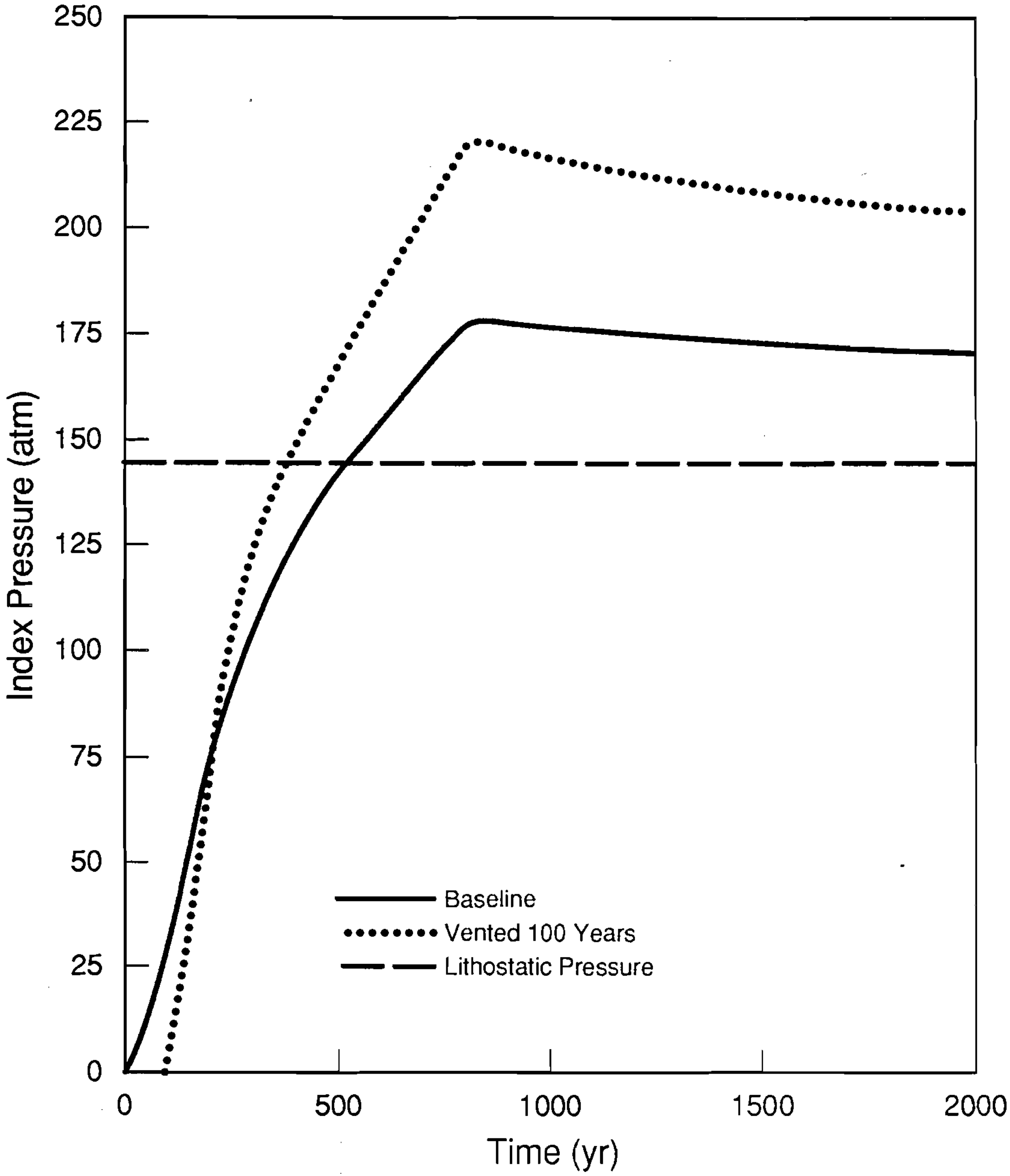

Figure 4-3
Index Pressure Versus Time Curves Evaluating the Effectiveness of Venting the WIPP Repository

Venting the repository could also potentially increase the cumulative inflow of brine to the storage rooms during the venting period. This increased inflow would result from maintaining a high pressure gradient toward the excavation during the venting period.

Venting may raise additional concerns with respect to compliance with the no-migration requirement (EPA, 1990e) of the Resource Conservation and Recovery Act (RCRA). Compliance with RCRA requires that there be no migration of specific volatile organic compounds past the Rustler/Salado contact in concentrations that are in excess of applicable health-based standards.

4.1.4 Effects of Varying Microbial Gas Generation Rates on Room Pressurization

Two significant factors that affect the pressurization of the storage rooms are the total number of moles of gas that are generated and the rates at which they are generated. The baseline assumptions regarding microbial gas generation are that microbial degradation of the organic component of the waste will yield a total of 606 moles/drum, and will be generated at a rate of 0.85 moles/drum/year for a period of approximately 715 years following the establishment of anaerobic conditions (Lappin et al., 1989). There are, however, large uncertainties in these assumptions that will be resolved by the bin-scale experimental program (Molecke, 1990a) and the laboratory experimental program (Brush, 1990). These two experimental programs are designed to provide the project with realistic estimates of the total gas generation rates and potentials anticipated from the disposal of TRU waste in the WIPP environment. Since these data are currently unavailable, a sensitivity study was performed using the Design Analysis Model to evaluate the effects of varying these assumptions on the pressurization of the storage room environment. Four cases were evaluated:

- The baseline rate of 0.85 moles/drum/year and baseline duration of approximately 715 years
- One-half of the baseline rate and twice the baseline duration
- One-quarter of the baseline rate and four times the baseline duration
- Twice the baseline rate and one-half the baseline duration.

In all of the cases, the total baseline potential of 606 moles/drum from microbial gas generation was maintained.

Index pressure versus time curves for these four cases are shown in Figure 4-4, and include the contribution to gas generation from anoxic corrosion. These results show that both the peak index pressure and the timing of the peak are very sensitive to variations in the assumed microbial gas generation rate and duration, even though the total number of moles generated was held constant. In general, lower rates (with proportionally longer durations) result in higher and later peak index pressures. As an example, when the generation rate is reduced by a factor of four, the peak index pressure increases from 180 to 204 atmospheres and is delayed from 800 to 3,000 years (Figure 4-4). This is caused by the coupled nature of creep closure

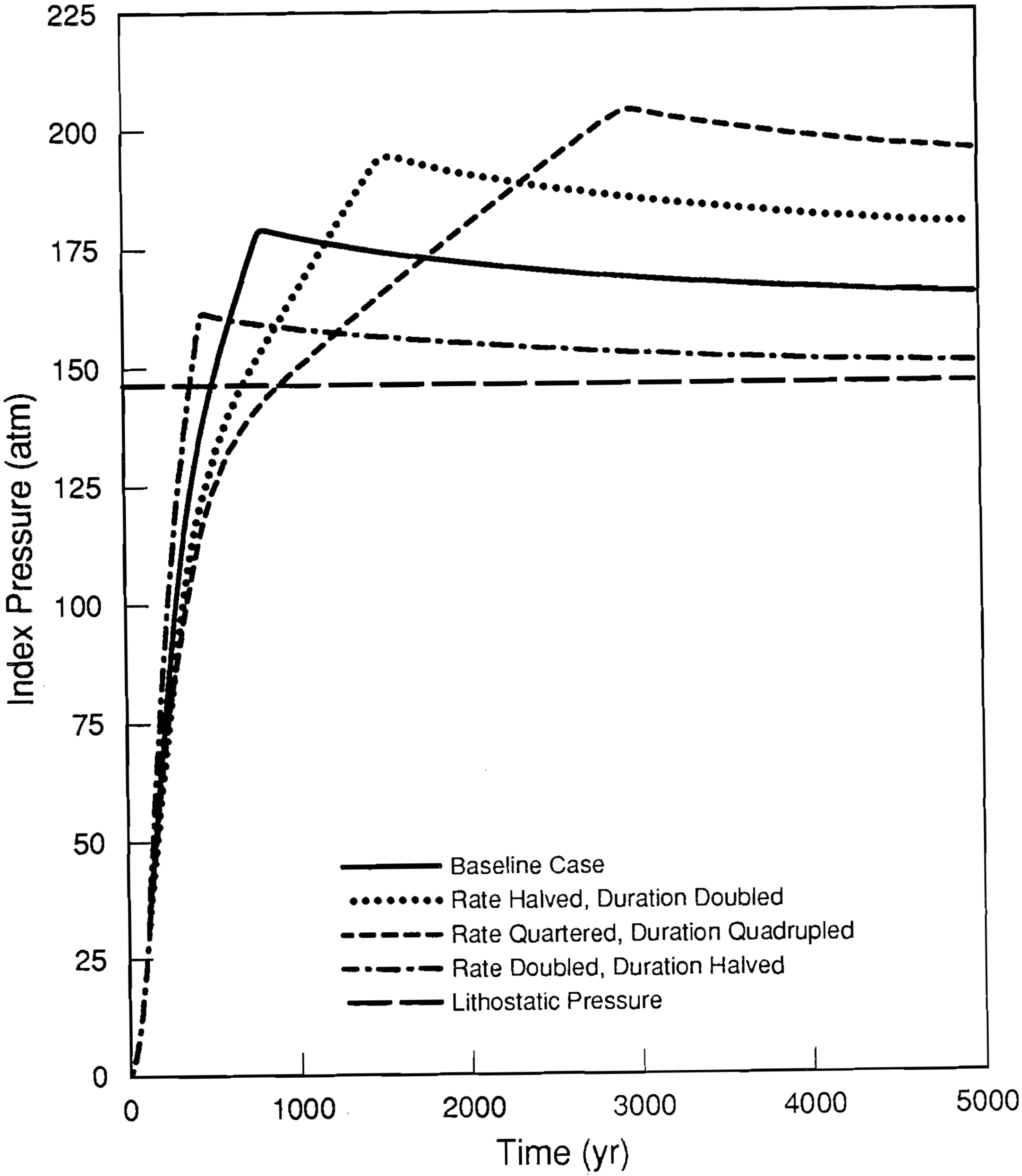

Figure 4-4
Index Pressure Versus Time Curves Varying Rates and Duration of Microbial Gas Generation

and gas generation. When the generation rate is assumed to be low, creep closure proceeds faster and results in rapid establishment of low room porosity. Continued gas generation then pressurizes a smaller volume, yielding higher pressures.

The lowest peak index pressures were achieved in the case where the rate was doubled. In this case, the room rapidly pressurized with gas, which props open voids and reduces the amount of creep closure required to bring the room to lithostatic pressure. This also allows the room to retain a larger percentage of the initial void volume, providing a larger volume for gas to occupy. This suggests that peak index pressures can be reduced if the majority of the gas is generated during the period immediately following decommissioning, when the gas pressure in the room is still below lithostatic pressure.

These results indicate that the void volume available for any generated gas is directly proportional to the rate of gas generation. However, since the peak index pressures are inversely proportional to the available void volume, they are also inversely dependent on the rate of gas generation. Thus, an increase in the gas generation rate is expected to result in a lower peak index pressure. Lowering gas generation rates may not be effective in reducing peak index pressures unless the gas generation potential (total number of moles generated) is also reduced. These results highlight the need for more accurate gas generation rates than are currently available, so that the acceptability of the current unprocessed waste forms can be determined.

4.1.5 Effects of Varying Anhydrite Bed Hydraulic Properties on Room Pressurization

A sensitivity analysis was performed on two hydraulic properties of anhydrite beds to evaluate their effects on room pressurization. The two major properties evaluated were the permeability and the far-field pore pressure of the intact anhydrite beds. A set of runs using the Design Analysis Model were completed, varying permeability over three orders of magnitude (10^{-17} to 10^{-20}). Figure 4-5 shows the results of these sensitivity runs in terms of index room pressure versus time curves for the assumed permeabilities of the anhydrite beds. This figure shows that only for the most extreme case (a permeability of 10^{-17}) does the peak index room pressure change significantly. It should be noted, however, that even though there is a reduction of the peak index pressure, it remains well above the lithostatic pressure of 146 atm. This reduction is attributed to the increased flow of brine from the disturbed to the intact anhydrite beds, providing a larger gas expansion volume, rather than a significant increase of advection of gases into the intact anhydrites (see Appendices B and D). In other words, the higher permeability allows the pressure to build up in the room, and drives a greater amount of the brine from the disturbed zone into the intact anhydrite beds, increasing the available void volume for pressurization.

The second set of sensitivity runs performed considered the effects of varying the far-field pore pressure of the intact anhydrite beds. For this analysis, the far-field pore pressure was varied from 60% to 90% of lithostatic pressure in 10% increments. Figure 4-6 shows the results of these sensitivity runs in the same format as the permeability sensitivity. This figure shows that while the rate of pressure decay changes with the assumed far-field pore pressure,

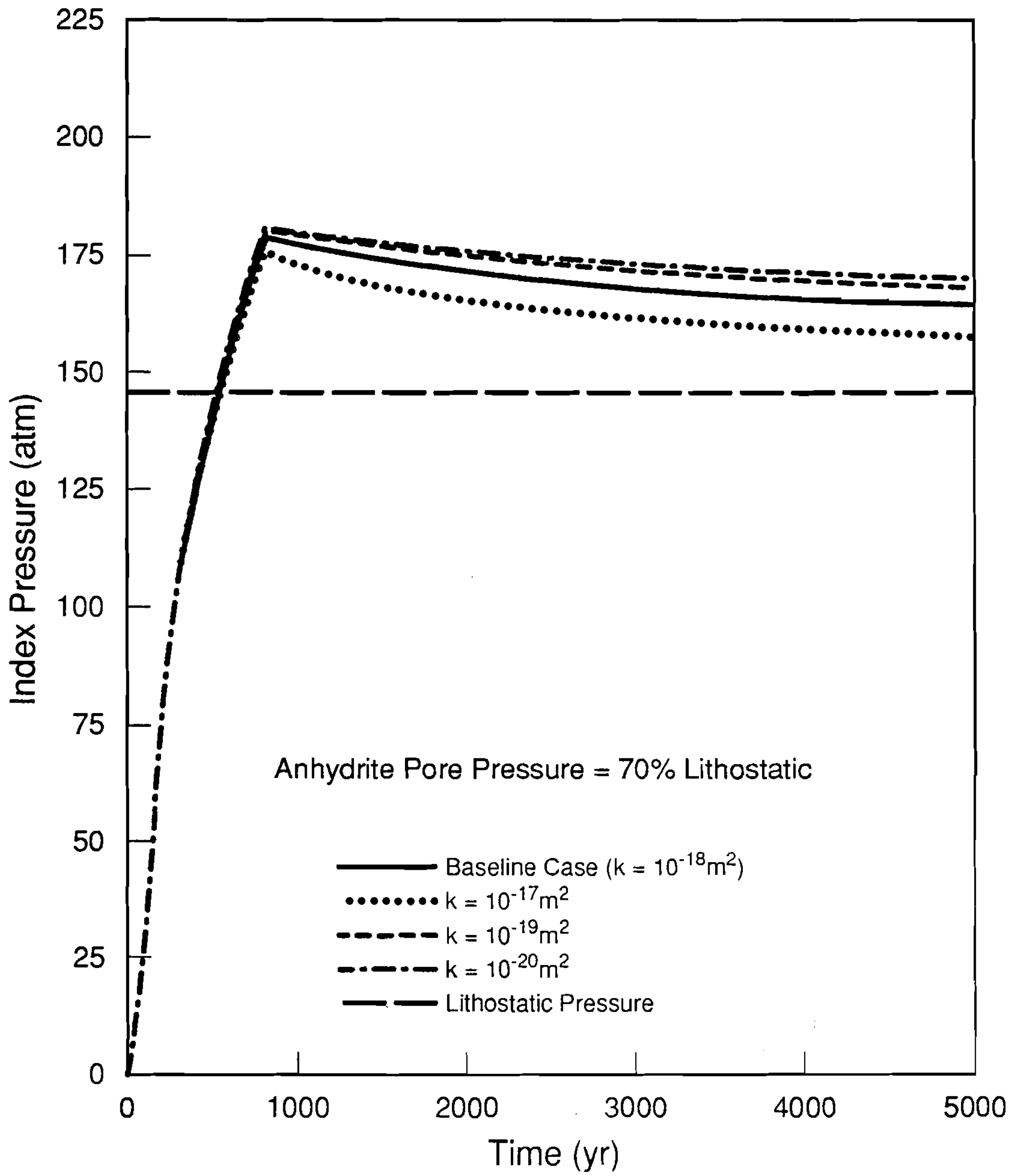

Figure 4-5
Index Pressure Versus Time Curves Varying Permeability of the Anhydrite Beds

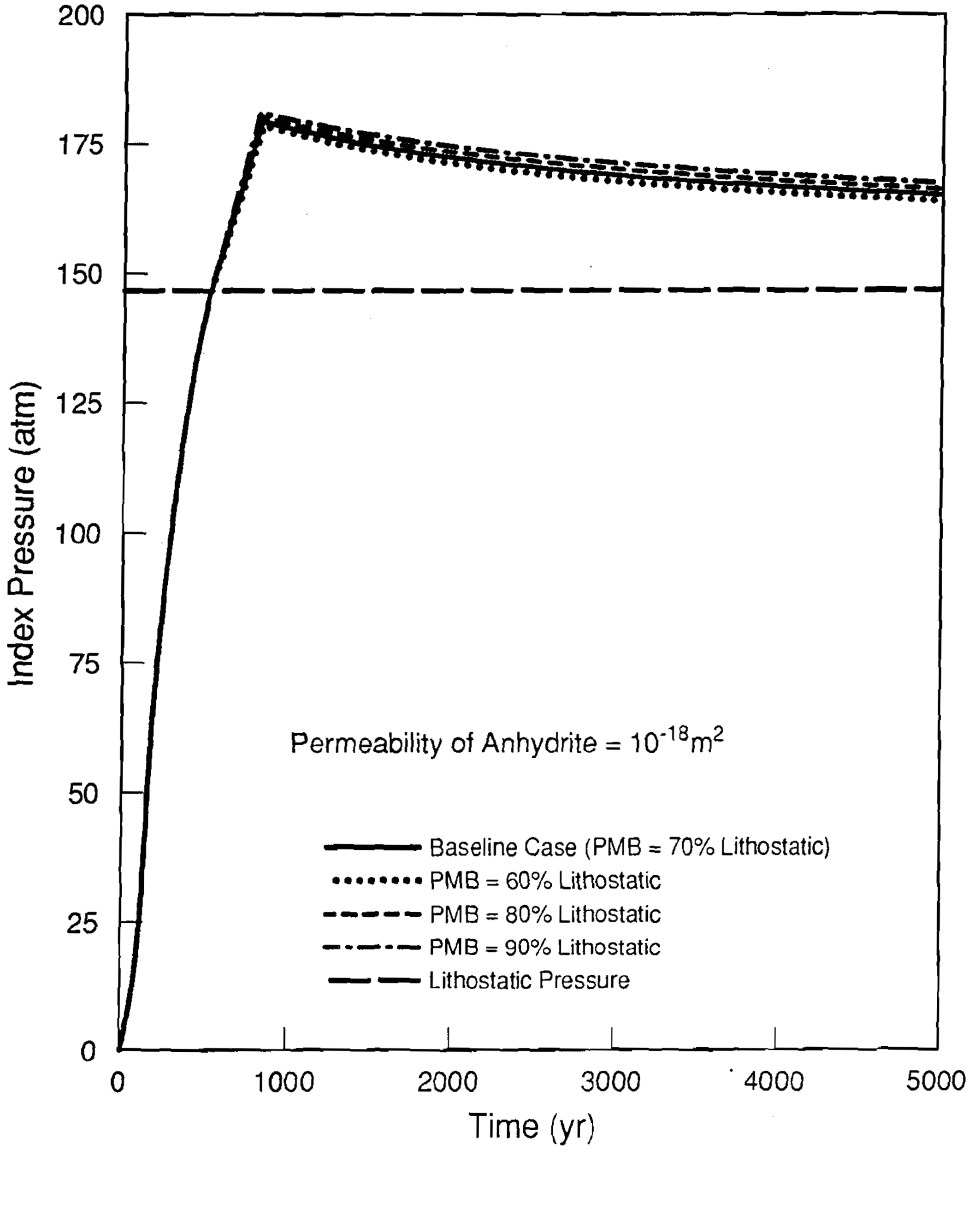

Figure 4-6
Index Pressure Versus Time Curves Varying Far-Field Pore Pressure (PMB) in the Anhydrite Beds

the overall peak index pressures are not significantly affected by varying this parameter over this range.

The results of the sensitivity analyses indicate that the gas advection rates are relatively small compared to the gas generation rates, even under conditions reflecting increased permeability and decreased far-field pore pressure. It should be noted that the following processes impact the gas advection rates but are not incorporated into this model.

- Localized depressurization
- Gas exsolution from brines.

It is apparent from the plots that the advection rate into the anhydrite beds increases linearly with the decrease in far-field pore pressure and log-linearly with the increase in permeability. But for the case of varying the far-field pore pressures, this change is only apparent once gas generation ceases at approximately 815 years and the room slowly begins to return to lithostatic pressure.

These results suggest that while the anhydrite beds are a conduit for gases to advect out of the repository, the low rate of advection (relative to gas generation) may not be effective in reducing peak index pressure to values below lithostatic. However, engineered alternatives that lower gas generation rates to values similar to the rate at which gas can advect away from the storage rooms may be effective in reducing peak index pressures. It should be noted that the results of the model are limited by the assumptions inherent in the model. Therefore, caution should be exercised in interpreting the results until a better understanding is obtained for the gas advection pathways.

4.1.6 Effects of Varying the Initial Brine Inflow Rate on Peak Index Pressure

Small volumes of brine have been observed seeping into brine monitoring holes at several locations in the underground excavations (Deal and Case, 1987). Most of the brine that is currently seeping into the excavations evaporates and is removed by the ventilation system; however, there is concern that some volume of brine may accumulate in the storage rooms during the period between decommissioning and repressurization. The baseline initial brine inflow rate of 0.43 cubic meters/room/year was chosen because it is the largest published value for that parameter (Nowak, et al., 1988). However, there is considerable uncertainty in that value. Published estimates of brine inflow rates vary over a considerable range due to uncertainties in the following processes or parameters:

- Far-field permeability

- The validity of a Darcy model for flow in low-permeability salt. The EATF recognizes that the phenomenon of brine inflow may be attributed to several different mechanisms. However, for the sake of consistency, the brine inflow rate based on the SNL modeling approach has been used.

- The contribution from near-field dewatering versus far-field flow

- The contribution from preferential flow along anhydrite and clay seams
- The role of the disturbed zone surrounding the excavation in controlling brine inflow
- The role of the exsolution of dissolved gases in driving brine inflow.

Due to the uncertainty in brine inflow rates, a sensitivity study was performed to evaluate the effects of varying this parameter on room pressurization.

The results of this analysis are shown in Figure 4-7. Five initial inflow rates were chosen: the baseline rate, one-half of the baseline rate, one-quarter of the baseline rate, twice the baseline rate, and four times the baseline rate. These results indicate that the peak index pressure reached assuming the baseline rate, one-half of the rate, and one-quarter of the rate, are all similar. Only when the baseline rate is doubled or quadrupled does the peak index pressure increase significantly. This phenomena is due to the assumed coupling between brine inflow and anoxic corrosion, as discussed in Section 4.1.1. A maximum hydrogen generation rate limit of 1.7 moles/drum/year (Lappin et al., 1989) is assumed; however, this limit is not reached if the baseline or lower initial brine inflow rates are assumed. Under these conditions, hydrogen generation is limited by brine availability so that brine inflow and hydrogen generation stop when lithostatic pressure is reached. When the initial brine inflow rate is raised above the baseline value, hydrogen generation becomes limited by the 1.7 moles/drum/year maximum rate. Under these conditions, both brine and steel are present in the storage rooms when lithostatic pressure is reached so that hydrogen generation continues after brine inflow stops, yielding higher peak index pressures. These results suggest that peak index room pressures are only sensitive to the initial brine inflow rate if that rate is above some critical value that is somewhere between the assumed rate of 0.43 cubic meters/room/year and twice that value. It is doubtful that the actual value is above 0.43 cubic meters/room/year, because revised inflow rates published after the Nowak, et al. (1988) value are considerably lower. For instance, the SEIS analyses were based on a brine inflow rate of 0.1 cubic meters/room/year (Lappin et al., 1989, page 4-14).

4.1.7 Estimate of the Effects of Alternatives on Peak Index Pressure

The baseline case and 14 combinations of alternatives, shown earlier in Table 1-2, were analyzed using the Design Analysis Model to estimate the peak index gas pressures that will exist in the storage rooms. The goal of these analyses is to provide a relative ranking of the effectiveness of alternatives in reducing peak index pressures, should that be necessary.

These 14 combinations of alternatives include the primary waste forms recommended by the EATF for incorporation into the WIPP Experimental Test Program (DOE, 1990b). Alternatives 1, 2, and 3 involve shredding and cementing of solid organics and metals, which reduce gas generation rates but do not reduce the total gas generation potential. Alternatives 4, 5, 6, 7, 8, 9, and 13 involve thermal treatment (incineration or vitrification) of solid organics to eliminate the source of microbial gas generation. Alternatives 8, 9, and 13 do not have solid

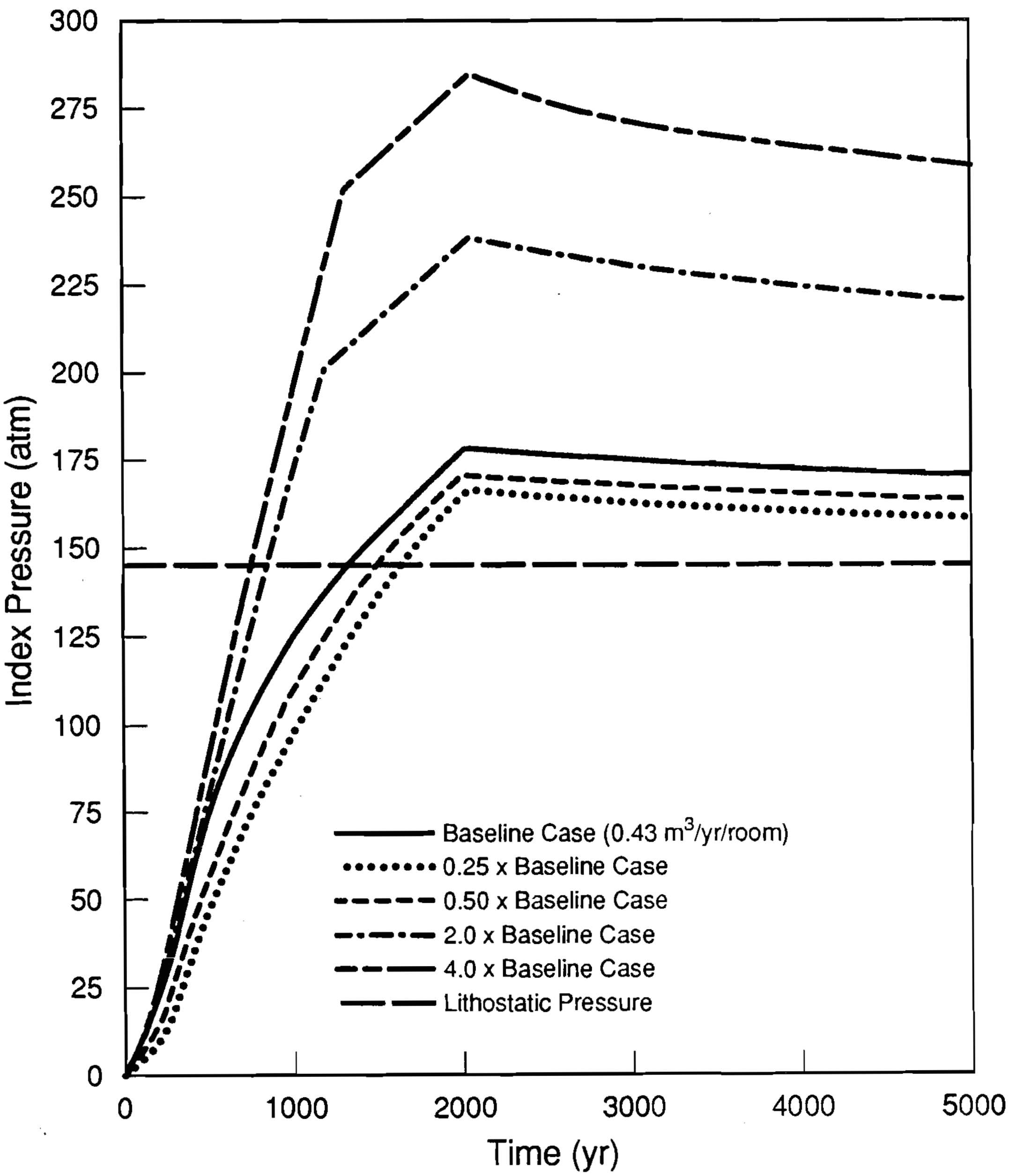

Figure 4-7
Index Pressure Versus Time Curves Varying the Initial Brine Inflow Rate

organics or metals present in the inventory, and thereby eliminate both the microbial and the anoxic corrosion sources of gas generation. Alternative 10 eliminates the metals from the inventory and, hence, the source of gas generation by anoxic corrosion. Alternatives 11, 12, and 14 involve supercompaction of the solid organics and inorganics but do not reduce the total gas generation potential.

Predicted peak index room pressures for the baseline design and 14 alternative combinations of waste forms are shown in Table 4-1. The two principal factors that affect peak index pressures are the mass of organic materials present in the room and the void volume available in the room for pressurization. Also shown in Table 4-1 is a tabulation of peak index pressures expressed as a percentage of lithostatic pressure, excess gas energy, and additional volume required. Excess gas energy is defined here as the excess peak index pressure (peak index pressure minus lithostatic pressure) multiplied by the void volume that the excess pressure occupies. Additional volume is defined as the additional void volume required to reduce the peak index pressure to lithostatic pressure.

The alternatives that involve thermal treatment of solid organics (Alternatives 4 through 9, and 13) show peak index pressures of 146 atm, which corresponds to lithostatic pressure.

For these alternatives, thermal treatment has completely eliminated microbial gas generation so that the main gas generation process is the production of hydrogen from the anoxic corrosion of ferrous metals and aluminum (metallic waste and steel drums and boxes) in the room. The assumed coupling between anoxic corrosion and brine inflow provides a self-limiting mechanism for hydrogen generation, where the generation rate and brine inflow approach zero as the fluid pressure in the room approaches lithostatic (as discussed in Section 4.1.1). Although anoxic corrosion contributes to room pressurization, the process halts when lithostatic pressure is reached.

The coupling of brine inflow and anoxic corrosion assumes that brine is required to be present for corrosion to proceed, and that the brine available for corrosion is finite in volume and is consumed in the process of generating hydrogen. If an additional source of water is present, such as diffusion of water vapor through a disturbed zone surrounding a room, and if corrosion can proceed in the presence of water vapor, then it is possible that hydrogen generation may still occur after lithostatic pressure is reached. The hydrogen generation rate under these conditions will be considerably lower than the rate in a brine-saturated environment, and will be limited either by the diffusion rate of water vapor through the disturbed zone or the corrosion rate of metals in a humid environment.

The assumed coupling between brine inflow and anoxic corrosion is a reasonable assumption at this time, however, it does require experimental verification. Experiments have been initiated by SNL to quantify corrosion rates of steel drum alloys in both brine-saturated and humid environments (Brush, 1990), and a prediction of the extent and degree of interconnected porosity existing in a disturbed zone surrounding a panel is also planned by SNL (DOE, 1990d). The analyses presented in this report can be updated to reflect any revised assumptions that may result from these on-going experimental and modeling activities.

TABLE 4-1

MAXIMUM GAS PRESSURE AND RELATIVE INDEX PRESSURE RESULTS

DESIGN	P_{MAX}* (atm)	PERCENTAGE OF LITHOSTATIC PRESSURE	EXCESS GAS ENERGY (KJ)	ADDITIONAL VOLUME REQUIRED (M^3/PANEL)
BASELINE	180	123	3.76×10^7	2407
ALTERNATIVE 1	222	152	6.24×10^7	3899
ALTERNATIVE 2	215	147	5.97×10^7	3760
ALTERNATIVE 3	175	120	3.65×10^7	2362
ALTERNATIVE 4	146	100	0	0
ALTERNATIVE 5	146	100	0	0
ALTERNATIVE 6	146	100	0	0
ALTERNATIVE 7	146	100	0	0
ALTERNATIVE 8	146	100	0	0
ALTERNATIVE 9	146	100	0	0
ALTERNATIVE 10	215	147	$4.39x10^7$	2779
ALTERNATIVE 11	224	153	$4.31x10^7$	2682
ALTERNATIVE 12	195	134	$3.53x10^7$	2233
ALTERNATIVE 13	146	100	0	0
ALTERNATIVE 14	312	214	$5.40x10^7$	2939

*P_{MAX} = Peak Index Pressure.

Peak index pressures in excess of lithostatic are predicted for the baseline design and Alternatives 1, 2, 3, 10, 11, 12, and 14, all of which use shredded and cemented or supercompacted waste forms. These peaks range from 20 percent above lithostatic for Alternative 3, to 114 percent above lithostatic for Alternative 14. The model predicts that lithostatic pressures are reached within a few hundred years after decommissioning when hydrogen generation stops, but microbial gas generation is assumed to proceed at a linear rate for approximately 815 years. Although advection and diffusion of excess gas pressure away from the storage room is accounted for in the model, the assumed microbial gas generation rate of 0.85 moles/drum/year (Lappin et al., 1989) is much greater than the rate at which excess gas pressure can dissipate, resulting in a period following a few hundred years after decommissioning during which lithostatic pressures are temporarily exceeded.

Variations in the peak index pressures predicted for these first three alternatives shown in Table 4-1 are due to differences in void volumes and differences in the mass of organic materials per room. Alternatives 2 and 3 differ by the use of crushed salt versus grout backfill. Salt backfill initially possesses a higher void volume than grout backfill; however, salt will consolidate under a load to extremely low porosities, whereas a rigid grout will maintain a fixed porosity for a long period. Alternative 3 (grout backfill) reaches a lower peak index pressure than Alternative 2 (salt backfill) because the porosity in the grout contributes to the volume available for pressurization, whereas the initially high porosity in the crushed salt backfill rapidly decreases to low values in response to creep closure, providing a smaller total volume available for pressurization.

An additional factor affecting peak index pressures is the mass of organics per room. For the baseline design, a room is assumed to hold 6,000 55-gallon drums. Shredding and cementation of waste results in a volume reduction of 13 percent, so that a storage room filled with 6,000 drums of shredded and cemented waste will contain the equivalent of approximately 6,800 drums of unprocessed waste (see Section 3.5). The gas generation rates and potentials for Alternatives 1, 2, and 3 are thus assumed to be 13 percent higher than the baseline waste forms because of the greater number of equivalent drums of unprocessed waste.

Fractures may develop at some critical pressure above lithostatic, but if the volume of pressurized gas is small, then the fractures will not propagate very far before the driving force returns to zero at lithostatic pressure. However, if the volume of pressurized gas is large, then fractures may propagate greater distances before the driving force is dissipated. Thus, peak index pressure is a relative measure of the tendency to initiate fractures, and excess gas energy, being a product of excess pressure and volume, is a relative measure of the tendency to propagate fractures once they are initiated.

The excess gas energies, and additional volumes required for Alternatives 4 through 9, and 13, are zero since there is no excess pressure (i.e., peak index room pressures are not greater than lithostatic). For the baseline, and Alternatives 1, 2, 3, 10, 11, 12, and 14, the excess gas energies do not vary by more than a factor of two, and rank in the same relative order as peak index pressures.

The values for the Additional Volume Required, shown in Table 4-1, provide a means to evaluate the uncertainty in the predicted peak index pressures. According to the Ideal Gas Law, in a closed system at constant pressure containing a fixed number of moles of gas, the product of pressure (P) and volume (V) is equal to a constant. If V is small and P is large, a small uncertainty in V corresponds to a large uncertainty in P. As an example, if the additional volume required to return the peak pressures to lithostatic is very small relative to the total void volume of the panel at the time that the peak pressure is reached, the predicted peak pressures may well be an artifact of the uncertainties in the total panel void volume. However, if the additional volume required is a significant percentage of the total panel void volume, there is greater confidence in the predicted peak pressures. The values for the additional volume required, shown in Table 4-1, range from 19 percent (for Alternative 3) to 92 percent (for Alternative 14) and average 47 percent of the total void volume in the panel at the time of peak pressurization. This significant amount of additional void volume required to return the peak pressures to lithostatic suggests that the predicted peak pressures are not artifacts of uncertainties in the predicted void volumes.

These analyses of the effects of alternative waste forms on peak index room pressures suggest the following:

- The most important factors that affect peak index pressures are the mass of organic materials present in the room and the void volume available for pressurization.
- The baseline waste forms will generate peak index gas pressures that are in excess of lithostatic.
- Alternatives 1, 2, 3, 10, 11, 12, and 14 also generate pressures in excess of lithostatic due to the presence of organic materials. Thus, these alternatives appear to be ineffective in reducing peak index pressures, but they may have application in reducing the consequences of human intrusion events.
- Alternatives that involve thermal treatment of organic materials (Alternatives 4 through 7) do not exceed lithostatic pressure even though metals are present. This is caused by the assumed coupling between anoxic corrosion and brine inflow.
- Alternatives 8, 9, and 13 do not exceed lithostatic pressures because organics and metals have been removed.

4.2 ANALYSIS OF HUMAN INTRUSION SCENARIOS

Analyses were performed to determine the relative effectiveness of 14 alternative combinations of waste forms, described in Table 1-2, for reducing the consequences of human intrusion events. Three human intrusion scenarios designated E1, E2, and E1E2 were simulated using the methodology described in Appendix B. These scenarios, described in Section 2.2 and depicted in Figure 2-2, are the same as those used in the Performance Assessment

Methodology Demonstration Report (Marietta et al., 1989) where more detailed descriptions of these scenarios appear.

For all three scenarios, releases due to the slow flow of contaminated brine into the Culebra Dolomite are added to the releases due to the rapid removal of drill cuttings from the repository horizon to the surface. Scenarios E1 and E2 each remove cuttings from a single penetration of a borehole, and the E1E2 scenario includes the removal of cuttings from two boreholes. The methodology used to estimate the releases due to the removal of cuttings is described in Appendix B, Section 2.22.

The two most important parameters that control releases from the repository due to the migration of contaminated brine are radionuclide solubilities and the hydraulic conductivity of the storage rooms. Releases due to the removal of cuttings are controlled by the volumetric waste loadings, the height of the waste stack, and the shear strength of the waste forms. The methodology for estimation of waste element solubilities and storage room conductivity is described in Appendix B, Section 2.21.

<u>Discussion of Results of Human Intrusion Scenarios</u>

For each engineered alternative, the Design Analysis Model was used to calculate measures of relative performance for each of the three human intrusion scenarios. Two measures of relative effectiveness were calculated for each alternative/scenario pair; one based on the slow release of contaminated brine, and one that sums the slow release of contaminated brine with the contribution from the removal of drill cuttings. The results of these calculations are shown in Table 4-2.

Of the three scenarios considered, the Castile Brine scenario (E1) releases the largest volume of contaminated brine. This is caused by the slow migration of a potentially large volume of brine from the Castile Formation up the borehole, through the storage room, and on up to the Culebra Dolomite. The immediate release of drill cuttings to the surface causes a change in the Measure of Relative Effectiveness (MRE) only in the third or fourth decimal place which is why the pairs of values for the E1 scenario in Table 4-2 are similar. (The MRE is calculated by dividing the Measure of Effectiveness for the alternative by the Measure of Effectiveness for the baseline case; an MRE greater than one indicates a decrease in performance, and an MRE less than one indicates an increase in performance relative to the baseline case).

The use of grout backfill instead of the reference crushed salt backfill, in all cases, results in an improvement in performance as indicated in the relative improvement of Alternative 5 over 4, Alternative 7 over 6, and Alternative 12 over 11, as shown in Table 4-2. This is most clearly demonstrated in the E2 scenario where the consequence is dominated by the release of contaminated brine that has accumulated in the storage room during the initial repressurization period. The use of a grout backfill results in lower permeability of the waste/backfill composite, providing a greater resistance to the flow of contaminated brine toward the borehole.

TABLE 4-2

MEASURE OF RELATIVE EFFECTIVENESS RESULTS WITHOUT CUTTINGS AND MEASURE OF RELATIVE EFFECTIVENESS RESULTS WITH CUTTINGS FOR THE E1, E2, and E1E2 SCENARIOS

DESIGN	E1	E2	E1E2
BASELINE	1.00(a) 1.00(b)	1.00(a) 1.00(b)	1.00(a) 1.00(b)
ALTERNATIVE 1	0.40(a) 0.40(b)	0.96(a) 0.96(b)	6.4×10^{-4}(a) 8.3×10^{-4}(b)
ALTERNATIVE 2	0.38(a) 0.38(b)	0.92(a) 0.90(b)	4.7×10^{-4}(a) 6.5×10^{-4}(b)
ALTERNATIVE 3	0.27(a) 0.27(b)	2.1×10^{-2}(a) 2.8×10^{-2}(b)	4.1×10^{-5}(a) 2.1×10^{-4}(b)
ALTERNATIVE 4	0.55(a) 0.56(b)	1.21(a) 1.19(b)	2.0×10^{-4}(a) 5.0×10^{-4}(b)
ALTERNATIVE 5	0.39(a) 0.39(b)	3.6×10^{-2}(a) 4.7×10^{-2}(b)	2.1×10^{-5}(a) 2.9×10^{-4}(b)
ALTERNATIVE 6	0.25(a) 0.26(b)	4.4×10^{-2}(a) 7.1×10^{-2}(b)	3.4×10^{-5}(a) 6.6×10^{-4}(b)
ALTERNATIVE 7	1.2×10^{-2}(a) 1.3×10^{-2}(b)	3.3×10^{-3}(a) 2.8×10^{-2}(b)	4.5×10^{-7}(a) 5.5×10^{-7}(b)
ALTERNATIVE 8	4.6×10^{-2}(a) 4.9×10^{-2}(b)	0.14(a) 0.20(b)	2.6×10^{-6}(a) 1.5×10^{-3}(b)
ALTERNATIVE 9	2.9×10^{-2}(a) 3.2×10^{-2}(b)	0.11(a) 0.16(b)	3.1×10^{-7}(a) 1.4×10^{-3}(b)
ALTERNATIVE 10	1.14(a) 1.15(b)	2.19(a) 2.17(b)	2.0×10^{-2}(a) 2.1×10^{-2}(b)
ALTERNATIVE 11	0.66(a) 0.66(b)	0.67(a) 0.66(b)	0.71(a) 0.71(b)
ALTERNATIVE 12	0.41(a) 0.41(b)	1.3×10^{-2}(a) 2.4×10^{-2}(b)	6.6×10^{-3}(a) 6.9×10^{-3}(b)
ALTERNATIVE 13	4.7×10^{-3}(a) 8.2×10^{-3}(b)	1.7×10^{-4}(a) 9.4×10^{-2}(b)	1.6×10^{-8}(a) 2.1×10^{-3}(b)
ALTERNATIVE 14	0.17(a) 0.18(b)	2.7×10^{-2}(a) 9.8×10^{-2}(b)	1.5×10^{-4}(a) 1.6×10^{-3}(b)

(a)Without drill cuttings.
(b)With drill cuttings.

The greatest relative improvement for the E1 scenario is offered by Alternative 13, which is vitrified waste forms placed in nonferrous rectangular containers, thereby eliminating the need for backfill. The critical performance parameter for this scenario is the relative contrast in hydraulic conductivity between the material filling the borehole (sand and silt) and the material filling the storage room (waste and backfill). If the conductivities of these two materials are similar, a significant fraction of the brine flowing up from the Castile will interact with the waste, but if the conductivity of the materials in the storage room is low relative to the material filling the borehole (as it is for Alternatives 7, 8, 9, and 13), there is little waste/brine interaction.

The most dramatic improvement in performance for the E1E2 scenario occurs using Alternative 13. A three-order-of-magnitude improvement is predicted, with two sets of drill cuttings included. However, an improvement of eight orders of magnitude is predicted using Alternative 13 if the contribution from drill cuttings is neglected, indicating that the contribution from drill cuttings dominates the release. This contribution can further be reduced by changing the initial height of the waste stack from the reference design of drums stacked three layers high (nine feet) to a lower configuration, as demonstrated by Alternatives 11 and 12 where the drill cuttings cause a change in the MRE only in the fourth decimal place.

4.3 SUMMARY OF RESULTS FOR DESIGN ANALYSES

The results of design analysis have shown that, if needed, a number of engineered alternatives could be implemented to improve the repository long-term performance. The combinations of engineered alternatives evaluated by the EATF include alternatives that have varying degrees of effectiveness to address possible gas generation and future inadvertent human intrusion scenarios. However, the exact choice of an engineered alternative can only be determined after the extent of the problem, and the degree of effectiveness required, have been identified by the performance assessment studies.

Table 4-3 summarizes the interpretations of the EATF regarding the effectiveness of 14 combinations of engineered alternatives in addressing gas generation issues and three human intrusion scenarios.

The effectiveness of an alternative for addressing gas generation has been summarized in terms of the effect of an alternative on the peak index pressure, and its effect on the gas generation rates by either microbial/radiolytic processes or by anoxic corrosion. If the peak index pressures due to an alternative (as estimated by the Design Analysis Model) do not exceed the lithostatic pressure, the alternative is considered to be effective, and is assigned a blank circle in Table 4-3. On the contrary, if the peak index pressure exceeds the lithostatic pressure, the alternative is considered to be ineffective, and is assigned a dark circle in Table 4-3.

As an example, from the results of the Design Analysis Model, the peak index pressures due to Alternative 2 exceed the lithostatic pressure and therefore this alternative is assigned a dark circle in Table 4-3. Similarly, Alternative 4, which does not exceed the lithostatic pressure, is assigned a blank circle for its effectiveness for addressing peak index pressure.

TABLE 4-3
INTERPRETATION OF THE RESULTS OF THE DESIGN ANALYSIS MODEL

Treatment level[a]	ALTERNATIVE DESCRIPTION						ALTERNATIVE EFFECTIVENESS					
							Peak Index Pressure	Gas Generation Rate		Human Intrusion		
	Number	Sludges	Solid Organics	Solid Inorganics	Backfill	Waste Container		Microbial & Radiolytic	Anoxic Corrosion	E1	E2	E1E2
II	1	AR	S&C	S&C	SLT	AR	●	◒	◒	◒	●	○
II	2	CMT	S&C	S&C	SLT	AR	●	◒	◒	◒	●	○
II	3	CMT	S&C	S&C	CGT	AR	●	◒	◒	◒	○	○
II/III	4	CMT	I&C	S&C	SLT	AR	○	○	◒	●	●	○
II/III	5	CMT	I&C	S&C	CGT	AR	○	○	◒	◒	○	○
III	6	VTR	I&V	MM	SLT	AR	○	○	◒	◒	◒	○
III	7	VTR	I&V	MM	CGT	AR	○	○	◒	○	○	○
III	8	VTR	I&V	MRM	SLT	NFE	○	○	○	○	◒	○
III	9	VTR	I&V	MRM	CGT	NFE	○	○	○	○	◒	○
III	13	VTR	I&V	MRM	N/A	NFR	○	○	○	○	◒	○
I/III	10	AR	AR	DRM	N/A	NFR	●	●	○	●	●	○
I	11	AR	SPT	SPT	SLT	AR	●	●	●	●	●	●
I	12	AR	SPT	SPT	CGT	AR	●	●	●	◒	○	○
I	14	AR	SPT	SPT	SAG	AR	●	●	●	◒	◒	○

AR - AS RECEIVED
CMT - CEMENT
VTR - VITRIFY
S&C - SHRED & CEMENT
I&C - INCINERATE & CEMENT
I&V - INCINERATE & VITRIFY
N/A - NOT APPLICABLE

MRM - MELT AND REMOVE METALS
DRM - DECONTAMINATE AND REMOVE METALS
SLT - SALT
CGT - CEMENT GROUT
SAG - SALT AGGREGATE GROUT
SPT - SUPERCOMPACT

◒ - PARTIALLY EFFECTIVE
○ - EFFECTIVE
● - NO EFFECT
NFR - NON FERROUS, RECTANGULAR
NFE - NON FEROUS
MM - MELT METALS

[a] CLASSIFICATION BY TREATMENT LEVELS IS SOMEWHAT GENERALIZED; FOR EXAMPLE, ALTERNATIVE 1 INCLUDES BOTH LEVEL I AND LEVEL II TREATMENTS.

The effect of an alternative on the gas generation rates has been summarized in Table 4-3, based on the knowledge of processes involved in these alternatives. An alternative is considered to be effective for addressing gas generation from a given mechanism, if it is expected to reduce the generation rates to near zero (i.e., it practically eliminates the potential for gas generation from that mechanism). This is denoted by a blank circle in Table 4-3. Similarly, if an alternative reduces the gas generation rate but does not completely eliminate it, it is considered to be partially effective (denoted by a shaded circle in Table 4-3). An alternative which is not expected to have any effect on the generation rates is termed ineffective, and is assigned a dark circle in Table 4-3.

As an example, Alternative 6 which incinerates and vitrifies the solid organics, and vitrifies the sludges, practically eliminates gas generation from microbial/radiolytic processes, and reduces generation rates from this mechanism to zero. Therefore, it is assigned a blank circle in Table 4-3 for addressing gas generation rates from microbial/radiolytic processes. However, the melting of metals into ingots (as done in Alternative 6) does not eliminate metals from the inventory, but helps to reduce the rate of gas generation from anoxic corrosion. This is denoted by a shaded circle in Table 4-3. Similarly, supercompaction of the waste has no effect on the gas generation rate, and is therefore assigned a dark circle in Table 4-3.

The apparent inconsistency between predicted peak index pressures and predicted effect on gas generation rates is a function of the simplifying assumptions inherent in model development. The Design Analysis Model includes various assumptions about gas generation rates from waste forms, creep closure rates, brine inflow, coupling of brine inflow and anoxic corrosion, and room response to gas pressure. These assumptions are based on data about the WIPP available at the time of model development, with almost all of the data obtained from SNL publications. Although these assumptions are reasonable at this time, they may change as ongoing experimental and modeling activities continue to provide additional data. If necessary, the Design Analysis Model can be updated to incorporate new assumptions as revised data becomes available.

Table 4-3 also summarizes the effectiveness of the 14 alternatives in addressing the three hypothetical human intrusion scenarios. The summary is based on the results obtained by the Design Analysis Model for the MRE of an alternative for these scenarios. As explained in Section 4.2, the MRE of an alternative must be less than 1 to signify an improvement in performance relative to the baseline design. The performance progressively improves as the MRE approaches zero. Although any value of MRE less than 1 signifies an improvement, the EATF has used a conservative upper limit of 0.5 for rating an alternative partially effective (denoted by a shaded circle). If the MRE is greater than 0.5 for a given scenario, the alternative is considered to be ineffective for addressing that particular scenario, and is assigned a dark circle in Table 4-3. Similarly, an MRE of less than 0.05 has been used to classify an alternative to be most effective (denoted by a blank circle in Table 4-3). As an example, Alternative 7 is effective for all three intrusion scenarios, and is assigned a blank circle under each column. In contrast, Alternative 1, which is partially effective for scenario E1, effective for E1E2, and is ineffective for E2, is assigned a shaded circle, a blank circle, and a dark circle under the respective columns. As with predictions of effectiveness for addressing gas generation, it should be noted that the results of the Design Analysis Model for human intrusion scenarios are also influenced by the assumptions inherent in model development.

Table 4-3 provides a comparison between the relative effectiveness of 14 combinations of engineered alternatives for addressing both gas generation and human intrusion issues. If a problem is identified by performance assessment, Table 4-3 will help focus the choice of an effective alternative to a small group of alternatives. As an example, if performance assessment determines that merely reducing gas generation rates will help demonstrate compliance, then either one of Alternatives 1, 2, or 3 would be sufficient, and there would be no need for any Level III combinations. Alternatively, if it is determined that it is necessary to eliminate gas generation of any kind in order to demonstrate compliance, then the choice of alternatives would be limited to Alternatives 8, 9, and 13. Similar logic can be applied to the human intrusion scenarios to arrive at a set of alternatives sufficient to address any problems identified by performance assessment.

It should be noted that although Table 4-3 provides comprehensive information about the effectiveness of engineered alternatives, it cannot be used to determine the final choice of an alternative, because it does not distinguish between the alternatives regarding the feasibility of implementing them. Once a group of alternatives have been identified that have the minimum effectiveness necessary to address the extent of the problem, a comparison of their overall feasibility is required to arrive at a final conclusion. The subsequent sections (Sections 5.0 through 8.0) provide a detailed discussion of the feasibility of implementing engineered alternatives with respect to various issues.

5.0 OVERVIEW OF FEASIBILITY EVALUATION OF ENGINEERED ALTERNATIVES

In addition to assessing the effectiveness of various engineered alternatives, the EATF has also evaluated the feasibility of implementing each combination of alternatives presented in Table 1-2.

5.1 TYPES OF ENGINEERED ALTERNATIVES EVALUATED

The engineered alternatives evaluated by the EATF for feasibility of implementation have been classified into three categories:

- Waste treatment alternatives
- Backfill alternatives
- Other engineered alternatives.

Modifications to waste container material or shape have been discussed under "Other Engineered Alternatives." Waste treatment alternatives are the most complex to implement, and require construction of specialized facilities or use of existing facilities in order to implement the alternative. Therefore, the EATF has focused a substantial part of its feasibility evaluation efforts in assessing the feasibility of waste treatment alternatives.

The remainder of this section identifies the criteria against which the feasibility of alternatives has been evaluated. Section 6.0 discusses the feasibility of waste treatment alternatives, and Sections 7.0 and 8.0 discuss the feasibility of backfill and other alternatives, respectively.

5.2 CRITERIA FOR EVALUATION OF FEASIBILITY

The feasibility of implementing waste treatment alternatives has been evaluated relative to four criteria: availability of technology, regulatory issues, cost, and schedule. The Program Plan for Engineered Alternatives (Hunt, A., 1990) identified the following critical issues requiring investigation:

- Status of Development - The technology must have the potential for full-scale demonstration in order to be considered a viable option.

- Existing Capacity Versus Treatment Need - The usable capacity of treatment of TRU waste will be considered.

- Regulatory Constraints to Implementation - Issues such as extended permit cycles and transportation.

- Institutional Constraints to Implementation - Issues such as local waste treatment facility restrictions.

- Estimate of Implementation Costs - Cost effectiveness of the treatment.
- Implementation Schedules - Timeliness of treatment relative to overall program schedules.
- Potential Facility Locations.
- Worker, General Public, and Environmental Safety - Comparison of the risks of processing existing waste or changes in waste generating processes at the DOE sites, with transport of untreated wastes to WIPP.

The feasibility of implementing backfill or other engineered alternatives (waste management changes, facility design modifications, and passive surface markers) has been evaluated by using the following information:

- Status of development of technology
- Regulatory considerations
- Cost and schedule for full-scale implementation.

In addition to assessing the effectiveness of various engineered alternatives, the EATF has also evaluated the feasibility of implementing each combination of alternatives presented in Table 1-2.

6.0 FEASIBILITY OF IMPLEMENTING WASTE TREATMENT ALTERNATIVES

6.1 INTRODUCTION

The EATF developed the following categories for assessing the feasibility of implementation of waste treatment alternatives based on criteria identified in the Program Plan for Engineered Alternatives (Hunt, A., 1990):

- Development Status of Waste Treatment Technologies (Section 6.3.1)
- Location of Stored Waste and Waste Generation Rates by Site (Section 6.3.2)
- Tabulation of Existing Treatment Capacity (Section 6.3.3)
- Waste Treatment Cost Estimates (Section 6.3.4)
- Implementation Schedule (Section 6.3.5)
- Regulatory Considerations (Section 6.3.6)
- Worker, General Public and Environmental Risk Assessment (Section 6.3.7).

The data collected for each of these categories have a dual function. First, the data collectively form the basis for selecting a potential treatment technology. Trade-offs of effectiveness in improving repository performance are qualitatively weighted relative to cost, schedule, regulatory concerns, and health effects. Once the treatment is selected, the data are then used in the site selection process. Location of wastes, cost of treatment, transportation cost, risk, and permitting constraints are all considered for selecting the location and number of treatment facilities.

The EATF findings on the feasibility of waste-treatment alternatives in Section 6.0 are organized into three sections. Section 6.2 reviews the components of Level II and Level III treatment facilities. Section 6.3 presents the preliminary data required to evaluate waste treatment alternative feasibility. Results may then be factored into the decision methodology presented in Section 6.4 to select locations for treatment facilities, as well as the decision methodology for selecting treatment alternatives presented in Section 9.0.

The EATF mission of providing a preliminary analysis of alternative feasibility precluded detailed collection or development of information such as facility costs, implementation schedules, or institutional or regulatory requirements. The more quantitative data required in selection of a waste treatment, if waste treatment is determined to be required, is best collected once the WIPP performance assessment issue(s) become defined. Where appropriate, the EATF has identified additional information that should be developed before a final decision on waste treatment.

6.2 WASTE TREATMENT FACILITY DESCRIPTION

Waste treatment requires a facility or facilities that consists of both treatment operations (e.g., shredder, incinerator, solidification systems) and an array of support functions. Support functions for waste treatment include administration, maintenance, receiving, shipping, storage, etc. This section provides a brief description of the various waste treatment facility components and potential operations which may be required to treat TRU waste prior to disposal at the WIPP.

6.2.1 Support Functions of a Waste Treatment Facility

Facility structures and systems required to support the waste treatment operations are major contributors to the overall facility cost and schedule. Figure 6-1 depicts typical elements of a waste treatment facility. The elements common to most waste treatment facilities, independent of the treatment processes, are presented below.

6.2.1.1 Unloading Bay

This area provides space for unloading trucks carrying the TRUPACT-II or other authorized packages that are used to transport TRU waste to the waste treatment facility.

6.2.1.2 Receiving Bay

This area provides space and equipment for unloading waste containers from the shipping packages, inspecting the waste containers and the interior of the shipping package for surface contamination, and preparing the waste containers for temporary storage.

6.2.1.3 Waste Storage Area

This area is storage space for incoming waste. The purpose of maintaining a stored waste inventory at the facility is to provide efficient flow of waste into the waste treatment area.

6.2.1.4 Incoming Waste Inspection Area

The heterogeneity of the incoming TRU waste forms suggests that some inspection or confirmation may be required to assure that the waste contents are appropriate for the specific waste treatment being conducted at the facility. Therefore nondestructive testing may be conducted before the waste is transferred to the waste treatment area. Testing might consist of real-time radiography, radionuclide assays, and weighing of the waste, as well as verifying transportation records.

6.2.1.5 Waste Transfer Area

This area serves as the loading point for waste entering the waste treatment area. The waste transfer area will either be an airlock, or have an airlock between itself and the waste treatment area. The airlock serves as a barrier between clean areas of the facility and potentially contaminated areas. If sampling of waste is required prior to treatment, this area could meet these needs.

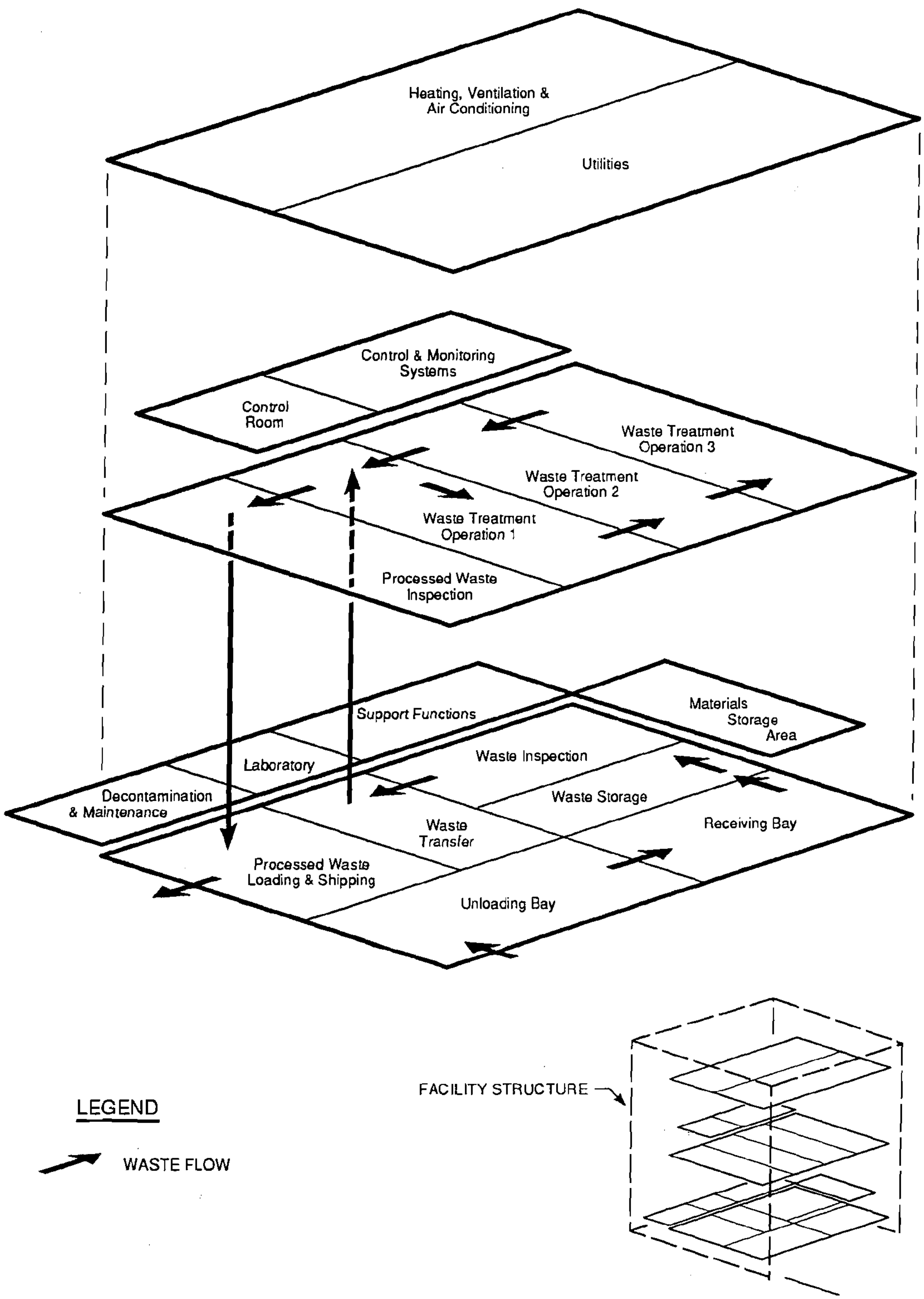

FIGURE 6-1
WASTE TREATMENT FACILITY SCHEMATIC

6.2.1.6 Heating, Ventilation, and Air Conditioning (HVAC) Systems

The HVAC systems control air flow and maintain temperature and negative pressure in all parts of the facility. These systems include high-efficiency particulate air (HEPA) filters to prevent TRU radionuclides from leaving the building with the ventilation air. All areas that contain TRU waste will be maintained at negative pressure relative to the exterior of the building. This assures that, in the unlikely event that radioactive materials contaminate an area of the facility, the contaminants will not be released to the environment.

6.2.1.7 Control and Monitoring Systems

These systems include fire protection and alarms, radioactive contamination monitoring, physical security, confinement control, utility instrumentation and control, and computer systems.

6.2.1.8 Control Room

Treatment processes may be controlled from a single control room, or individual control stations. For the more complex operations, waste treatment will probably be controlled via a central control room computer with local control options.

6.2.1.9 Processed Waste Inspection

After the waste has been treated, it is moved into an inspection area where it will be non-destructively tested or sampled to ensure that adequate treatment has taken place. Waste will be certified for shipment to WIPP in the processed waste inspection area.

6.2.1.10 Processed Waste Loading

This area is similar to the unloading and receiving bays. The waste containers will be prepared for loading (such as bundling drums into a seven-pack array) and loaded into the TRUPACT-II.

6.2.1.11 Decontamination and Maintenance

Equipment used to handle and treat the waste will require periodic maintenance and/or decontamination. This area of the facility serves as a decontamination and repair or maintenance function, and may consist of remote operations including a highbay area for maintaining large equipment.

6.2.1.12 Laboratory

Periodic sampling and analysis of incoming or outgoing waste will be required at the facility. A laboratory is necessary for analysis of the samples for certification purposes.

6.2.1.13 Materials Storage Area

Waste treatment may require bulk quantities of Portland cement, glass frit, or other materials associated with the process. This area will store and provide these materials to the waste treatment area. A separate area may also be reserved for spare parts, lubricating oils, and other materials and equipment as may be needed to support day-to-day operations.

6.2.1.14 Utilities

This function will be spread throughout the facility, and consists of: electrical, heating and cooling, water supply, emergency power, sanitary sewage systems; and process-related utilities such as emergency showers and personnel radiation detection. Recycling of wastewater may also occur within this function.

6.2.1.15 Facility Structure

A building will be required to house the waste treatment systems and supporting elements. Portions of the building, such as the waste treatment and receiving and loading areas, will probably require multistory construction to accommodate equipment and operations. Roads, parking, fences, and utility supplies complete the facility. The building would be designed and constructed to meet the requirements of DOE Order 6430.1A, General Design Criteria (DOE, 1987b), which includes an assessment of the hazard level of operation. It is expected that the facility will be considered a medium or high hazard facility as defined by this order.

6.2.1.16 Other Support Functions

These functions consist of administration, health physics, change areas, communications, and any unique operation required at the specific facility.

6.2.2 Treatment Operations

Treatment operations, such as incineration, shredding, cementation, and vitrification, together with ancillary equipment such as off-gas systems, material hoppers, instrumentation and controls, and the supporting structures, represent the waste treatment portion of the facility. This area will be maintained at a negative pressure relative to other areas of the facility containing TRU waste.

The waste treatment alternatives considered feasible by the EATF result in five basic waste forms: glass or concrete monoliths, compacted waste, metal ingots, and the unprocessed waste form with pH buffers. The treatment operations needed to produce these basic products are:

- Vitrification
- Solidification (with a cement-based grout)
- Compaction
- Incineration (followed by vitrification or solidification)
- Metal melting (which produces metal ingots; a slag may be produced which can then be vitrified; see Section 6.3.1.9)
- Addition of pH buffers
- Shredding (as a precursor to other processes).

A treatment operation consists of the process equipment needed to produce the waste forms listed above, as well as support systems and structures directly associated with the particular treatment operation.

Figure 6-2 shows the treatment operations associated with each waste treatment alternative considered feasible by the EATF. One or more treatment operations are generally required to produce each waste form. For instance, a cemented waste form might require shredding, incineration, and cementation if the waste specification requires elimination of organics and solidification of the waste. These treatment operations, together with appropriate support elements, constitute the facility required to process TRU waste into the desired waste form. The facilities evaluated by the EATF include treatment operations capable of treating unprocessed waste forms as follows:

- Shred and cement solid organics
- Incinerate and cement solid organics
- Incinerate and vitrify solid organics
- Shred and cement solid inorganics
- Melt metals into TRU ingots
- Melt metals and eliminate from WIPP inventory (vitrified slag will be shipped to WIPP)
- Cement sludges
- Vitrify sludges
- Decontaminated metal with residue solidification.

6.3 DESCRIPTION OF FACTORS CONSIDERED IN IMPLEMENTING TREATMENT ALTERNATIVES

The EATF assembled information on the feasibility of implementing waste treatment alternatives at facilities consisting of components described in Section 6.2. This information is organized by factors considered in implementing treatment alternatives and is described below. Selection of a treatment technology requires integration of data on waste treatment technology status (Section 6.3.1), treatment cost (Section 6.3.4), schedule issues (Section 6.3.5), regulatory considerations (Section 6.3.6), and the assessment of risk (Section 6.3.7). Once a treatment technology or technologies are selected, siting of treatment facilities requires analysis of location of waste and waste-generation rates (Section 6.3.2), current or planned treatment capacity (Section 6.3.3), waste transportation costs versus capital and operating costs for

WASTE TREATMENTS	SHRED	COMPACT	CEMENT OR GROUT	INCINERATE	VITRIFY	MELT METALS (INGOTS)	MELT METALS (SLAG)	ADD pH BUFFERS, SALT OR SORBENTS	DECONTAMINATE METALS
Sludges									
VITRIFICATION					●				
CEMENTATION			●						
ADD pH BUFFERS								●	
Solid Organics									
COMPACTION		●							
SHRED AND CEMENTATION	●		●						
SHRED, ADD SALT, COMPACTION	●	●						●	
SHRED AND ADD BENTONITE	●							●	
INCINERATION AND CEMENTATION	●		●	●					
INCINERATION AND VITRIFICATION	●			●	●				
ADD pH BUFFERS								●	
Solid Inorganics									
SHRED AND COMPACTION	●	●							
SHRED AND CEMENTATION	●		●						
SHRED, ADD SALT, COMPACTION	●	●						●	
VITRIFICATION [1]					●		●		
MELT METALS [2]						●			
SHRED AND ADD BENTONITE	●							●	
ADD pH BUFFERS								●	
DECONTAMINATE METALS [3]	●		●						●

[1] Metals are Melted with Glass/Glass Frit; Radionuclides Partition into the Slag and Metals are Eliminated from the WIPP Inventory

[2] Metals are Melted into TRU Waste Ingots

[3] Solidify Process Residue by Cementation

FIGURE 6-2
TREATMENT OPERATIONS

various numbers of facilities (Section 6.3.4), required treatment schedules versus construction schedules for various numbers of facilities (Section 6.3.5), permitting facilities and regulations governing shipment of wastes (Section 6.3.6), and differences in public and occupational health-based risk for various numbers of facilities (Section 6.3.7).

6.3.1 Development Status of Waste Treatment Technologies

The waste treatment alternatives recommended by the EATF for inclusion in the WIPP Experimental Program (DOE, 1990b) range from relatively simple operations, such as the addition of pH buffering materials to the waste, to the more complex waste treatment technologies, such as vitrification or incineration. While most of these alternatives are technologically feasible, others will require development for application to TRU waste. This section presents the development status of the technologies necessary to produce the combinations of waste forms described in Table 1-2, as well as the status for all the technologies necessary to produce the waste forms identified by the EATF.

6.3.1.1 Vitrification

A small commercial glass furnace has been tested at Mound Laboratories (Mound) for application to nuclear power plant solid wastes. It has been used for the demonstration of the incineration/vitrification of combustible wastes, ion exchange resins, filter cartridges, and sludges (Klingler and Armstrong, 1986).

Microwave melting of sludge wastes is another method of generating a vitrified waste form. Microwave systems are being tested at Rocky Flats Plant (RFP) (Petersen et al., 1988) and Oak Ridge National Laboratory (ORNL) (White et al., 1989). These vitrification systems appear to be viable technologies, but additional development will be required before operation of full scale systems is possible, since tests have been run on only TRU waste analogs. Development here is primarily a function of scale up of existing equipment, as well as feed preparation, metering, and control of radioactive materials.

6.3.1.2 Incineration

The EPA considers incineration a demonstrated technology for hazardous waste. Incineration has also been demonstrated internationally for radioactive applications, but the practical application to TRU waste has been limited in the U.S.

The DOE has used incineration for volume reduction of low level wastes in a number of locations, such as the Waste Experimental Reduction Facility (WERF) at Idaho National Engineering Laboratory (INEL) (McFee and Gillins, 1986) and the TSCA incinerator at the Oak Ridge Reservation K-25 Plant (Kroll and Rogers, 1989). A commercial low level waste incinerator operated by the Scientific Ecology Group (SEG) of Westinghouse Electric Corporation is accepting waste at Oak Ridge, Tennessee (Dalton and Arrowsmith, 1990). The Los Alamos National Laboratory (LANL) Controlled Air Incinerator (CAI) has been used for demonstrating TRU waste incineration since 1976, but is currently not operational due to mechanical system upgrades and regulatory issues (Vavruska et al., 1989). The CAI has a capacity of 45 kilograms per hour and is designed to process liquid and packaged solid waste that is low in solid inorganic content.

In summary, hazardous and low level waste incineration are well developed technologies. However, there are no TRU waste incinerators currently operating in the United States due to either technical or regulatory factors.

6.3.1.3 Cementation

Cementation to stabilize or solidify materials is a well demonstrated technology for TRU waste and other low-level nuclear wastes. Types of cementation agents vary somewhat, and are dependent on the material to be solidified. Similarly, the capacities of the demonstrated systems range from simple "in-drum" operations in which waste and solidification agents are mixed and solidified in the final disposal package, to large continuous operation systems. However, the longevity of cemented waste forms in the WIPP environment is uncertain and will require additional studies and modeling for confirmation of applicability. The EATF assembled a panel of cement experts who suggested that properly formulated cemented waste forms will probably be durable for long periods of time. The details of the Cement/Grout Panel deliberations are presented in Appendix G.

The United Kingdom Atomic Energy Authority has selected cementation as the process for treating stored intermediate-level wastes, which include TRU waste (Lee and Wilding, 1989). In Sweden, metallic low level waste has been solidified in Envirostone, a commercial product using gypsum with an organic binder (Sjoblom et al., 1985). The EATF has found 21 separate applications of cementation used by the DOE for either low level or TRU waste solidification (IT Corp., 1989). There are several commercial suppliers of radioactive waste cementation systems and at least one cementation service available to commercial nuclear power plants. Cementation is a well developed technology, although development of specific cementitious formulations may be required for use in the WIPP environment.

6.3.1.4 Shredding

Shredding technology is fully demonstrated, and commercially available shredders can be incorporated into facilities designed for TRU waste handling. It should be noted that shredding equipment can require extensive maintenance. Many of the proposed waste treatment technologies either require or can be enhanced if preceded by shredding. For example, addition of pH buffers to waste packages would be enhanced if preceded by shredding.

6.3.1.5 Metal Melting

Scrap metal melting is an integral part of steel industry practice worldwide. Some melting techniques, such as induction heating, may be particularly suitable for melting TRU contaminated metals. A plasma process, which melts materials using heat from a plasma furnace, is in the demonstration stage (Peters and Ross, 1989; Peters et al., 1990) and may be useful for melting metal wastes mixed with glass, combustibles, soils, and other materials. Metal melting experimental efforts at ORNL (Heshmatpour et al., 1983) have produced partition factors (mass of radionuclide in slag/mass of radionuclides originally in metal) that allow reclassification of metals as low level waste. In general, the application of melting metals as a waste treatment will require engineering development for scale up, application to specific types of metals, and containment of radioactive components.

6.3.1.6 Compaction

Waste compactors are available from commercial suppliers. The EATF has identified three DOE compactor programs and several others appear to be in the planning phase. Low level waste compactors exist at the INEL (Gillins and Larsen, 1987) and at the West Valley Demonstration Project (WVDP) (Frank et al., 1988). The Supercompaction and Repackaging Facility (SaRF) at RFP is the first permanent installation for TRU waste in the United States (Barthel, 1988). A commercial low level waste supercompactor is operated by SEG at their facility in Oak Ridge, Tennessee, and mobile compactor services exist for nuclear power plants (Jessop, 1989). Waste compaction is therefore, considered a developed technology.

6.3.1.7 Encapsulation

The use of polymers or bitumen to encapsulate radioactive waste is a relatively straightforward process. Encapsulation of radioactive waste in bitumen has been used by Duke Power Company (Jones et al., 1985). Low level radioactive waste encapsulation, using polyester as the encapsulation medium, has been developed in the United States (Dillman et al., 1985). Encapsulation of low and medium level waste in epoxy resins is being used in France (Gauthey, 1989). Although this alternative is a technologically proven waste solidification process, it has the potential for increasing biological and radiolytic gas generation due to addition of large quantities of organic binder materials, and is therefore not being recommended for TRU waste treatment at the present time.

6.3.1.8 Addition of pH Buffers

Addition of buffers may be useful for increasing the pH of repository brine. Radionuclides tend to be less soluble at high pH conditions. A benefit of lowered solubility is decreased mobility of radionuclides in brine. The addition of pH buffers, such as cement, lime, or activated alumina is a relatively simple process in comparison to other waste treatment alternatives. Preshredding may prove beneficial to the mixing process. The shredding, solids metering, and mixing steps required for this operation are commercially practiced in nonradioactive waste operations and are therefore, judged to be well developed for TRU waste application.

6.3.1.9 Metal Decontamination

Decontamination technology for converting metallic TRU waste to low level waste has been extensively studied at Pacific Northwest Laboratory (Allen and Hazelton, 1985). Several processes are available to decontaminate TRU waste forms to LLW. These processes include electropolishing, hand scrubbing, chemical washes/sprays, strippable coatings, and Freon spray-cleaning (Allen and Hazelton, 1985). Electropolishing and vibratory finishing techniques are proven effective in decontaminating TRU wastes to levels below standards defining TRU waste (Allen et al., 1982). In fact, at the time these decontamination techniques were studied, the 10 nCi/g limit applied to TRU waste. Electropolishing will remove TRU contamination from all metals with the exception of those that form highly insulating oxides such as Zircalloy (Allen et al., 1982). Vibratory finishing will remove TRU contamination from almost all classes of metals and alloys and from a wide range of surface-contaminated nonmetallic TRU wastes including plastic, glass, and rubber (Allen et al., 1982). Metal waste forms that do not have exposed surfaces (e.g., pipes) may require preprocessing such as shredding.

The obvious benefit of decontamination is that metals can be removed from the WIPP waste inventory, thus eliminating any anoxic corrosion potential. Decontamination processes can reduce TRU contaminated metals into LLW. These processes generate a secondary waste in the form of an aqueous rinsing solution that may also contain some solids. These contaminated liquids would require some form of solidification treatment, such as cementation, prior to disposal at WIPP.

6.3.2 Location of Waste and Waste Generation Rates

The quantity of transuranic waste generated or stored at the various DOE sites directly influences any treatment facility siting decision. Treatment facility capacity is dependent upon both the quantity of waste to be treated and the time frame or work-off period over which all treatment must be accomplished.

Transuranic waste is stored and/or generated at ten major DOE sites nationwide located throughout the nation. The data for location and quantity of newly generated waste and data on waste currently in storage at each TRU waste generating or storage site has been extracted from the DOE Inventories, Projections and Characteristics Data Base (DOE, 1988c) which is updated annually. This version of the data base has been used by the EATF because it is the most current version that includes uncompacted RFP wastes.

Transuranic waste at the DOE sites consists of: solid organics, combustibles, sludges, filters, noncombustibles, construction materials, and other miscellaneous materials. Sludges, solid organics, and glass and metals (solid inorganics) comprise approximately 85 percent by volume of the total TRU waste inventory. The remaining 15 percent of the inventory has been sorted into one of the three primary categories for the purposes of EATF work. Table 6-1 shows the quantities of waste currently in retrievable storage at INEL, Hanford, LANL, Savannah River Site (SRS), ORNL, and Nevada Test Site (NTS) plus the projected quantities expected to be generated during the next 26 years at these and other generator sites (DOE, 1988c). Table 6-2 shows the WIPP average annual expected emplacement rates (based on unprocessed wastes). The emplacement rates are based on Table 6-1 quantities, a five year WIPP test phase during which small quantities (EATF assumed 5 percent) of waste will be emplaced, plus a 20 year emplacement period during which the remainder of the production quantities of waste will be emplaced. These emplacement rates are representative of the

TABLE 6-1

TRU WASTE QUANTITIES AND LOCATIONS[1, 2]

FACILITY[3]	SLUDGES		SOLID ORGANICS		SOLID INORGANICS	
	RETRIEVABLY[4] STORED	NEWLY[5] GENERATED	RETRIEVABLY STORED	NEWLY GENERATED	RETRIEVABLY STORED	NEWLY GENERATED
ANL-E	0	44	0	31	0	19
INEL	9193	479	13852	1007	12518	472
LANL	2261	2143	1604	2802	3427	3297
LLNL	0	87	0	2367	0	433
Mound	0	1017	0	60	0	120
NTS	12	0	353	0	254	0
ORNL	6	10	350	577	227	375
Hanford	583	635	4182	4555	5548	6043
RFP	0	9555	0	17017	0	9828
SRS	105	563	2242	12055	643	3456
TOTALS	12160	14533	22583	40471	22617	24043

[1] Source (DOE, 1988c).
[2] Quantities shown are in cubic meters.
[3] RFP = Rocky Flats Plant; INEL = Idaho National Engineering Laboratory; Hanford = Hanford Site; LANL = Los Alamos National Laboratory; SRS = Savannah River Site; ORNL = Oak Ridge National Laboratory; NTS = Nevada Test Site; LLNL = Lawrence Livermore National Laboratory; ANL-E = Argonne National Laboratory-East; Mound = Mound Laboratory.
[4] Retrievably Stored = TRU waste in storage generated between 1970 and the end of 1987.
[5] Newly Generated = TRU waste generated from 1988 through the end of 2013.

TABLE 6-2

AVERAGE ANNUAL UNPROCESSED TRU WASTE EMPLACEMENT QUANTITIES[1, 2, 3]

FACILITY[4]	SLUDGES		SOLID ORGANICS		SOLID INORGANICS	
	RETRIEVABLY[5] STORED	NEWLY[6] GENERATED	RETRIEVABLY STORED	NEWLY GENERATED	RETRIEVABLY STORED	NEWLY GENERATED
ANL-E	0	2	0	1	0	1
INEL	437	23	658	48	595	22
LANL	107	102	76	133	163	157
LLNL	0	4	0	112	0	21
Mound	0	48	0	3	0	6
NTS	1	0	17	0	12	0
ORNL	0	0	17	27	11	18
Hanford	28	30	199	216	264	287
RFP	0	454	0	808	0	467
SRS	5	27	106	573	31	164
TOTALS	578	690	1073	1921	1076	1143

[1] Source (DOE,1988c).
[2] Quantities shown are in cubic meters/year.
[3] Annual quantities of emplaced waste are based on a 20 year WIPP operations period.
[4] RFP = Rocky Flats Plant; INEL = Idaho National Engineering Laboratory; Hanford = Hanford Site; LANL = Los Alamos National Laboratory; SRS = Savannah River Site; ORNL = Oak Ridge National Laboratory; NTS = Nevada Test Site; LLNL = Lawrence Livermore National Laboratory; ANL-E = Argonne National Laboratory-East; Mound = Mound Laboratory.
[5] Retrievably Stored = TRU waste in storage generated between 1970 and the end of 1987.
[6] Newly Generated = TRU waste generated from 1988 through the end of 2013.

annual waste treatment capacity that would be required in the event treatment becomes necessary.

6.3.3 Current or Planned DOE Waste Treatment Capacity

Treatment-facility siting decisions and the site's ability to ship wastes are, in part, influenced by existing or planned treatment capacity. Waste shipped to the WIPP must comply with the requirements of the Waste Acceptance Criteria (WAC) (DOE, 1989f), which delineate the requirements for acceptance of TRU waste for emplacement and disposal in WIPP. Some of the DOE waste generation and storage sites have responded to these requirements by building (or by planning to build) inspection and limited processing facilities for certifying TRU waste to WIPP WAC requirements. While these facilities are not expected to have sufficient capacity should large volumes of TRU waste require treatment, it is possible that one or more of these facilities could suffice either as is or with some modifications, for treating waste. Such a facility could also be considered as the front-end of a larger processing facility. An example of a modification is addition of process operations to existing facilities (at the sites of large TRU waste generators such as RFP and SRS). The EATF has identified existing and planned waste processing facilities as a factor that should be included in the feasibility analysis of potential waste treatment alternatives. These facilities are described below.

6.3.3.1 Size Reduction Facility (SRF)

The SRF is an existing prototype facility (currently not in operation) located at LANL (DOE, 1988a). The facility is designed to reduce the volume of and repackage various types of metallic waste contaminated with TRU radionuclides. Through FY 1985, a total volume of 88 cubic meters of TRU waste has been reduced in volume by a factor of 6.7 to 1 (IT Corp., 1988).

6.3.3.2 Treatment Development Facility (TDF)

The TDF is an existing facility (currently not in operation) located at LANL and utilizes a dual chamber, controlled air incinerator for processing solid organic TRU wastes with a nominal capacity of 45 kilograms per hour (Hutchins, 1990). Ash from the incineration process is cemented in drums.

6.3.3.3 Supercompaction and Repackaging Facility (SaRF)

The SaRF, located at RFP, is designed to process two separate categories of TRU waste. Solid organic waste will be precompacted in a 30-ton compactor prior to supercompaction. Solid inorganics will be compacted directly in the 2,200-ton supercompactor. The SaRF will compact approximately 1,800 cubic meters per year (Barthel, 1988). The compacted material will be overpacked in 55-gallon drums for off-site disposal. SaRF is currently awaiting completion of NEPA documentation review prior to startup.

6.3.3.4 Stored Waste Examination Pilot Plant (SWEPP)

SWEPP will examine and certify INEL retrievably stored TRU waste for shipment to WIPP. Examination of waste containers includes weighing, real time radiographic examination, radionuclide assay, container integrity examination and radiological surveys (EG&G Idaho, Inc., 1982).

6.3.3.5 Transuranic Waste Treatment and Storage Facility (TWTSF)

The TWTSF, located at INEL, is in the conceptual design phase and when built is planned to be capable of examining, shredding, compacting and repackaging TRU waste (DOE, 1989a). Capacity to examine TRU waste will be the equivalent of 10,000 drums per year. Shredding and compaction capacity will be 4,000 cubic meters per year (this includes low level waste).

6.3.3.6 Waste Receiving and Processing Facility (WRAP)

The WRAP facility at Hanford is being constructed in two phases, designated Module I and Module II, projected to be completed in FY 1996 and FY 1999, respectively (DOE, 1987a). It is currently scheduled to perform nondestructive assay/examination, and process retrievably stored and newly generated TRU waste, as needed, for certification and shipment to WIPP. The process capabilities will include shredding, grout solidification, and size reduction of oversize boxes of waste. The WRAP facility is expected to process approximately 1000 cubic meters of TRU waste each year, based on waste processing estimates of 3550 cubic meters of retrievably stored waste and 9560 cubic meters of newly generated waste over a thirteen year period (DOE, 1987a).

6.3.3.7 Waste Handling and Packaging Plant (WHPP)

The WHPP is a planned facility at ORNL designed for the purpose of characterizing, processing, repackaging and certifying remote-handled and special-case TRU waste located at ORNL and other DOE sites (White et al., 1989). The facility will process both liquid and solid TRU wastes. The liquid processing portion of the facility creates sludges that will be solidified by yet-to-be-determined processes. Microwave evaporation-solidification methods are being considered, including melt-solidification of the sludges. Facility construction is not expected to start until FY 1996. The facility is expected to process approximately 500 cubic meters of solids, 1,000 cubic meters of liquid and sludge over 15 years, and 6 cubic meters of newly generated solids per year (DOE, 1989d).

6.3.3.8 Transuranic Waste Facility (TWF)

The TWF is a proposed facility to be located at SRS (Daugherty et al., 1987). Its purpose is to process noncertifiable, retrievably stored, and newly generated waste. The facility will provide capabilities for retrieving stored waste, remote venting/purging of waste drums, real-time radiography and assay of drums, shredding and solidification of selected wastes, and repackaging. A small amount of the total waste will be solidified in a small-scale solidification glovebox. The total quantity of waste to be handled in the facility is approximately 595 cubic meters per year of retrievably stored waste, and 125 cubic meters of newly generated waste per year. The facility is scheduled to be completed in FY 1995.

6.3.3.9 Future Use of Planned and Existing Facilities

At the point in time that performance assessment determines what waste treatment is needed, if any, decisions can be made for the most effective use of facilities such as those noted above. If these facilities have adequate capacity to provide the needed waste treatment, or if these facilities could form the basis for waste treatment facilities at the respective sites, then cost and schedule benefits would be realized. The following summarizes how these facilities might contribute to waste treatment facility siting decisions:

Hanford - WRAP waste handling capacity may be adequate to serve as the front end of processing operations.

LANL - Small facilities inadequate for front end waste handling and processing of all LANL waste.

ORNL - Relatively small quantity of CH-TRU could be processed at WHPP.

SRS - TWF capacity may be sufficient to support process operations for part of SRS waste.

RFP - SaRF can support a compacted waste form. Current waste generating processes could be modified to support processing.

INEL - SWEPP, TWTSF may have enough capacity to serve as front-end to process operations.

6.3.4 Waste Treatment Cost Estimation

Costs associated with waste treatment include those for handling and transportation of wastes to and from the treatment facility, waste characterization required prior to transportation or treatment, treatment-facility capital, and operating costs. In all cases, the EATF mission of providing a preliminary analysis of feasibility precluded development of "bottoms-up" costs through aggregation of smaller cost components. The EATF recognizes that more detailed cost estimates are required before final decisions are made concerning and location of waste treatment facilities. Results of the EATF waste treatment cost study are presented in Section 6.3.4.5.

6.3.4.1 Treatment Facility Capital Cost Estimation

The EATF evaluated TRU waste treatment facility costs by relying on published data and discussions with DOE waste generator site personnel knowledgeable of costs for planned and existing facilities. Table 6-3 lists cost estimates for several of the existing and planned DOE TRU waste treatment facilities discussed in Section 6.3.3. These data are provided to give an indication of the broad cost range of TRU waste treatment facilities. Factors influencing facility costs are discussed in the following paragraphs and in detail in Appendix J.

Preliminary facility costs were developed for the fourteen combination alternatives described in Table 1-2. The basis for these cost estimates are the individual treatment operation costs, plus the support function cost. The purpose of developing separate costs for treatment operations is to simplify estimating costs of waste treatment facilities which utilize more than one treatment operation. The basis cost and capacity for each treatment operation and the required support facility (support functions) is determined through literature review. The cost of the support facility and each treatment operation can then be scaled with respect to capacity (see Appendix J). In this manner, capital costs for one through seven facilities for each of the fourteen combination alternatives presented in Table 1-2 were determined. Basis costs are escalated to 1990 dollars (see Appendix J). The EATF has assumed that cost escalation factors for chemical processing plants are also applicable to TRU waste treatment facilities.

The capacity of a facility depends on the waste forms to be treated, the number of facilities available to process the inventory, operating time, and inventory work-off period. Treatment operations that produce Level II waste forms, such as cementation or shredding, intuitively are less expensive than those needed to produce Level III waste forms, such as incineration and vitrification. However, when these treatment operations are installed in their respective facilities, the building, alpha containment and support systems costs tend to reduce the cost differential between Level II and Level III facilities. The EATF did not factor in triple confinement of plutonium handling facilities (addressed in DOE 6430.1A General Design Criteria) in its cost estimates, for the following reasons: treatment operation costs for existing facilities (which form the basis for EATF cost estimates) are computed on a double-confinement basis; design and number of confinement barriers are predetermined on a case-by-case basis (DOE, 1987b). As a result, the cost differential between Level II and Level III is further reduced once triple confinement is factored into the design.

Capacity, as noted in Table 6-4, is designated as a percent of the total TRU waste generated through 2013 as projected by the IDB, 1988. This capacity is the sum of retrievably stored and/or newly generated waste from sites that feed the processing facilities for each of the seven options. An attempt was made to match treatment sites and waste locations in such a way that preference for treatment facilities is given to larger waste generating or storage sites in order to minimize waste transportation. Note that the siting options of Table 6-4 are examples, as other choices may also be appropriate. For instance, if only one facility were to be built, other sites besides WIPP are also candidates to host a central facility.

TABLE 6-3

EXISTING AND PLANNED DOE TRU FACILITY COST EXAMPLES

Facility[1]	Facility Capacity (m^3/yr)	Cost Treatment (Millions, 1990 dollars)	Level[2]
TWF, SRS (Westinghouse, 1990)	720	181 M	II
WRAP, Hanford Module 1 (Kaiser, 1989)	3850	54 M	II
WRAP, Hanford Module 2[3]	TBD	150 M	II
TWTSF, INEL (DOE, 1989a)	5800	137 M	II
WHPP[4], ORNL (DOE, 1989d)	200	238 M	III
TDF, LANL (Hutchins, 1990)	850	7 M	III
SaRF, RFP (Barthel, 1988)	1800	6 M	II
SWEPP, INEL (DOE, 1982)	4100	7 M	NA

[1]For complete facility descriptions see Section 6.3.3.
[2]For Treatment Level descriptions see Section 3.3.3.
[3]Personal communication, Chris Petersen, 1990.
[4]WHPP is a RH-TRU facility. Cost is included for comparison purposes only. Capacity based on Turner (1991).
TBD = To be determined.

NOTE: Facilities are intended for CH-TRU waste unless indicated otherwise.

TABLE 6-4

POTENTIAL WASTE TREATMENT SITES AND WASTE DISTRIBUTION SCENARIOS FOR 1-7 FACILITIES

Number of Facilities	Facility Location	Treats Waste From:	Quantity of Waste Treated, Percent
1	WIPP	All Sites	100.0
2	INEL	Hanford, INEL, LANL LLNL, NTS, RFP	83.9
	SRS	ANL-E, Mound, ORNL, SRS	16.1
3	INEL	Hanford, INEL	43.3
	RFP	RFP	26.7
	WIPP	LANL, LLNL, NTS, Mound, ANL-E, ORNL, SRS	30.0
4	INEL	INEL, LANL, LLNL, NTS	41.5
	RFP	RFP	26.7
	SRS	ANL-E, Mound, ORNL, SRS	16.0
	Hanford	Hanford	15.8
5	INEL	INEL	27.5
	RFP	RFP	26.7
	SRS	ANL-E, Mound, ORNL, SRS	16.0
	Hanford	Hanford	15.8
	WIPP	LANL, LLNL, NTS	14.0
6	INEL	INEL	27.5
	RFP	RFP	26.7
	Hanford	Hanford	15.8
	SRS	ORNL, SRS	15.1
	LANL	LANL	11.4
	WIPP	ANL-E, LLNL, Mound, NTS	3.5
7	INEL	INEL	27.5
	RFP	RFP	26.7
	Hanford	Hanford	15.8
	SRS	SRS	14.0
	LANL	LANL	11.4
	WIPP	ANL-E, LLNL, Mound, NTS	3.5
	ORNL	ORNL	1.1

Waste work-off periods of five, ten, and twenty years have been considered for each of these cases. Continuously operated facilities are assumed to operate 24 hours per day for 240 days per year, allowing approximately 125 days per year for maintenance. An exception to this rule is noted in the discussion on operating costs, Section 6.3.4.2. If more than one treatment operation is required in a single facility, the effect of capacity on the cost of each treatment operation is computed, and these costs are added to the support facility costs. Table 6-5 shows the total processing capacities of facilities needed to treat all waste in five, ten, or twenty year work-off periods. The data presented in Table 6-5 has been generated under the assumption that processing would begin in the year 2000.

The EATF also determined the need for minimum facility costs. Minimum facility costs are determined to preclude unrealistically low estimates. Low estimates result when the design capacity for continuous operation equipment becomes excessively small relative to the basis capacity of process operations. Treatment facility cost estimates are presented in Section 6.3.4.5

6.3.4.2 Treatment Facility Operating Cost Estimation

The EATF has developed a method to estimate annual operating costs for continuous and batch operated TRU waste treatment facilities. This method is based on an empirical relationship between annual operating costs and facility capital costs. A review of literature (McKee et al., 1986; Ross et al., 1982) revealed that annual operating cost for continuous operation (24 hours/day, 200 days/year) is approximately 10 percent of facility capital cost. The EATF assumed operation for 240 days per year and thus estimates operating costs at 12 percent of capital costs.

Annual operating costs for batch processing facilities are estimated from operational requirements. A facility that does not operate continuously (based on capacity requirements) is defined as a batch operated facility. The EATF has assumed the minimum operation requirements of a batch operated facility to be one 8-hour shift per day, 240 days per year. Since operating costs for continuous operation is defined at 12 percent of capital, the annual operating costs for batch operated facilities are defined as a minimum of 4 percent of capital costs. Actual operating costs will vary between 4 and 12 percent of facility capital costs depending on the number of hours operated on a yearly basis. Operating cost estimates are present in Section 6.3.4.5.

6.3.4.3 Waste Transportation Cost Estimation

The EATF has developed transportation cost estimates for each of the fourteen engineered alternatives described in Table 1-2, using the potential waste treatment site locations outlined in Table 6-4. Transportation costs are a result of transporting waste between sites and loading and unloading operations at storage and/or generator sites, treatment sites, and finally the WIPP. Three basic cost components have been defined by the EATF:

- Costs associated with loading waste into TRUPACT-IIs
- Costs associated with unloading TRUPACT-IIs
- Costs of transporting waste between sites.

Capital and maintenance costs for TRUPACT-IIs and tractor-trailer rigs are not included.

TABLE 6-5

TOTAL WASTE TREATMENT FACILITY CAPACITY REQUIREMENTS
(m^3/yr)

THIS TABLE PRESENTS TOTAL PROCESSING CAPACITY OF FACILITIES NEEDED TO TREAT ALL WASTE IN 5, 10, OR 20 YEARS, BEGINNING IN THE YEAR 2000.

SITES	SOLID ORGANICS	SOLID INORGANICS	SLUDGES	TOTAL
		5 YEAR WORK-OFF		
ANL-E	6	4	9	19
INEL	2972	2598	1934	7504
LANL	881	1345	881	3107
LLNL	473	87	17	577
Mound	12	24	203	239
NTS	71	51	2	124
ORNL	185	121	3	309
Hanford	1747	2318	243	4309
RFP	3403	1966	1911	7280
SRS	2859	820	133	3812
TOTAL	12611	9332	5338	27280
		10 YEAR WORK-OFF		
ANL-E	3	2	4	9
INEL	1486	1299	967	3752
LANL	441	672	440	1553
LLNL	237	43	9	289
Mound	6	12	102	120
NTS	35	25	1	62
ORNL	93	60	2	155
Hanford	874	1159	122	2154
RFP	1702	983	956	3640
SRS	1430	410	67	1906
TOTAL	6305	4666	2669	13640
		20 YEAR WORK-OFF		
ANL-E	2	1	2	5
INEL	743	650	484	1876
LANL	220	336	220	777
LLNL	118	22	4	144
Mound	3	6	51	60
NTS	18	13	1	31
ORNL	46	30	1	77
Hanford	437	580	61	1077
RFP	851	491	478	1820
SRS	715	205	33	953
TOTAL	3153	2333	1334	6820

Note: Numbers above are rounded figures.

Transportation costs are influenced by the location of waste relative to treatment facilities and the WIPP, and the final weight of processed waste form. Overall transportation costs are determined by the number of transports required to ship the entire TRU inventory from generator and/or storage sites to treatment locations first and to then the WIPP. The number of transports determines the number of loading and unloading operations required as well as the total distance traveled.

Costs associated with transporting processed waste are not equivalent to the cost of transporting unprocessed waste. Processed waste will be much heavier than unprocessed waste, due to the reduction (or elimination) of void space. The increased weight of processed waste will reduce the volume of waste which can be shipped in TRUPACT-IIs, given the estimated 13,595 pounds (6,166 kilograms) per shipment payload restriction for three TRUPACT-IIs (Gregory, 1991). Although decreasing the waste volume per shipment will increase the number of transports relative to the baseline case (untreated waste), reductions in waste volume that result from processing will partially offset this increase by decreasing the total number of shipments required. The volume reduction for Level III options are sufficiently large enough that the number of transports is reduced from the baseline case. However, for Level II treatment alternatives (e.g., shredding and cementing), the volume reduction is not large enough to compensate for the effects of increased weight of the waste. This results in an increase in the number of transports relative to the baseline design for Level II treatment alternatives.

There are three shipping scenarios considered in computing waste transportation costs:

- Transportation of unprocessed waste to treatment facilities, followed by transportation of processed waste to the WIPP
- Transportation of unprocessed waste to the WIPP for treatment followed by disposal
- Transportation of processed waste to the WIPP, after treatment at the generator/storage site.

Site-to-site mileage estimates for the ten TRU waste generator/storage sites and the WIPP (Table 6-6) have been used to develop total TRUPACT-II miles (Table 6-7) required for each engineered alternative and siting option. Total TRUPACT-II miles are defined as the distance traveled in transporting all TRU waste to treatment locations and subsequently to the WIPP (including return trips with empty TRUPACT-IIs). Total TRUPACT-II mileage estimates take into account properties of processed waste in relation to TRUPACT-II payload restrictions. The methodology, assumptions, and numbers used by the EATF to generate transportation cost estimates are outlined in Appendix J. Waste transportation cost estimates are presented in Section 6.3.4.5.

6.3.4.4 Waste Characterization Costs

Characterization costs are needed in the evaluation of waste-treatment locations. As characterization costs, including construction of characterization facilities and sampling/analysis costs, approach treatment costs, it is anticipated that waste treatment becomes an increasingly viable option.

TABLE 6-6

ESTIMATE OF DISTANCES BETWEEN DOE FACILITIES (MILES)

	ANL-E	INEL	LANL	LLNL	Mound	NTS	ORNL	Hanford	RFP	SRS
ANL-E										
INEL	1427									
LANL	1212	988								
LLNL	2173	936	1209							
Mound	343	1674	1333	2455						
NTS	1839	443	545	629	2065					
ORNL	626	1856	1485	2485	491	2030				
Hanford	1832	581	1133	855	2191	1019	2382			
RFP	1021	551	337	1255	1229	817	1344	1101		
SRS	767	2070	1664	2682	554	2198	240	2573	1582	
WIPP	1404	1484	352	1345	1460	1017	1493	1847	666	1447

REFERENCE: Site-to-site and site-to-WIPP (NuPac, 1989; Rand McNally, 1989).

TABLE 6-7

ROUND TRIP TRUPACT-II MILE ESTIMATES, 1-7 FACILITIES, FOR COMBINATION ALTERNATIVES 1-14

Miles Traveled For Each Option and Alternative[1, 2]
(Millions)

COMBINATION ALTERNATIVE	NUMBER OF FACILITIES[3] 1	2	3	4	5	6	7
1	32	105	64	89	74	75	75
2,3	32	112	68	95	79	80	80
4,5	32	72	46	59	48	48	48
6,7	32	40	29	31	25	25	25
8,9,13	32	25	19	17	13	12	12
10	32	44	30	34	27	27	27
11,12,14	32	40	27	30	24	23	23

[1] Values computed using Table 6-6 distance information, 10 cubic meters of unprocessed waste per transport (Batchelder, 1990), and waste volume (sum total of retrievably stored and newly generated) at each site.
[2] TRUPACT-II shipments are limited to 13595 pounds (Gregory, 1991) of waste.
[3] Refer to Table 6-4 for facility locations.

At the present time, the extent of waste characterization required before wastes can be emplaced at WIPP, is uncertain. It is for this reason that the EATF did not estimate characterization costs. The EATF did identify factors that affect characterization costs:

- Construction of additional facilities at DOE sites to provide capabilities for meeting TRAMPAC requirements and possibly RCRA sampling and analysis
- Resources for operating the above facilities
- Quantity of waste requiring characterization, i.e., extent of process knowledge
- Existing and planned characterization capabilities.

The degree of characterization required will depend on the regulations imposed (Section 6.3.6) and how much is known about the generation process of the waste. Compliance with TRAMPAC parameters will be required for transportation whereas RCRA compliance may be required for both transportation and disposal. Less is known about retrievably stored waste than newly generated waste categorized by content code (DOE, 1989e).

6.3.4.5 Waste Treatment and Transportation Cost Estimate Results

Results of the EATF waste treatment facility cost study are presented in Table 6-8. The table presents capital costs, annual operating costs, life cycle operating costs, and total project costs for each engineered alternative and potential treatment location described in Table 1-2 and Table 6-4, respectively. Life cycle operating costs represent the cost in 1990 dollars required to begin waste processing in the year 2000. The total project cost is the sum of capital cost and life cycle operating costs. Varying the period of time over which the total inventory of TRU waste is processed (5, 10, and 20 years) serves to illustrate the relationship between cost and treatment capacity. The results presented in Table 6-8 lead to the following observations:

- Level III treatment alternatives (thermal) are more expensive than Level II treatment alternatives by factors ranging from approximately two to four. Level III treatment operations are more expensive than Level II treatment operations for any given capacity.
- Treatment facility capital costs significantly increase with the number of individual treatment operations required to produce a particular waste form. That is, the more treatment operations required to produce a particular waste form the more expensive the facility.
- Multiple facilities (total system capacity is constant) are more expensive relative to a single facility by approximately 25 percent for five-year work-off periods and approximately 75 percent for 20-year work-off periods.

TABLE 6-8a

FACILITY CAPITAL AND ANNUAL OPERATING COST[1,2] - FIVE-YEAR WORK-OFF (Cost In Millions)

Combination Alternative		One Facility	Two Facilities	Three Facilities	Four Facilities	Five Facilities	Six Facilities	Seven Facilities
1	Capital Cost	390	410	440	460	470	480	510
	Annual Operations Cost	47	50	53	55	57	57	58
	Life Cycle Operations Cost	90	95	100	110	110	110	110
	1990 Project Cost	480	510	550	560	580	590	620
2,3	Capital Cost	440	470	500	520	540	550	570
	Annual Operations Cost	53	56	61	62	64	65	65
	Life Cycle Operations Cost	100	110	120	120	120	120	130
	1990 Project Cost	550	580	620	640	660	670	700
4,5	Capital Cost	870	920	990	1000	1000	1100	1100
	Annual Operations Cost	100	110	120	120	130	130	130
	Life Cycle Operations Cost	200	210	230	230	240	250	250
	1990 Project Cost	1100	1100	1200	1300	1300	1300	1400
6,7	Capital Cost	1200	1200	1300	1400	1400	1400	1500
	Annual Operations Cost	140	150	160	170	170	170	170
	Life Cycle Operations Cost	270	290	310	320	330	330	330
	1990 Project Cost	1400	1500	1700	1700	1800	1800	1800
8,9,13	Capital Cost	1500	1600	1700	1800	1800	1900	1900
	Annual Operations Cost	180	190	210	210	220	220	220
	Life Cycle Operations Cost	350	370	400	410	420	420	430
	1990 Project Cost	1900	2000	2100	2200	2200	2300	2400
11,12,14	Capital Cost	260	280	300	300	310	330	340
	Annual Operations Cost	31	33	36	37	38	38	39
	Life Cycle Operations Cost	60	63	68	70	72	73	74
	1990 Project Cost	320	340	360	380	390	400	420
10	Capital Cost	730	770	830	860	880	900	940
	Annual Operations Cost	88	93	100	100	110	110	110
	Life Cycle Operations Cost	170	180	190	200	200	210	210
	1990 Project Cost	900	950	1000	1100	1100	1100	1100

[1]Number above are rounded figures.
[2]1990 Project Cost = Sum of Capital Cost and Life Cycle Operations Cost.

TABLE 6-8b

FACILITY CAPITAL AND ANNUAL OPERATING COST[1,2] - TEN-YEAR WORK-OFF (Cost in Millions)

Combination Alternatives		One Facility	Two Facilities	Three Facilities	Four Facilities	Five Facilities	Six Facilities	Seven Facilities
1	Capital Cost	210	220	240	250	260	280	300
	Annual Operations Cost	25	27	29	30	31	31	32
	Life Cycle Operations Cost	72	76	82	84	87	88	90
	1990 Project Cost	280	300	320	330	340	360	390
2,3	Capital Cost	240	250	270	280	290	310	340
	Annual Operations Cost	29	31	33	34	35	35	36
	Life Cycle Operations Cost	82	87	93	96	99	100	100
	1990 Project Cost	320	340	370	380	390	410	440
4,5	Capital Cost	470	500	540	550	570	600	640
	Annual Operations Cost	57	60	65	67	69	69	71
	Life Cycle Operations Cost	160	170	180	190	190	200	200
	1990 Project Cost	630	670	720	740	770	800	840
6,7	Capital Cost	640	680	730	750	770	820	880
	Annual Operations Cost	77	81	87	90	93	94	96
	Life Cycle Operations Cost	220	230	250	260	260	270	270
	1990 Project Cost	860	910	980	1000	1000	1100	1200
8,9,13	Capital Cost	820	870	930	960	990	1000	1100
	Annual Operations Cost	98	100	110	120	120	120	120
	Life Cycle Operations Cost	280	300	320	330	340	340	350
	1990 Project Cost	1100	1200	1300	1300	1300	1400	1500
11,12,14	Capital Cost	140	150	160	170	170	190	210
	Annual Operations Cost	17	18	19	20	20	21	21
	Life Cycle Operations Cost	48	51	55	56	58	59	60
	1990 Project Cost	190	200	220	220	230	250	270
10	Capital Cost	400	420	450	470	480	510	550
	Annual Operations Cost	48	50	54	56	58	58	60
	Life Cycle Operations Cost	140	140	150	160	160	170	170
	1990 Project Cost	530	560	610	620	640	680	720

[1]Number above are rounded figures.
[2]1990 Project Cost = Sum of Capital Cost and Life Cycle Operations Cost.

TABLE 6-8c

FACILITY CAPITAL AND ANNUAL OPERATING COST[1,2] - TWENTY-YEAR WORK-OFF (Cost in Millions)

Combination Alternatives		One Facility	Two Facilities	Three Facilities	Four Facilities	Five Facilities	Six Facilities	Seven Facilities
1	Capital Cost	120	130	130	150	160	190	210
	Annual Operations Cost	14	15	16	16	17	17	18
	Life Cycle Operations Cost	43	46	49	51	52	54	57
	1990 Project Cost	160	170	180	200	210	240	270
2,3	Capital Cost	130	140	150	160	170	200	220
	Annual Operations Cost	16	17	18	18	19	19	20
	Life Cycle Operations Cost	49	52	56	58	59	61	64
	1990 Project Cost	180	190	210	220	230	260	290
4,5	Capital Cost	260	270	290	300	310	360	410
	Annual Operations Cost	31	33	35	36	37	38	40
	Life Cycle Operations Cost	97	100	110	110	120	120	120
	1990 Project Cost	350	370	400	410	430	480	530
6,7	Capital Cost	350	370	400	410	430	500	570
	Annual Operations Cost	42	44	48	49	50	52	54
	Life Cycle Operations Cost	130	140	150	150	160	160	170
	1990 Project Cost	480	510	550	560	590	670	740
8,9,13	Capital Cost	450	470	510	530	550	640	740
	Annual Operations Cost	53	57	61	63	65	66	69
	Life Cycle Operations Cost	170	180	190	200	200	210	220
	1990 Project Cost	610	650	700	720	760	850	950
11,12,14	Capital Cost	77	81	87	100	110	130	160
	Annual Operations Cost	9	10	10	11	11	12	12
	Life Cycle Operations Cost	29	31	33	34	35	36	39
	1990 Project Cost	110	120	120	140	150	170	190
10	Capital Cost	220	230	250	260	280	320	370
	Annual Operations Cost	26	27	29	30	31	32	34
	Life Cycle Operations Cost	81	86	92	95	98	100	110
	1990 Project Cost	300	320	340	360	380	420	480

[1]Number above are rounded figures.
[2]1990 Project Cost = Sum of Capital Cost and Life Cycle Operations Cost.

- Cost is dependent on work-off period. Capital cost of facilities with a 20-year work-off period will cost less than those with a five-year work-off period. The system capacity required for a five-year work-off period is four times the system capacity required for a 20-year work-off period.

Results of the EATF waste transportation cost study are presented in Table 6-9 as life cycle transportation costs. These results illustrate the dependency of transportation costs on the level of treatment, and on the number and location of waste treatment facilities. These results have led to the following conclusions:

- A single treatment facility located at the WIPP results in transportation costs that are equal to the baseline case. No change in the baseline (current) transportation scheme would be required for this siting scenario.

- The significant increase in total TRUPACT-II miles and corresponding transportation costs associated with multiple Level II treatment facilities is a result of additional transports required to comply with TRUPACT-II payload limitations. These limitations force partial shipments of waste, thereby increasing the total number of shipments required. In discussions with site personnel (Gregory, 1991), the EATF has learned that efforts are under way to reevaluate the payload restrictions on the TRUPACT-II and develop modified designs that will be able to accommodate larger payloads. Such developments in the future will help to reduce the transportation costs estimated for Level II waste forms.

- Transportation costs and corresponding total TRUPACT-II miles for Level III engineered alternatives are less than Level II alternatives for a given treatment/siting scenario (except the one-facility option). This is due to the larger volume reductions associated with Level III treatment alternatives. The cost savings for transporting Level III waste forms as opposed to Level II waste forms partially offset the greater capital expenditures required for Level III treatment facilities.

- Transportation costs for Level III waste treatment alternatives decrease as the number of treatment facilities is increased. An increase in the number of treatment facilities reduces the volume of unprocessed waste requiring shipment to intermediate treatment locations, and thus results in a reduction of the overall transportation cost.

6.3.5 Implementation Schedules

The EATF relied on published data and discussions with DOE waste generator site personnel (rather than detailed development of schedules as part of facility conceptual design) to estimate waste-treatment implementation schedules. More detailed schedules can be developed only after conceptual designs of appropriate waste treatment facilities are completed. The schedules presented below are intended to provide a comparison between alternative

TABLE 6-9

LIFE CYCLE TRANSPORTATION COSTS
(Cost in Millions of 1990 Dollars)

Combination Alternative	One Facility[1]	Two Facilities[1]	Three Facilities[1]	Four Facilities[1]	Five Facilities[1]	Six Facilities[1]	Seven Facilities[1]
1	71	230	140	190	160	170	170
2,3	71	240	150	210	170	180	180
4,5	71	160	100	130	110	110	110
6,7	71	90	63	68	55	55	55
8,9,13	71	57	42	37	29	27	27
10	71	99	66	74	60	60	60
11,12,14	71	89	60	65	52	51	51

[1]Refer to Table 6-4 for facility locations.

combinations. Overestimates or underestimates in categories such as technical feasibility studies are generally proportional to the complexity of the treatment alternative, and hence may change the absolute schedule, but should not change the relative differences between treatment alternatives.

Implementation schedules evaluated by the EATF for waste treatment facilities cover facility conception through start-up. Four components were included in the development of schedules: preconstruction, engineering, construction, and start-up. Table 6-10 lists tasks included in each category. The EATF has not assigned schedules to each task or category because many of the tasks, e.g., construction and engineering, overlap.

The schedule factors considered by the EATF to have the greatest uncertainty are regulatory/compliance issues (refer to Section 6.3.6), budget-cycle constraints, and technology demonstration using TRU waste. The EATF has not attempted to quantify the potential for extended permitting or review cycles, or the effect of budgetary constraints, but has instead used schedules published for DOE facilities. It should be noted that permitting time during various stages of waste processing facility development (preconstruction, engineering, construction, and start-up) can be extensive and difficult to quantify. The EATF has assumed that regulatory permitting issues are part of the preconstruction period of implementation schedules, and that permitting issues are not rate-limiting.

The time frames for demonstrating technical feasibility of various TRU waste treatment alternatives are difficult to determine due to the lack of published data. Although the effort involved in technology demonstrations are frequently underestimated, the EATF has assumed that this effort will proceed in parallel with other activities and not be a rate-limiting step. Initial demonstration will be required prior to a decision on waste treatment. Production of small quantities of modified waste forms for laboratory or field experiments is the likely driver for these early demonstrations. Pilot-plant demonstration is assumed to coincide with early design work on one or more treatment facilities and is assumed to culminate in time to be factored into final treatment facility design.

Table 6-11 provides examples of published construction schedules for DOE waste processing facilities. The table indicates a relationship between level of treatment and length of the construction schedule. These observations lead the EATF to conclude that implementation schedules for waste treatment alternatives will be influenced by the level of waste treatment (II or III) required. For example, construction of a Level II waste treatment facility requires between three and four years (refer to Table 6-11). Construction of a Level III waste treatment facility requires between four and six years. Because no other data exist, the upper bound on construction time for Level III treatment was selected from the construction time required for High-Level Waste (HLW) treatment facilities (DOE, 1989b).

The time required for preconstruction activities for Level II treatment facilities is assumed to be two to three years based on published overall project schedules for the Level II waste treatment facilities listed in Table 6-11. On the same basis, the time required for Level III facility preconstruction activities is assumed to be three to four years. The upper bound for

TABLE 6-10

SCHEDULING CONSIDERATION EXAMPLES

Preconstruction -

- Site Characterization
- Feasibility Study
- Environmental Assessment
- Environmental Impact Statement
- Preliminary Safety Analysis
- Applicable Permits

Engineering -

- Conceptual Design
- Preliminary Design
- Title I Design
- Title II Design
- Final Design

Construction -

- Procurement/Fabrication
- Construction
- Project Management
- Final Safety Analysis Report

Start-Up -

- Personnel Training & Qualifications
- Cold Testing
- Hot Start-Up

TABLE 6-11

EXAMPLES OF EXISTING AND PLANNED DOE FACILITY CONSTRUCTION SCHEDULES

Facility[1]	Facility Capacity (m^3/yr)	Construction Schedules[2] (years)	Treatment Level[3]
TWF, SRS (Westinghouse, 1990)	720	3	II
WRAP, Hanford Module 1 (Kaiser, 1989)	3850	3	II
TWTSF, INEL (DOE, 1989a)	5800	4	II
WHPP[4], ORNL (DOE, 1989d)	200	5	III

[1]Complete facility descriptions in Section 6.2
[2]Facility construction schedules from (DOE, 1989b)
[3]For Treatment Level descriptions see Section 3.3.3
[4]WHHP is a RH-TRU facility. Capacity based on Tumer (1991).

NOTE: Facilities are intended for CH-TRU waste unless indicated otherwise, information on RH is intended for comparison purposes only.

preconstruction activities is based on WHPP conceptual design (DOE, 1989d), which states that approximately four years will be required for site characterization activities.

The duration between completion of construction and full operation start-up is assumed to require six months to one year for Level II treatment facilities, and one to two years for Level III facilities based on DOE TRU and HLW facility schedules summarized in the Environmental Restoration and Waste Management Five-Year Plan (DOE, 1989b).

By summing the various schedule components, the EATF has developed rough estimates of implementation schedules for treatment facilities. Generic estimates of implementation schedules are:

Level II Waste Treatment	5-7 years
Level III Waste Treatment	8-11 years

No additional time is included for research and development.

Schedules are influenced by facility size, complexity, and the time required to complete preconstruction activities such as permitting, site characterization, and environmental assessments. The lower bound of the implementation schedule range applies to single treatment operation facilities with low waste treatment capacity, while the upper bound applies to facilities with multiple treatment operations and higher treatment capacity.

The estimated facility implementation schedules for each of the 14 combination alternatives evaluated by the EATF are presented in Table ES-2.

6.3.6 Regulatory Considerations

Regulatory requirements and institutional constraints governing new waste treatment facilities, as well as controlling the transportation and characterization of waste, were evaluated by the EATF for three reasons:

- Possibility that a treatment option may prove to be unfeasible because of insurmountable regulatory requirements
- Costs associated with regulatory compliance
- Impact on schedules from regulatory compliance.

Unfortunately, regulatory requirements and institutional constraints are the components of feasibility evaluated by the EATF over which DOE has the least control. Consequently, regulatory issues have the greatest degree of uncertainty in the EATF's quantification of these factors.

The following are regulatory/institutional factors identified by the EATF that affect waste treatment facilities, as well as the transportation and characterization of TRU wastes before and after waste treatment.

6.3.6.1 Federal Regulations for Waste Treatment Facilities

Current and previous DOE experience in building waste treatment facilities has been used by the EATF to assemble a list of federal regulations which affect the permitting process for waste treatment facilities (Table 6-12). Facility permitting complexity grows with the complexity of waste treatment being considered.

6.3.6.2 Institutional Factors Affecting Waste Treatment Facilities

The EATF defines institutional factors as a condition (e.g., local regulation) which is unique to the site and has an effect on waste treatment. The EATF surveyed the DOE TRU waste generators for institutional and regulatory information regarding the siting of waste treatment facilities in those states that are hosts to major TRU waste generator sites. Information was provided by Hanford (Roberts, 1991); SRS (Dyches, 1991); RFP (O'Leary, 1990); ORNL (Mason, 1990); INEL (Solecki, 1991); and WIPP (Carrell, 1990; Kouba, 1990). This information encompassed the following:

- Applicable State Regulations
- State Jurisdictions
- Comparison of State and Federal Regulations
- Costs Associated With State Regulatory Compliance
- Effect on Schedule of State Regulation
- State/DOE Interfaces
- Institutional Sentiments Regarding New Waste Treatment Facilities.

The following conclusions were drawn from this information:

- Collectively, the respondents noted above do not anticipate institutional factors having adverse effects on siting new waste treatment facilities provided that storage of treated waste does not occur on site. Rocky Flats appears to be an exception regarding the construction of new waste treatment facilities, although add-ons to existing waste generating facilities might be more acceptable.

- Cost and schedule are not expected to be unduly affected by state or federal permitting requirements. Although in some cases RCRA permits can require several years to obtain, the permitting process is generally conducted in parallel with design, construction, and NEPA processes. Permitting costs are generally factored into the overall estimates, and extraordinary costs for permitting are not expected.

TABLE 6-12

POTENTIAL REGULATORY REQUIREMENTS

WASTE TREATMENT	REGULATORY REQUIREMENTS
Cementation	RCRA, HSWA, NESHAP, NEPA
Compaction, Metal Decon	RCRA, NESHAP, NEPA
Thermal Treatments Incineration Vitrification Metal Melting	RCRA, CAA, CWA[1], TSCA, NESHAP, PSD, NAAQS, NSPS, NEPA
Shredding/Sorting	RCRA, NESHAP, NEPA
Addition of pH Buffers	RCRA, NESHAP, NEPA

[1] For waste water discharged off site. Waste water retained on site may be regulated by certain states.

Definitions

RCRA	- Resource Conservation and Recovery Act of 1976
HSWA	- Hazardous Solid Waste Amendment of 1984
NESHAP	- National Emission Standards for Hazardous Air Pollutants 40 CFR Part 61
NEPA	- National Environmental Protection Act, 1969
CAA	- Clean Air Act, Air Quality Act and associated state implementation
CWA	- Clean Water Act
TSCA	- Toxic Substances Control Act
PSD	- Potential for Significant Deterioration (40 CFR Part 52.21)
NAAQS	- National Ambient Air Quality Standards
NSPS	- New Source Performance Standards

- Although some minor regulatory differences are apparent from state to state, these differences are not sufficient to affect the siting evaluation.
- There do not appear to be any significant conflicts between state and federal regulations, although ORNL reports that state regulations are generally more stringent than federal.

In summary, there appears to be cautious optimism at most DOE sites that institutional and regulatory considerations would not be major factors for siting a waste treatment facility at their respective locations. This optimism must be tempered, given that these same facilities have little or no experience in permitting TRU-waste treatment facilities. Intuitively, the logistics of regulatory compliance at multiple sites versus a single site suggests that limiting the number of treatment facilities should simplify regulatory compliance. However, limiting facilities increases transport of wastes from other sites, which will dramatically increase public opposition to these facilities. Unfortunately, resolution is only possible through experience in permitting radioactive waste treatment facilities in candidate states. There is little likelihood that such data will exist at the time a decision on treatment and siting of facilities must be made. The best that can be expected is that the permitting process is begun concurrent with facility conceptual design and that the preliminary results of the process are available at the time of treatment and site selection.

6.3.6.3 Regulations and Institutional Requirements Governing Waste Transport/Characterization

The waste transportation and waste characterization issues have the potential to limit siting options and to significantly influence costs of and schedules for waste treatment facilities. For example, characterization of TRU waste will be required to comply with the Nuclear Regulatory Commission (NRC) Certificate of Compliance for the TRUPACT-II, including the TRAMPAC requirements outlined in Appendix 1.3.7 of the Safety Analysis Report (NuPac, 1989). For example, the NRC Certificate of Compliance for the TRUPACT-II is explicit with regard to allowable hydrogen concentration (generated by radiolysis of organic material) permitted during the time waste is enclosed in the TRUPACT-II in order to ensure that excessive build-up of flammable gases is avoided. This criterion applies to hydrogen concentration in the innermost waste bag as well as between the layers of waste bags surrounding the waste (NuPac, 1989). Knowledge of how the waste is packaged is important to demonstrating that the waste will meet the NRC hydrogen concentration requirement. Similarly, knowledge of levels of flammable volatile organic compounds (VOC) and of gas generating materials is required. Significant quantities of waste may have to be characterized at each DOE site unless sufficient process knowledge exists to satisfy this requirement and regulatory bodies are amenable to accepting process knowledge in lieu of analysis.

The data presented in Table 6-13 was submitted in response to NRC requests for information concerning transportability of retrievably stored and newly generated waste (as is) under the initial Certificate of Compliance (NuPac, 1989). This table represents the amount of waste (based on quantities reported in DOE, 1988c) in retrievable storage and newly generated,

TABLE 6-13

FIRST CERTIFICATE OF COMPLIANCE SHIPPABLE WASTE QUANTITIES[1,2]

	RETRIEVABLY STORED		NEWLY GENERATED	
SITE	Percent[1]	Volume,[3] (M^3)	Percent	Avg. Volume (M^3/yr)
ANL-E	--[4]	--	0[6]	0
Hanford	0[7]	0	43	186
INEL	50	17782	80	60
LLNL	--	--	100	111
LANL	70	5104	75	238
Mound	--	--	100	46
NTS[5]	100	620	--	--
ORNL	0[6]	0	0[6]	0
RFP	--	--	95	1330
SRS	0[7]	0	70	433

[1]The figures are based on input from CH-TRU waste generators response to the question, "What percentage of newly generated and/or retrievably stored waste at each site is shippable under the current TRUPACT-II C or C (August 1989)?" The results of the questionnaire assumes no changes to existing waste processes or packaging procedures at each site other than installation of a carbon composite filter and puncturing of rigid liners if present.
[2]Drez, 1989.
[3]Volume based on DOE 1988c, retrievably stored and average generation rate.
[4]-- indicates no retrievably stored or newly generated waste at this DOE site.
[5]Excluding oversized boxes.
[6]Site uses heat-sealed bags (not allowed under TRUPACT-II Certification of Compliance).
[7]Insufficient knowledge of packaging and chemistry of waste to meet TRAMPAC requirements.

which could be transported at this time. This table illustrates the difficulty with meeting well-defined characterization requirements.

In addition to the NRC requirements for transporting TRU waste, RCRA requires characterization to meet the following requirements:

- Waste generator (40 CFR Part 262) - requires that a generator determine if solid wastes produced are a hazardous waste. The characterization is accomplished through process knowledge and/or sampling and analysis of the waste.
- Treatment/storage/disposal facility (40 CFR Part 265) - requires that WIPP verify that the waste shipped to WIPP is the waste specified on the accompanying manifest.
- Land disposal restrictions (40 CFR Part 268 and Hazardous and Solid Waste Amendments) - WIPP has been granted a Conditional No-Migration Determination for the test phase (maximum of 10 years) of WIPP, which specifies waste characterization requirements. These requirements are intended to provide the data needed to support a No-Migration Variance Petition for the operations phase of WIPP.

6.3.7 Assessment of Risk

The final component of feasibility investigated by the EATF is the health-based risk to workers, the public, and the environment due to waste treatment. Engineered alternatives involving treatment of wastes can be expected to increase some short-term occupational and health-based risk due to waste treatment, with some corresponding level of reduction in long-term risk. The EATF examined in detail the risks inherent in treating and emplacing differently treated wastes at WIPP (Appendix I). The total risk of planned (no waste treatment) operations at WIPP is chosen as the baseline risk. The baseline risk is based on waste characteristics as defined by the Waste Acceptance Criteria (WAC) and on experience gained with wastes already produced, handled, and characterized (DOE, 1989f; Clements and Kudera, 1985). Among the many possible treatments of the wastes, a few options are chosen to represent the span of characteristics of treated wastes.

A risk assessment of the entire WIPP operation over its operating lifetime and the subsequent postclosure period includes risks for a variety of different operations, incidents, and accidents. Most prominent are those connected with the transportation of the wastes, the corresponding handling operations, and the emplacement of the wastes underground. Once a decision is made to treat the wastes, the risks of the additional handling and all treatment operations will have to be included.

The assessment includes 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 hazardous components in the wastes. For all these risk components, both routine exposures and exposures under accident conditions must be considered, and the corresponding risks to the public and the work force calculated. In addition, long-term risks to workers involved in the hypothetical human intrusion scenarios and to nearby residents must be included in the assessment.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, potentially resulting in both injuries and fatalities. Also, some waste treatments will result in an increase, others in a decrease, in the number of TRUPACT-II transports to the WIPP. Transportation risks were found to have the largest number of expected fatalities and injuries of all risk components. It is important to keep in mind, however, that even for this component, consequences are low relative to risks faced by the general population.

The largest radiological risk components of the actual disposal operations are expected to arise from direct irradiations of the work crew, and are not expected to be strongly affected by implementation of engineered alternatives. This simplifying assumption arises from the fact that the same amount of radioactivity has to be handled and emplaced underground, regardless of its physical form. In the incident and accident scenarios, however, smaller risk components should be significantly reduced for some waste treatments. For example, untreated wastes have some volatile organic compounds (VOCs) in the inventory, for which the risks of both carcinogenic and noncarcinogenic health effects must be considered. Treatment of wastes to eliminate VOCs will essentially eliminate this risk, even if it is quite small.

Risks from disposal operations fall into two major categories, nonradiological accidents (e.g., forklift accidents) and worker exposure to radiological and toxic substances. For radiation exposures, the risks are primarily the small risk of cancer, as well as of genetic damages. Chemical toxicants potentially could have both carcinogenic and noncarcinogenic health effects. Any release from WIPP should be assumed to result in exposures of the public. Although strongly weakened by surface deposition and filtration and being further diluted by atmospheric dispersion, there are small risks to the public near the installation, risks that are expected to be substantially reduced by treatment of the wastes.

All components of the overall risk that involve treatment of the wastes lead to the potential for additional injuries and fatalities, which do not exist if the wastes were emplaced at WIPP untreated. Both the workers and the public have some small additional risk due to radiological and hazardous-material exposure, even though internal deposition in the plant, filtration, and environmental dilution are expected to reduce public exposures. Thus, it is mostly occupational risks that increase with waste treatment. Routine exposures can be assumed to be low due to the health and safety programs instituted at the treatment facility. The requirements of the ALARA (As Low As Reasonably Achievable) concept in particular are expected to be followed rigorously. Nevertheless, penetrating radiations will lead to a radiation exposure in the work place and consequently the potential for a small occupational risk of cancer and of genetic damage. Accidental events may increase these direct external exposures and their corresponding risks.

As an example, emissions of radioactive aerosols from the enclosures of the treatment devices during routine operations will lead to 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 result of the EATF Risk Assessment is a comparison, relative to the baseline (no waste treatment), of selected waste treatment alternatives and facility location options based on indices for overall risk reduction factors. One of the primary tasks of the EATF comparative risk assessment is to scale all components of the total risks to the level of activity required by the different treatment options. A total of four combination alternatives (1, 2, 4, and 8 as reported in Table 1-2) and four treatment location options (WIPP, three facilities, five facilities, and seven facilities, as reported in Table 6-4) have been evaluated. Table 6-14 presents the results of the EATF risk assessment activities in the form of consequence augmentation indices. Appendix I presents a complete discussion of the risk assessment methods, input data, and results in greater detail.

The consequence augmentation index ranges presented in Table 6-14 may be interpreted as follows: a number greater than unity (unity implies treatment and baseline risks are the same, giving a ratio of one) is considered to be an increase in risk relative to the baseline; a number less than unity implies a decrease in risk relative to relative to the baseline. In fourteen of the sixteen treatment cases presented in Table 6-14 more risk is incurred relative to no waste processing. This finding is the combined result of additional risks incurred by waste processing activities and in some cases by increased transportation requirements. In the Level III treatments at five and seven facilities, the consequence augmentation index is less than 1, suggesting actual risk reduction. An index close to one indicates no overall difference in risk relative to the baseline.

Because transportation risks dominate, changes in risk for a given treatment due to the selection of different numbers of treatment sites are mostly due to increases or decreases in the distances over which wastes are transported. After treatment, increases or decreases in waste volume and weight, as well as restrictions in total weight for TRUPACT-II packages, may result in a different number of transports and transport miles from the originator to the treatment facility and from there to the WIPP. With transportation risks (nonradiological) contributing the largest numbers of fatalities and injuries to the total risk associated with WIPP operations, any change in transport miles will affect the total risk significantly.

Another contribution is the cancer risk due to the exposure of the public due to the routine operations, incidents, and accidents in the treatment facility. Different population distributions at different distances from the facility will result in different risks for different sites.

The following conclusions can be drawn from the EATF Risk Assessment:

- Baseline risks are small and increases resulting from the treatment/location options are also small

TABLE 6-14

CONSEQUENCE AUGMENTATION INDICES[1]

COMBINATION[2] ALTERNATIVE	NUMBER OF WASTE TREATMENT FACILITIES[3] 1	3	5	7
1	1.38 - 1.42	1.47 - 1.55	1.36 - 1.46	1.32 - 1.42
2	1.41 - 1.45	1.54 - 1.62	1.44 - 1.54	1.40 - 1.50
4	1.60 - 1.64	1.32 - 1.50	1.12 - 1.34	1.08 - 1.30
8	2.03 - 2.09	1.26 - 1.30	0.85 - 0.90	0.80 - 0.85

[1] Table may be interpreted as follows (refer to Appendix I for in-depth discussion): ranges more than 1 indicate more risk relative to the baseline; ranges encompassing 1 indicate risk approximately the same as baseline; ranges less than 1 mean risk reduction relative to the baseline.

[2] See Table 1-2 for definition of combination alternatives 1, 2, 4, and 8.

[3] See Table 6-4 for location options of 1, 3, 5, and 7 facilities.

- Increases in overall risk due to Level II treatment options are independent of the treatment location
- Increases in overall risk due to Level III treatment options are minimized by treating nearest the generator/storage sites, due to reduced quantities of wastes requiring transport to WIPP
- Long-term risk components are very small and thus weighted as almost inconsequential. It is the balance between the short-term risk transportation and treatment components that dominate the comparison.

6.4 FACILITY SITING

The objective of this section is to establish a basis for determining where facilities should be located once the decision is made to treat some or all of the wastes. As is the case in any decision analysis involving quantitative and qualitative parameters, this evaluation can be very complex. The EATF concentrated on identifying factors that favor either facilities at each major DOE site, or at a central location. A single facility at WIPP is considered the centralized location for the purposes of this evaluation. The evaluation cannot be finalized until additional information, such as the level of waste treatment required (if any) becomes available. Should performance assessment identify that design changes are needed to meet 40 CFR Part 191 requirements, a more detailed siting analysis will be required in order to finalize the siting decision.

Many pertinent issues needed for this assessment are nonquantifiable at this time. Issues such as waste characterization (for processing, transportation or disposal) that must be included in this assessment are not fully defined. The EATF took the approach of collecting relevant information and determined the potential impact of factors for which requirements are uncertain at this time. For this reason, the recommendations made regarding facility siting are presented in the following form: identification of factors (or conditions of factors) that favor a single facility at the WIPP and the factors favoring facilities in multiple locations.

6.4.1 Basis for Determining Facility Location

The EATF considered several approaches to the siting evaluation of waste treatment facilities, ranging from multiattribute utility analysis to qualitative evaluations based on available information. Schedule and scope of work for the EATF dictated analysis of quantitative and qualitative factors versus more use of decision theory tools. The selected approach consisted of identifying the factors that influence preference between facility siting at individual DOE sites and a centralized location, gathering available data, and analyzing this data to establish qualitative results. Any of the ten sites of interest, in addition to WIPP itself, could be considered a potential location for a processing facility. This analysis has been simplified to limit the maximum number of sites for new waste processing facilities to the six largest DOE sites (Hanford, INEL, RFP, LANL, ORNL, SRS) and the WIPP.

Economies-of-scale will be used in the facility siting decision. In other words, a single large facility is preferred to several small facilities from the economic standpoint. Should the analysis identify existing conditions that preclude use of a single TRU waste processing facility, the analysis is then extended to multiple facilities. Such conditions are referred to as "No-Go Factors" and may be unique to individual sites of interest. "No-Go Factors" may be defined as conditions that preclude a TRU waste storage or generating site from hosting a TRU waste processing. Examples of potential "No-Go Factors" include:

- State and local regulatory controls
- Unique waste characteristics (e.g., decay heat, size)
- Extensive waste characterization followed by the need for preparation for transportation
- Institutional constraints (a factor unique to the site or its host state).

In support of the above approach, information on the following factors has been collected and analyzed:

Waste Characterization - Waste characterization or preparation required at individual sites prior to shipping waste off site

Waste Volumes and Locations - Waste generation rate and/or location of stored waste by site

Existing and Planned Facilities - Potential use of existing facilities as the core for a new facility

Transportation - TRUPACT-II miles required for a centralized or multiple locations

Risk - The risk to workers, the general public and the environment associated with the construction and operation of waste treatment facilities at one or more sites

Schedule - The time required to design and construct a single centralized facility versus multiple facilities

Economic Considerations

- Cost off-set for any planned facilities that are not required if a treatment facility is located at individual DOE sites

- Cost of multiple facilities
- Cost of a centralized facility
- Transportation cost factors
- Work-off period

Institutional Analyses - Factors unique to the specific major DOE sites (or their host states) that can or do affect the siting of facilities. Rather than providing absolute direction, these are factors for DOE to consider before making a final siting decision.

Decision models (see Section 6.4.2) have been developed to illustrate the effect of key parameters on the facility siting decision.

6.4.2 Evaluation Methodology

The EATF has developed two facility-siting decision models. The first, presented in Figure 6-3, concentrates on identifying regulatory issues that limit each DOE site's ability to:

- Treat waste on site
- Accept waste from other sites for treatment
- Ship waste elsewhere for treatment.

This information must be determined for all potential host sites and collectively is used as input into the second decision model (Figure 6-4), which is used to optimize site locations. A coupled decision process is the principal component of the second decision model. The benefit of this two-model approach is that both individual site and the system (all sites) considerations are factored into the waste treatment facility siting decision.

6.4.2.1 Decision Issues of Waste Characterization and Certification for Shipment

Factors which force certain siting options must be identified early in the evaluation process. As portrayed in Figure 6-4, waste characterization/certification requirements have the potential to limit such options because of the high cost of characterization. The first three decision nodes in the siting analysis are as follows:

Characterization/Certification Issues that Preclude Shipping Untreated Waste?

Shipment of waste from a DOE site is predicated upon satisfying state, federal and institutional transportation regulations. These regulations include TRUPACT-II Authorized Methods of Payload Control (TRAMPAC) (NuPac, 1989), WIPP Waste Acceptance Criteria (DOE, 1989f), and the requirement for RCRA characterization prior to waste shipment (see Section 6.3.6.3).

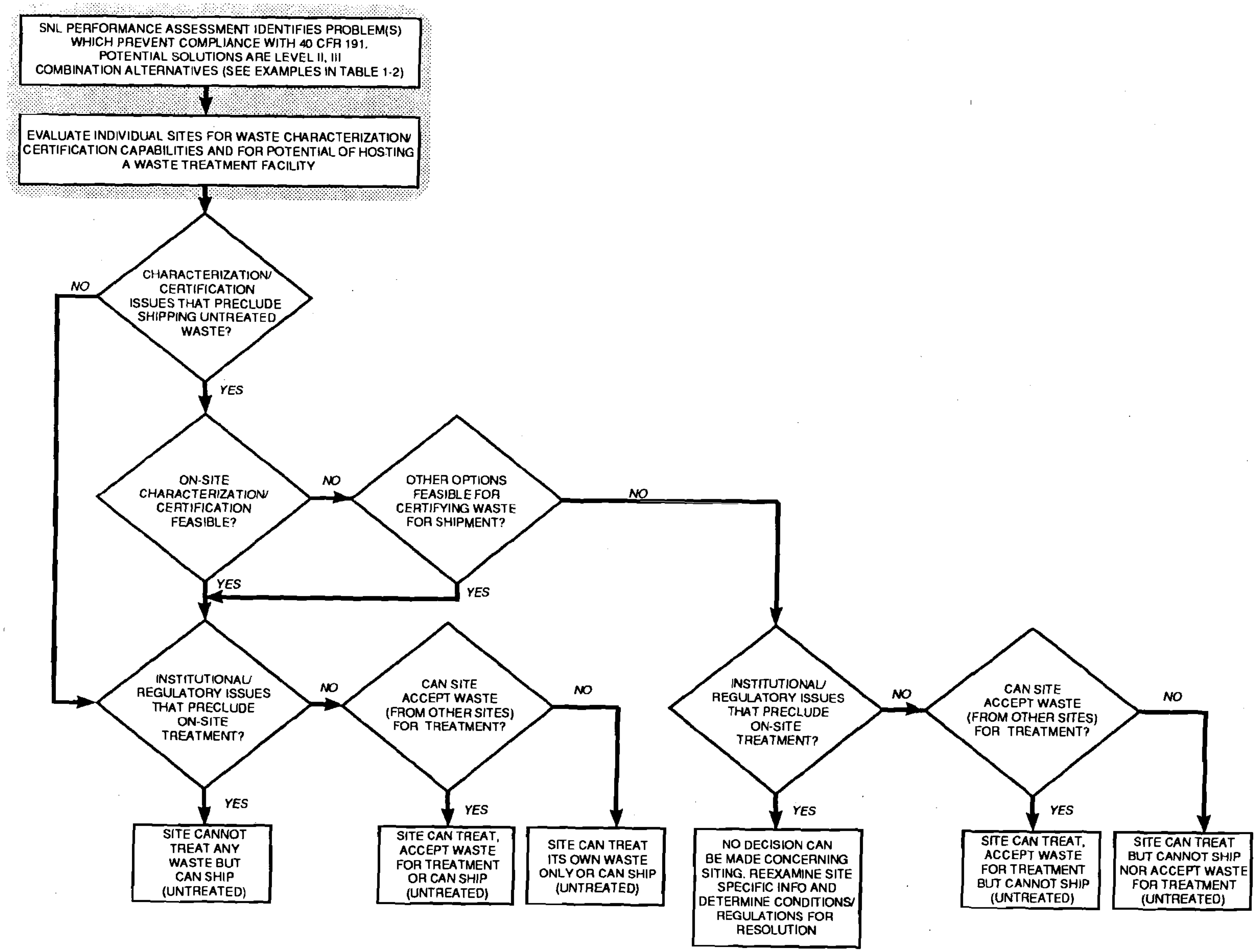

FIGURE 6-3 SITE-SPECIFIC FACTORS INFLUENCING DECISION TO LOCATE WASTE PROCESSING FACILITIES

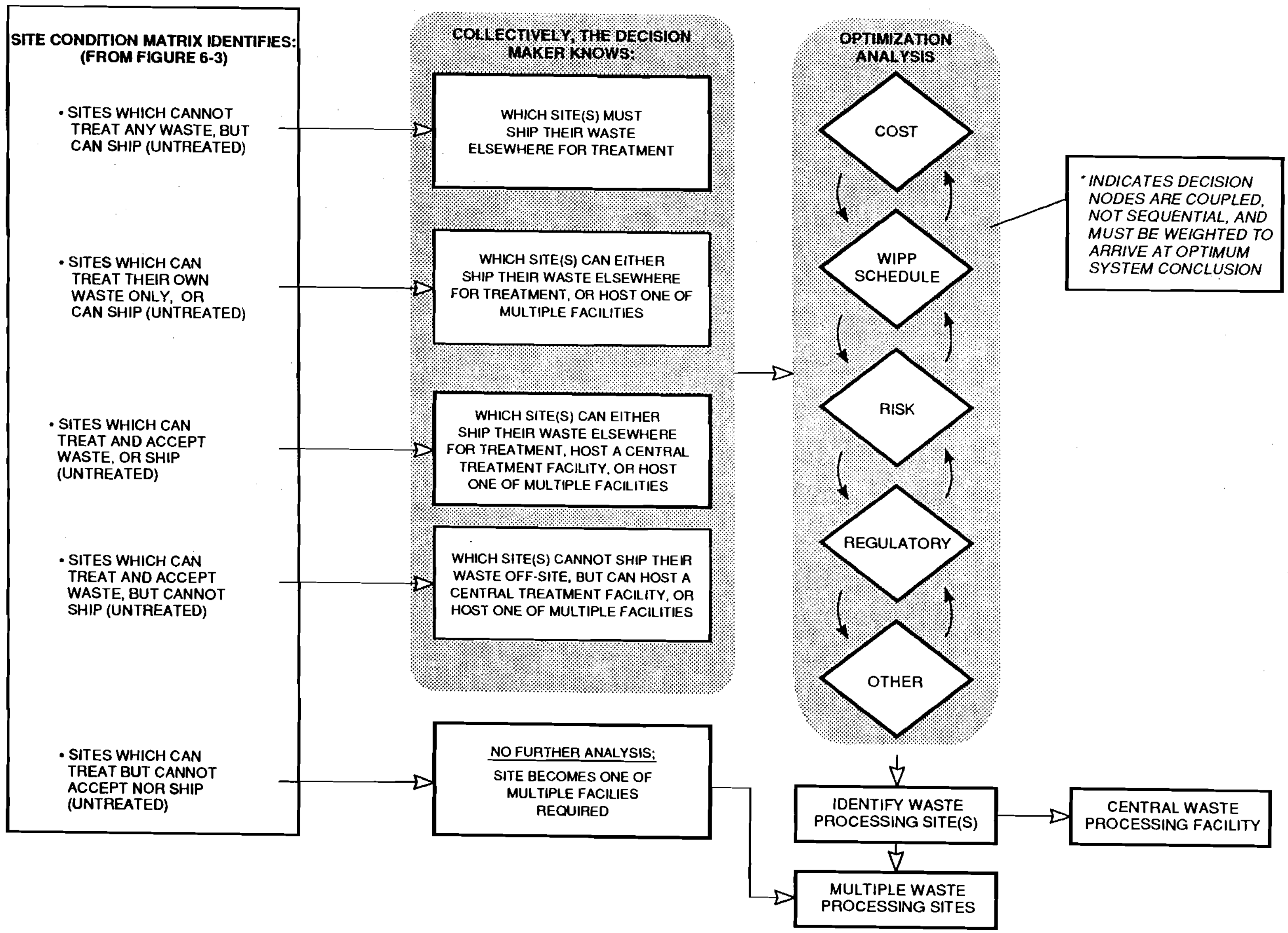

FIGURE 6-4
SYSTEM LOGIC DIAGRAM FOR FACILITY SITING

For waste forms where there are no characterization/certification issues that preclude shipment, the siting options are limited only by institutional/regulatory issues that preclude on-site treatment.

On-Site Waste Characterization/Certification Feasible?

If waste characterization or certification issues preclude shipping untreated waste off-site, then the feasibility of characterizing waste on-site must be addressed. Feasibility is defined as a comparison of the cost of characterization (see Section 6.3.4.4) and availability of characterization facilities (see Section 6.3.3) versus the cost (see Section 6.3.4.1), schedule (see Section 6.3.5), and regulatory requirements (see Section 6.3.6) for treating wastes on site. The cost of characterization is dependent upon the level of understanding of waste composition, extracted from existing information such as process knowledge (how the waste was generated).

RCRA compliance is an example of one of the major factors affecting a facility's waste-characterization requirements. RCRA characterization potentially requires sampling a large number of waste containers, which may require expansion or construction of waste-characterization facilities. For wastes where additional data are required for certification prior to shipment, the cost of certification may be sufficiently close to the cost of treatment that the benefit in treating waste on-site is clear.

Other Options Feasible for Certifying Waste for Shipment?

In the unlikely event that regulatory requirements prevent on-site characterization/certification, all other options should be explored before a decision is made to treat wastes on site.

Options available depend upon the characterization/certification issue. If the concern is difficulty in compliance with regulatory requirements of the State of New Mexico before wastes can enter the state, then the siting option for wastes (from that particular site) may be limited to a treatment facility outside of New Mexico. Similarly, if the issue is one of TRAMPAC certifiability for shipment in TRUPACT-II, other transportation options may be investigated.

6.4.2.2 Regulatory/Institutional Requirements That Prevent a Site From Treating Waste

The first three decision nodes of Figure 6-3 lead the site to one of three conclusions:

- Characterization/Certification issues do not exist for a given site's waste
- Characterization/Certification issues exist and an on-site method for resolution is available
- Characterization/Certification issues exist and no on-site method for resolution is available.

Superimposed on the issue of whether a site can ship waste is the issue of whether the site can treat wastes. Note that in Figure 6-3 a parallel examination of institutional and regulatory factors influencing treatment is applied to two conditions: where characterization/certification issues do not prevent shipment off site, and where such issues prevent the site from shipping off site.

Institutional or Local Regulatory Factors Preclude On Site Waste Treatment?

The analysis of institutional and local regulatory factors is focused on identification of constraints that might preclude construction or operation of a waste treatment facility on site. An example of such a factor is local opinion regarding waste treatment in general (See Section 6.3.6.2).

As indicated in Section 6.3.6, institutional and local regulatory factors currently are an area of considerable uncertainty and have the potential to change significantly over time. The fact that few radioactive-waste treatment facilities have been permitted suggest that a considerable effort will be required before adequate data are available to assess the time involved for permitting a facility at a given location. One approach to clarifying the institutional/regulatory issues is to initiate the permitting process at several candidate sites. On-site treatment is potentially removed as an option at sites where institutional requirements are insurmountable. (Note that such difficulty is not expected to be encountered.)

If waste cannot be shipped off site, and if institutional/regulatory factors preclude waste treatment, the site is at an impasse that must be resolved by negotiation with the appropriate regulatory agencies. If shipping is possible but institutional/regulatory factors preclude treatment on site, options are limited to waste treatment elsewhere. If waste can be shipped off site then, depending on the effect of institutional and regulatory constraints, options include waste shipment to another site for treatment or treatment on site.

Can A Site Treat Waste from Other Sites?

In all cases, if institutional/regulatory issues do not prevent on-site waste treatment, a final decision can be made regarding the ability of the site to accept waste for treatment. The answer to this question (can the site treat waste from other sites) could be affected by institutional or local regulatory constraints other than those concerning treatment of the site's own waste. For instance, if a state has declared that it will not allow TRU waste within its borders unless generated there, the transportation of waste from other DOE sites is prevented. As in the previous decision node, additional analysis of institutional/regulatory requirements is required before candidate sites can be identified.

6.4.2.3 Results of Site Categorization Evaluation

As a result of the shipment and treatment analysis, each site is classified into one of five categories (excluding a situation where the site can neither ship nor process waste), which is presented in Table 6-15 and summarized as follows:

TABLE 6-15

LOGIC FOR SITE CATEGORIZATION

DECISION	RESULTS
Ship waste to treatment site	• Waste does not need to be characterized, or • On-site waste characterization is feasible, or • Other options are feasible, and • Institutional or regulatory factors preclude on-site waste treatment
Waste treated on site or shipped to another location for treatment	• Waste can be shipped off site, and • Institutional/regulatory factors do not preclude waste treatment on site, and • Site can treat other sites' waste
<u>Site waste or other sites' waste can be treated on site, or ship waste off site for treatment (candidate for central facility)</u>	• Waste can be shipped off site, and • Institutional/regulatory factors do not preclude waste treatment on site, and • Site can treat other sites' waste
<u>Site waste treated on site; cannot ship untreated waste off site (candidate for central facility)</u>	• Waste cannot be shipped off site, and • Site can treat other sites' waste
Can only store its own treated waste on site; cannot ship untreated waste off site	• Waste cannot be shipped off site, and • Site cannot treat other sites' waste

- Sites that can only ship waste off site for treatment
- Sites that can only treat their own waste and cannot ship untreated waste off site
- Sites that can treat their own waste and waste from other sites but cannot ship untreated waste off site
- Sites that have the option to either treat their own waste on site or ship their waste off site for treatment
- Sites that have the option to either treat waste from any location on site or ship their waste off site for treatment.

Classification of each site into one of the five categories serves as input to the second decision model, where a decision of which DOE sites will host waste processing facilities is made.

6.4.2.4 Selection of Site Specific Waste Treatment Locations

The objective of the second part of the assessment is to determine optimum locations of waste treatment facilities, based on the results of the site categorization evaluation and is represented graphically by Figure 6-4. A data base of site-specific and system-wide information, including cost (Section 6.3.4), schedule (Section 6.3.5), risk (Section 6.3.7), regulatory considerations (Section 6.3.6), and other possible factors, will provide the technical support for conducting the analysis.

The following discussion provides an overview of the evaluation needed to establish optimum facility siting locations.

Site Condition Matrix

The starting point for this optimization analyses is the development of a site condition matrix which is developed from the site categorization evaluation. All DOE TRU waste sites fall into one of the five categories described in Section 6.4.2.3. A matrix can be developed by classifying each of the sites into one of these categories.

Collective Knowledge Available to the Decision Maker

The requirement for further optimization analysis is a function of the condition category to which a particular site belongs. Four out of the five categories described in Section 6.4.2.3 warrant siting optimization analysis. For a site that cannot ship untreated waste or accept waste from other sites for treatment, no further analysis is required; such a site would be required to treat its own waste before it can be shipped off site.

Optimization Analyses

Based on the collective knowledge available to the decision maker, an optimization analysis can be used to reach a conclusion of which sites will host treatment facilities. The decision maker now knows which sites can or cannot treat wastes and which sites can or cannot accept waste. This information may then be used in a weighted factor analysis to arrive at a decision. Such an analysis emphasizes factors which more greatly influence a decision.

The following factors are involved in this analysis:

- The life cycle costs associated with the construction and operation of the waste treatment facilities
- The effects on WIPP schedules of locating waste treatment facilities at specific locations, and for the number of facilities constructed
- The health and safety risks associated with construction and operation of facilities at specific locations, and the risks of transporting waste to and from those locations
- The effect that regulations may have on optimum facility siting decisions
- Other factors not identified at this time.

In addition, there could be other factors selected as considered appropriate for inclusion in the analysis. The relative importance of each of these factors needs to be determined, and appropriate weighting needs to be applied to each so that their relative contributions to the siting decision can be collated.

When these factors have been evaluated for each site, a comparative analysis can be made to determine the optimum facility siting locations. The following discussions describe how these factors can be applied in the analysis:

<u>Life Cycle Cost</u>

The cost of constructing and operating a waste treatment facility, and transporting waste to and from the facility, will vary depending on the DOE site chosen. Facility costs are a function of the quantity of waste that will be treated at the facility, which in turn is based on the total number of facilities constructed to treat all TRU waste. Facility costs can also be affected by planned or existing facilities that may support waste treatment at a DOE site. After the site-specific costs have been identified, a comparative analysis of the total life cycle costs for all facility locations can be made. The results can be factored into the overall analysis method chosen to optimize facility locations. Section 6.3.4 of this report provides capital and operating cost estimates if only a single, or as many as seven facilities, are constructed. Section 6.3.4.3 discusses the transportation considerations, using facility siting locations based on construction of up to seven facilities.

Schedule Effects on Facility Siting

Schedule effects on the siting decision tend to be focused on how many facilities are constructed, and any considerations that are unique to a specific DOE site. If multiple facilities are planned, it may be possible to show that the first of these facilities would be in operation before a single larger plant is operational. This may improve the waste disposal schedule by making shippable wastes available to WIPP sooner. There could also be unique conditions at various DOE sites that would improve or hinder the overall schedule. For instance, the availability of an existing facility which could be used (in whole or in part) to support waste treatment at the site would advance the schedule and make the site attractive as a facility host. Conversely, if there are negative factors unique to a site, the schedule would be adversely affected. Data required in assessing schedules is provided in Section 6.3.5.

Health and Safety Risks

Health effects due to treatment vary depending upon the number of treatment facilities and the type of treatment required. The assessment of risk in waste treatment relative to the risk in transportation and emplacement of untreated wastes is discussed in detail in Appendix I. As with the broader optimization analysis, the various components of the relative risk can be evaluated and weighted to arrive at total relative risks. The relative risks will then require an assignment of a weighting factor similar to those for the other components of the optimization analysis.

Effect of Regulations

Regulations vary with time and can be assessed only at the time the siting decision is being made. As an example, regulations should be evaluated to assure that restrictions for building a single facility are not insurmountable. Restrictions could be in the form of transportation requirements, or emissions criteria that would be more easily achieved by numerous smaller facilities. In Section 6.3.6.1, the EATF has identified federal regulations that apply to the treatment of waste.

Identification of Optimum Treatment Locations for Each Site's Waste

The completion of the optimization evaluations will result in:

- Optimum waste treatment site locations
- Designation of waste treatment site locations for all waste requiring treatment.

If as a result of the facility siting analyses only one site is identified as suitable, then all waste will be treated at this centralized facility. If more than one site is optimum, then DOE will have the option of designating multiple facility locations.

6.4.2.5 Data Uncertainties

This report provides much of the data needed to assess where waste treatment facilities should be located. However, uncertainties exist that must be resolved before a final siting decision can be made. The various uncertainties are included in the discussion of the various decision nodes presented in Sections 6.4.2.2 and 6.4.2.3.

The acceptable level of uncertainty for the various components is a function of how each component is weighted in the optimization analysis. For components weighted heavily, the acceptable level of uncertainty will be lower than for components assigned a relatively lower weight. The acceptable level of uncertainty should be analyzed as part of the overall evaluation of siting options.

6.5 SUMMARY OF RESULTS FOR FEASIBILITY OF IMPLEMENTING WASTE TREATMENT ALTERNATIVES

6.5.1 Feasibility of Waste Treatment

The EATF findings indicate that a broad range of waste treatments are feasible. Technologies exist to produce a broad range of processed waste forms (e.g., compacted, vitrified) from TRU waste and research efforts are ongoing in many areas.

There are, however, issues such as regulatory compliance, budget (waste treatment costs may range from tens of millions to over one billion dollars), and schedule (up to eleven years for Level III treatment) which complicate the feasibility of waste treatment. Such factors present obstacles but are not considered to be insurmountable if waste treatment is necessary. Waste processing will involve small additional short-term risks, but long term performance is improved for many alternatives.

The EATF considers waste treatment to be feasible but much work will be necessary before it can be implemented.

6.5.2 Facility Siting

Facility siting has been summarized by the EATF in the form of two cases: factors favoring a single site (at the WIPP) or multiple locations for waste processing facilities. This facility siting evaluation is based on the information collected and presented in Section 6.4. As noted in the various subsections of 6.4, firm requirements (or their effect) have not been delineated for factors that influence facility siting decisions. Specifically, final requirements needed for decision parameters are:

- Extent of waste characterization
- Finalization of transportation requirements
- Definition of regulatory requirements (specifically facility permitting) in order to establish costs and schedules for compliance
- Whether or not waste treatment is necessary (to comply with 40 CFR Part 191 or 40 CFR Part 268 requirements).

Table 6-16 summarizes the influence of factors presented in Section 6.4 on facility siting. Note that as directed in the EATF Program Plan (Hunt, 1990), qualitative assessments of factors and their influence on siting are made where quantitative information is not available.

TABLE 6-16

SUMMARY OF DECISION FACTORS FAVORING A SINGLE OR MULTIPLE FACILITY

DECISION FACTOR	CONDITIONS FAVORING FACILITY AT WIPP	CONDITIONS FAVORING MULTIPLE FACILITIES
Waste Characterization	Current characterization plans sufficient for transportation	Extensive characterization (RCRA, NRC) required prior to transporting
Transportation	Current transportation scheme already in place Minimizes TRUPACT-II miles and transportation cost if Level II treatment	Minimizes TRUPACT-II miles and transportation cost if Level III treatment
Waste Location		Consideration of buried TRU waste Precludes additional preparation for transportation
Planned and Existing Facilities		Planned and existing facilities exist at major sites and could be utilized as front-end to waste processing facility
Total Cost for Waste Treatment Facilities	Economy of scale realized for single facility	
Institutional Factors and Regulatory Concerns	Permitting requirements anticipated easier for a single facility	Institutions may not be able to accept waste from other sites RCRA requirements may force processing on site
Implementation Schedule		Anticipated that processed waste would begin arriving at WIPP earlier than if a single facility is built
Risk Reduction (Note: Level II independent of location)		Highest overall risk reduction at multiple sites for Level III treatment

The EATF has identified the following set of factors that favor a single waste processing facility (at the WIPP):

- Characterization - TRAMPAC characterization only (at planned or existing facilities)
- Cost - economy of scale achieved with a single integrated facility; transportation costs for Level II waste treatment are also minimized with a single facility
- Regulatory - permitting a single facility may be easier to accomplish.

Similarly, the following set of factors favors waste processing at multiple locations:

- Characterization - if extensive waste characterization is required, the cost differential between waste characterization and waste processing may be sufficiently small that treatment at multiple sites is preferred
- Transportation - transportation requirements are minimized for Level III treatment because of volume and mass reductions
- Schedule (WIPP) - it is anticipated that some of the multiple facilities would be operational more quickly than a single facility. Thus, processed waste would be sent to the WIPP in a more timely manner
- Risk Assessment (Safety) - the highest overall risk reduction (albeit small) for the alternatives examined was realized at multiple facilities for Level III treatment.

A specific "answer" on optimum facility siting cannot be ascertained due to data uncertainties in key decision parameters. Ground work in the form of a data base and a decision methodology have been completed to the point where a decision can be made as soon as the existing uncertainties are considered acceptable. Where uncertainties must be reduced, a decision awaits the collection of the required additional data.

6.5.3 Additional Data Requirements

The following information requirements identified by the EATF are needed before a waste treatment feasibility assessment (and facility siting decision) can be finalized:

- Waste treatment level (if any) defined by SNL performance assessment
- Extent of waste characterization
- Better understanding of institutional factors (influences whether or not site can be a host for a TRU waste treatment facility).

A recommendation for waste treatment cannot be made by the EATF at this time. This decision will be made as compliance issues of 40 CFR Part 191 pertaining to the current design are answered by the SNL performance assessment for the repository. Clearly, some work remains to be done before definitive conclusions can be drawn.

7.0 FEASIBILITY OF IMPLEMENTING BACKFILL ALTERNATIVES

The EATF evaluation of backfill alternatives emphasizes cement and salt-based backfills. Cement and salt-based backfill materials were recommended for inclusion in the WIPP experimental program by the EATF (DOE, 1990b). The following feasibility evaluation of backfill alternatives is based on development status, cost, schedule, and regulatory issues. Backfill alternatives are being evaluated in combination with various waste treatment techniques (Table 1-2). Initial work by the EATF indicates that regulatory considerations for backfill modifications will be minimal and should not impact the overall WIPP schedule (see Appendix A, Table A-6).

7.1 STATUS OF DEVELOPMENT

Three backfill modification alternatives have been recommended for inclusion in the WIPP Experimental Program (DOE, 1990b):

- Salt with Brine Absorbent - Addition of an absorbent, such as bentonite, introduces brine absorbing capability to reduce the potential for brine penetration into the waste.

- Salt with pH Buffer - Addition of a pH buffer, such as calcium oxide, will raise the pH of any brine coming in contact with the backfill. At elevated pH, radionuclide solubility, microbial activity, and corrosion of iron-based metals decreases (see Appendix G).

- Cement Grout - Cement grout backfill may offer several advantages, such as raising pH, or reducing permeability of waste storage rooms (Appendix G).

In addition to the above, the Expert Panel on Cementitious Materials recommended the following backfill:

- Salt Aggregate Grout - A grout with a high percentage of salt aggregate is anticipated to provide deformability, will be self-healing, and maintain low permeability under the anticipated 2,000 psi isostatic confining stress (Appendix G).

Mining technology exists to crush, blend, and transport salt and additives. Some engineering work will be required for backfill emplacement equipment. Similarly, grout backfill preparation and emplacement equipment does not involve research and development. Grouting in deep underground formations is common practice at DOE's Nevada Test Site (Ellis and Bendinelli, ND). The salt aggregate grout will require a development program.

7.1.1 Salt with Brine Absorbent

Mining of the WIPP facility produces bulk salt, which is stored above ground at the WIPP site. Granulation of this salt to a consistency required for efficient emplacement and the addition of a brine sorbent such as bentonite clay will not require a research and development program. Bentonite is expected to possess the beneficial characteristics of radionuclide sorption, and brine absorption (Butcher, 1990b).

7.1.2 Salt with pH Buffers

The addition of pH buffers to crushed salt backfill is similar to the addition of bentonite from the process standpoint. No process development is anticipated. Some additional investigations into the effectiveness of the pH buffers may be needed, depending on the specific requirements for such buffers in the WIPP underground environment.

7.1.3 Cement Grout

Many formulations of grout exist and other formulations can be prepared, depending on the specific application. An expert panel was convened by the EATF to qualitatively evaluate the use of cement or grout as a backfill medium. The panel concluded that the use of cementitious materials may be feasible for use as backfills in the WIPP underground environment. The report of the expert panel's findings is presented in Appendix G.

7.1.4 Salt Aggregate Grout

A grout formulation containing a high percentage of salt aggregate and brine (to provide hydration water) has not been produced to date (Appendix G); however, concretes with aggregate contents as high as 95 percent have been used in underground applications at the Nevada Test Site (Appendix G). It is anticipated that such a grout will have properties approaching those of host rock at the WIPP, and potentially allows more rapid closure.

7.2 BACKFILL PREPARATION FACILITY DESCRIPTION

The preparation of backfill requires equipment for bulk material crushing, blending, and handling operations. Storage of raw materials such as cement, bentonite, and calcium oxide are also necessary. Equipment needed for material staging, handling, and mixing are commercially available. Dry material mixers and concrete batch plants are commonly used in the construction and mining industries. It is understood that materials such as salt are hygroscopic and will absorb water; for the purposes of specifying backfill equipment, salt is a "dry material." Specification of a backfill preparation facility requires only a designation of the appropriate capacities and design parameters for staging, handling, and mixing equipment.

7.2.1 Cement Grout Preparation Facility Description

The cement grout preparation facility operations include material handling, batching, and mixing of backfill. A commercially available concrete batch plant may be used for preparation of the cement grout. The major components of a concrete batch plant are: storage silos for cement, aggregates, fillers, or other additives; a batch mixing system for weighing and blending dry materials; pneumatic and/or conveyor systems to move dry materials; and mixing equipment for preparation of the grout mixture.

Concrete batch plants are commercially available in a wide range of sizes, from small mobile equipment to large stationary facilities. The location of the batch plant should be near shafts for transporting the cement grout underground in order to minimize the time between mixing and emplacement. Once prepared, the cement grout can be moved to agitating holding tanks or emplaced directly. Agitator holding tanks may be required for temporary storage to prevent settling prior to emplacement.

7.2.2 Dry Material Preparation Facility Description

A dry material preparation facility will be required for crushed salt (or crushed salt plus additives) backfill. The crushing of bulk materials (if needed) and mixing (for addition of additives) operations are the primary functions of the facility. A roller impact or hammer mill may be used to process bulk salt to a specified granular size. Bulk materials such as bentonite or calcium oxide (unslaked lime) may also require some pre-processing (to break chunks) prior to being mixed with crushed salt. Commercially available dry mixing equipment may be used to produce homogeneous mixtures of salt and additives.

7.3 BACKFILL EMPLACEMENT EQUIPMENT DESCRIPTION

The EATF assumed backfill emplacement occurring in parallel with waste emplacement: as waste is emplaced in one portion of the facility, retaining walls will be erected and backfill emplaced over the waste in other areas. Upon completion of backfilling, the retaining walls can be removed and the process repeated elsewhere. The backfill volume that can be emplaced at one time will depend on capacity and design of the emplacement equipment.

Emplacement will require containers for transportation of backfill material and equipment for placing it in and around the waste. Backfill materials must be transported from storage or feed locations to partitioned waste stacks. The backfill must be elevated above the retaining walls and placed between and over the waste containers. The emplacement equipment must be designed to direct the flow of backfill into void spaces within and around the waste stack. The physical size of emplacement equipment must be compatible with the repository.

Available methods for emplacing backfill may be described as mechanical, pneumatic, or a combination of both. Commercially available equipment such as conveyors, augers, and pneumatic systems may be specified with modifications for application at the WIPP. Concepts presented here are preliminary in nature and are presented as examples of systems which may be used in the future.

7.3.1 Cement Grout Emplacement Equipment

Hydraulic emplacement involves pumping cement grout from storage tanks, Moran Cars, or feed tanks to the partitioned waste stack. The storage or feed tank can receive cement grout from the above-ground batch plant via a system of pumps. The emplacement equipment might consist of an agitated feed tank or Moran Car from which cement grout will be pumped into place via a boom mounted trunk. A telescopic boom would allow the operator flexibility in the placement of the cement grout. Cement grout should be emplaced at low pressures to avoid damaging waste containers.

Another method of grout emplacement will require conveyors in combination with augers for mechanical emplacement. Conveyors may be used for horizontal movement, whereas augers may be used for lifting grout. This method might consist of a conveyor moving cement grout from storage/feed tanks to the waste stack. An inclined auger could then lift cement grout to a conveyor extending over the waste stack. The final length of conveyor would be cantilevered and adjustable to allow the flow of cement grout to be directed to any portion of the waste stack. Cement grout could either free fall into the waste stack or be directed through a flexible hose. It is assumed that cement grout backfill will be free-flowing and unobstructed from filling void space within the waste stack. It is anticipated that some engineering development will be required to specify a grouting system.

7.3.2 Dry Material Emplacement Equipment

Emplacement of dry materials can be accomplished by methods similar to emplacing cement grout. For mechanical emplacement, a feed hopper located near the waste stack would supply backfill to an auger/conveyor system, which moves backfill to sections of waste being backfilled. The backfill material could either free fall from the end of the conveyor/auger or be directed through a flexible hose. The flexible hose would allow control over emplacement, as well as reduce potential dust problems resulting from re-suspended particles (Pfiefle, 1985). It is assumed that dry backfill will adequately fill void space within the waste stack if this method of emplacement is used.

Dry backfill material could also be pneumatically emplaced. The backfill could be crushed to an appropriate size and blown over the waste stack. The backfill is then allowed to settle in to void spaces within and around the waste stack. This method may require isolating the waste stack to avoid ventilation problems resulting from suspended particulates. Furthermore, special equipment may be required to avoid worker exposure to dust. Low pressure emplacement will be necessary to prevent damaging waste containers. An engineering development program will also be required for the dry material emplacement system.

7.4 COST OF FACILITIES AND EQUIPMENT

The EATF has calculated rough cost estimates for cement grout and crushed salt backfill preparation facilities. Capital cost estimates for material preparation facilities have been obtained from vendors of industrial construction equipment. Actual cost estimates are not practical since backfilling methods and requirements have not been specified. In order to account for this uncertainty, a 50 percent contingency factor has been added to the preparation facility capital costs for emplacement equipment.

In order to specify a design capacity for a backfill preparation facility at the WIPP, a basis volume of backfill must be assumed. The volume in each room available for backfill is estimated to be approximately 2,100 cubic yards [design basis room volume (13x33x300 feet) less the volume of 6,000 drums and a 2-foot air gap]. The design basis volume of backfill is assumed to be one-third of the total backfill volume, approximately 700 cubic yards. If the basis volume is to be backfilled in one shift (eight hours), a capacity of approximately 90 cubic yards per hour is required.

Small scale backfilling equipment is being used for test purposes at the WIPP. This equipment includes a small capacity screen and conveyor. Screening/blending (preparation) equipment for salt-bentonite backfill is available with a capacity of approximately 2 cubic yards per hour (Stenson, 1989). A portable conveyor elevator for emplacing dry backfill is also available (Gonzales, 1990). This equipment is to be used in experimental programs such as backfilling demonstrations and alcove experiments. The existing equipment may supplement the additional equipment required for backfilling operations. The cost of the existing equipment has not been included in EATF cost estimates.

7.4.1 Cement Grout Backfill Capital Costs

A capital cost estimate for a cement grout preparation facility was obtained from a vendor of industrial construction equipment (Prange, 1991). Many options are available for batch plants, and the actual costs will vary with the options specified. The batch plant cost reported here represents a facility capable of preparing cement grout at a rate of 110 cubic yards per hour. An estimate of the total capital cost for a cement grout backfill preparation facility and associated emplacement equipment is prescribed in Table 7-1.

Larger capacity, stationary batch plants are also available. These facilities are capable of producing larger amounts of cement grout backfill more rapidly. Larger capacity, stationary batch plants will cost approximately $750,000 (Prange, 1991). The capacity of larger facilities is considered to be beyond the needs of the WIPP backfilling efforts during the disposal phase.

7.4.2 Dry Material Backfill Capital Costs

Capital cost estimates have been prepared for both crushed salt and crushed salt plus additives backfill preparation facilities. These capital cost estimates are based on industrial

TABLE 7-1

BACKFILL PREPARATION FACILITIES AND EMPLACEMENT EQUIPMENT CAPITAL COSTS

BACKFILL ALTERNATIVE	COST (THOUSANDS, 1990 DOLLARS)
Crushed Salt	225
Crushed Salt plus Additives*	290
Cement Grout	435

*Additives include pH buffers and sorbents.

TABLE 7-2

BACKFILL OPERATING COSTS[1]

ALTERNATIVE[2]	BACKFILL MATERIAL	ANNUAL COSTS (THOUSANDS, 1990 DOLLARS)
Baseline	Salt	1,200
1	Salt	1,000
2	Salt	1,000
3	Cement-Grout	1,900
4	Salt	620
5	Cement-Grout	1,100
6	Salt	310
7	Cement-Grout	570
8	Salt	120
9	Cement-Grout	230
10	NA[3]	NA
11	Salt	1,100
12	Cement-Grout	1,500
13	NA	NA
14	Salt Grout	4,800

[1] Includes Labor, raw materials, required supplies.
[2] Refer to Table 1-2 for complete alternative description.
[3] NA - Not Applicable, these alternatives do not use backfill.

construction equipment from a commercial vendor (Prange, 1991). The capital cost estimate for crushed salt includes costs for an impact mill capable of processing 300 to 500 tons of backfill per hour. The capital cost for crushed salt plus additives includes cost for the same impact mill, in addition to cost for a conveyor pugmill plant with variable capacity, depending on the required mix time. The emplacement equipment required for crushed salt and crushed salt plus additives is assumed to be the same. The capital cost estimates for dry backfill preparation facilities and emplacement equipment are shown in Table 7-1.

The capacity of equipment used in the mining and construction industries is far greater than backfilling needs at the WIPP. Larger capacity equipment could be used to produce backfill in quantities large enough to stockpile. This could reduce the total operating time of the preparation facility, as well as enable simultaneous backfilling campaigns or more continuous backfilling operations.

7.4.3 Operating Costs

Annual operating costs of backfilling for each of the 14 combination alternatives has been estimated on the basis of backfill material requirements and emplacement costs. The baseline backfill requirement is calculated to be enough to fill 121 equivalent waste disposal rooms over a 25-year period. The Test Phase has not been considered. Each disposal room will require approximately 2,100 cubic yards of backfill. Emplacement of dry backfill is assumed to be 50 percent efficient in filling void space between drums, whereas grout is assumed to be 100 percent efficient in filling available void volume. An increase or decrease in total disposal volume is estimated from the number of equivalent drums per room (Table 3-5) for each combination alternative. For example, combination Alternatives 4 and 5 result in disposal of 11,250 unprocessed equivalent drums per room. Thus, in comparison to the baseline, the original disposal volume required for combination Alternatives 4 and 5 is decreased by the ratio of 6,000 to 11,000 (that is, original design volume times the ratio of unprocessed drum equivalents to processed drum equivalents).

Concrete emplacement costs for commercial applications have been used as the basis for estimating cement grout backfill operating costs (Kosel, 1991). Estimated concrete emplacement costs have been escalated by 20 percent as a contingency factor to account for the unique requirements of application at the WIPP. These emplacement costs include labor, raw materials, and any necessary supplies (other than cement grout ingredients). Emplacement costs for crushed salt have been estimated from concrete emplacement costs by subtracting materials cost. Labor costs are assumed to be the same for cement grout emplacement and crushed salt emplacement. The operating costs for cement grout backfill and crushed salt backfill are assumed to bound all possible backfill alternative operating costs. The estimated operating costs for the 14 combinations of alternatives are shown in Table 7-2.

7.5 IMPLEMENTATION SCHEDULES

The EATF has concluded that implementation schedules for backfill alternatives will have no impact on the overall WIPP schedule. Backfill preparation facilities are commercially available and can be erected on-site in relatively short periods of time. Off-the-shelf emplacement equipment which may need modification will require additional time above commercial ordering lead times. Overall, the backfill preparation facilities and emplacement equipment should be available before the WIPP Experimental Program has been completed, and are therefore not considered critical schedule items.

7.6 SUMMARY

The feasibility of implementing backfill alternatives has been evaluated by the EATF on the basis of development status, cost, schedule, and regulatory considerations. Equipment necessary for preparation of cement grouts, dry material crushing, blending, and handling are commonly used in the mining and construction industries (including nuclear applications at NTS). Backfill preparation equipment and facilities are commercially available and may be used with minor modifications for WIPP purposes. Backfill emplacement equipment may require an engineering development program. Material handling and transportation equipment is also commercially available and may be adequate for backfill emplacement. Capital and operating costs for backfill alternatives are relatively inexpensive in comparison to waste treatment. Backfill preparation facilities and emplacement equipment are estimated to cost less than one million dollars for all backfill alternatives. Lead time for ordering commercially available equipment defines the implementation schedules for backfill preparation facilities; additional schedule time must be allowed for modification or development of emplacement equipment. Regulatory requirements for backfill alternatives are minimal and should not impact the overall WIPP schedule. It is not known at this time whether a cement grout, salt (or salt and additives), or a high salt aggregate grout is the best choice for use at the WIPP. A development program will be necessary to specify an optimal composition for backfill material. The EATF concludes that all backfill alternatives presented in this report are feasible for implementation at the WIPP.

8.0 FEASIBILITY OF IMPLEMENTING OTHER ALTERNATIVES

This section provides a brief description of alternatives for WIPP waste management, facility design, waste container shape and material, and passive institutional controls. With the exception of waste containers, the nature of these alternatives dictates that they will be located or implemented at the WIPP site. Some of these alternatives may have regulatory impacts (e.g., facility redesign) whereas others will have minimal regulatory impact. The same observation can be made concerning cost. Some alternatives are potentially expensive, while others have minimal effects on total project costs.

8.1 STATUS OF DEVELOPMENT

Alternatives included in the categories of waste management and facility design modifications are not expected to require research and development. An engineering development effort will be required in most cases. For the most part, these alternatives are variations of existing operations or previous constructions and were judged to require only sound engineering or operations planning. For instance, minimizing space around the waste in WIPP is an operational consideration.

Facility design alternatives, such as changing the waste disposal room configuration, are variations of current mining practices which are commonly applied in the mining industry. Exceptions that will require further development are modifications to the waste container material and compartmentalization of the waste. The former may require the development of manufacturing techniques that will allow use of the material chosen, while waste compartmentalization may require development of special backfill materials. The preferred approach may be to investigate materials similar to shaft and drift sealing materials. Shaft sealing studies involving various sealing materials, such as concrete and salt, are underway. (DOE, 1989c). Passive institutional controls are the subject of extensive work recently initiated by Sandia National Laboratories (Bertram-Howery and Swift, 1990). The program has not reached the level of maturity required to discuss regulatory, technological, cost, and schedule considerations, and therefore passive institutional controls have not been evaluated by the EATF.

8.2 WASTE MANAGEMENT ALTERNATIVES

8.2.1 Minimize Space Around Waste

The WIPP waste disposal room dimensions were chosen so that retrieval of waste after a five-year demonstration period would not be precluded by premature room closure (DOE, 1989c). Space must exist between the waste stack and the walls and ceiling of the rooms immediately after waste emplacement to compensate for closure. The current design includes backfilling this space with crushed salt, while leaving a ventilation space above the backfill. By minimizing the space around the waste stack, room consolidation and repressurization may occur more quickly, thereby reducing the potential for brine inflow. At the same time, it should be noted that retrievability will be significantly curtailed and any gases generated by radiolysis, biodegradation, or anoxic corrosion will pressurize the room more quickly as total void volume of the room is decreased.

Space around the waste can be minimized further by changing the waste container shape. The interstitial space within the waste stack and along its edges represents approximately 15 percent of the total waste stack volume. Reduction of interstitial space can substantially reduce the waste disposal void volume, which in turn reduces the time for room reconsolidation. The potential modifications to the waste container shape and material are discussed in Section 8.4.

8.2.2 Waste Segregation

Waste segregation could prove beneficial in reducing or isolating potential problems (e.g., gas generation) within the WIPP. Segregating high gas-generating waste forms to specified locations within the WIPP will isolate the area over which other engineered alternatives may be required (i.e., alternative backfills) to reduce the gas generation rate of that segregated waste. Another segregation method may involve separating the inorganic sludges containing nitrates from the solid organic waste to slow down biological processes in the solid organic waste.

The decision to implement waste segregation requires changes in waste handling practices and an administrative effort for success. Regulatory and institutional consideration will not be as significant relative to other alternatives. The additional costs (above baseline disposal operating costs), resulting from increased waste handling and administrative efforts to implement the alternative, are expected to be small.

8.3 FACILITY DESIGN ALTERNATIVES

8.3.1 Compartmentalize Waste

The EATF has extended the alternative "Seal Individual Rooms", as discussed by the EAMP, to the concept of compartmentalizing waste. Much latitude in assumptions can be taken when formulating an approach for compartmentalizing the waste. The key objective is to segregate a known quantity of curies in an isolated compartment. The benefit of this waste management practice ensures that only a fixed (within regulatory constraints) quantity of TRU isotopes would be released if human intrusion occurred. The EATF concluded that one promising approach would be compartmentalizing waste using salt dikes to separate compartments containing three 7-packs of waste. This design was evaluated as part of Combination Alternative 14, described in Table 1-2.

Based on the report of Cement/Grout Expert Panel (Appendix G), the EATF has concluded that a salt-aggregated concrete could be formulated for use in waste separation. If a specific quantity of curies is placed in each compartment, only that amount could be washed out with the drill cuttings. Thus, the amount of curies placed in each compartment would be such that 40 CFR Part 191 will not be violated if human intrusion occurs sometime in the future.

8.3.2 Modified Room Dimensions

Although some design changes would be required, there should not be any significant regulatory or institutional actions required to proceed with this change. Mining new room dimensions does not present any additional risk of worker radiological exposure or industrial hazard. In fact, by eliminating the need for backfill around the waste stack, some radiological exposure to workers is eliminated because backfill emplacement operations taking place in close proximity to the waste would no longer be necessary.

Cost increments for mining waste disposal rooms to different dimensions will be small and will depend on whether smaller or larger rooms are needed to achieve the purpose of this alternative. More substantial cost increases could result if remote-handled waste emplacement equipment must be redesigned due to narrower room dimensions, and the ventilation system adequacy must be reanalyzed.

8.4 WASTE CONTAINERS

8.4.1 Waste Container Materials

Waste containers commonly in use are manufactured of mild steel, though some sites have used stainless steel. Given that a majority of steel in the WIPP waste inventory is in the form of waste containers, use of an alternative container material will substantially reduce gas generation potential due to anoxic corrosion. The EATF convened an expert panel to recommend alternative container materials. The Waste Container Materials Panel report is presented in Appendix H. The materials considered by the panel included copper and its alloys, titanium, ceramics, and cement-based materials.

8.4.2 Waste Container Shape

Minimizing the space around the waste stack has the benefit of minimizing potential conduits for brine immediately adjacent to the waste stack. The use of waste containers that can be tightly packed was investigated by the EATF. The EATF considers rectangular or hexagonal containers as most effective in eliminating void spaces between containers, relative to the present ringed, cylindrical waste drums and standard waste boxes. Hexagonal containers have an advantage in that geometries are similar enough to the cylindrical waste containers that they can fit into TRUPACT-II shipping package, while rectangular containers are easier to fabricate.

8.4.3 Cost Estimates for Alternative Containers

The cost of manufacturing (materials and fabrication) alternative containers is estimated to range from one to thirty-five times that of mild steel containers, depending on the material used (see Appendix H). Metal alloys such as titanium, zirconium, and high-nickel fall into the high end of the cost range; copper, stainless steel, polymers, glass, and ceramics are on the low end of the cost range.

It should be noted that some materials may require significant development costs to meet specific design criteria (e.g., mechanical properties, manufacturability). Further, significant costs may also result from construction of new manufacturing facilities. Estimation of these costs will be required before a decision can be reached as to the use of alternative containers.

8.4.4 Implementation Schedules

An implementation schedule for use of an alternative container requires definition of the following variables (see Appendix H):

- Time required to establish the effectiveness of the container in meeting gas generation requirements

- Time required to develop fabrication capabilities and to produce a full-scale prototype container.

Ceramic and glass materials do not require time to establish a program to determine gas generation potential. However, metal, cement, and polymers can require from one to five years for studies concerning gas generation potential. Note that microbial gas generation research is not included in the schedule estimate.

Stainless steel containers have been produced for the nuclear industry. However, a development program may be required for containers manufactured of other materials. Development time estimates are: two years for other metals; three to eight years for ceramics; two to four years for glass and cement (Appendix H).

8.4.5 Regulatory Issues

The single regulatory consideration for alternative containers is compliance with Department of Transportation (DOT) Type A requirements which is a Waste Acceptance Criteria at WIPP (DOE, 1989f). Compliance with DOT Type A requirements entails satisfactory completion of Type A Packaging Tests (DOT, 1989). These tests are designed to ensure the mechanical integrity of containers during standard handling operations and potential accident scenarios.

9.0 SUMMARY OF EATF FINDINGS AND RECOMMENDATIONS FOR APPLYING EATF RESULTS

The results of the EATF can be applied for final selection of engineered alternatives that improve the performance of the WIPP repository. Sections 1.0 through 8.0 and Appendices A through J, of this report present the data developed by the EATF related to the effectiveness and feasibility of various engineered alternatives. The data developed provide the knowledge base required for assessment and comparison of various candidate alternatives.

The EATF has also developed a methodology by which these data can be evaluated, and a decision can be made regarding which single alternative or combination of alternatives is preferred for a given performance problem. The recommended methodology includes an assessment of the limitations or uncertainties in the existing data. Identification of these uncertainties will help to assess the significance of simplifying assumptions. It will also help to prioritize any additional data requirements, so that the uncertainties in the most critical data sets are reduced to acceptable levels.

The following sections summarize the data developed by the EATF, present the recommended methodology for selecting an optimal alternative, identify additional data requirements at each step of the selection process, and present the conclusions of the EATF to date.

9.1 SUMMARY OF DATA DEVELOPED BY THE EATF

The EATF evaluated 14 alternatives with respect to their effectiveness for addressing gas generation and human intrusion issues (see Sections 2.0 to 4.0), and the feasibility of implementing them with respect to status of technology, cost, schedule, regulatory issues, and health and safety risks (see Sections 5.0 to 8.0). Table 9-1 lists the 14 alternatives and summarizes their evaluation.

The capability of each alternative for addressing gas generation has been summarized in terms of the effect of an alternative on the peak index pressure, and its effect on the gas generation rates by either microbial/radiolytic processes or by anoxic corrosion. If the peak index pressures due to an alternative (as estimated by the Design Analysis Model) do not exceed the lithostatic pressure, then the alternative is considered to be effective, and assigned a blank circle in Table 9-1. On the contrary, if the peak index pressure exceeds the lithostatic pressure, the alternative is considered to be ineffective, and is assigned a dark circle in Table 9-1. Similarly, the effect of each alternative on gas generation rates, and on the three human intrusion scenarios, are also presented in Table 9-1. These results have been discussed earlier in Section 4.3.

In addition to summarizing the effectiveness of alternatives, Table 9-1 also presents the feasibility of implementing each alternative in terms of the availability of technology, cost, likely schedules for implementation, regulatory requirements, and the health and safety risk relative to the baseline. The availability of technology is summarized in terms of the level of development of technology for the treatment processes. In case of processes like

TABLE 9-1
SUMMARY OF EFFECTIVENESS AND FEASIBILITY OF ENGINEERED ALTERNATIVES

Treatment level[b]	ALTERNATIVE DESCRIPTION						ALTERNATIVE EFFECTIVENESS						ALTERNATIVE FEASIBILITY					
	Number	Sludges	Solid Organics	Solid Inorganics	Backfill	Waste Container	Peak Index Pressure	Gas Generation Rate: Microbial & Radiolytic	Gas Generation Rate: Anoxic Corrosion	Human Intrusion: E1	Human Intrusion: E2	Human Intrusion: E1E2	Level of Development	Treatment Facility Lifecycle Capital and Operating Cost 10 yr Work-Off Period ($M)	Lifecycle Transportation Costs[a] ($M)	Implem. Schedule (yr)	Regulatory Requir.	Risk
II	1	AR	S&C	S&C	SLT	AR	●	◒	◒	◒	●	○	H	270-380	71-170	5-7	*	△
II	2	CMT	S&C	S&C	SLT	AR	●	◒	◒	◒	●	○	H	310-420	71-180	5-7	*	△
II	3	CMT	S&C	S&C	CGT	AR	●	◒	◒	◒	○	○	H	310-420	71-180	5-7	*	△
II/III	4	CMT	I&C	S&C	SLT	AR	○	○	◒	●	●	○	H	610-820	71-110	8-11	**	△
II/III	5	CMT	I&C	S&C	CGT	AR	○	○	◒	◒	○	○	H	610-820	71-110	8-11	**	△
III	6	VTR	I&V	MM	SLT	AR	○	○	◒	◒	◒	○	M	830-1100	71-55	8-11	**	NE
III	7	VTR	I&V	MM	CGT	AR	○	○	◒	○	○	○	M	830-1100	71-55	8-11	**	NE
III	8	VTR	I&V	MRM	SLT	NFE	○	○	○	○	◒	○	M	1100-1400	71-27	8-11	**	▩
III	9	VTR	I&V	MRM	CGT	NFE	○	○	○	○	◒	○	M	1100-1400	71-27	8-11	**	▩
III	13	VTR	I&V	MRM	N/A	NFR	○	○	○	○	◒	○	M	1100-1400	71-27	8-11	**	▩
I/III	10	AR	AR	DRM	N/A	NFR	●	●	○	●	●	○	H	510-700	71-60	5-7	*	NE
I	11	AR	SPT	SPT	SLT	AR	●	●	●	●	●	●	H	180-260	71-51	5-7	*	NE
I	12	AR	SPT	SPT	CGT	AR	●	●	●	◒	○	○	H	180-260	71-51	5-7	*	NE
I	14	AR	SPT	SPT	SAG	AR	●	●	●	◒	◒	○	H	180-260	71-51	5-7	*	NE

AR - AS RECEIVED
CMT - CEMENT
VTR - VITRIFY
S&C - SHRED & CEMENT
I&C - INCINERATE & CEMENT
I&V - INCINERATE & VITRIFY
SPT - SUPERCOMPACT
MM - MELT METALS
N/A NOT APPLICABLE

MRM - MELT AND REMOVE METALS
DRM - DECONTAMINATE AND REMOVE METALS
SLT - SALT
CGT - CEMENT GROUT
SAG - SALT AGGREGATE GROUT
NFE - NON FERROUS
NFR - NON FERROUS, RECTANGULAR
● - NO EFFECT
NE - NOT EVALUATED

◒ - PARTIALLY EFFECTIVE
○ - EFFECTIVE
H - HIGH
M - MEDIUM
* - RCRA/HSWA, DOE ORDERS, NEPA, NESHAP
** - RCRA/HSWA, DOE ORDERS, NEPA, NESHAP, CAA, CWA, TSCA, PSD, NAAQS, NSPS
△ SLIGHT RISK INCREASE RELATIVE TO BASELINE
▩ SLIGHT RISK INCREASE FOR SINGLE FACILITY, TO SLIGHT DECREASE FOR 7 FACILITIES

[a] COSTS FOR ONE TO SEVEN PROCESSING FACILITIES

[b] CLASSIFICATION BY TREATMENT LEVELS IS SOMEWHAT GENERALIZED; FOR EXAMPLE, ALTERNATIVE 1 INCLUDES BOTH LEVEL I AND LEVEL II TREATMENTS.

vitrification, where additional development is required for application to TRU waste, the availability of technology has been rated as moderate. The capital costs listed for each alternative reflect the range of costs estimated by the EATF for one to seven processing facilities. The regulatory issues associated with implementing each alternative are presented in terms of the likely permitting requirements, and the schedules for each alternative are presented in terms of the number of years likely to implement the alternative. Risks are presented as a qualitative assessment relative to the "baseline" (all wastes transported and emplaced "as received"). Because backfill has no influence on the assessment of risk, alternative combinations 3, 5, and 9 have the same relative risk increases or reductions as alternative combinations 2, 4, and 8 respectively.

The information presented in Table 9-1 provides a matrix that can be used as a quick reference for comparing the pros and cons of the various alternatives. It can be observed from Table 9-1 that, in general, Level III alternatives (e.g., 8, 9, 13) are more effective than Level II alternatives (e.g., 1, 2, 3), in addressing both gas generation and human intrusion. It should be noted, however, that the improved effectiveness is not obtained without paying a price. Level III alternatives tend to be more expensive, take longer to implement, and require facilities that are harder to permit than Level II alternatives. Consequently, the greater effectiveness of an alternative does not necessarily make it preferable over others, because the selection of an alternative with the optimal effectiveness will depend upon the extent of any problem identified by performance assessment studies.

9.2 METHODOLOGY FOR FINAL SELECTION OF AN ALTERNATIVE

The 14 alternatives that have been evaluated were selected to provide a broad range of improvement in performance by treatment of all three major waste forms (sludges, solid organics, and solid inorganics). While it is expected that these 14 alternatives would be sufficient to address any potential issues of gas generation and human intrusion, this does not imply that the choice of an optimal alternative is limited to the 14 alternatives evaluated by the EATF. For example, if performance assessment determines that merely destroying the solid organics would be sufficient to demonstrate compliance, then thermal treatment of the organics should provide the necessary improvement in performance, and there would be no need of any treatment of the sludges and solid inorganics. In other words, it is possible that one of the single alternatives forming the combination alternatives 1 through 14, could be selected as an optimal alternative.

The EATF has developed a methodology for selecting an optimal alternative using the results of evaluation of the 14 alternatives. The decision process for using the EATF results are presented in Figure 9-1. This figure outlines the usefulness of the EATF evaluations in relation to the overall framework of the system, and provides a tool for reaching a final decision.

As shown in Figure 9-1, the decision process starts with an assessment of the current design with respect to demonstration of compliance with 40 CFR Part 191, 40 CFR Part 268, and any other applicable regulations. If compliance can be demonstrated using the current design, then there would be no need for an engineered alternative. On the contrary, if the current design fails to demonstrate compliance, then performance assessment will identify which performance

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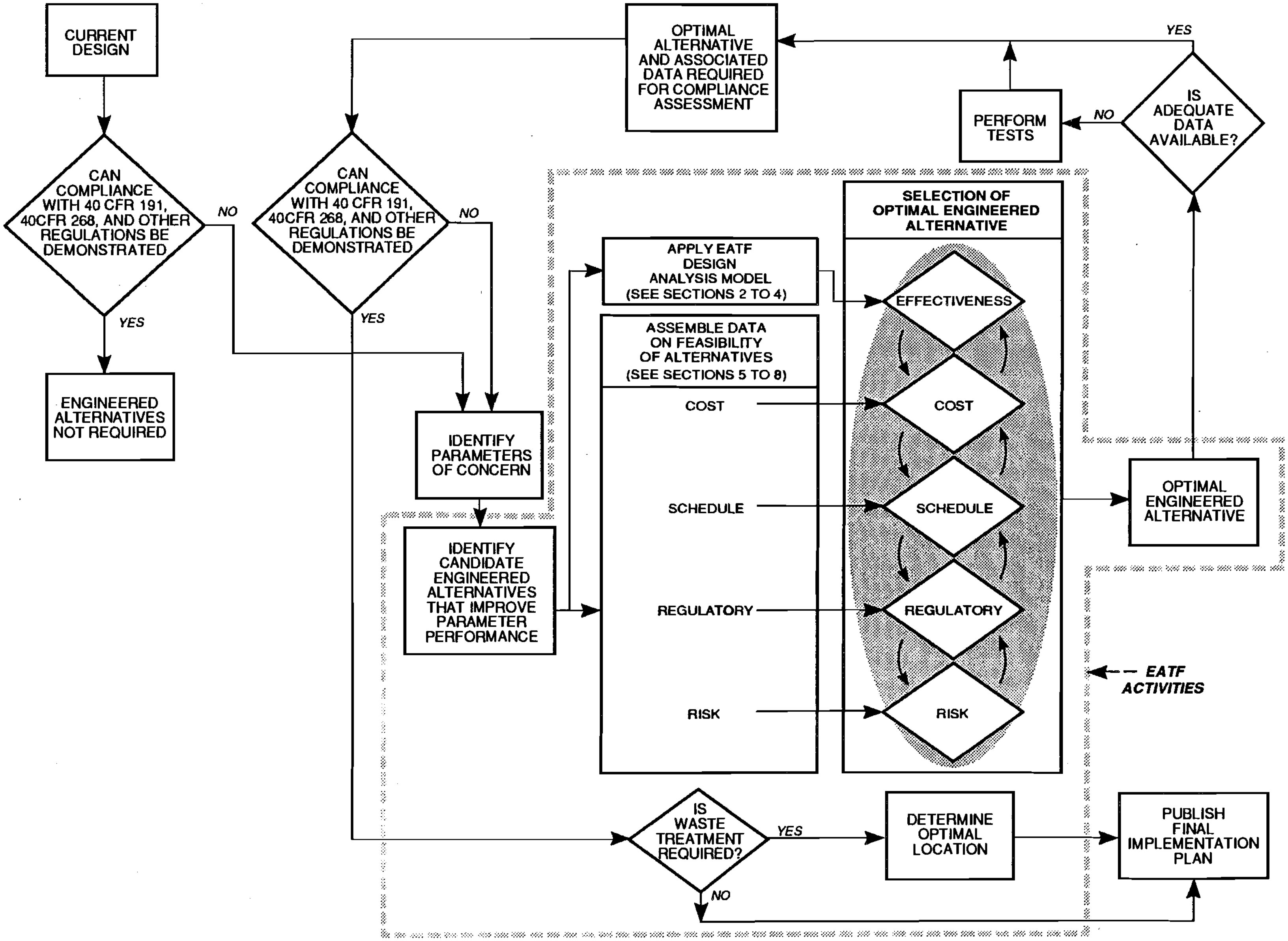

Figure 9-1
Methodology for using EATF results

parameters (e. g., permeability, radionuclide solubility, microbial/radiolytic gas generation, etc.) are the cause for concern.

9.2.1 Identification of Candidate Engineered Alternatives

Once a problem is identified by performance assessment, the data developed by the EATF will help to identify a list of candidate alternatives that would be sufficient to alter the performance parameters of concern in order to achieve the required performance. The objective would be to focus the choice of alternatives to a small group of candidate engineered alternatives for further evaluation. For example, if it is determined that merely lowering the gas generation rates will demonstrate compliance, one of Alternatives 1, 2, or 3, from Table 9-1 would be sufficient, and there would not be any need of any Level III alternatives. If, on the other hand, it is determined that it is necessary to eliminate gas generation of any kind, then the group of candidate alternatives would be limited to Alternatives 8, 9, and 13. Similarly, based on the results of performance assessment, candidate alternatives can be chosen from Table 9-1 to address the human intrusion scenarios if the current design is predicted to result in noncompliance with any of the three intrusion scenarios.

9.2.2 Evaluation of Candidate Alternatives

Once a group of candidate alternatives has been identified, the next step is to utilize the EATF results to assemble the data required for optimization of candidate alternatives. The specific tasks involved are discussed in the following sections.

9.2.2.1 Application of the EATF Design Analysis Model

The effectiveness of the candidate alternatives with respect to various effectiveness criteria such as peak index pressure from gas generation, and the MRE for the three intrusion scenarios, can be estimated by the EATF Design Analysis Model. The results for the 14 alternatives analyzed by the EATF were presented earlier in Section 4.0. A similar analysis is required for each candidate alternative. It should be noted that if the underlying assumptions in the model change as additional data are obtained, or if the data base of model input parameters is expanded, then the Design Analysis Model should be updated and the effectiveness of the alternatives estimated using the revised assumptions.

9.2.2.2 Assemble Data for Evaluation of the Feasibility of Candidate Alternatives

In addition to the analysis of the effectiveness of an alternative, data are required for the evaluation of the feasibility of implementing each candidate alternative. As mentioned earlier, feasibility refers to the combination of criteria such as cost, schedule, regulatory issues, and health and safety risks. These criteria are discussed below:

- Application of EATF Cost Analysis - The factors considered by the EATF for cost analysis include the capital cost of new treatment facilities, operating cost of facilities, cost of alternative materials (e. g., backfill, waste container, etc.) cost of waste characterization/certification (if applicable), and the cost of waste transport. The cost of implementing different alternatives was estimated in Section 6.0 for waste treatment, Section 7.0 for backfill alternatives, and Appendix H for alternate waste container materials. The applicable information in each of these sections will help to develop the cost for implementing each alternative. The level of detail required in cost analyses depends upon the level of precision required. It should be noted that the costs presented in this report are not "bottom-up" costs (i.e., specific costs of equipment, material, and services have not been specified). Instead, these costs have been compiled from various DOE publications. These costs provide an excellent comparison between alternatives. However, if cost is of primary importance in the selection of optimal alternatives, then additional cost analysis may be required to reduce uncertainties to an acceptable level.

- Application of EATF Schedule Analysis - The schedules for implementing candidate treatment alternatives can be estimated from the EATF results presented in Section 6.0. The schedules estimated by the EATF include preconstruction, engineering, construction, and start-up, and are based upon results from various DOE publications. The regulatory issues have been assumed to be part of the preconstruction period of implementation schedules. The EATF feels that regulatory/compliance issues and budgetary constraints that delay construction, present the greatest uncertainties in the estimation of schedules. The acceptability of these estimates depends upon the relative importance assigned to schedule concerns during the selection of an optimal alternative (Section 9.2.3). Thus, the uncertainties involved must be weighed against the relative importance of schedule concerns, to decide if additional data are required to make a decision.

- Application of EATF Regulatory Analysis - The EATF analysis presented in Section 6.0 shows that significant uncertainty exists in the area of regulatory compliance, and therefore it is difficult to estimate the time periods required for licensing a facility. The EATF has considered the experience of other projects in various states, and also the different state and federal regulations that affect the permitting process. It has been observed that, in general, the timeframe required for facility permitting varies with the type of facility being considered (i.e., Level II or Level III), and the proposed facility location.

  As discussed in Section 6.0, waste characterization may be required to comply with the State of New Mexico or RCRA requirements. The extent of waste characterization required by RCRA will have a significant influence on the choice of an alternative, especially if the cost of such characterization is comparable to the cost of processing the waste. Presently, the extent of characterization required by RCRA is not well defined. This increases the uncertainties of estimating the requirements for regulatory compliance. Although the various factors that affect the regulatory issues have been explained in Section 6.0, the EATF has refrained from presenting precise estimates of facility permitting time.

- Application of EATF Risk Assessment - The risks associated with implementing candidate alternatives can be compared with the baseline design using the results of the risk assessment summarized in Section 6.0 and discussed in detail in Appendix I. Although the analysis presented in Section 6.0 relates to Alternatives 1, 2, 4, and 8, and does not include all 14 alternatives, the four options analyzed by the EATF represent the total range of treatments involved in the 14 alternatives. For example, the waste treatment involved in Alternatives 3, 5, and 9 is identical to that of Alternatives 2, 4, and 8, except for different backfills. Because backfills used have no influence on the risk assessment, risk associated with Alternatives 3, 5, and 9 are assumed to be identical to those for Alternatives 2, 4, and 8, respectively.

  The results of the EATF risk assessment demonstrate that Level II treatments result in a slight increase in risk relative to the baseline design, and this increase is generally independent of the number of facilities. In contrast, for Level III treatments, the dominance of transportation risks favors treatment of wastes at multiple facilities before transporting the wastes to WIPP. This is because the Level III treatment of waste before shipment substantially reduces the transportation risks, and this reduction more than compensates for the increase in occupational risks associated with the Level III treatment of waste.

  Since risk is an abstract quantity, the results of any risk analysis are often used by equating risk to some tangible quantity (e. g., the number of lives saved by an unit decrease in absolute risk). However, the use of such an approach is not recommended for the results of the EATF risk assessment for reasons outlined below.

  The EATF analysis has involved estimating the risks of alternatives as ratios relative to the baseline case. This approach was used to cancel the uncertainties that are common to the baseline case and the alternatives. In theory, one could take the relative risk reduction ratios estimated by the EATF, and combine these numbers with the absolute baseline risk provided in the FSEIS/FSAR to arrive at an absolute risk for each alternative. However, it should be noted that this would only serve to bring back the uncertainties present in the FSEIS/FSAR calculations, and therefore not advisable.

  If it is not possible to make a decision without the absolute risk values for the alternatives, then the EATF recommends either one of two optional approaches. The first approach involves an estimate of the absolute baseline risks using a more rigorous method than the one used in the FSEIS/FSAR. This should reduce the uncertainties, and the EATF results of relative risk could then be combined to arrive at absolute risks for the alternatives. The second approach is less rigorous, and involves expressing the value of relative risk reduction for each risk component (e.g., transportation fatalities, etc.) in terms of a tangible quantity such as the number of lives saved, etc. Once each of the eight components considered by the EATF has been expressed in terms of a tangible quantity, they could then be aggregated using societal weights for each component to arrive at a tangible value of risk reduction for each alternative.

The limited scope of this study should be noted while applying the results of the risk assessment. As explained in detail in Figure I.ES-1 in Appendix I, the different combinations of alternatives and treatment locations fall into four different risk groups. While a more rigorous analysis might change the numerical values of the risk reduction factors within each of the four groups, it is unlikely to result in reclassification of any option from one group to another.

9.2.3 Selection of an Optimal Engineered Alternative

Once the data on the effectiveness and feasibility of candidate alternatives have been compiled, the next step is to use the data to select an optimal alternative. As shown in Figure 9-1, the optimal alternative should be decided by simultaneous consideration of five different components for each alternative. These are effectiveness, cost, schedule, regulatory considerations, and the health and safety risk associated with an alternative. While a relative measure of these factors can be obtained for each alternative using the results of the EATF, their relative importance must be evaluated in any final decision process. Unless the relative importance of these factors is established, the results of the EATF for each factor will remain mutually exclusive, and therefore cannot be aggregated for optimizing the choice of an alternative.

The interactive processes that are expected to be involved in such an optimization process are illustrated below with an example. Assuming that the candidate alternatives are limited to Alternatives 3 and 4, the analysis of the EATF would provide the following results:

Effectiveness - Alternative 4 would reduce peak index pressures to lithostatic. Alternative 3 would be ineffective in reducing pressures to lithostatic, and the maximum peak index pressures predicted for this alternative are 20 percent higher than the lithostatic pressure. In general, Alternative 3 may be more effective against human intrusion, whereas Alternative 4 is more effective for addressing gas generation.

Cost - Project costs for Alternative 4 are expected to be substantially higher than for Alternative 3.

Schedule - Alternative 3 would take 5-7 years for implementation, whereas Alternative 4 would take 8-11 years.

Regulatory Considerations - Since Alternative 4 involves thermal treatment, it would be expected that the regulatory requirements for this alternative would be more extensive than Alternative 3.

Risk - If the number of waste treatment facilities is less than or equal to three, then the risks due to the two alternatives are roughly equal. For more than three treatment facilities, the risk due to Alternative 4 is marginally less than Alternative 3.

Given the above results, the relative importance of the above factors has to be determined in influencing the decision. For example, it must be decided whether the improvement in effectiveness using Alternative 4 is worth the additional cost as well as the more extensive regulatory requirements. If schedule is the most important factor, Alternative 3 would seem to have an advantage over Alternative 4.

The decision maker should also take note of the uncertainties involved in the EATF evaluations and, based on the relative importance of a factor, it should be decided if a more detailed analysis is warranted. For example, future experimental data regarding properties of modified waste forms might show that Level II alternatives such as Alternative 3 would not exceed the lithostatic pressure. Therefore, if the relative importance of effectiveness is considered to be greater than the other factors, then it would be advisable to carry out additional analysis of alternatives using revised properties of modifed waste forms as input to the Design Analysis Model, and thus minimize the uncertainties before selecting an optimal alternative. Similarly, if the EATF estimates of project costs for the candidate alternatives are roughly equivalent, and cost is the most important factor, then it would be advisable to estimate "bottom-up" costs for each candidate before reaching a decision.

In summary, the decision methodology proposed by the EATF can serve as a "guide" in the process of selecting an optimal alternative. However, this optimization process involves the aggregation of the EATF results based on the relative importance of influential factors. It is beyond the scope of the EATF to make a judgement on the relative importance of the five factors mentioned previously, and therefore the EATF has left the process of selecting an optimal alternative to the eventual decision maker.

Thus, there are three tasks that must be completed as part of any final selection of an optimal alternative. Since the EATF formulated the list of alternatives in the early part of 1990, the list of alternatives might require a review and update in the future as new technologies continue to evolve. The relative importance of the five factors involved in selecting an optimal alternative should also be decided by some sort of weighting or prioritization. Finally, the existing data developed and presented by the EATF in this report should be reviewed to understand its uncertainties and limitations. The completion of these tasks, together with the methodology described in Figure 9-1, should guide the selection of an optimal alternative, in case one is needed.

9.2.4 Verification of Compliance for Optimal Alternative

Once an optimal alternative has been selected, compliance with the applicable regulations must be demonstrated. An assessment of compliance for the alternative by the use of performance assessment codes will require adequate data regarding the properties of the waste forms resulting from the alternative. If such data are not available, experiments should be conducted to obtain the required data. The data for the optimal alternative will be used as input to the performance assessment codes to verify if the selected alternative can indeed demonstrate compliance with all applicable regulations. If compliance is demonstrated, optimal locations for implementing the alternative can be determined using the EATF facility siting logic described in Section 6.4. In case the optimal alternative fails to demonstrate compliance with applicable regulations, the parameters of concern associated with the alternative must be identified, and the whole selection process repeated until compliance can be demonstrated.

9.3 CONCLUSION OF THE EATF

The EATF has concluded that a number of engineered alternatives could be implemented to improve repository performance if WIPP performance assessment determines that either gas generation or human intrusion presents a problem in demonstrating compliance. Waste treatment is generally the most effective type of engineered alternative, but is by far the most difficult to implement. Within waste treatment, Level III treatments are the most effective in addressing multiple performance parameters, but tend to be the most expensive, the most difficult and time-consuming to implement, and have the greatest regulatory requirements. Level II treatments are less expensive, faster, require less extensive permitting, and utilize off-the-shelf technology, but are less effective in addressing multiple performance parameters. Depending upon the performance parameter, Level I alternatives such as alternative backfills, alternative waste containers, or modified repository design should be thoroughly evaluated and eliminated before any decision is made to treat the waste.

The present uncertainty in the degree to which the baseline WIPP design complies with 40 CFR Part 191 and 40 CFR Part 268 precludes specific recommendations at this time. The broad range of potential alternatives, with significant variations in cost, implementation schedules, regulatory requirements, etc. between alternatives, requires that performance improvements are better defined before the EATF can make specific recommendations. The decision methodology provided (see Section 9.2 for optimal alternative selection and Section 6.4 for treatment site selection) provides a means to evaluate options once the needed improvement in performance is known. In the interim, there is the option of using the decision methodology to perform sensitivity analyses or to evaluate potential alternatives based upon preliminary results of the WIPP performance assessment.

10.0 MEMBERS OF THE EATF

The Engineered Alternatives Task Force is comprised of WIPP-management and more than 50 technical personnel from the DOE, DOE-contractors, and commercial organizations (Figure 10-1). The core EATF team includes staff from DOE-WPO, Westinghouse Waste Isolation Division (WID), International Technology Corporation (IT), and Sandia National Laboratories. The work of the task force was supported by input from several "expert panels" that addressed specific technical issues. The Engineered Alternatives Multidisciplinary Panel (Appendix A), the Cement/Grout Expert Panel (Appendix G), and the Waste Container Materials Panel (Appendix H) were three such expert panels convened to provide technical guidance to the EATF.

External and internal DOE peer reviews were used to develop and refine the EATF Program Plan, the Design Analysis Model, data on the feasibility of alternatives, and this EATF Final Report. Comments from the DOE/HQ WIPP Task Force staff and the National Academy of Sciences WIPP Panel were particularly instrumental in formulating the approach taken by the EATF. The Independent Review Panel, composed of the now-deceased Dr. Doug Brookins [Professor of Geochemistry and prior contributor to WIPP and Office of Civilian Radioactive Waste Management (OCRWM) programs], Dr. Eric Nuttall (Professor of Chemical Engineering and contributor to modeling of geological repositories), Mr. Donald Shaw (expert in rock mechanics and prior contributor to modeling of WIPP), and Dr. Robert Budnitz (expert in probabilistic risk assessments) reviewed a draft version of this EATF Final Report and suggested numerous improvements.

The work of the EATF was supported by the technical staff at Westinghouse and IT Corporation. Text processing and graphics support at IT produced high-quality documentation. Administrative support was provided by Kathleen Logan and Cindy Morrison of IT and Rhonda Molgaard of Westinghouse. Contracts support was provided by Peter Tackett of Westinghouse and Ron Freeny and Linda Baker of IT.

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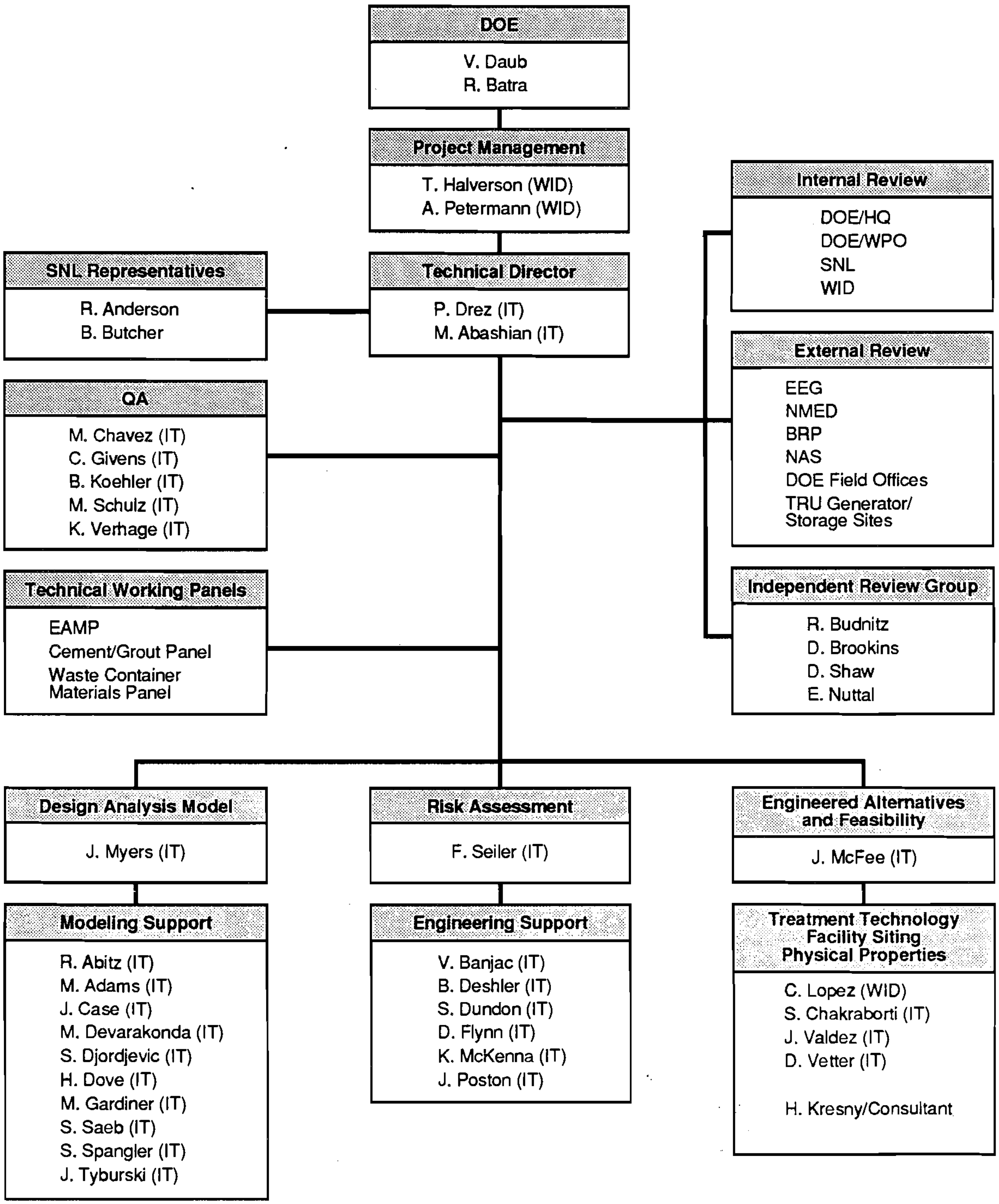

Figure 10-1
Engineered Alternatives Task Force Project Organization

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12.0 GLOSSARY

Accessible Environment - The accessible environment means to (1) the atmosphere, (2) land surfaces, (3) surface waters, (4) oceans, and (5) all of the lithosphere that is beyond the controlled area (see 40 CFR Part 191.12[k]).

Activity - The number of nuclear disintegrations occurring in a given quantity of material per unit time.

Advection - The transport of fluid by bulk motion through a porous solid due to a difference in absolute fluid pressure across the solid.

Alpha Particle - A positively charged particle made up of two protons and two neutrons (therefore, identical to a Helium atom). Emitted in the radioactive decay of certain nuclides, it is the least penetrating of the three types of radiation: alpha, beta, and gamma.

AIRDOS - A computer code used to calculate health risks due to the atmospheric dispersal of radiaoctivity.

Anhydrite - A mineral consisting of anhydrous calcium sulfate ($CaSO_4$). It is equivalent to gypsum without water, and is denser, harder and less soluble than gypsum.

Anoxic - Without oxygen.

Argillaceous - Pertaining to, largely composed of, or containing clay-sized particles or clay forming minerals.

Argillaceous Rocks - Rocks containing appreciable amounts of clay.

Attribute - the value of utility assigned to a particular component of the risk.

Backfill - Material (such as crushed salt or grout) placed around the waste containers to fill the open spaces in the room.

Becquerel (Bq) - The SI unit of radioactivity. One Bq equals one disintegration per second.

Bell Canyon Formation - A sequence of rock strata (sandstones, shales and limestones) that form the uppermost unit of the Delaware Mountain Group; of significance because it is the first regionally continuous water-bearing formation beneath the WIPP underground workings (Lappin et al., 1989).

Bentonite - A commercial term applied to clay materials containing montmorillonite (smectite) as the primary mineral.

Biomass - The dry weight of living matter, including stored food, present in a species population and expressed in terms of a given area or volume of the habitat.

Borehole - (1) A manmade hole in the wall, floor, or ceiling of a subsurface room used for verifying the geology, observation, or the emplacement of waste canisters. The horizontal wall holes are used for remote-handled transuranic (RH-TRU) waste; (2) A hole drilled from the surface for purposes of geologic or hydrologic testing, or to explore for resources, sometimes referred to as a borehole.

Brine Pocket - Pressurized brine of unknown origin but of limited extent contained in fractured anhydrite within the Castile Formation located 210 m below the WIPP repository.

Cancer Risk Coefficient - The factor used to convert radiation dose in Sievert (Sv) to Latent Cancer Fatalities. Numerical value taken from the BEIR III (National Research Council, 1980) Report is equal to 0.028 Sv^{-1}.

Carcinogens - A substance that causes or enhances the processes which turn a normal cell into a cancerous cell.

Castile Formation - A formation of evaporite rocks (interbedded halite and anhydrite) of Permian age that stratigraphically underlies the Salado Formation.

Cement/Cementious Material - A dry substance with the capacity to absorb fluid.

CH-TRU Waste - Contact-Handled TRansUranic waste, packaged TRU waste whose external dose rate does not exceed 200 mrem per hour.

Cloudshine - The exposure from cloudshine is the direct external dose from the passing cloud of atmospherically dispersed radioactive material.

Committed Effective Dose Equivalent (CEDE) - The weighted sum of the dose equivalent to organs or other tissues that will be received following an intake of radioactive material for a 50-year period following that intake.

Compaction - Mechanical process by which the pore space in the waste is reduced prior to waste emplacement.

Composite - A single, homogeneous mixture of waste and backfill material which has physical and chemical characteristics resulting from the incorporation of a particular engineered alternative.

Compressibility - The property of a substance capable of being reduced in volume by application of pressure; quantitatively, the reciprocal of the bulk modulus.

Conceptual Model - The set of hypotheses and data that postulate the description and behavior of the disposal system.

Concrete - A mixture of grout and some type of aggregate (such as stone pebbles or salt rock).

Conservative - When used with predictions or estimates, a conservative estimate is one in which the uncertain values are used in a way that maximizes their negative or undesirable impact on the system.

Continuous Air Monitor (CAM) - Instrument that continuously monitors the air for certain present concentrations of toxic substances or radioactivity.

Controlled Area - The controlled area means (1) a surface location, to be identified by passive institutional controls, that encompasses no more than 100 km and extends horizontally no more than 5 km in any direction from the outer boundary of the original location of the radioactive wastes in a disposal system; and (2) the subsurface underlying such a surface location (40 CFR Part 191.12[G]).

Creep - A very slow deformation of solid rock resulting from constant stress applied just below the elastic limit; refers to the geologic phenomenon experienced as salt under high compressive loading begins to deform plastically.

Creep Closure - Closure of underground openings, especially openings in salt, by plastic flow of the surrounding rock under pressure.

Culebra Dolomite Member - The lower of two dolomite units (the other being the Magenta Dolomite Member) within the Rustler Formation that are locally water bearing; the first laterally continuous unit above the repository to display significant permeability (Lappin, et al., 1989).

Curie - The SI unit of activity. One curie (Ci) equals 3.700×10^{10} nuclear disintegrations per second.

Darcy - An English standard unit of permeability, defined by a medium for which a flow of 1 cm^3/s is obtained through a section 1 cm^2 for a fluid viscosity of 1 cP and a pressure gradient of 1 atm/cm. (One Darcy is equal to 9.87×10^{-11} m^2).

Darcy's Law - The law which states that the rate at which a fluid flows through a permeable substance per unit area is equal to the permeability (a property of the substance through which the fluid is flowing) times the pressure drop per unit length of flow, divided by the viscosity of the fluid.

Decay (radioactive) - Process in which a nucleus emits radiation in the form of ionizing and/or particle radiations undergoing spontaneous transformation into one or more different nuclei.

Decontamination - The removal of unwanted material (especially radioactive material) from the surface of, or from within, another material.

Delaware Basin - The part of the geologic Permian Basin in southeastern New Mexico and adjacent parts of Texas where an ancient sea deposited thick layers of evaporites approximately 200 million years ago. It is partially surrounded by the Capitan Reef.

Design Analysis Model - The main program used to analyze the relative effectiveness of various modifications to the WIPP facility and waste forms when compared to the WIPP disposal system reference design and current waste forms.

Deterministic - Pertaining to an exact mathematical relationship between the dependent and independent variables in a system.

Dewey Lake Red Beds - A formation that overlies the Rustler Formation and is composed of reddish brown marine mudstones and siltstones interbedded with finegrained sandstone.

Diffusion - Is the transport process whereby ionic or molecular constituents move under the influence of their kinetic activity in the direction of their concentration gradient, from higher concentrations to lower concentrations.

Diffusion Coefficient - The proportionality constant in Fick's Law of Diffusion defined as the amount of solute material per unit time that diffuses through a unit cross-sectional area under a unit concentration gradient; with fundamental dimensions of area per unit time.

Diffusive - Characterized by the transfer of chemical components from a region of higher to one of lower concentration.

Dispersion Function - Function that models the dispersion of a substance through the environment.

Disposal Phase - The 20 year period by which DOE proposes to permanently emplace TRU wastes in the WIPP.

Dolomite - A sedimentary rock consisting primarily of the mineral dolomite ($CaMg(CO_3)_2$); commonly associated with limestone.

Dose - A general form denoting the quantity of radiation or energy absorbed. For special purposes it must be appropriately qualified. If unqualified, it refers to absorbed dose. (The SI unit of absorbed dose is the gray; the old unit is the rad.)

Drift - A horizontal mine passageway.

E1 - An event or scenario: intrusion of a borehole through a disposal panel into a pressurized brine occurrence in the Castile Formation (Marietta et al., 1989).

E1E2 - The combined scenario involving a borehole intrusion into a disposal panel and into pressurized brine followed by the intrusion of another borehole into the same panel.

E2 - An event or scenario: intrusion of a borehole into a disposal panel (Marietta et al., 1989).

Effectiveness Measure - A parameter used in the analysis of human intrusion events which provides a convenient means of comparing improvements offered by alternative designs over the baseline design. The "Effectiveness Measure" is calculated for the baseline design, as well as for each alternative design and is proportional to the cumulative release of twelve individual isotopes into an overlying water-bearing strata (the Culebra Dolomite) over a 10,000-year period, plus the activity associated with the direct release of contaminated drill cuttings to the surface.

Effective Waste Volume - The volume of the waste/backfill composite minus the volume of the backfill along the sides of the waste stack; parameter used in the Design Analysis Model to calculate radionuclide releases to the surface due to the removal of drill cuttings.

Exposure - A measure of the ionization produced in air by gamma or x-ray radiation. It is the sum of the electrial charges on ions of one sign produced in air when all electrons liberated by photons in a volume element of air are completely stopped in air, divided by the mass of the air in the volume element. The special unit of exposure is the Roentgen.

Fick's Law - The law which states that the rate of diffusion of matter across a plane is proportional to the negative of the rate of change of the concentration of the diffusing substance in the direction perpendicular to the plane; in other words, a species "i" diffuses (moves relative to the mixture in the direction of decreasing mole fraction "i").

Fissile - Describing a nuclide that readily undergoes fission (splitting) by absorption of neutrons within discrete energy bands.

Fugacity - An idealized vapor pressure; equal to the vapor pressure when the vapor behaves as an ideal gas.

40 CFR Part 191 - EPA standard for managing and disposing of spent nuclear fuel, high-level, and transuranic wastes. Subpart A deals with managing and storing of wastes, while Subpart B covers long-term isolation and disposal.

40 CFR Part 268 - EPA regulation governing land disposal restrictions; consists of five subparts as follows: Subpart A - General; Subpart B - Schedule for Land Disposal Prohibition and Establishment of Treatment Standards; Subpart C - Prohibitions on Land Disposal; Subpart D - Treatment Standards; and Subpart E - Prohibitions on Storage (Code of Federal Regulators, p. 748).

Gamma - Penetrating electromagnetic radiation emitted in some nuclear decays.

GBq - GigaBecquerel (10^9 Bq).

Gray - The SI unit of absorbed dose. One gray is produced by the absorption of one Joule of energy in a mass of one kg.

Groundshine - The exposure from groundshine is the direct external dose from radioactive material that has deposited on the ground after being dispersed from an accident site.

Grout - The material which results when a cement is combined and well mixed with a fluid.

Half-life - The average time required for an unstable element or nuclide to lose one-half of its radioactive intensity in the form of alpha, beta, or gamma radiation.

Halite - The mineral rock salt, NaCl.

Hazard Index (HI) - The ratio between the daily intake of a chemical and an acceptable reference level.

Hazardous Waste - Restricted nonradioactive wastes that exceed standards or do not meet other requirements of 40 CFR Part 268 with regard to toxicity or mobility reduction (DOE, 1990d, Vol. 1, p. 1-1).

Headspace - Gas volume in a closed waste drum.

HEPA Filters - High Efficiency Particulate Air Filters.

Hydraulic Conductivity - The rate of aqueous flow, in volume per time, through a cross-section of area under a unit hydraulic gradient at the prevailing temperature.

Hydraulic Diffusivity - The ratio of the hydraulic conductivity to the specific storage with fundamental dimensions of area per unit time.

Immediate Danger to Life and Health (IDHL) - Level or concentration of toxic agent that causes an immediate danger to life and health.

Isotope - A species of atom having the same number of protons but differing in the number of neutrons in its nucleus. In most instances, an element can exist as several isotopes differing in the atomic mass. Isotopes can be either stable isotopes or radioactive isotopes (also called radioisotopes or radionuclides).

Isotropic - Having the same properties in all directions.

Joule - SI unit of energy, equal to the energy expended by a force of 1 Newton over a distance of 1 meter.

kg - Kilogram

km - Kilometer

Lithostatic Pressure - Subsurface pressure caused by the weight of overlying rock or soil (14.8 MPa at the WIPP repository level).

m - Meter

MB 139 - Marker Bed 139: One of 45 siliceous or sulfatic units within the Salado Formation consisting of about 1 m of polyhalitic anhydrite and anhydrite. MB 139 is located within the WIPP horizon.

MBq - MegaBecquerel (10^6 Becquerel).

mJ - Milli-Joule (10^{-3} J). Subunit of energy.

Morbidity - An early morbidity, premature death due to causal agent.

MPa - Megapascal (10^6 Pa)

Newton - SI unit of force: 1 N is the force needed to accelerate a mass of 1 kg by 1 m s^{-2}.

Nuclide - A species of atom characterized by the number of protons (Z), number of neutrons (N), and energy state.

Occupational Risks - Risk of occupational work due to the treatment, transport, handling, or emplacement of Contact-Handled transuranic waste at the WIPP.

Pa - Pascal; basic unit of pressure produced by a force of 1 Newton applied over an area of 1 m^2.

Panel - Within the WIPP, a panel consists of seven underground rooms connected by 33-ft-wide drifts at each end.

Particulates - Fine liquid or solid particles such as dust, smoke, or fumes found in the air or in emissions.

PE-Bq - A radiactive hazard index factor; relates the radiotoxicity, a given activity, of TRU radionuclides to that of Plutonium-239.

Performance Assessment - The process of assessing the compliance of a deep, geologic waste repository with the Containment Requirements of 40 CFR Part 191 Subpart B. Performance assessment is defined by Subpart B as an analysis that (1) identifies the processes and events that might affect the disposal system, (2) examines the effects of these processes and events on the performance of the disposal system, and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant processes and events. These estimates are incorporated into an overall probability distribution of cumulative release to the extent practicable (40 CFR Part 191.12(q)).

Permeability - A measurement of the ability of a rock or soil to transmit fluid under hydraulic gradient dependent upon the interconnectedness of the interstices.

Permian Basin - A region in the south-central United States, where during Permian times (248 to 286 million years ago), basin configuration created many shallow sub-basins which resulted in the position of vast beds of marine evaporites.

Person-sievert - A unit of population dose, equivalent to man-sievert.

Polyhalite - A hard, poorly soluble evaporite mineral: $K_2MgCa_2(SO_4)_4 \cdot 2H_2O$.

Porosity - The porosity of a rock or soil is its property of containing interstices or voids and may be expressed quantitatively as the ratio of the volume of its interstices to its total volume.

Portlandite - Calcium hydroxide, $Ca(OH)_2$; a mineral belonging to the brucite group.

Potentiometric Surface - The surface of the hydraulic potentials of an aquifer. It is usually represented as a contour map in which each contour indicates how high the water would rise in a well tapping that aquifer at any point on that contour.

rad - An old measure of radiation dose absorbed by a tissue or other material. 1 rad corresponds to the absorption of 10 mJ/kg of material.

Radioactive Waste - Solid, liquid, or gaseous material of negligible economic value that contains radionuclides in excess of threshold quantities.

Radioactivity - The property of certain nuclides of spontaneously emitting particles or energy or of undergoing spontaneous fission.

Radiolysis - Chemical decomposition by the action of radiation.

Radionuclide - see Isotope.

Radionuclide Inventory - A list of the types and quantities of radionuclides in a container or source. Amounts are usually expressed in activity units: curies or curies per unit volume.

RADTRAN - Computer code used to calculate radiological risks of transportation (Madsen et al., 1986).

Reference Level - The level at which no observable effects are obtained from a certain chemical exposure.

Rem - An old unit for dose equivalent. It is numerically equal to the absorbed dose in rads multiplied by a quality factor of the radiation type.

RH-TRU Waste - Remote-Handled TRansUranic waste. Packaged TRU waste whose external surface dose rate exceeds 200 mrem per hour, but not greater than 1,000 rem per hour.

Risk - The product of probability and consequence. The radiological risk of a scenario is the population dose equivalent resulting from that scenario multiplied by that scenario's probability of occurence and the risk coefficient such as a cancer risk coefficient.

Risk Assessment - Qualitative or quantitative evaluation of health and environmental risks resulting from exposure to chemical, radioactive, or physical agents.

Room - An excavated underground cavity; within the WIPP, a room has the following dimensions; width = 33 ft; height = 13 ft; and length = 300 ft.

Rustler Formation - A sequence of Upper Permian age clastic and evaporite rocks that contains two dolomite marker beds (the Magenta and the Culebra Dolomite members), and overlies the Salado Formation.

s - Second

Salado Formation - A sequence of Upper Permian age evaporite rocks containing 45 numbered "anhydrite" marker beds (MB 101 through MB 145) interbedded with halites of varying purity and accessory minerals such as clay and polyhalite.

Scenario - A combination of events and processes that represent a possible future condition of the repository; factors examined include geologic and groundwater systems that could contribute to the escape of radionuclides from the repository, and release into the accessible environment.

Sealing - Formation of barriers within man-made penetrations (shafts, boreholes, tunnels, drifts).

Shaft - A manmade hole, either vertical or steeply inclined, that connects the surface with the underground workings of a mine.

Sievert (Sv) - The SI unit of radiation dose equivalent which is the product of the absorbed dose (in Gray), the quality factor of the radiation, and other factors.

Solute - The substance dissolved in a solvent.

Specific Activity - Total activity of a given radionuclide per gram of a compound, element, or radionuclide.

Storativity - The volume of water released by an aquifer per unit surface area per unit decrease in hydrologic head.

TBq - TeraBecquerel (10^{12} Bq).

Threshold Limit Value (TLV) - Basis for Hazard Index. A time-weighted average for an 8-hour period intended to protect workers over a career of exposure.

Threshold Pressure - The capillary pressure corresponding to full saturation under drainage conditions required to overcome capillary forces at the gas/brine interface and create an incipient interconnected gas filled pore network.

Tortuosity - Measurement of actual path of flow through a porous medium.

Transmutation - Any process by which a nuclide is transformed into a different nuclide, or more specifically, when transformed into a different element by a nuclear reaction.

Transuranic Radioactive Waste (TRU Waste) - Waste that, without regard to source or form, is contaminated with more than 100 nCi per gram of waste of alpha-emitting transuranic isotopes with atomic numbers greater than 92 and half-lives greater than 20 yr, except for: (1) HLW; (2) wastes that the DOE has determined, with the concurrence of the EPA Administrator, do not need the degree of isolation required by 40 CFR Part 191; or (3) wastes that the NRC has approved for disposal on a case-by-case basis in accordance with 10 CFR Part 61. Heads of DOE field organizations can determine that other alpha-contaminated wastes, peculiar to a specific site, must be managed as TRU waste.

Treatment Facility - Place(s) at which contact-handled waste is to be treated by different means either before, during, or after transportation.

TRUPACT-II - The DOT Type B package designed to transport Contact-Handled transuranic waste to the WIPP site. It is a cylinder with a flat bottom and a domed top that is transported in the upright position. Each containment vessel is nonvented and capable of withstanding a pressure of 50 psi (345 kPa). Capacity of each TRUPACT-II is fourteen 55-gallon drums (208 L), two standard waste boxes, or one box and seven drums.

Utility Index - The value of the Multi-Attribute Utility Theory function. This function describes the value assigned to a particular combination of attributes.

Viscosity - The resistance that a gaseous or liquid system offers to flow when it is subjected to a shear stress.

Vitrification - Term which implies the melting or fusing of residue into a glass matrix.

Void Volume - The total volume in a matrix not occupied by the matrix material.

Waste Acceptance Criteria (WAC) - The DOE document describing the criteria by which unclassified transuranic waste will be accepted for emplacement at the WIPP and the basis upon which these criteria were established (U.S. Department of Energy, 1989b).

Waste Form - The condition of the waste, its type, and physical form. Provides information on the waste contents, how the waste is processed, and on the chemistry of the constituents (TRUPACT-II Content Codes, p. v.).

Waste Handling Building (WHB) - The area at the WIPP which receives waste and where waste is assayed, if necessary, to prepare for emplacement.