Waste Isolation Pilot Plant

Compliance Certification Application

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Criteria For The Certification And Re-Certification Of The Waste Isolation Pilot Plant's Compliance With The 40 CFR Part 191 Disposal Regulations

Background Information Document For 40 CFR Part 194

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40 CFR Part 194

BACKGROUND INFORMATION DOCUMENT FOR THE CRITERIA FOR THE CERTIFICATION AND RE-CERTIFICATION OF THE WASTE ISOLATION PILOT PLANT'S COMPLIANCE WITH THE 40 CFR PART 191 DISPOSAL REGULATIONS

January 1996

U.S. Environmental Protection Agency
Office of Radiation and Indoor Air
Washington, D.C. 20460

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List of Abbreviations

AEA	Atomic Energy Act
AEC	Atomic Energy Commission
AECB	Atomic Energy Control Board
ALMRS	Automated Land and Minerals Records System
ANDRA	Agence National pour la Gestion des Dechets Radioatifs
ANL-E	Argonne National Laboratory-East
ANL-W	Argonne National Laboratory-West
ANPR	advance notice of proposed rulemaking
AO	Announcement of Opportunity
ASME	American Society of Mechanical Engineers
ASTP	Actinide Source Term Program
BID	Background Information Document
BLM	Bureau of Land Management
BSEP	Brine Sampling and Evaluation Program
CAO	Carlsbad Area Office
CCDF	complementary cumulative distribution functions
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CH-TRU	contact-handled transuranic waste
CRW	Committee on Radioactive Waste Management
CSRS	Cooperative States Research Service
DHHS	Department of Health and Human Services
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DQO	data quality objective
DSIN	Directorate for the Safety of Nuclear Installations
EATF	Engineered Alternatives Task Force
EAMP	Engineered Alternatives Multidisciplinary Panel
EEG	Environmental Evaluation Group
EM	electromagnetic
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
ERDA	Energy Research and Development Administration
ERP	Environmental Restoration Project
ESA	European Space Agency
FACA	Federal Advisory Committee Act
FEIS	Final Environmental Impact Statement
FERC	Federal Energy Resources Council
FFCA	Federal Facility Compliance Act
FLPMA	Federal Land Policy and Management Act
GCDB	geographic coordinate data base
GTP	Generator Treatment Plan

List of Abbreviations (Cont'd)

HANF	Hanford Site
HITF	Human Interference Task Force
HLW	high-level radioactive waste
HSWA	Hazardous and Solid Waste Amendments
ICPMS	inductively coupled plasma / mass spectrometry
ICRP	International Commission on Radiological Protection
INEL	Idaho National Engineering Laboratory
IQR	interquartile range
IRG	Interagency Review Group
IWPF	Idaho Waste Processing Facility
KPLA	Known Potash Leashing Arca
LANL	Los Alamos National Laboratories
LHS	Latin hypercube sampling
LLNL	Lawrence Livermore National Laboratory
LLW	low-level radioactive waste
LMR	Life-of-Mine potash Reserves
LWA	Land Withdrawal Act
MAD	mean absolute deviation
MCL	maximum contaminant level
MOU	Memorandum of Understanding
MOUND	Mound Plant
MRE	measure of relative effectiveness
MWIR	Mixed Waste Inventory Report
NAC	National Advisory Council
NACEPT	National Advisory Council on Environmental Policy
NAGRA	National Cooperative for the Storage of Radioactive Waste
NAS	National Academy of Sciences
NAS-NRC	National Academy of Sciences - National Research Council
NASA	National Aeronautics and Space Administration
NCP	National Contingency Plan
NEA	Nuclear Energy Agency
NICS	Nuclear Safety Research
NIH	National Institutes of Health
NMED	New Mexico Environment Department
NNWSI	Nevada Nuclear Waste Storage Investigations
NPL	National Priorities List
NPRM	notice of proposed rule making
NRA	NASA Research Announcement
NRC	U.S. Nuclear Regulatory Commission
NSF	National Science Foundation
NTPO	National TRU Program Office
NTS	Nevada Test Site

NWPA	Nuclear Waste Policy Act
NWTS	National Waste Terminal
NYDEC	New York Department of Ecology
OCD	Oil Conservation Division
OECD	Organization for Economic Co-operation and Development
OMB	Office of Management and Budget
ONWI	Office of Nuclear Waste Isolation
OPA	Office of Program Analysis
ORNL	Oak Ridge National Laboratory
PA	performance assessment
PAN	passive active neutron
PCB	polychlorinated biphenyl
PDP	performance demonstration program
PHS	Public Health Service
PI	Petroleum Information
PLSS	Public Land Survey System
PNL	Pacific Northwest Laboratory
PRC	peer review committee
QA	quality assurance
QAO	quality assurance objective
QAP	quality assurance program
QAPD	Quality Assurance Program Description
QAPP	Quality Assurance Program Plan
QAPjP	Quality Assurance Project Plan
QARD	Quality Assurance Requirements & Description document
QMT	Qualification Methods Team
RCRA	Resource Conservation and Recovery Act
RF	radio frequency
RFETS	Rocky Flats Environmental Technology Site
RFP	Rocky Flats Plant
RH-TRU	remote-handled transuranic waste
RME	Reasonable Maximum Exposure
RMWTF	Remote Mixed Waste Treatment Facility
RTR	real time radiography
RYW	Rhodes-Yates Waterflood Area
SAB	Science Advisory Board
SAFSTOR	safe storage
SAR	Safety Analysis Report
SDWA	Safe Drinking Water Act
SGS	segmented gamma scan
SKB	Swedish Nuclear Fuel and Waste Management Company
SKI	Swedish Nuclear Power Inspectorate

SNL	Sandia National Laboratories
SNR	signal to noise ratio
SOG	Seismicity Owners Group
SQA	Software Quality Assurance
SRS	Savannah River Site
STP	Source Team Panel
STTP	Source Term Test Program
SWB	Standard Waste Boxes
SWCF	Sandia WIPP Central File
SWDA	Solid Waste Disposal Act
TASC	The Analytical science Corporation
TDS	total dissolved solids
TRU	transuranic
TRU QAPD	Transuanic Waste Characterization Quality Assurance Program Plan
TRUCON	TRUMPACT-II Content Codes
TRUMPAC	TRUMPACT-II Authorized Methods for Payload Control
TSCA	Toxic Substances Control Act
UIC	underground injection control
ULF	ultra low frequency
UMTRCA	Uranium Mill Tailings Radiation Control Act
USDA	U.S. Department of Agriculture
USDW	underground source of drinking water
USGS	U.S. Geological Survey
VLF	very low frequency
VOC	volatile organic compound
WAC	Waste Acceptance Criteria
WACCC	Waste Acceptance Criteria Certification Committee
WHPP	Waste Handling and Packaging Plant
WID	Waste Isolation Division
WIPP	Waste Isolation Pilot Plant
WMC	waste matrix code
WMCG	waste matrix code groups
WTAC	WIPP Technical Support Contractor
WTWBIR	WIPP Transuranic Waste Baseline Inventory Report

1. Introduction

The Environmental Protection Agency's (EPA) regulation, 40 CFR part 194, sets forth criteria for determining if the Waste Isolation Pilot Plant (WIPP) will comply with EPA's environmental radiation protection standards for the disposal of radioactive waste, found at 40 CFR part 191 subparts B and C. If the Administrator of EPA determines that the WIPP will comply with the standards for disposal, then the Administrator will issue to the Secretary of Energy a certification of compliance which will allow the emplacement of transuranic waste in the WIPP to begin, provided that all other statutory requirements have been met. If a certification is issued, EPA will also use 40 CFR part 194 to determine if the WIPP has remained in compliance with EPA's environmental radiation protection standards, once every five years after the initial receipt of waste for disposal at the WIPP. The final preamble and regulation to 40 CFR part 194, as they appear in the Federal Register, take precedence over any descriptions or interpretations of the final rule that appear in this document.

This document provides much of the necessary background information and technical analyses which the Agency used during the development of 40 CFR part 194. The document explicates fourteen issues considered by EPA in establishing the individual criteria contained in 40 CFR part 194.

1.1 EPA'S REGULATORY OVERSIGHT OF THE WIPP

1.1.1 Purpose of 40 CFR Part 194

The criteria for compliance, 40 CFR part 194, implement the Environmental Protection Agency's (EPA) environmental radiation protection standards, 40 CFR part 191, by applying them to the proposed disposal of transuranic radioactive waste in the Waste Isolation Pilot Plant (WIPP). The EPA previously promulgated 40 CFR part 191, "Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes," to provide standards that will apply to all sites (except Yucca Mountain) for the deep geologic disposal of highly radioactive waste. Complete descriptions of 40 CFR part 191 were published in the *Federal Register* in 1985 (50 Fed. Reg. 38066-38089, Sep. 19, 1985) and 1993 (58 Fed. Reg. 66398 - 66416, Dec. 20, 1993). The WIPP is subject to 40 CFR part 191, and is being constructed by the Department of Energy (DOE) near Carlsbad, New Mexico as a potential repository for the safe disposal of transuranic radioactive waste. The EPA is required by the WIPP Land

Withdrawal Act of 1992 (Pub. L. 102-579) to evaluate whether the WIPP will comply with subparts B and C of 40 CFR part 191 -- known as the "disposal regulations" -- and to issue or deny a certification of compliance. The Department of Energy is required to submit an application to EPA that will be the basis of EPA's evaluation of whether a certification of the WIPP's compliance with the disposal regulations should be issued. The Department of Energy may not begin to emplace transuranic waste underground for disposal at the WIPP until such time as a certification of compliance has been issued and all other requirements of section 7(b) of the WIPP Land Withdrawal Act have been satisfied. With 40 CFR part 194, the Agency establishes criteria by which to judge whether the WIPP is in compliance with the "disposal regulations" and sets forth procedural requirements for this determination.

The criteria for compliance, 40 CFR part 194, also apply to the periodic re-certification of the WIPP's compliance with the disposal regulations. The process of periodic re-certification, established by section 8(f) of the WIPP Land Withdrawal Act, calls for EPA to determine whether the WIPP continues to be in compliance with the disposal regulations, assuming that an initial certification of compliance has been issued. The Secretary of Energy must submit to the Administrator of EPA documentation of the WIPP's continued compliance with the disposal regulations, every five years after the initial receipt of transuranic waste for disposal at the WIPP, until the end of the decommissioning phase. The Agency will use the criteria in determining whether or not the WIPP will have continued to be in compliance.

The WIPP was authorized in 1980 under section 213 of the Department of Energy National Security and Military Applications of the Nuclear Energy Authorization Act of 1980 (Pub. L. 96-164, 93 Stat. 1259, 1265), "for the express purpose of providing a research and development facility to demonstrate the safe disposal of radioactive wastes resulting from the defense activities and programs of the United States." The waste proposed for disposal in the WIPP, transuranic radioactive waste (TRU waste), is waste consisting of materials such as rags, equipment, tools, protective gear and sludges which have become contaminated during atomic energy defense activities. The WIPP Land Withdrawal Act defines transuranic waste to be waste containing more than 100 nano-curies per gram of alpha-emitting radio-isotopes, with half-lives greater than twenty years and atomic number greater than 92, per gram of waste. The Act further stipulates that radioactive waste shall not be transuranic waste if such waste also meets the definition of high-level radioactive waste, has been specifically exempted from the disposal regulations with the concurrence of the Administrator, or has been approved for an alternate method of disposal by the Nuclear Regulatory Commission. The radioactive component of transuranic waste consists of man-made elements created during the process of nuclear fission, chiefly isotopes of plutonium.

1.1.2 Overview of 40 CFR part 194

The regulation, 40 CFR part 194, sets forth the criteria against which the WIPP's compliance with the disposal regulations of 40 CFR part 191 will be evaluated and is divided into four subparts, consisting of:

1) Subpart A, which specifies the protocols for submission of certification applications, the terms of any certification, and the process for any subsequent suspension, modification, or revocation of compliance status.

2) Subpart B, which outlines the information to be included with compliance applications to ensure that EPA has adequate information to evaluate the basis for any demonstration of compliance. Subsequent applications for continued compliance must note any changes in such information that have occurred since the previous certification.

3) Subpart C, which implements the specific containment, assurance, individual, and groundwater protection requirements of the disposal regulations at 40 CFR part 191. General requirements, such as those for quality assurance and waste characterization, are included to ensure that compliance applications are based on reliable information; they also allow EPA inspection authority to confirm conditions reported in applications. Assessments of disposal system performance are expressed to show the likelihood of release or exposure occurring. Performance assessments for releases must account for the frequency and consequences of potential human intrusion into the repository over the 10,000-year regulatory time frame, as specified by 40 CFR part 194. Assurance requirements, designed to increase confidence in the performance of the disposal system, include criteria for monitoring of repository performance, and implementation of engineered barriers to protect against releases from the disposal system.

4) Subpart D, which provides opportunities for public participation in the rulemaking processes for initial certification of compliance and for modification or revocation of any certification. It also provides for public input at critical junctures in the re-certification process. The subpart specifies criteria for notification of the public at each stage of rulemakings, holding of public hearings, opportunity for public comment, and creation and maintenance of public dockets in Washington, DC, and New Mexico.

1.1.3 Statutory and Regulatory Basis

40 CFR part 194 was mandated by Congress in section 8(c) of the WIPP Land Withdrawal Act. The criteria promulgated in 40 CFR part 194 implement only those subparts of 40 CFR part 191 that apply to the disposal of transuranic radioactive waste. 40 CFR part 194 does not amend 40 CFR part 191. Subpart A of 40 CFR part 191 applies to the management of spent nuclear fuel, high-level and transuranic radioactive wastes at sites designated for the disposal of these wastes and is not the subject of 40 CFR part 194. However, section 9(a) of the WIPP Land Withdrawal Act stipulates that the Secretary of Energy shall comply with respect to the WIPP with Subpart A of 40 CFR part 191. With the Energy Policy Act of 1992, Congress mandated the development of regulations to replace 40 CFR part 191 for the Yucca Mountain site only, but the entire standard, 40 CFR part 191, remains applicable to the WIPP. See 106 Stat. 2921, section 801(a)(1). The entire 40 CFR part 191 standard was developed to establish generally applicable standards for the protection of the general environment from radioactive materials, specifically those disposed of in mined geologic repositories. The standard was developed pursuant to the Agency's authorities under the Atomic Energy Act (AEA) of 1954, as amended, and Reorganization Plan No. 3 of 1970 (NIX70). A more complete description of the development of 40 CFR part 191 may be found later in this chapter.

1.1.4 Compliance with Other Environmental Laws and Regulations

The WIPP is regulated under the Resource Conservation and Recovery Act (RCRA) and is subject to both the Part B licensing requirements and the land disposal restrictions of that statute. The WIPP must comply with other environmental laws, including, among other statutes, the Clean Air Act (40 U.S.C. 7401 et seq), the Toxic Substances Control Act (15 U.S.C. 2601 et seq) and the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (42 U.S.C. 9601 et seq). The promulgation of 40 CFR part 194 does not affect the need for DOE to comply with these and all other applicable environmental laws with respect to the WIPP.

Much of the waste proposed for disposal in the WIPP is mixed waste, i.e., waste composed of both radioactive and hazardous constituents, the latter's disposal being controlled by the regulations set forth under RCRA. As mandated by section 7(a) of the WIPP Land Withdrawal Act, the Secretary of Energy must obtain from the Administrator a determination of no-migration under the land disposal restrictions of RCRA, prior to commencing the emplacement of waste in the WIPP. A conditional no-migration determination for the now withdrawn test phase was granted by EPA on November 14, 1990. This conditional determination must be amended and formal approval granted before disposal of radioactive waste can begin.

1.2 HISTORY OF U.S. POLICY ON GEOLOGIC DISPOSAL

Since the 1940s, the Federal Government has assumed ultimate responsibility for the care and disposal of high-level radioactive wastes, regardless of whether they are produced by commercial or national defense activities. To respond to this need, in 1949 the Atomic Energy Commission (AEC) initiated research and development work on the conversion of high-level radioactive liquid wastes into a stable, solid form. Then, in 1955, at the request of the AEC, a National Academy of Sciences - National Research Council (NAS-NRC) Advisory Committee was established to consider the disposal of high-level radioactive wastes within the United States. Its report (NAS57), issued in 1957, recommended the following:

1. The AEC continue to develop processes for the solidification of high-level radioactive liquid wastes, and

2. Naturally occurring salt formations are the most promising medium for the long-term isolation of these solidified wastes.

Project Salt Vault, conducted from 1965 to 1967 by the AEC in an abandoned salt mine near Lyons, Kansas, was initiated to demonstrate the safety and feasibility of handling and storing solid wastes in salt formations (MCC70).

In 1968, the AEC again asked the NAS-NRC to establish a Committee on Radioactive Waste Management (CRWM) to advise the AEC concerning its long-range radioactive waste management plans and to evaluate the feasibility of disposing of solidified radioactive wastes in bedded salt. The CRWM convened a panel to discuss the disposal of radioactive wastes in salt mines. Based on the recommendations of the panel, the CRWM concluded that bedded salt is satisfactory for the disposal of radioactive wastes (NAS70).

In 1970, the AEC announced the tentative selection of a site at Lyons, Kansas, for the establishment of a national radioactive waste repository (AEC70). During the next two years, however, in-depth site studies raised several questions concerning the safe plugging of old exploratory wells and on proposals for expanded salt mining activities. These questions and growing public opposition to the Lyons site prompted the AEC in late 1971 to pursue alternatives (DOU72).

The Federal Government intensified its program to develop and demonstrate a permanent disposal method for high-level radioactive wastes and the Office of Management and Budget (OMB) established an interagency task force on commercial wastes in March, 1976. The OMB interagency task force defined the responsibility of each Federal agency involved in high-level waste management, including the preparation of environmental standards for high-level wastes by EPA (LYN76, ENG77a, ENG77b).

A status report on the management of commercial radioactive nuclear wastes, published in May 1976 by the President's Federal Energy Resources Council (FERC), emphasized the need for coordination of administration policies and programs relating to energy. The FERC established a nuclear subcommittee to coordinate Federal nuclear policy and programs to assure an integrated government effort. This report called for an accelerated, comprehensive government radioactive waste program plan and recommended the formation of an interagency task force to coordinate activities among the responsible Federal agencies. EPA was given the responsibility for establishing general environmental standards governing waste disposal activities (FER76).

In 1976, President Ford issued a major policy statement on nuclear waste. As part of his comprehensive statement, he announced new steps to assure that the United States would have facilities for the long-term management of nuclear waste from commercial power plants. The President's actions were based on the findings of the OMB interagency task force formed in March 1976. He announced that the experts had concluded that the most practical method for disposing of high-level radioactive wastes is in geologic repositories located in stable formations deep underground. EPA's responsibilities were better defined to include issuing general environmental standards governing nuclear waste facility releases to the biosphere above natural background radiation levels (FOR76). These standards were to place a numerical limit on long-term radiation releases outside the boundary of the repository.

In December 1976, EPA announced its intent to develop environmental radiation protection criteria for radioactive wastes to assure the protection of public health and the general environment (EPA76). These efforts resulted in a series of radioactive waste disposal workshops, held in 1977 and 1978 (EPA77a, EPA77b, EPA78a, EPA78b).

In 1978, President Carter established the Interagency Review Group (IRG) to recommend an administrative policy for addressing the long-term management of nuclear waste. The IRG was to recommend programs that would support the policy when adopted. The IRG report re-emphasized EPA's role in developing generally applicable standards for the disposal of high-level wastes, spent nuclear fuel, and transuranic wastes (DOE79). In a message to Congress on February 12, 1980, the President outlined the content of a comprehensive national radioactive waste management program based on the IRG recommendations. The message called for an interim strategy for disposal of high-level and transuranic wastes that would rely on mined geologic repositories. The message repeated that EPA was responsible for creating general criteria and numerical standards for nuclear waste management activities (CAR80).

1.2.1 EPA's Development of the Generally Applicable 40 CFR part 191

In November 1978, EPA published proposed "Criteria for Radioactive Wastes," which were intended as Federal Guidance for storage and disposal of all forms of radioactive wastes (EPA78c). In March 1981, however, EPA withdrew the proposed criteria because the many different types of radioactive wastes made the issuance of generic disposal guidance too problematic (EPA81).

In 1982, under the authority of the Atomic Energy Act of 1954, EPA proposed a set of standards under 40 CFR part 191, "Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes" (EPA82). Shortly after the publication of EPA's proposed rule, Congress passed the Nuclear Waste Policy Act of 1982, wherein EPA was to "...promulgate generally applicable standards for the protection of the general environment from off-site releases from radioactive material in repositories..." not later than January 1984 (NWP83).

After the first comment period on the proposed rule ended on May 2, 1983, EPA held two public hearings on the proposed standards--one in Washington, D.C., on May 12-14, 1983, and one in Denver, CO, on May 19-21, 1983--and during a second public comment period requested post-hearing comments (EPA83a, EPA83b). More than 200 comment letters were received during these two comment periods, and 13 oral statements were made at the public hearings. Responses to comments received from the public were subsequently published and released in August 1985 (EPA85a).

In parallel with its public review and comment effort, the Agency conducted an independent scientific review of the technical basis for the proposed 40 CFR part 191 standards through a special Subcommittee of the Agency's Science Advisory Board (SAB). The Subcommittee held nine public meetings from January 18, 1983, through September 21, 1983, and later prepared and released a final report on February 17, 1984 (EPA83c, SAB84). The SAB review found that the Agency's analyses in support of the proposed standards were comprehensive and scientifically competent, but contained several recommendations for improvement. The report was publicly released on May 8, 1984, and the public was requested to comment on the findings and recommendations (EPA84). Public responses to the SAB report were subsequently presented and released in August 1985 (EPA85b).

On February 8, 1985, the Natural Resources Defense Council, the Environmental Defense Fund, the Environmental Policy Institute, the Sierra Club, and the Snake River Alliance brought suit against the Agency and the Administrator because they had failed to comply with the January 7, 1984, deadline mandated by the NWPA for promulgation of the standards. A consent order was negotiated with the plaintiffs that required the standards to be promulgated on or before August 15, 1985. EPA issued the final rule under 40 CFR part 191 on that date (EPA85c, EPA85d, EPA85e).

EPA standards were divided into two main sections, Subparts A and B. Subpart A addressed the management and storage of waste. For any disposal facility operated by DOE and not regulated by the Nuclear Regulatory Commission (NRC) or by Agreement States, under Subpart A of the standard, the exposure limits to any member of the general public were 25 millirem (mrem) to the whole body and 75 mrem to any critical organ. For facilities regulated by the Nuclear Regulatory Commission or Agreement States, the standards adopt the annual dose limits given in 40 CFR part 190, the environmental standards for the uranium fuel cycle: 25 mrem to the whole body, 75 mrem to the thyroid, and 25 mrem to the critical organ.

Subpart B imposed limits on the release of radioactive materials into the environment following closure of the repository. The key provisions of Subpart B were:

- Limits on cumulative releases of radioactive materials into the environment over 10,000 years;
- Assurance requirements to compensate for uncertainties in achieving the desired level of protection;
- Individual exposure limits based on the consumption of groundwater and any other potential exposure pathways for 1,000 years after disposal; and
- Groundwater protection requirements in terms of allowable radionuclide concentrations and associated doses for 1,000 years after disposal.

§191.15 and §191.16 of Subpart B limited the annual dose to any member of the general public to 25 mrem to the whole body and 75 mrem to any critical organ. The groundwater concentration for beta or gamma emitters was limited to the equivalent yearly whole body or organ dose of 4 mrem. The allowable water concentration for alpha emitters (including radium-226 and radium-228, but excluding radon) was 15 picocuries/liter. For radium-226 and radium-228 alone, the concentration limit was 5 picocuries/liter. Appendix A of the standards provided cumulative release limits for other radionuclides.

In March 1986, five environmental groups, led by the Natural Resources Defense Council, and four States filed petitions for a review of 40 CFR part 191 (USC87). These suits were consolidated and argued in the U.S. Court of Appeals for the First Circuit in Boston. The main challenges concerned:

1. Violation of the Safe Drinking Water Act (SDWA) underground injection requirements;
2. Inadequate notice and comment opportunity on the groundwater protection requirements; and
3. Arbitrary standards, not supported in the record or not adequately explained.

In July 1987, the Court rendered its opinion and noted three findings against the Agency and two favorable judgments. The Court's action resulted in the remand of the standards. The Court began by looking at the definition of "underground injection," which is the "subsurface emplacement of fluids by well injection." A "well" is defined by the SDWA and EPA as a shaft "bored, drilled, or driven where the depth is greater than the largest surface dimension." A "fluid" is a material or substance that flows or moves whether in a semi-solid, sludge, gas, or any other form or state." In the view of the Court, the method envisioned by DOE for disposal of radioactive wastes in underground repositories might fit both of the latter definitions and would "likely constitute an underground injection under the SDWA."

Under the SDWA, the Agency is required to assure that underground sources of drinking water will not be endangered by any underground injection. With regard to such potential endangerment, the Court supported part, but not all, of the Agency's approach. A dichotomy appeared when endangerment was considered inside the "controlled area" versus beyond the controlled area (i.e., in the accessible environment). Inside the controlled area, the Court ruled that endangerment of groundwater was permitted. Therefore, EPA's approach of using the geological formation as part of the containment was valid. However, outside the controlled area where endangerment would not be permitted, the Court found that §191.15 as promulgated would endanger drinking water supplies. In the context of the SDWA, "endangerment" occurs when doses are higher than that allowed by the Primary Drinking Water Regulations. §191.15 permits an annual dose of 25 mrem to the whole body and 75 mrem to any critical organ from all pathways. On the other hand, the regulations under the SDWA allow only 4 mrem doses from drinking water. The Court recognized that less than 4 mrem may result from the groundwater pathway; however, it rejected this possibility because the Agency stated that radioactivity may eventually be released into the groundwater system near the repository which could result in substantially higher doses. Therefore, the Court decided that a large fraction of the 25 mrem could be received through the groundwater exposure pathway. Accordingly, the Court found that the high-level waste standards should have been consistent with the SDWA, or the Agency should have explained that a different standard was adopted and justified its position.

The Court also noted that the Agency was not incorrect in promulgating the proposed standards, but that the Agency neither acknowledged the interrelationship of the SDWA and HLW rules, nor did it adequately explain the divergence between them. The Court also supported the petitioner's argument that the Agency arbitrarily selected the 1,000-year limit for individual protection requirements (§191.15) under undisturbed performance. The Court indicated that the 1,000-year criterion is not inherently flawed, but the administrative record and the Agency's explanations did not adequately support this choice. The criterion was remanded for reconsideration and a more thorough explanation for its basis. Finally, the Court found that the Agency did not provide adequate opportunity for notice and comments on §191.16 (Groundwater Protection Requirements), which was added to Subpart B after the standards were proposed. This section was remanded for a second notice and comment opportunity.

In August 1987, the Justice Department petitioned the First Circuit Court to reinstate all of 40 CFR part 191 except for §191.15 and §191.16, which were originally found defective. The Natural Resources Defense Council filed an opposing opinion. In response, the Court issued an Amended Decree that reinstated Subpart A, but continued the remand of Subpart B.

On October 30, 1992, the President signed the WIPP LWA. This Act reinstated Subpart B of 40 CFR part 191, except §191.15 and §191.16, and required the Administrator to issue final disposal standards. The reinstatement of these regulations does not apply to the characterization, licensing, construction, operation, or closure of any site required to be characterized under the NWPA Section 113(a) of Public Law 97-425. On December 20, 1993, EPA issued amendments to 40 CFR part 191 which: eliminated §191.16 of the original rule; altered the individual protection requirements; and added Subpart C on groundwater protection. The amended standards represent the Agency's response to the above legislation and to the issues raised by the court pertaining to individual and groundwater requirements. EPA did not revisit any of the regulations reinstated by the WIPP LWA.

1.3 PURPOSE AND SCOPE OF THE BACKGROUND INFORMATION DOCUMENT

This Background Information Document (BID) provides much of the necessary background information and technical analyses which support the Agency's development of 40 CFR part 194. The BID explicates fourteen issues considered by EPA in establishing the individual criteria contained in 40 CFR part 194. For clarity of presentation, the issues generally have been arranged to correspond to their relative placement in 40 CFR part 194. Following are brief descriptions of the remaining chapters:

GENERAL REQUIREMENTS

- Chapter 2 - An assessment of the DOE Quality Assurance (QA) program as it relates to site characterization, data gathering, data analysis, and data modeling at the WIPP. DOE, EPA, NRC, and other QA guidance are examined.

- Chapter 3 - A discussion of the use of appropriate models in the WIPP performance assessment.

- Chapter 4 - A review of the DOE TRU waste characterization program.

- Chapter 5 - A review of background information and technical analyses relevant to future state assumptions.

- Chapter 6 - A discussion of the formal use of expert judgment in scientific investigation and how the technique has been applied at the WIPP.

- Chapter 7 - A review of peer review procedures and a discussion of their application in the WIPP assessments.

CONTAINMENT REQUIREMENTS

- Chapter 8 - A discussion of background information on evaluation of uncertainty, and a summary of regulatory approaches for dealing with uncertainty, including "reasonable expectation."

- Chapter 9 - A discussion of resource drilling and mining.

ASSURANCE REQUIREMENTS

- Chapter 10 - A discussion of regulatory requirements relevant to active institutional controls at the WIPP and DOE proposed action.

- Chapter 11 - A review of issues relevant to monitoring, including the necessity for monitoring and potential techniques for pre- and post-disposal monitoring.

- Chapter 12 - A discussion on the use of passive institutional controls, including permanent markers, public records and archives, and government ownership and regulations.

- Chapter 13 - A review of the regulations concerning engineered barriers and consideration of engineered barriers at the WIPP.

- Chapter 14 - A discussion on the development of compliance criteria for individual and groundwater protection requirements.

1.4 REFERENCES

AEC70 Atomic Energy Commission Press Release No. N-102, dated June 17, 1970.

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2. Quality Assurance Program

2.1 INTRODUCTION

Quality assurance is the set of planned and systematic actions necessary to provide adequate confidence that a structure, system, or component will perform satisfactorily in service (ASM89a). Standard "good practice" may lead to a quality outcome and it is possible that quality outcomes will result without the imposition of a formal program. However, formalizing this process helps to assure a quality outcome and the lack of formality can impede the demonstration of the outcome's inherent quality. Because of the need to provide confidence that the WIPP will comply with federal and state disposal standards, a carefully structured quality assurance (QA) program is essential.

DOE's ability to demonstrate compliance with the regulatory requirements of 40 CFR part 191 Subpart B, Environmental Standards for Disposal, and Subpart C, Environmental Standards for Ground Water Protection, depends in large part on the adequacy of its quality assurance (QA) program. Demonstration of an appropriately implemented QA program can provide confidence in the soundness of information and scientific data, thus enabling greater defensibility for the technical basis of those measures intended to ensure waste isolation. This is especially true in relation to establishing and maintaining the integrity of data and models which form the technical basis of the WIPP's performance assessment (PA) process. In §194.22, EPA has specified criteria aimed at ensuring the soundness of DOE's QA program for modeling and data collection and analysis. Specific items which the QA program must address include:

- waste characterization activities and assumptions;
- environmental monitoring, monitoring of the performance of the disposal system, and sampling and analysis activities;
- field measurements of geologic factors, groundwater, meteorologic, and topographic characteristics;
- computations, computer codes, models, and methods used to demonstrate compliance with the disposal regulations;
- procedures for implementation of expert judgment elicitations used to support applications for certification or re-certification of compliance;

- design of the disposal system and actions taken to ensure compliance with design specifications;

- collection of data and information used to support compliance applications; and

- other systems, structures, components, and activities important to the containment of waste in the disposal system.

40 CFR part 191 establishes the disposal system's performance requirements by specifying criteria for containment, assurance of performance, individual protection, and groundwater protection, but does not specify requirements for "Quality Assurance." However, §191.13(b) requires a "reasonable expectation" that compliance with the requirements will be achieved based upon the total record before the implementing agency. This statement implicitly requires a mechanism to (1) produce such a record, and (2) to provide a basis for that record to support the concept of "reasonable expectation." Quality assurance is an integral element in the formalization of this mechanism. A fully implemented quality assurance program that is in compliance with the appropriate requirements justifies a high level of confidence in the scientific protocols and data which form the basis for waste isolation estimates.

To ensure that calculations of compliance with 40 CFR part 191 are based on sound data and information, EPA requires in 40 CFR part 194 that DOE implement a QA program that meets the requirements of the following documents:

- American Society of Mechanical Engineers' (ASME) "Quality Assurance Program Requirements for Nuclear Facilities" (NQA-1-1989 edition) (ASM89a);

- ASME's "Quality Assurance Requirements of Computer Software for Nuclear Facility Applications" (NQA-2a-1990 addenda (part 2.7) to ASME NQA-2-1989 edition) (ASM89b); and

- ASME's "Quality Assurance Program Requirements for the Collection of Scientific and Technical Information for Site Characterization of High-Level Nuclear Waste Repositories" (NQA-3-1989 edition excluding Section 2.1(b) and (c)) (ASM89c).

The ASME national consensus standards are well established within the U.S. nuclear industry. They have a long history of use and provide extensive supplemental guidance. EPA believes the use of these standards offers the most comprehensive/credible and specific set of QA requirements for all compliance-related elements of the disposal system. For example:

- NQA-1 sets forth requirements for the "establishment and execution of quality assurance programs for the siting, design, construction, operation, and decommissioning of nuclear facilities."

- NQA-2 (part 2.7) establishes requirements for "the development, procurement, maintenance, and use of computer software, as applied to the design, construction, operation, modification, repair, and maintenance of nuclear facilities;" and applies to computer software "used to produce or manipulate data which is used directly in the design, analysis, and operation of structures, systems, and components."

- NQA-3 sets forth quality assurance requirements for "the collection of scientific and technical information for site characterization of high-level nuclear waste repositories;" and applies to "activities which could affect the quality of scientific and technical information collected as part of the site characterization phase of high-level nuclear waste repositories...[which include] as a minimum: (a) readiness reviews; (b) peer reviews; (c) data and sample management; (d) data collection and analysis; (e) coring; (f) sampling; (g) in situ testing; and (h) scientific investigations."

This chapter describes the current DOE quality assurance program for the WIPP, describes how NRC addresses similar regulatory requirements, and provides additional background on the basis for selecting the ASME NQA requirements for 40 CFR part 194.

2.2 DOE QUALITY ASSURANCE PROGRAM

2.2.1 Management and Oversight

DOE Office of Environmental Management

Within the DOE headquarters organization, the Office of Environmental Management (EM-1) is responsible for the overall management of DOE waste management programs. Under EM-1, responsibilities of the Office of Waste Management (EM-30) include programmatic management of site operations for storage, treatment, or disposal of radioactive, hazardous and mixed waste materials including defense-generated TRU waste. Additionally, EM-30 is responsible for assuring that waste is properly characterized, packaged, labeled, and transported to the WIPP in accordance with DOE priorities and objectives; and providing management direction to the waste generators.

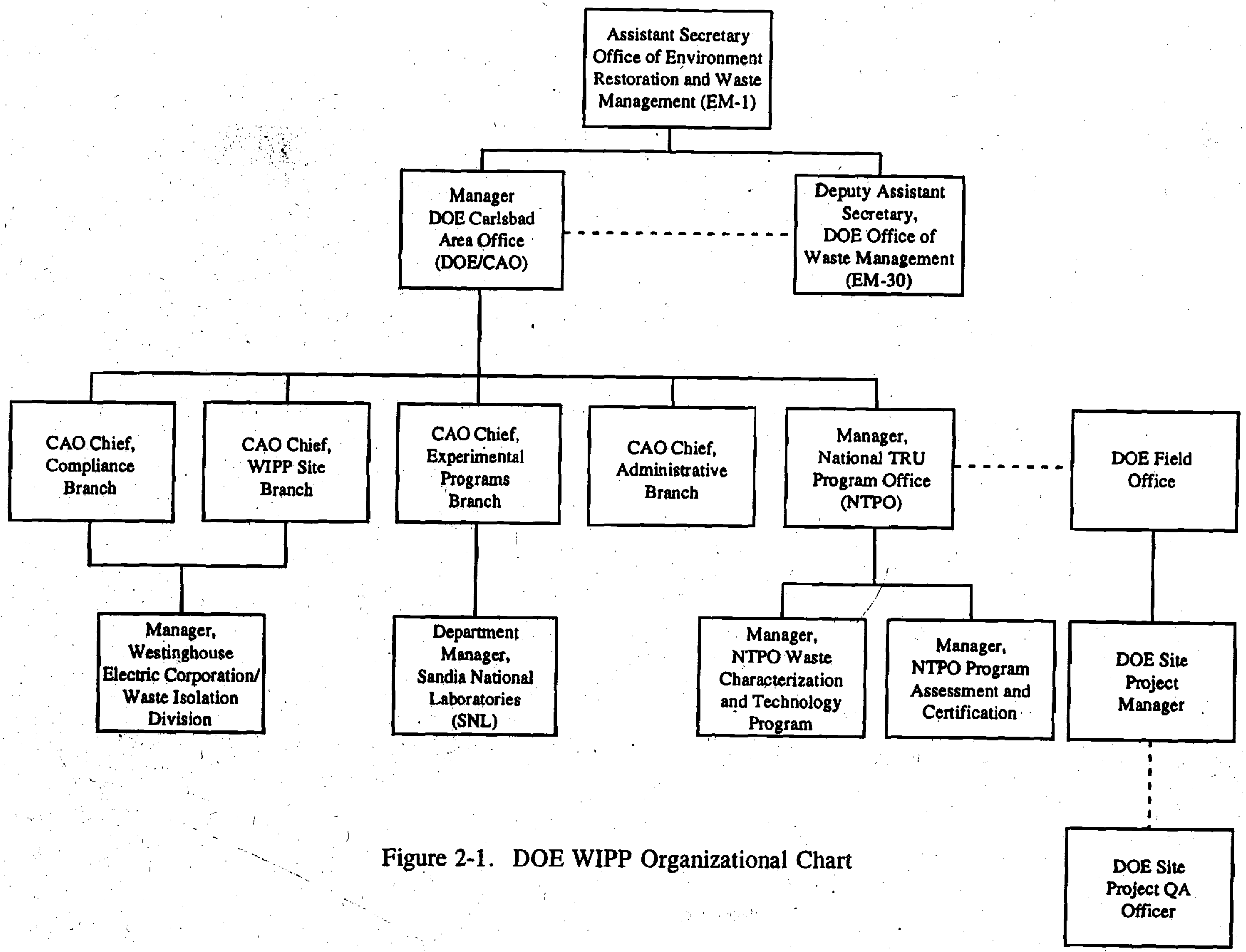

Figure 2-1. DOE WIPP Organizational Chart

Carlsbad Area Office

The WIPP management structure contained many organizational levels among DOE headquarters and field activities until early 1994 when DOE streamlined the organizational structure. This streamlining resulted in the vesting of major responsibilities for WIPP in the Carlsbad Area Office (CAO)[1] (DOE93a, DOE93b). The current WIPP organization is illustrated in Figure 2-1 (DOE94).

The mission of the CAO is to integrate the national transuranic (TRU) waste generator activities and carry out the actions necessary to facilitate DOE's decision to operate the WIPP as a disposal facility (REF). Overall responsibility for the development and implementation of the CAO quality assurance program for all WIPP related activities resides with the CAO Manager who reports directly to EM-1 as shown in Figure 2-1. The activities under CAO can be assigned to three main areas, as listed below:

- WIPP site activities are performed by the WIPP Site Management and Operating Contractor, Westinghouse Waste Isolation Division (WID) located at the WIPP Site outside of Carlsbad, NM. WID fulfills the requirements of a contract managed by CAO under the direction of the CAO Manager and is responsible for WIPP site operation (including support of experiments) and maintenance and for monitoring the site environment.

- WIPP experimental programs are conducted under the direction of the WIPP Scientific Advisor, Sandia National Laboratories (SNL) located in Albuquerque, NM. SNL fulfills the requirements of a contract managed by DOE Albuquerque Operations and overseen by the CAO Manager. In this capacity, SNL is responsible for developing, confirming, and validating models used to simulate long-term disposal system performance (i.e., performance assessment); and conducting research, experiments, and tests to collect the data needed for input to the models (DOE92). SNL sets forth its QA requirements through its Sandia National Laboratories Waste Isolation Pilot Plant Quality Assurance Program Description and implementing procedures (SNL95).

- TRU Waste Generator Site activities at the TRU waste generator sites are managed by DOE Field and Site Offices, as discussed below. A detailed description of site

[1] For example, in 1991, DOE EM-1 provided policy guidance and centralized management through EM-30 to DOE Albuquerque Operations, which reported to the WIPP Project Integration Office. Policy guidance and management now flow directly from DOE EM-1 to the Manager of the DOE Carlsbad Area Office. DOE EM-30 still ensures that program plans and operations are coordinated, integrated, and consistent with DOE Headquarters.

activities is beyond the scope of this report. The TRU waste generator sites are responsible for TRU and mixed TRU waste characterization and for the waste certification programs. The National TRU Program Office (NTPO) Team Leader is responsible for the day-to-day implementation of DOE Headquarters policy and technical direction. The NTPO Team Leader is also responsible for overseeing waste characterization activities and for providing an interface between DOE field offices and CAO. NTPO is divided into two functional areas, described below:

- Waste Characterization and Technology is responsible for the development, issuance and distribution of technical documents that control the TRU Waste Characterization Program.

- Assessment and Certification is responsible for the verification of compliance with the TRU Waste Characterization Program requirements at participating TRU waste generator sites through audits (DOE94).

The CAO QA Manager has the overall responsibility to independently assess the effective implementation of the QA program. Other responsibilities of the QA Manager include:

- Interfacing with CAO technical staff on quality related matters;

- Maintaining a liaison with the QA organizations of WIPP participants and other affected organizations; and

- Review and approval of CAO procedures and contractor quality assurance program descriptions.

TRU Waste Generator Sites

Each of the DOE sites that currently generate, process or store TRU wastes intended for disposal at WIPP must comply with applicable federal and state regulations regarding waste characterization, storage, transportation, etc. While these sites vary considerably in size, complexity and function, each site prepares a site specific Quality Assurance Project Plan (QAPjP). The QAPjP translates the applicable CAO and other federal and state regulations into procedures for that site. As stated previously, the daily operations at TRU generator sites are managed by DOE field and site offices with guidance provided by NTPO. CAO assesses generator site activities through Quality Assurance audits and surveillances, focusing primarily on waste characterization activities.

2.2.2 Key Regulatory Issue

The Quality Assurance documents described in this section provide requirements for activities associated with the generation, storage, transport and characterization of TRU waste intended for disposal at WIPP. However, the ultimate compliance criterion is the determination that once the appropriate Quality Assurance practices and criteria have been identified that they are *adequately implemented*. This must be determined empirically by conducting compliance audits and surveillances at all levels of operation. DOE is currently in the process of evaluating the implementation of its QA program, identifying problem areas and preparing a documentation record of these activities. EPA must evaluate DOE's program by a thorough evaluation of records in conjunction with selected independent verification.

2.2.3 Key DOE Quality Assurance Documents

DOE has established a hierarchy of quality assurance documents consistent with the organizational framework (See Figure 2-2). Some of the major documents are described in this section.

2.2.3.1 DOE Order 5700.6C - Quality Assurance

This document establishes the basic quality assurance framework for the Department (DOE91) and includes the following:

- Placing responsibility for mission accomplishment and Quality Assurance Program (QAP) implementation with senior management;
- Training and qualification of all personnel performing assigned work; all important work will be described in documents and records will be kept;
- Performance of all work to established standards using approved instructions; all equipment used for data collection shall be calibrated and maintained;
- Verification and validation of the adequacy of all designed products by independent personnel; and
- Periodic management assessment of the QAP to assure results, and independent assessments to assess quality; all assessments conducted by personnel technically qualified and knowledgeable in the areas under assessment.

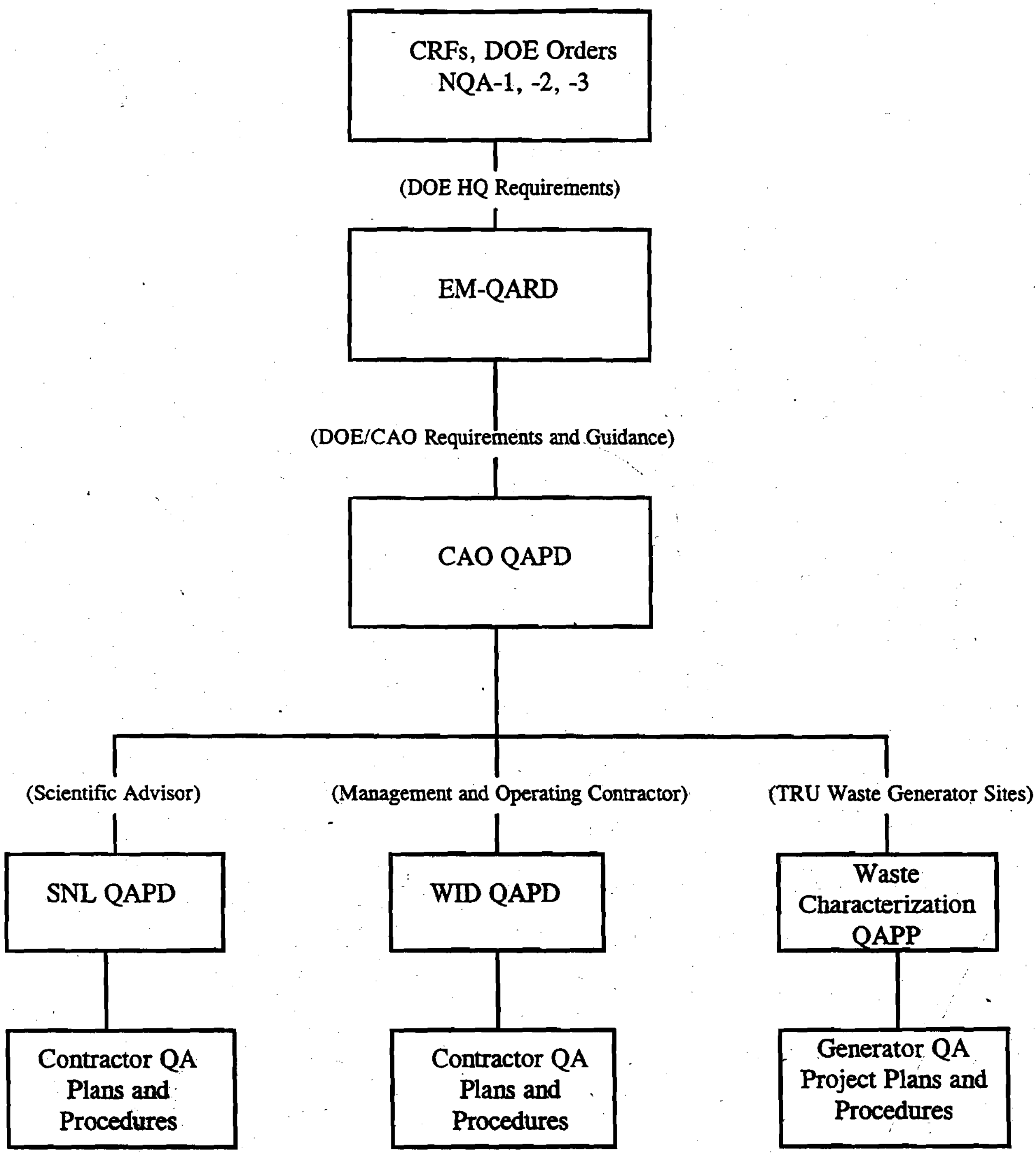

Figure 2-2. Hierarchy of DOE WIPP QA Program Documents

2.2.3.2 Quality Assurance Requirements and Description Document

Based on requirements in Order 5700.6C, DOE EM developed the Quality Assurance Requirements and Description document (QARD) (DOE91a). The QARD is intended to state DOE/EM's commitment to specific requirements and to integrate their requirements, for example, ASME NQA-1, NQA-2 (part 2.7) and NQA-3; and EPA QAMS-005/80. QARD requirements include the following:

- Organizations shall develop, implement, and maintain a written Quality Assurance Program (QAP) as identified in DOE Order 5700.6C. Appropriate standards, such as ASME NQA-1 shall be used, wherever applicable, to develop and implement QAPs. The QAP Description shall delineate the organizational structure, functional responsibilities, levels of authority, and interfaces for those managing, performing, and assessing adequacy of work.

- Personnel shall be trained and qualified to ensure they are capable of performing their assigned work. Personnel shall be provided continuing training to ensure that job proficiency is maintained.

- Organizations shall establish and implement processes to detect and prevent quality problems and to ensure quality improvement. Items and processes that do not meet established requirements shall be identified, controlled, and corrected. Correction shall include identifying the causes of problems and preventing recurrence.

- Organizations shall ensure that procured items and services meet established requirements and perform as specified. Prospective suppliers shall be evaluated and selected on the basis of specified criteria.

- Inspection and acceptance testing of specified items and processes shall be conducted using established acceptance and performance criteria. Equipment used for inspections and tests shall be calibrated and maintained.

- Senior management shall periodically assess the integrated quality assurance program and its performance. Problems that hinder organizations from achieving their objectives shall be identified and corrected.

- Planned and periodic independent assessments shall be conducted to measure item quality and process effectiveness, and to promote improvement.

2.2.3.3 Carlsbad Area Office Quality Assurance Program Description

The Carlsbad Area Office Quality Assurance Program Description (CAO QAPD) is the quality management document that identifies the federal and industry quality requirements applicable to the CAO quality assurance program (DOE 94). The CAO QAPD Revision 1.0 states that compliance to its requirements, responsibilities, and authorities "is mandatory for CAO personnel" while organizations supporting CAO are expected to use the CAO QAPD for "guidance." The federal and industry quality program requirement source documents it identifies are divided into three categories:

- Regulatory documents - these define the requirements necessary for WIPP to receive a certificate of compliance and operational permits by the federal and state governments, respectively;
- Commitment documents - these have been imposed on WIPP operations by DOE management; and
- Guidance documents - these provide additional information that may be useful in developing quality assurance programs for WIPP activities.

A listing of QAPD source documents by category is provided in Figure 2-3. The CAO QAPD provides a description of general, management, performance, and assessment requirements, as well as supplementary quality assurance requirements for specific application areas, such as Scientific Investigation Quality Assurance and Software Quality Assurance, incorporating the applicable portions of ASME NQA-3 and NQA-2, part 2.7, respectively. CAO QAPD requirements include the following:

- Identifying the responsibilities and authorities of those organizational line management positions responsible for achieving and verifying quality.
- Allowing the CAO QA Manager direct access to responsible management at a level where appropriate action can be effected.
- Performing and documenting planning to ensure work is accomplished under suitably controlled conditions.
- Establishing and implementing processes to detect and prevent adverse quality conditions and to ensure quality improvement.

REGULATORY REQUIREMENTS DOCUMENTS	TITLE
10 CFR part 830	Nuclear Safety Management
40 CFR part 261	Identification and Listing of Hazardous Waste
40 CFR part 268.6	Land Disposal Restrictions
10 CFR part 71	Subpart H, Quality Assurance, Packaging and Transportation of Radioactive Material
40 CFR part 284	Standards for Owners and Operators of Hazardous Waste Treatment Storage and Disposal Facilities
COMMITMENT DOCUMENTS	**TITLE**
DOE Order 5700.6C	Quality Assurance
EM-1 QARD	Quality Assurance Requirements and Description
ASME NQA-1 (1989), with all supplements	Quality Assurance Program Requirements for Nuclear Facilities
ASME NQA-2 (1990) Part 2.7	Quality Assurance Requirements of Computer Software for Nuclear Facility Applications
ASME NQA-3 (1989) (with exceptions)	Quality Assurance Program Requirements for the Collection of Scientific and Technical Information for Site Characterization of High-Level Waste Repositories
NUREG-1298 (1988)	Staff Position - Qualification of Existing Data for High-Level Nuclear Waste Repositories
GUIDANCE DOCUMENTS	**TITLE**
NUREG/BR-0167 (1993)	Software Quality Assurance Program and Guidelines

Figure 2-3. DOE QAPD Source Documents by Category

- Analyzing performance data that affect quality and identifying lessons learned to improve items, activities, and processes.

- Preparing, approving, issuing, and controlling documents which prescribe processes, specify requirements, or establish design.

- Records shall be specified, prepared, reviewed, approved, controlled, and maintained to accurately reflect completed work and facility conditions and to comply with statutory or contractual requirements.

- Classifying Quality Assurance records as either "permanent" or "non-permanent."

- Performing work under controlled conditions using approved instructions, procedures, drawings or other appropriate means.

- Items and processes shall be designed using sound engineering/scientific principles and appropriate standards. The adequacy of design products shall be verified by individuals or groups other than those who performed the work.

- Ensuring that procured items and services meet established technical and quality assurance requirements and that they perform as specified. Prospective suppliers shall be evaluated and selected on the basis of documented criteria.

- Inspecting and testing specified items and processes, and calibrating and maintaining equipment used for such tests.

- Conducting planned and periodic assessments to measure management effectiveness, item quality and process effectiveness, and to promote improvement. Persons conducting assessments shall be technically qualified and knowledgeable in their assigned roles.

- Controlling and identifying samples in a manner consistent with their intended use.

- Shall be defining, controlling, verifying and documenting scientific investigations.

- Verification of software shall include reviews that ensure that the requirements are complete and correct, and shall include the appropriate testing.

EPA Office of Radiation and Indoor Air (ORIA) has conducted two formal reviews of the CAO QAPD and transmitted comments on Revisions 0 and 1 to DOE CAO. DOE appears to be revising the QAPD to address EPA concerns.

2.2.3.4 TRU Waste Characterization Quality Assurance Program Plan (TRU QAPP)

The TRU QAPP presents detailed technical information focusing on analytical techniques for the collection and analysis of samples at a stated, statistically derived confidence interval for physical, chemical and radiological parameters. In addition to technical information, the TRU QAPP provides Quality Assurance information, much of which overlaps with areas covered in the CAO QAPD (DOE95). The TRU QAPP identifies the quality of data necessary and the techniques designed to attain and ensure the required quality to meet the objectives of the WIPP Waste Characterization Program (DOE94), and also contains specific Quality Assurance Objectives for TRU waste. The waste characterization requirements presented in the TRU QAPP focus on the Resource Conservation and Recovery Act (RCRA) and Department of Transportation (DOT) regulations (DOE94). §194.24 requires DOE to perform an analysis which identifies waste characteristics influencing waste containment within the disposal system. Once DOE has completed the analysis, the QAPP should be revised to address the requirements of 40 CFR part 194. According to CAO, the TRU QAPP addresses all of the basic requirements of ASME NQA-1 (DOE94); any exceptions to ASME NQA-1 requirements must be noted in each site's QAPjP. Each TRU generator site's QAPjP must integrate the TRU QAPP's requirements for all TRU waste intended for shipment to WIPP, which is accomplished by NTPO/CAO reviewing and approving the generator site QAPjPs (DOE94).

2.2.4 Key WIPP Scientific Advisor Documents

In their capacity as the WIPP Scientific Advisor, Sandia National Laboratories (SNL) has developed the SNL WIPP Quality Assurance Program Description (SNL QAPD) (SNL95b) and an extensive list of implementing procedures to address specific WIPP related Quality Assurance and technical activities. These activities are generally classified as experimental programs and they cover a wide range of technical and QA activities from certifying pressure relief valves to Root Cause Analysis. As of 9-14-95, SNL lists forty one Quality Assurance Procedures as "Active WIPP Controlled Documents" (REF). EPA needs to determine the conformance of these SNL documents to the ASME NQA standards and the degree of their implementation.

2.2.5 Management and Operating Contractor Documents

Westinghouse Waste Isolation Division (WID) functions in the capacity of the WIPP Site Management and Operations Contractor. As such, WID is required to comply with all applicable federal and state regulations. These requirements are integrated in the WID Quality Assurance Program Description (WID92) and associated implementing procedures and instructions.

2.2.6 TRU Waste Generator Sites

There are approximately ten major TRU generator sites. Each site is required to develop a site specific Quality Assurance Project Plan (QAPjP) and supporting procedures. These documents are the means whereby the site translates CAO and other federal requirements into operating procedures. The TRU generator site QAPjPs must be approved by CAO (DOE94).

2.2.7 Qualification of Existing Data

2.2.7.1 Background

An important factor in performance assessment is the use of data that were not generated under a Quality Assurance Program that complies with the requirements of ASME NQA-1.[2] These data are referred to as *existing data* or *old data*[3]. The majority of the early experimental work performed under and above ground at the WIPP was conducted by the SNL, beginning in the early 1980's. SNL has only recently begun to configure its Quality Assurance Program to be consistent with ASME NQA-1, and therefore many of the technical data generated since the early 1980s in support of various scientific investigations concerning waste isolation are considered existing data. Under 40 CFR part 194, data that were not

[2] In the context of Section 2.2.7, ASME NQA-1 means ASME-NQA-1-1988, ASME NQA-2A-1990, addenda part 2.7 to ASME NQA-1-1989, and ASME NQA-3-1989 [excluding Section 2.1(b) and (c) in Section 17.1].

[3] "Existing data is data developed prior to the implementation of an NQA-1, -2, -3 QA program by SNL and its contractors, or data developed outside the SNL-WIPP program, such as by oil companies, national laboratories, universities, or data published in technical or scientific publications. Existing data does not include information that is accepted by the scientific and engineering community as established fact (e.g., engineering handbooks, density tables, gravitational laws, etc.)." (SNL95)

generated under an ASME NQA-1 quality assurance program must be qualified in a manner consistent with one of the following four approaches:

- peer review
- confirmatory testing
- use of corroborating data
- a quality assurance program that is equivalent in effect to ASME NQA-1

Additionally, the specific methodology used must be approved by the administrator.

In commenting on EPA's Advance Notice of Proposed Rule-making on compliance criteria, DOE proposed the following steps to verify data used in compliance assessment (DOE93c):

- The data will be examined against currently approved QA procedures. This examination will be directed to show that if the data had been obtained under current QA practices, the results would be equivalent to the ongoing data collection.

- If QA equivalency of the data cannot be shown, and the data are crucial to compliance demonstration, an independent peer review group will be established to assess the validity of the data, and DOE will submit the findings to EPA.

- If an acceptable QA level cannot be demonstrated to EPA, and the data are crucial to compliance, DOE will do statistical resampling to establish the quality of the data or initiate an activity to reacquire the needed data. However, the original data will not be discarded. Instead, they will be evaluated for use as confirmation of the newly acquired data.

2.2.7.2 SNL Program For Qualifying Existing Data

In 1994, SNL began to address the issue of *qualifying existing data* (QED). The process initially followed the approach outlined by the US NRC (NRC88a) and consisted of three main areas:

- Identifying those data necessary for compliance calculations, for settlement of compliance issues or for submission of DOE's certificate of compliance and organizing them into groups called Data Records Packages (DRPs);

- Determining whether the selected DRPs are acceptable with respect to technical and Quality Assurance criteria through the use of a team of qualified, independent personnel with expertise in the areas of interest, called Independent Review Teams

(IRT). Each data package is evaluated by an IRT that determines whether the data were collected under a QA program equivalent to ASME NQA-1, and whether the Technical/Scientific Protocols employed during data collection are acceptable when evaluated against a pre-established check list.

- Remediating those data that were judged to be unacceptable by virtue of technical and/or Quality Assurance flaws by IRT assessment. If a DRP is determined to be inadequate for technical and/or Quality Assurance reasons by an IRT, alternative methods for qualifying the data are to be identified by a Qualification Methods Team (QMT). Such methods include the use of corroborating data, confirmatory testing and peer review. Data that cannot be suitably qualified must be abandoned.

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- Remediating those data that were judged to be unacceptable by virtue of technical and/or quality assurance flaws by IRT assessment. If a DRP is determined to be inadequate for technical and/or quality assurance reasons by an IRT, alternative methods for qualifying the data are to be identified by a Qualification Methods Team (QMT). Such methods include the use of corroborating data, confirmatory testing and peer review. Data that cannot be suitably qualified must be abandoned.

2.2.7.4 Current Status

The assessment of existing data focused on data in four technical areas: natural barriers, disposal system design and engineered barriers, waste interactions, and human initiated processes and events. As of August 30, 1995, 46 DRPs had been identified as high priority, meaning that it was likely that DOE would use them in whole or part for the submission of their compliance application. Of these, 26 were assessed as not adequate to support compliance; 20 were assessed as adequate to support compliance. Of the 26 DRPs assessed as not adequate, 23 were pending QMT review.

SNL began the QED process by evaluating DRPs in November 1994, and has made considerable progress to date, as discussed previously. Personnel from EPA Office of Radiation and Indoor Air-Las Vegas Facility and their technical support contractor have observed IRT assessments of approximately ten DRPs, some as late as June, 1995. Additionally, CAO performed a Quality Assurance Audit of the SNL QED process in September, 1995 (DOE CAO Audit A-95-05). These observations have provided EPA with insight into SNL's approach to the QED process. The governing document for the QED process (SNL QAP 20-3) (SNL95a) has been evolving as SNL has progressed through the QED process. Once SNL's methodology is completed, it would be presented to EPA for approval.

2.2.8 Quality Assurance for Models and Codes

Sandia National Laboratories is conducting iterative performance assessments to provide interim guidance prior to preparing a final compliance evaluation (SNL92). These performance assessments describe the conceptual basis for consequence modeling and performance assessment methodology, including the selection of scenarios for analysis, the determination of scenario probabilities, and the estimation of scenario consequences (SNL92).

The modeling process described in references SNL92 and SNL92a includes significant participation of peer review groups external to Sandia. The iterative nature of the work leads to a constant updating of models. If, during review of a compliance application, it is determined that one or more parts of the model(s) is based upon data obtained in the early stages of the WIPP program when a less stringent QA program was used, the model's validity could become an issue. If found to exist, such issues must be settled using the QA standards and criteria applicable to the performance assessment process itself.

WIPP procedure No. PAP02, Computer Software Supporting Performance Assessments of the Waste Isolation Pilot Plant, describes four classes of software:

- A- Adjudicated (full QA status)
- C- Candidate (partial QA status, possibly undergoing continued refinement)
- D- Dormant (obsolete software formerly in Class A or C)
- X- Experimental (entry level, software in early stages of development or experimentation, no QA requirements)

A Software Review Committee decides whether to classify software as Class A. It is SNL policy to use only Class A software for the performance assessment to support the application for certification of compliance. This procedure is not as rigorous as that specified in NQA-2 (part 2.7).

2.3 SUMMARY OF U.S. NRC REQUIREMENTS

The purpose of this section is to identify the NRC QA requirements for data gathering, analyses, and modeling applicable to high-level radioactive waste disposal systems.[4] Useful parallels may be drawn between NRC and EPA requirements since both involve modeling of geologic nuclear waste repositories.

Quality assurance requirements for disposal of high-level radioactive wastes in geologic repositories are specified in Subpart G of 10 CFR part 60. Subpart G requires DOE to implement a QA program based on the criteria of Appendix B of 10 CFR part 50 as applicable[5], and which is appropriately supplemented by additional criteria. Specific QA criteria which the NRC staff use to review the DOE QA program are provided in "Review Plan for High-Level Waste Repository Quality Assurance Program Descriptions" (NRC89). This document provides NRC's position on the meaning of the term "as applicable" as used in Appendix 2B of the disposal system program.

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[4] References to DOE in this section refer to DOE's Office of Civilian Radioactive Waste Management.

[5] 10 CFR Part 50 does not address requirements for software or data collection for siting such as are addressed by ASME NQA part 2.7 and ASME NQA-3.

The NRC Review Plan endorses ASME NQA-1-1986 and incorporates the lessons learned from the Ford Study (NRC84), such as the use of technical audits and readiness reviews. This document also accounts for differences between power reactor projects and the high-level nuclear waste disposal system program and references the NRC staff's Technical Positions.

Each section of the Review Plan corresponds to one of the 18 criteria of 10 CFR part 50, Appendix B, and provides the acceptance criteria the NRC staff uses to evaluate QA program descriptions or plans. The areas addressed by each of these 18 criteria are listed below:

Criterion 1	Organization
Criterion 2	Quality Assurance Program
Criterion 3	Design Control
Criterion 4	Procurement Document Control
Criterion 5	Instructions, Procedures, and Drawings
Criterion 6	Document Control
Criterion 7	Control of Purchased Material, Equipment, Items and Services and Software
Criterion 8	Identification and Control of Items, Services, and Software
Criterion 9	Control of Special Processes
Criterion 10	Inspection
Criterion 11	Test Control
Criterion 12	Control of Measuring and Test Equipment
Criterion 13	Handling, Storage, and Shipping
Criterion 14	Inspection, Test, and Operating Status
Criterion 15	Nonconformances
Criterion 16	Corrective Action
Criterion 17	Quality Assurance Records
Criterion 18	Audits

As stated in §60.151, the QA program applies to all systems, structures, and components "important to safety," to design and characterization of barriers "important to waste isolation," and to activities related thereto. These activities include site characterization, facility and component construction, facility operation, performance confirmation, permanent closure, and decontamination and dismantling of surface facilities.

Section 60.2 defines the term "important to safety" as those "engineered structures, systems, and components essential to the prevention or mitigation of an accident that could result in a radiation dose to the whole body, or any organ, of 0.5 rem or greater at or beyond the nearest boundary of the unrestricted area at any time until the completion of permanent closure."

NUREG-1318, "Technical Position on Items and Activities in the High-Level Waste Geologic Repository Program Subject to QA Requirements" (NRC88b) provides guidance for the identification of items important to safety and waste isolation. The NRC QA requirements relating to data that are important to safety or to waste isolation are summarized in Sections 2.3.1, 2.3.2 and 2.3.3, below.

2.3.1 Data Gathering

Site characterization involves data gathering. As required by Subpart B of 10 CFR part 60, DOE must conduct a program of site characterization in accordance with the following:

- Investigations to obtain the required information shall be conducted in such a manner as to limit adverse effects on the long-term performance of the geologic disposal system to the extent practical.

- The number of exploratory boreholes and shafts shall be limited to the extent practical consistent with obtaining the information needed for site characterization.

- To the extent practicable, exploratory boreholes and shafts in the geologic disposal system operations area shall be located where shafts are planned for underground facility construction and operation or where large unexcavated pillars are planned.

- Subsurface exploratory drilling, excavation, and in situ testing before and during construction shall be planned and coordinated with geologic disposal system operations area design and construction.

DOE must submit to the NRC a description of the QA program to be applied during the site characterization phase. As a result of meeting the requirements of the QA Plan, Q-lists will be generated. The criteria developed in preparing Q-lists are essential to identifying quality-affecting activities and, of necessity, require a disciplined, systematic analysis of the entire project (NRC88b).

The Q-list identifies structures, systems, and components important to safety and engineered barriers important to waste isolation. A quality activities list identifies the site characterization activities that may provide data for use in assessments of the waste isolation and containment capabilities of natural and engineered barriers, those activities related to the actual assessments, and those activities that may adversely impact the waste isolation capabilities of these barriers.

Data and information needs are identified by compliance assessments, performance allocation[6] among the various components of the natural and engineered barrier systems, design, and modeling of the geologic disposal system. The need to collect additional data depends on the availability and quality of existing data. The QA criteria for data gathering are provided in Criteria 3, 5, 8, 9, 10, 11, 12, 13, 17, and 18 listed above.

2.3.2 Data Analysis

Data analysis is a design activity subject to the requirements of design control, design verification, and design changes control. The QA criteria for data analysis are provided in Criteria 3, 17 and 18.

2.3.3 Data Modeling

The data needed for construction of an adequate model of the disposal system and compliance assessments, and the associated computer modeling, are subject to 10 CFR 60 Subpart G QA requirements.

Computer programs should be developed, controlled, and used in accordance with the QA program. Guidance for documentation of computer codes is provided by NUREG-0856, "Final Technical Position on Documentation of Computer Codes for High-Level Waste Management" (NRC83)[7]. Documentation includes five categories: software summary, description of mathematical models and numerical methods, user's manual, code assessment and support, and continuing documentation and code listing.

General recommendations for software quality assurance programs are provided in NUREG/CR-4640 "Handbook of Software Quality Assurance Techniques Applicable to the Nuclear Industry" (NRC87). The handbook is intended to be used by the nuclear power industry as an aid for structuring QA programs and assessing the adequacy of existing software practices including development and use.

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[6] Performance allocation: This term applies to the process of deriving subsystem and component performance goals from performance objectives. A systematic process of assigning confidence levels with their desired, associated performance goals for the mined geologic disposal systems, subsystems, and components (NRC88b).

[7] NUREG-0856 does not comply completely with ASME NQA Part 2.7.

Guidance for NRC organizations and NRC contractors in the development and maintenance of software for use by NRC staff is provided in NUREG/BR-0167 "Software Quality Assurance Program and Guidelines" (NRC93). Those guidelines apply to technical application software used in safety decisions by the NRC. The applicability of those guidelines depend on the purpose and use of the software and management's judgment of the cost-effectiveness of each software quality activity. Most projects incorporate verification and validation, configuration management, and documentation control activities.

Verification is the process of ensuring that the products and processes of each of the major life cycles' activities meet the standards for the products and the objectives of that activity. Validation is the process of demonstrating that the as-built software meets its requirements and is accomplished by review and demonstration in a live or simulated environment.

Verification and validation activities include planning, formal life cycle reviews and audits, peer inspections, and testing. Testing is the process of detecting errors and verifying performance. Testing typically includes unit integration, qualification, and acceptance testing.

Fundamental to configuration management are the concepts of a baseline and change control. A baseline is a document or software that has been formally reviewed and agreed upon by the developer and sponsor, and thereafter serves as the basis for further development. It can be changed only through formal change control procedures. Change control is the process by which a change to a baseline is proposed, evaluated, approved or rejected, scheduled, and tracked.

Peer reviews may be employed for data modeling and computer models. Guidance on the use of the peer review process is provided in NUREG-1297 "Peer Review for High-Level Nuclear Waste Repositories" (NRC88). A peer review is a documented, critical review performed by experts who are independent of the work being reviewed. NUREG-1297 provides guidance on areas where a peer review is appropriate, the acceptability of peers, and the conduct and documentation of a peer review. Peer review is discussed in greater detail in Chapter 7.

The QA criteria relating to data and computer modeling are provided in Criteria 3, 6, 8, 9, 11, 14, 15, 17 and 18 from the above list.

2.3.4 Management and Oversight

NRC QA procedures describe how DOE and prime contractors exercise responsibility for the overall QA program. DOE and its prime contractors are required to identify a management position within each respective organization that retains overall authority and responsibility for the QA program. This position must:

- Be at the same or higher organization level as the highest line manager directly responsible for performing activities affecting quality and be sufficiently independent from cost and schedule;
- Have effective communication channels with other senior management positions; and
- Have no duties or responsibilities unrelated to QA that would prevent full attention to QA matters.

Persons and organizations performing QA functions must have sufficient authority and organizational freedom to:

- Identify quality problems;
- Initiate, recommend, or provide solutions through designated channels;
- Verify implementation of solutions; and
- Assure that further processing, delivery, installation, or operation is controlled until a nonconformance, deficiency, or unsatisfactory condition has been corrected.

The QA program should provide control over all activities affecting the quality of the identified activities, structures, systems, and components to an extent consistent with their required performance (NRC88b).

The QA criteria related to management and oversight are provided in Criteria 1, 2, 15, 16, and 18.

2.3.5 Qualification of Older Data

Data pertinent to waste isolation systems and/or components may exist that were developed before the implementation of a 10 CFR part 60 Subpart G QA program by DOE and its contractors. Additionally, data that were developed outside of the DOE disposal system program may be identified as pertinent and used by DOE for purposes of waste isolation, such as data generated by oil companies, national laboratories, universities, or data that have been published in technical or scientific publications. These are considered "existing data". This category does not include information accepted by the scientific and engineering community as established facts such as are found in engineering handbooks, density tables, gravitational laws.

NRC specifies that procedures should be established describing methods of reviewing and qualifying existing data. NUREG-1298 "Qualification of Existing Data for High-Level Nuclear Waste Repositories, Generic Technical Position" (NRC88a) describes four general approaches, but does not provide implementation guidance for this process.

2.4 ASME NQA-1, NQA-2, AND NQA-3 STANDARDS

EPA is requiring that DOE implement a QA program that meets the requirements of the American Society of Mechanical Engineers' "Quality Assurance Program Requirements for Nuclear Facilities" (NQA-1-1989 edition); "Quality Assurance Requirements of Computer Software for Nuclear Facility Applications" (NQA-2a-1990 addenda (part 2.7) to ASME NQA-2-1989 edition); and "Quality Assurance Program Requirements for the Collection of Scientific and Technical Information for Site Characterization of High-Level Nuclear Waste Repositories" [NQA-3-1989 edition, excluding Section 2.1(b) and (c)][8]. EPA has mandated

[8] EPA proposes the use of the ASME NQA 1989 editions instead of the ASME NQA 1994 edition for the following reasons:

- The ASME NQA 1994 edition allows a reduction in the level of structure for personnel qualification and certification for designers/verifiers, inspection personnel, testing and audit personnel to only a subjective level by supervisory analysis.
- ASME NQA-3-1989 contains added amplification requirements related to Scientific and Technical Data (S&TD) applications to support the WIPP that are not included in ASME NQA 1994 edition. These areas include: (1) planning,quality standards and criteria for the collection of S&TD; (2) surveillance, including in-process, deficiencies, and follow-up; (4) communication; (5) design control; (6) peer reviews; (7) data processing; and (8) qualification of existing data.

the use of the ASME standards because these national consensus standards offer the most comprehensive and specific set of QA requirements for all compliance-related elements of the WIPP disposal system. NRC has taken a similar approach by specifying equivalent criteria in 10 CFR part 50, Appendix B.

2.4.1 ASME NQA-1

This Standard sets forth requirements for the establishment of a quality assurance program for the siting, design, construction, operation, and decommissioning of nuclear facilities. This Standard's requirements apply to activities which could affect the quality of structures, systems, and components of nuclear facilities. These activities include:

- attaining quality objectives;
- assuring that an appropriate quality assurance program is established; and
- verifying that activities affecting quality have been correctly performed.

Activities affecting quality include siting, designing, purchasing, fabricating, handling, shipping, receiving, storing, cleaning, erecting, installing, inspecting, testing, operating, maintaining, repairing, modifying and decommissioning (ASM89a).

2.4.2 ASME NQA-2, Part 2.7

Part 2.7 provides requirements "for the development, procurement, maintenance, and use of computer software, as applied to the design, construction, operation, modification, repair, and maintenance of nuclear facilities" (ASM89b). It supplements the requirements of NQA-1.

2.4.3 ASME NQA-3

NQA-3 was developed specifically for site characterization of high-level nuclear waste repositories. (The same QA considerations apply to repositories for transuranic wastes.) NQA-3 is to be used in conjunction with NQA-1 to set forth QA program requirements and guidance for the collection of scientific and technical information for site characterization of high-level nuclear waste repositories. "The requirements of NQA-1 and NQA-3 are intended to meet and clarify the criteria of 10 CFR 50, Appendix B, and 10 CFR 60, Subpart G, for high-level nuclear waste repositories" (ASM89c).

2.5 REFERENCES

ASM89a American Society of Mechanical Engineers, "Quality Assurance Program Requirements for Nuclear Facilities," ASME NQA-1-1989 Edition.

ASM89b American Society of Mechanical Engineers, "Quality Assurance Requirements of Computer Software for Nuclear Facility Applications," Part 2.7, ASME NQA-2-1990 Edition (First Addenda to ASME NQA-2-1989 Edition).

ASM89c American Society of Mechanical Engineers, "Quality Assurance Program Requirements for the Collection of Scientific and Technical Information for Site Characterization of High-Level Nuclear Waste Repositories," ASME NQA-3-1989 Edition.

DOE91 U.S. Department of Energy, "Quality Assurance," DOE Order 5700.6C, August 21, 1991.

DOE91a U.S. Department of Energy, Office of Environmental Restoration and Waste Management, "Quality Assurance Requirements and Description (QARD)," Revision 0, October 31, 1991.

DOE92 U.S. Department of Energy, "Quality Assurance Program Plan for the Waste Isolation Pilot Plant Experimental-Waste Characterization Program," Waste Isolation Pilot Project, DOE/EM/48063-1, Final Draft, Revision 2.0, October 1992.

DOE93a U.S. Department of Energy (M. Frei) letter dated July 9, 1993, to EPA (J. William Gunter), identification of issues.

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DOE95 U.S. Department of Energy, Carlsbad Area Office, "Quality Assurance Program Description," CAO-94-1012, DRAFT, Revision 1.0, August, 1995.

EPA80 U.S. Environmental Protection Agency Interim Guidelines and Specifications for Preparing Quality Assurance Program Plans, QAMS-005-080.

NRC83 U.S. Nuclear Regulatory Commission, S. A. Silling, Office of Nuclear Materials Safety and Safeguards, "Final Technical Position on Documentation of Computer Codes for High-Level Waste Management," NUREG-0856, June 1983.

NRC84 U.S. Nuclear Regulatory Commission, Altman, W., et al.,"Improving Quality and the Assurance of Quality in the Design and Construction of Commercial Nuclear Power Plants, NUREG-1055, May 1984.

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NRC88 U.S. Nuclear Regulatory Commission, Altman, W.D., et al., "Peer Review for High-Level Nuclear Waste Repositories," NUREG-1297, February 1988.

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NRC88b U.S. Nuclear Regulatory Commission, A. B. Duncan, S. J. Bilhorn, J. E. Kennedy, Office of Nuclear Materials Safety and Safeguards, "Technical Position on Items and Activities in the High-Level Waste Geologic Repository Program Subject to Quality Assurance Requirements," NUREG-1318, April 1988.

NRC89 U.S. Nuclear Regulatory Commission, "Review Plan for High-Level Waste Repository Quality Assurance Program Descriptions," Revision 2, March 1989.

NRC93 U.S. Nuclear Regulatory Commission, "Software Quality Assurance Program and Guidelines," NUREG/BR-0167, February 1993.

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SNL95a Sandia National Laboratories, Waste Isolation Pilot Plant, Quality Assurance Procedure QAP 20-3, "Qualification of Existing Data", Revision 2, June 28, 1995.

SNL95b Sandia National Laboratories, "Waste Isolation Pilot Plant Quality Assurance Program Description," Rev. R, July, 1995.

WTA94 WTAC Independent Review Team (IRT) Desk Instruction IRT DI 1.0, Revision 1, Independent Review Team Qualifications, Selection and Roles, November, 1994.

3. Issues for the Selection and Development of Models and Computer Codes

3.1 INTRODUCTION

In assessing the containment characteristics of the WIPP disposal system, DOE will need to consider many complex processes upon which their decisions regarding performance assessment will be based. Although some decisions can be made using engineering judgment, many analyses must be performed where human reasoning alone is inadequate to synthesize the many factors involved in complex problems. The best tool available to help scientists meet the challenge of such analyses and predictions is a model.

A model is a system designed to represent a simplified version of a real system. Models, can be valuable predictive tools for performance assessment if properly constructed. The validity of the predictions will depend on how well or conservatively the model approximates the physical system being modeled.

DOE is currently developing models and computer codes to meet performance assessment objectives for the WIPP. EPA will ultimately accept or reject DOE's selection and application of models and computer codes. This section identifies the issues considered by EPA in the development of criteria for WIPP model and code selection, description, implementation, and justification (§194.23). These criteria are based on full implementation of quality assurance procedures and the complete documentation of the procedures.

DOE has already selected a number of computer codes at the WIPP to gain an insight into the kinds of problems that may be encountered in the modeling analyses that will be conducted for the performance assessment. In the process of DOE's continued formulation and testing of the various components of the disposal system conceptual models, attention is given to many aspects of the system and possible avenues of analysis. This includes developing a conceptual model of the site that defines the physical framework, relevant processes, boundary conditions, and what approaches are justifiable and relevant to meeting performance objectives. After the conceptual model has been formulated, appropriate codes are selected by matching a detailed description of the modeling needs with well-defined, quality-assured characteristics of existing codes, while taking into account the compliance assessment objectives of the study. If a good match between model requirements and code characteristics cannot be found, modification of an existing code or the development of a new code may be considered.

In the 1992 PA, DOE presented components of its site conceptual model. These components focused on the Culebra Dolomite Member of the Rustler Formation overlying the Salado Formation. The Culebra Dolomite is thought to present the most likely avenue for radioactive waste to reach the accessible environment in addition to direct releases to the accessible environment. However, there is considerable uncertainty regarding the physical system boundary conditions and flow and transport mechanisms.

Another consideration is that computer codes are generally not designed to be universally applicable. Code development is normally aimed at solving a specific environmental problem or range of problems. Therefore, a single code will not simulate all of the components of the conceptual model. For example, most WIPP performance assessment scenarios consider three time-dependent gas-generation processes which are expected to be involved in the degradation of transuranic (TRU) waste in the disposal system: (1) oxic and anoxic corrosion of metals, (2) aerobic and anaerobic microbial degradation of cellulosic materials, and (3) radiolysis. The potential for large quantities of gas has strong links to other processes associated with closure of the disposal rooms and panels. After the repository is closed, the surrounding halite will close (creep) inward upon and compact the waste and backfill. Gas generating processes in the waste and the impact of creep closure will potentially increase pressure in the room. The pressure within these materials may force the brine and compressed gas through natural and induced fractures toward the regulatory boundaries.

Section 3.2 of this chapter discusses how a code review would first determine if the selected code was compatible with the modeling objectives set forth in the performance assessment. Section 3.3 focuses on the code development process, code capabilities, and the quality of the accompanying documentation. Issues related to the application of a computer code are considerably different than those associated with code development and selection (i.e., a properly selected code can be improperly applied). Although the primary objective of this chapter is to present issues related to model and code selection rather than code application, Section 3.4 discusses code application criteria in a global sense.

3.2 REVIEW OF COMPUTER CODE BY EVOLUTION EVALUATION

Computer code selection is the process of choosing the appropriate software capable of simulating the characteristics of the physical system to be modeled. The evolution of the computer code can be traced from the inception of the conceptual model to the formulation of the mathematical model, and finally to the development of the computer code where computer instructions for performing the operations specified in the mathematical model are programmed. The formulation of a conceptual model is an integral component of the modeling process. Components of the conceptual model may be simplified to meet either limited objectives or limitations in the data. It is often useful to simulate only certain components of the conceptual model. For instance, even if there are data that indicate different geologic zones in the hydrogeologic unit, it is common practice to evaluate the system as a function of average values. While different aspects of the conceptual model may be simulated in a variety of ways, the selected approach must remain consistent with the objectives. The review and acceptance of a model is an evolutionary process that depends upon the modeling goals and availability of data. The following illustration is focused on hydrogeologic models although the process would be nearly identical for other models.

3.2.1 Conceptual Models

The performance assessment will use numerous conceptual models to describe the physical, biological and chemical processes expected to occur at WIPP. At the most basic level, conceptual models describe very fundamental processes, for example, the type of microorganisms present in the repository, their population size and metabolic rates. These basic conceptual models are integrated further to form the basis for more complete conceptual models that predict processes such as gas generation, room closure rates, and contaminant transport mechanisms.

The conceptual model of a groundwater system is an interpretation of the characteristics and dynamics of the physical hydrogeologic system. The purpose of the conceptual model is to consolidate site and regional hydrogeologic and hydrologic data into a set of assumptions and concepts that can be evaluated quantitatively. The system conceptualization should include: the geologic and hydrologic framework, characteristics of geologic formations (e.g., fractured or porous), the nature of relevant physical and chemical processes, time dependent processes, geometry of the system, initial and boundary conditions, hydraulic properties; and sources and sinks (water budget). A brief discussion of each of the typical components of the hydrogeological conceptual model that should be considered and reviewed is presented below.

Geologic framework. The geologic framework is the distribution and configuration of various rock units (e.g., fractured dolomite or intact halite). Of primary interest are the thickness, continuity, lithology, and geologic structure of those units that are relevant to the purpose of the study.

Hydrologic framework. The hydrologic framework in the conceptual model includes the physical extent of the flow system, hydrologic features that impact or control the groundwater flow system, analysis of groundwater flow directions, and media type. The conceptual model must address the degree to which the system behaves as a porous media. If the system is significantly fractured or solution channeled, the conceptual model must address these issues.

Hydraulic properties. The hydraulic properties include the transmissive and storage characteristics of the rocks and properties of the fluids. Specific examples of rock and fluid properties include transmissivity, hydraulic conductivity, storativity, fluid viscosity and densities. Hydraulic conductivity may also have directionality (anisotropy).

Sources and sinks. Sources or sinks of water or gas impact the pattern and rate of flow and may affect the transport of radionuclides from the repository. The most common examples of sources and sinks include pumping or injection wells, infiltration, evapotransporation, drains and flow from surface water bodies. At the WIPP reactions between brine and waste in the repository may provide a source of gas.

Boundary and initial conditions. Boundary conditions are the conditions the modeler specifies, typically on the perimeter of the model domain, in order to solve for the unknowns in the problem domain. These values may be associated with either the groundwater flow or the contaminant transport aspects of the problem. Groundwater boundaries may be described in terms of where water and/or gas are flowing into the groundwater system and where water and/or gas are flowing out. Many different types of boundaries exist, including: surface water bodies, groundwater divides, rainfall, wells, and geologic features such as faults and sharp contrasts in lithology. For example, at the WIPP, pressure boundary conditions for the Salado have been set to far field fluid pressures.

The most common contaminant-source boundaries specify the source concentration or prescribe the mass flux of contamination entering the system. Both type of source boundaries are currently used in the modeling at the WIPP.

Initial conditions are defined as values of groundwater elevation, pressure, flow volumes, or contaminant concentrations which are initially assigned to interior areas of the modeled regions. At the WIPP, pressures in the repository are initially set to atmospheric conditions.

Transport processes. The transport of radionuclides by flow through either a porous matrix or a fracture system in a porous matrix will be affected by various mechanical and geochemical processes. The dominant mechanical processes are advection, dispersive effects (hydrodynamic dispersion, channeling) and diffusion. The chemical processes potentially affecting radionuclide transport include: adsorption on mineral surfaces (both internal and external to the crystal structure), speciation, precipitation, colloidal transport, radiolysis, biofixation, natural organic matter interactions, anion exclusion, and complexation.

Spatial dimensionality. Groundwater flow and contaminant transport are seldom constrained to one or two dimensions. However, in some instances, it may be appropriate to restrict the analysis to one or two dimensions. The decision to model a site in a particular number of dimensions should be based upon the modeling objectives and the availability of field and/or laboratory data.

Temporal dimensionality. Either steady-state or transient flow simulations can be performed. At steady-state, it is assumed that the flow field remains constant with time, whereas a transient system simply means one that changes with time. Steady-state simulations produce average or long-term results and require that a true equilibrium case is physically possible. Transient analyses are typically performed when boundary conditions are varied through time or when study objectives require answers at more than one time.

The conceptual model is based on the modeler's experience, technical judgment and represents the modeler's understanding of the physical system being modeled. The conceptual model will become more complex as more processes are identified and interrelationships of important components within the systems are considered. The transformation of the conceptual model into a mathematical model is only an extrapolation of a basic understanding of the system will result in simplifications of the system. For example, the mathematical models assume that there is a direct scaling between the model simulations and the scale at which the data are collected. The lack of knowledge about the system resulting from limited information also contributes to simplifications of the mathematical models.

In addition to the unavoidable simplifications of the conceptual model, there are simplifications in which the modeler decides what physical characteristics and processes are important to the model application. Examples of these kind of simplifying assumptions include:

- Flow through the unsaturated zone is vertical and in one dimension.
- Chemical reactions are reversible and instantaneous.
- Soil or rock medium is isotropic and/or homogeneous.
- Flow field is uniform and under steady-state conditions.

As more data become available, simplifying assumptions are removed and the conceptual model complexity increases. This process creates mathematical model development which allows for the systematic integration of previously neglected conceptual model components.

3.2.2 Mathematical Models

A conceptual model describes the present condition of the system. To make predictions of future behavior it is necessary to develop mathematical models. Laboratory sand tanks are physical scale models that simulate groundwater flow directly. The flow of groundwater can also be implied using electrical analog models. Mathematical models, including analytical and numerical methods, discussed below, are more widely used because they are easier to develop and manipulate.

A mathematical model is essentially a mathematical representation of a process or system conceptual model. For example, the mathematical model for groundwater flow is derived by applying principles of mass conservation and conservation of momentum. The generally applicable equation of motion in groundwater flow is Darcy's law for laminar flow, which originated in the mid-nineteenth century as an empirical relationship. Later, a mechanistic approach related this equation to the basic laws of fluid dynamics. In order to solve the flow equation, both initial and boundary conditions are necessary.

Solution Methodology

Every groundwater model is based upon a set of mathematical equations. Solution methodology refers to the strategy and techniques used to solve these equations. The equations are normally solved for water elevations in the subsurface (head) and/or contaminant concentrations.

Mathematical methods developed to solve groundwater flow and transport equations can be broadly classified as either deterministic or stochastic. Deterministic methods assume that a system or process operates such that the occurrence of a given set of events leads to a uniquely definable outcome. Stochastic methods presuppose the outcome to be uncertain and are structured to account for this uncertainty.

Most of the stochastic methods are not purely stochastic because they often utilize a deterministic representation of soil processes and derive their stochastic nature from their representation of inputs and/or spatial variation of soil characteristics and resulting chemical movement. While the deterministic approach results in a specific value of a soil variable (e.g., solute concentration) the stochastic approach provides the probability of a specific value occurring at any point.

The development of stochastic methods for solving groundwater flow is a relatively recent endeavor that has occurred as a result of the growing awareness of the importance of intrinsic variability of the hydrogeologic environment. Stochastic methods are still primarily research tools; however, as computer speeds continue to increase, stochastic methods will be able to move further away from the research-oriented community and more into mainstream management applications. This discussion focuses primarily on deterministic methods.

Deterministic methods may be classified as either analytical or numerical. Analytical methods usually involve approximate or exact solutions to simplified forms of the differential equations for water movement and solute transport. Simple analytical methods are based on the solution of differential equations which give qualitative estimates of the extent of contaminant transport. Such methods are simpler to use than numerical methods and can generally be solved with the aid of a calculator or computers. Analytical methods are restricted to simplified representations of the physical situations and generally require only limited site-specific input data. They are useful for screening sites and scoping the problem to determine data needs or the applicability of more detailed numerical methods.

Analytical methods are used in groundwater investigations to solve many different kinds of problems. For example, aquifer parameters (e.g., transmissivity, storativity) are obtained from aquifer tests through the use of analytical methods. To avoid confusion, only analytical methods designed to estimate groundwater flow and radionuclide transport rates are discussed in this section.

Analytical methods that solve groundwater flow and contaminant transport in porous media are comparatively easy to use. Analytical solutions are generally restricted to either radial flow problems or to cases where velocity is uniform over the area of interest. Except for some radial flow problems, almost all available analytical solutions are developed for systems having a uniform and steady flow. This means that the magnitude and direction of the velocity throughout the system are invariable with respect to time and space.

Equations of flow and continuity in the form of partial differential equations do not lend themselves easily to rigorous analytical solutions when boundaries are complex. Generally, a realistic analytical expression for hydraulic head or concentration as a function of space cannot be written from the governing equations, boundary and initial conditions, and therefore analytical methods are generally abandoned and replaced by more sophisticated numerical methods.

Numerical methods provide solutions to the differential equations describing water movement and solute transport using methods such as finite differences and finite elements. Numerical methods can account for complex geometry and heterogenous media, as well as for dispersion, diffusion, and chemical retardation processes (e.g., sorption, precipitation, radioactive decay, ion exchange, degradation). These methods always require a digital computer, greater quantities of data than analytical modeling, and an experienced modeler-hydrogeologist.

3.2.3 Numerical Models

A numerical model for groundwater flow consists of the mathematical framework for the solution of the material balance equations that govern laminar flow through porous or fractured media. These mass balance equations are dependent upon physical constraints and constitutive relationships. The constraints simply state conditions that components of the mass balance equations must satisfy, whereas the constitutive relationships describe the dependence of parameters, in the mass balance equations, on other physical processes. Furthermore, the mass balance equations are composed of both spatial and temporal terms both of which require discretization within the model domain. These terms describe the head or pressure in space and time. Either finite element or finite difference methods can be used to discretize the spatial term in the mass balance equations, whereas finite differences are almost always used to discretize the temporal term.

The mass balance equations, physical constraints, and constitutive relationships lead to a series of equations that must be solved in space and time. The means by which the equations are discretized, linearized (e.g. Newton-Raphson), organized (i.e, matrix construction) and solved with either direct or iterative methods is all part of the numerical model.

3.2.4 Computer Code

It is important that the progression from the conceptual model to the computer model is documented in detail. The discussion for each component of the conceptual model should begin with the laboratory or field studies that provide the fundamental characterization data. Next, the data analysis results that support a particular conceptualization should be presented. As part of the data analysis discussion the basis for screening out reasonable alternative conceptual models should be provided. This type of discussion should be presented not only for major components of the conceptual model (e.g., Darcian versus non-Darcian flow) but also for more obscure assumptions (e.g., sorption may be described by a linear isotherm). Following the development of each major and minor component of the conceptual model, the formulation of the mathematical models and numerical models should be presented.

The linkage between the conceptual model(s), mathematical model(s) and numerical model(s) should be clearly described. For example, conceptual models generally assume a continuum in space and time, whereas mathematical models frequently divide space and time into user specified segments. Furthermore, the implications that this type of simplifying assumption may have on the modeling predictions should be presented.

Following the formulation of the numerical model, the computer program is developed. The computer program consists of the assembly of numerical techniques, bookkeeping, and control language that represents the model from acceptance of input data and instructions to delivery of output.

In summary, the conceptual model is a working description of the characteristics and dynamics of a physical system. Model construction is the process of transforming the conceptual model into a non-unique, simplified, mathematical description of the physical system, coded in computer programming language together with a quantification of the simulated system. An intermediate step in the model transformation process is the mathematical model which consists of two aspects: a process equation and a solution technique to solve the process equation. An analytical solution solves a very simple process equation analytically by hand calculations. An analytical model solves a more complex, but still relatively simple, process equation analytically with a computer program. A numerical model solves a simple or complex process equation numerically with a computer program. In the context of this document, mathematical model refers to all three solution techniques of a process equation. The complexity of the process equation dictates the solution technique required. The model formulation process concludes with the coding of the mathematical model into computer programming language for performing a specified set of operations.

3.3 CODE-RELATED ISSUES

The determination of a computer code's acceptability for a particular application at the WIPP depends on whether the code can meet the modeling objectives. The code evaluation process must also consider attributes that are integral components of the computer code(s) including:

- Source Code Availability
- History of Use
- Quality Assurance
- Code Documentation
- Code Testing
- Hardware Requirements
- Solution Methodology
- Code Dimensionality

3.3.1 Source Code Availability

Detailed documentation of the software, source code and developmental history is required to facilitate independent review. Independent evaluation of the reproducibility of the verification and validation results require compiled version of the code (i.e., computer code in machine language) should be available to the reviewer, together with files containing the original test data used in the code's verification and validation.

3.3.2 History of Use

The evaluation process should rely on documented user experience, in addition to hands-on experience and testing. User experience is especially valuable in determining whether the code functions as documented or has significant errors and shortcomings. In some instances users independent of the developer should perform extensive testing and bench-marking.

3.3.3 Quality Assurance

Code acceptance issues are closely tied to the quality assurance procedures followed during the developmental process of the computer code. These criteria are associated with the adequacy of the code testing and documentation.

Quality assurance in modeling is the procedural and operational framework put in place by the organization managing the modeling program, to assure technically and scientifically adequate execution of all project tasks included in the program, and to assure that all modeling-based analysis is verifiable and defensible (TAY85).

The American Society of Mechanical Engineers (ASME) Committee on Nuclear Quality Assurance has developed standards for the development and use of computer software used in the design and operation of nuclear facilities (ASM90). The standard in NQA-2a-1990 Addenda (Part 2.7) was developed under procedures accredited as meeting the criteria for American National Standards. It addresses the following:

- general requirements
- software life cycle

- software verification and validation
- software configuration control
- documentation
- verification reviews
- problem reporting and corrective action
- access control
- software procurement
- records

Quality assurance requirements in 40 CFR part 194 (§194.23(b)) mandate the use of this standard as the basis for documenting any computer codes used to support a compliance application.

The two major elements of quality assurance are quality control and quality assessment. Quality control refers to the procedures that ensure the quality of the final product. These procedures include the use of appropriate methodology in developing and applying computer simulation codes, adequate verification and validation procedures, and proper usage of the selected methods and codes (HEI92). To monitor the quality control procedures and to evaluate the quality of the studies, quality assessment is applied (HEI89).

Software quality assurance (SQA) consists of the application of procedures, techniques, and tools through the software life cycle, to ensure that the products conform to pre-specified requirements (BRY87). This requires that in the initial stage of the software development project, appropriate SQA procedures (e.g., auditing, design inspection, code inspection, error-prone analysis, functional testing, logical testing, path testing, reviewing, walk-through) and tools (e.g., text-editors, software debuggers, source code comparitors, language processors) need to be identified and the software design criteria be determined (HE92).

Quality assurance for code development and maintenance implies a systematic approach, starting with the careful formulation of code design objectives (section 3.2), criteria, and standards, followed by an implementation strategy. The implementation strategy includes the design of the code structure and a description of the way in which software engineering principles will be applied to the code. In this planning stage, measures are to be taken to ensure complete documentation of code design and implementation, record-keeping of the coding process, description of the purpose and structure of each code segment (functions, subroutines), and record-keeping of the code verification process.

Records for the coding and verification process may include a description of the fundamental algorithms describing the physical process(es) to be modeled; the means by which the mathematical algorithms have been translated into computer code (e.g., FORTRAN); results of discrete checks on the subroutines for accuracy; and comparisons among the codes' numerical solutions with either analytical or other independently verified numerical solutions.

Software used for compliance assessment should have both internal and external documentation. Internal documentation, which is part of the source code, describes the operation of the program and includes the name of the author, other sources of the software, and its revision history. External documentation includes a software abstract, an on-line help file stored on the applicable computer system, records of verification and changes, and formal reports including a theory manual and a user's manual.

Code verification or testing ensures that the underlying mathematical algorithms have been correctly translated into computer code. The verification process varies for different codes and ranges from simply checking the results of a plotting routine to comparing the results of the computer code to known analytical solutions or to results from other verified codes.

Traceability describes the ability of the performance assessment analyst to identify the software that was used to perform a particular calculation, including its name, date, and version number, while retrievability refers to the availability of the same version of the software for further use.

3.3.3.1 Code Documentation

In general, the code documentation should describe the theoretical framework represented by the model on which the code is based, code structure and language standards applied, and code use instructions regarding model setup and code execution parameters. The documentation should also include a complete treatment of the equations on which the model is based, the underlying mathematical and conceptual assumptions, the boundary conditions that are incorporated in the model, the method and algorithms used to solve the equations, and the limiting conditions resulting from the chosen approach. The documentation should also include user's instructions for implementing and operating the code and preparing data files. It should present examples of model formulation (e.g., grid design, assignment of boundary conditions), complete with input and output file descriptions, and include an extensive code verification and validation or field testing report.

Code Documentation Issues. An integral part of the code development process is the preparation of the code documentation. This documentation of QA in model development consists of reports and files pertaining to the development of the model and could include:

- A report on the development of the code including the (standardized and approved) programmer's bound notebook containing detailed descriptions of the code verification process;
- Verification report including verification scenarios, parameter values, boundary and initial conditions, source-term conditions, dominant flow and transport processes;
- Orientation and spacing of the grid and justification;
- Time-stepping scheme and justification;
- Changes and documentation of changes made in code after baselining;
- Executable and source code version of baselined code;
- Input and output (numerical and graphical) for each verification run;
- Notebook containing reference material (e.g., published papers, laboratory results, programmer's rationale) used to formulate the verification problem.

Furthermore, the purpose of the software documentation is to (GAS79):

- record technical information that enables system and program changes to be made quickly and effectively;

- enable programmers and system analysts, other than software originators, to use and to work on the programs;

- assist the user in understanding what the program is about and what it can do;

- increase program sharing potential;

- facilitate auditing and verification of program operations;

- provide managers with information to review at significant developmental milestones so that they may independently determine that project requirements have been met and that resources should continue to be expended;

- reduce disruptive effects of personnel turnover;

- facilitate understanding among managers, developers, programmers, operators, and users by providing information about maintenance, training, and changes in and operation of the software;

- inform other potential users of the functions and capabilities of the software, so that they can determine whether it serves their needs.

The user's information could consist of items such as:

- an extended model description;

- model input data description and format;

- type of output data provided;

- code execution preparation instructions;

- sample model runs;

- trouble shooting guide; and

- contact person/affiliated office.

The programmer's information could consist of items such as:

- model specifications;
- model description;
- flow charts;
- descriptions of routines;
- database description;
- source listing;
- error messages; and
- contact person/affiliated office.

The analyst's information could consist of items such as:

- a functional description of the model;
- model input and output data;
- code verification and validation information; and
- contact person/affiliated office.

The code itself should be well structured and internally well documented; where possible, self-explanatory parameter, variable, subroutine, and function names should be used.

3.3.3.2 Code Testing

Before a code can be used as a planning and decision-making tool, its credentials must be established through systematic testing of the model's correctness and evaluation of the model's performance characteristics (HEI89). Of the two major approaches available, the evaluation or review process is qualitative in nature, while code-testing results can be expressed using quantitative performance measures. Code testing (or code verification) is aimed at detecting programming errors, testing embedded algorithms, and evaluating the operational characteristics of the code through its execution on carefully selected example test problems and test data sets. ASME standard in NQA-2a-1990 Addenda (Part 2.7) defines software verification as the process of determining whether or not the product of a given phase of the software development cycle fulfills the requirements imposed by the previous phase.

It is necessary to distinguish between generic simulation codes based on an analytical solution of the governing equation(s) and codes that include a numerical solution. Verification of a coded analytical solution is restricted to comparison with independently calculated results using the same mathematical expression, i.e., manual calculations, using the results from computer programs coded independently by third-party programmers. Verification of a code formulated with numerical methods might take two forms: (1) comparison with analytical solutions, and (2) code intercomparison between numerically based codes, representing the same generic simulation model, using synthetic data sets.

It is also important to distinguish between code testing and model testing. Code testing is limited to establishing the correctness of the computer code with respect to the criteria and requirements for which it is designed (e.g., to represent the mathematical model). Model testing (or model validation) is more inclusive than code testing, as it represents the final step in determining the validity of the quantitative relationships derived for the real-world system the model is designed to simulate.

Attempts to validate models must address the issue of spatial and temporal variability when comparing model predictions with limited field observations. If sufficient field data are obtained to derive the probability distribution of contaminant concentrations, the results of a stochastic model can be compared directly. For a deterministic model, however, the traditional approach has been to vary the input data within its expected range of variability (or uncertainty) and determine whether the model results satisfactorily match historical field measured values. This code-testing exercise is sometimes referred to as history matching.

See Chapter 2 for additional Quality Assurance discussions.

3.3.4 Hardware Requirements

In general, hardware requirements are rarely a discriminatory factor in the selection of a computer code. However, a number of the codes that DOE intends to use in modeling the WIPP will require very sophisticated hardware, not so much because of the intrinsic requirements of the code but because the processes to be modeled are very complex.

3.3.5 Mathematical Solution Methodology

Every groundwater or contaminant transport model is based upon a set of mathematical equations. Solution methodology refers to the strategy and techniques used to solve these equations. In groundwater modeling, the equations are normally solved for head and/or contaminant concentrations. Other disposal system processes will be modeled with codes that solve for gas-filled porosities and the quantity of radioactive material (in curies) brought to the surface as cuttings generated by a drilling operation that penetrates the disposal system.

Analytical solutions are used in modeling investigations to solve many different kinds of problems. For example, aquifer parameters are obtained from aquifer pumping and tracer tests through the use of analytical models, and groundwater flow and contaminant transport rates can also be estimated with the use of analytical models.

Numerical models provide solutions to the differential equations describing room collapse, water movement, and solute transport using numerical methods such as finite differences and finite elements. Numerical methods account for complex geometry and heterogeneous media, as well as dispersion, diffusion, matrix deformation, salt creep and chemical retardation processes (e.g., sorption, precipitation, radioactive decay, ion exchange, degradation). These methods almost always require a digital computer, greater quantities of data than analytical modeling, and experienced modelers.

The validity of the results from mathematical models depends strongly on the quality and quantity of the input data. Stochastic, numerical, and analytical codes have strengths and weaknesses inherent within their formulations.

3.3.6 Code Dimensionality

The determination as to the number of dimensions that a code should be able to simulate is based primarily upon the modeling objectives and the dimensionality of the processes the code is designed to simulate.

In determining how many dimensions are necessary to meet the objectives, a basic understanding is needed of how the physical processes (e.g., salt creep, groundwater flow, transport, dose rate) are affected by the exclusion or inclusion of an additional dimension.

The movement of groundwater and contaminants is usually controlled by advective and dispersive processes which are inherently three-dimensional. Advection is more responsible for the time (i.e., travel time) it takes for a contaminant to travel from the source term to a downgradient receptor, while dispersion directly influences the concentration of the contaminant along its travel path. This fact is very important in that it provides an intuitive sense for the effect dimensionality has on contaminant migration rates and concentrations.

As a general rule, the fewer the dimensions, the more the model results will over-estimate concentrations and under-estimate travel times. In a model with fewer dimensions, predicted concentrations will generally be greater because dispersion, which is a three-dimensional process, will be dimension limited and will not occur to the same degree as it actually would in the field. Similarly, predicted travel times will be shorter than the actual travel time, not because of a change in the contaminant velocities but because a more direct travel path is assumed. Therefore, the lower dimensionality models tend to be more conservative in their predictions and are frequently used for screening analyses.

One-dimensional simulations of contaminant transport usually ignore dispersion altogether, and contamination is assumed to migrate solely by advection, which results in a highly conservative approximation. Vertical analyses in one dimension are generally reserved for evaluating flow and transport in the unsaturated zone. In the 1992 PA modeling of the Culebra Dolomite, advective and dispersive flow and transport were modeled in two dimensions with SECO, whereas matrix diffusion was confined to one dimension. This type of mixed-dimensionality approach is not uncommon early in a modeling analysis.

Two-dimensional analyses of an aquifer flow system can be performed as either a planar representation, where flow and transport are assumed to be horizontal (i.e., longitudinal and transverse components), or as a cross-section where flow and transport components are confined to vertical and horizontal components. In most instances, two-dimensional analyses are performed in an areal orientation, with the exception of the unsaturated zone, and are based on the assumption that most contaminants enter the saturated system from above and that little vertical dispersion occurs. However, a number of limitations accompany two-dimensional planar simulations. These include the inability to simulate multiple layers (e.g., aquifers and aquitards) as well as any partial penetration effects. Furthermore, because vertical components of flow are ignored, a potentially artificial lower boundary on contaminant migration has been automatically assumed which may or may not be the case.

A two-dimensional formulation of the flow system is frequently sufficient for the purposes of risk assessment provided that flow and transport in the contaminated aquifer are essentially horizontal. The added complexities of a site-wide, three-dimensional flow and transport simulation are often believed to outweigh the expected improvement in the evaluation of risk. Complexities include limited site-wide hydraulic head and lithologic data with depth and significantly increased computational demands.

Quasi three-dimensional analyses remove some of the limitations inherent in two-dimensional analyses. Most notably, quasi three-dimensional simulations allow for the incorporation of multiple layers; however, flow and transport in the aquifers are still restrained to longitudinal and transverse horizontal components, whereas flow and transport in the aquitards are even further restricted to vertical flow components only. Although partial penetration effects still cannot be accommodated in quasi three-dimensional analyses, this method can sometimes provide a good compromise between the relatively simplistic two-dimensional analysis and the complex, fully three-dimensional analysis. This is the case particularly if vertical movement of contaminants or recharge from the shallow aquifer through a confining unit and into a deeper aquifer is suspected.

Fully three-dimensional modeling generally allows both the geology and all of the dominant flow and transport processes to be described in three dimensions. This approach is usually the most reliable means of predicting groundwater flow and contaminant transport characteristics, provided that sufficient representative data are available for the site.

3.4 MODEL APPLICATION

The application of a generic simulation model to a site-specific problem is often called "model application" or "(computer/simulation) code application." The application of a generic model to site-specific conditions should follow a well-structured model application protocol. Such protocols are described by Mercer and Faust (MER81), van der Heijde et. al (HEI88), and Anderson and Woessner (AND92), among others. Quality assurance in these types of studies follows the same pattern as discussed for generic model development projects and consists of using appropriate data, data analysis procedures, modeling methodology and technology, administrative procedures and auditing. To a large extent, the quality of a modeling study is determined by the expertise of the modeling and quality assessment teams. The following discussion is consistent with procedures found in an EPA-sponsored publication (HEI92).

Quality assurance in code application addresses all facets of the modeling process, including such issues as:

- Historical review of code verification and benchmarking process;
- Correct and clear formulation of problems to be solved;
- Project description and objectives;
- Type of modeling approach to the project;
- Decision whether modeling is the best available approach and if so, that the selected code is appropriate and cost-effective;
- Conceptualization of system and processes, including hydrogeologic framework, boundary conditions, stresses, and controls;
- Detailed description of assumptions and simplifications, both explicit and implicit (to be subject to critical peer review);
- Data acquisition and interpretation;
- Code selection considerations, or justification for modifying an existing code or developing a new one;
- Model preparation (parameter selection, data entry or reformatting, gridding);
- Validity of the parameter values used in the model application;
- Protocols for parameter estimation and model calibration to provide guidance, especially for sensitive parameters;
- Level of information in computer output (variables and parameters displayed; formats; layout);
- Identification of calibration goals and evaluation of how well they have been met (e.g., root-mean square errors, etc.);
- Role of sensitivity analysis in evaluating parameter uncertainties and creating probability distributions;

- Post-simulation analysis (including verification of reasonableness of results, uncertainty analysis, and the use of manual or automatic data processing techniques, as for contouring);

- Establishment of appropriate performance targets which should characterize the limits of the data;

- Presentation and documentation of results;

- Evaluation of how closely the modeling results answer the questions raised by management.

QA for model application should include complete record-keeping of each step of the modeling process. The paper trail for QA should consist of reports and files addressing the following items:

- Assumptions and limitations;

- Parameter or input values and sources including rationale for their selection, range, and distribution;

- Boundary and initial conditions;

- Nature of grid and grid design justification;

- Changes and verification of changes made in code;

- Actual input used;

- Output of model runs and interpretation;

- Validation (or at least calibration) of model.

As is the case with code development QA, all data files, source codes, and executable versions of computer software used in the modeling study should be retained for auditing or post-project re-use (in hard-copy and, at higher levels, in digital form) including:

- Version of the source and executable image of the code used;

- Calibration input and output;

- Verification input and output;

- Application input and output (e.g., for each of the scenarios studied).

If the code used in the modeling study is modified, then the code should be tested again according to a standard testing protocol; the code should be subject to the full QA procedure for code development, including accurate record-keeping and reporting. All new input and output files should be saved for inspection and possible re-use together with existing files, records, codes, and data sets.

3.5 REFERENCES

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4. Waste Characterization

4.1 INTRODUCTION

Proper characterization of the waste slated for disposal at the WIPP site is an essential element in assessing whether the repository meets the disposal standards set forth in 40 CFR part 191. To set the stage for the subsequent discussion, it is first necessary to define certain terms. Key definitions are as follows:

- A waste characteristic is a property of the waste that has an impact on the containment of the waste in the disposal system. Examples of waste characteristics include solubility of radionuclides, ability of the radionuclides to become part of stable colloids, gas generation potential from corrosion, microbial degradation or radiolysis, and various strength properties.

- A waste component is an ingredient of the total inventory of the waste that influences a waste characteristic. Examples of waste components include the quantity of metals, cellulosics and organic ligands, and the quantity of radioactivity (curies) associated with each radionuclide.

- Waste characterization is the process of determining the chemical, radiological, and physical properties of the waste. Waste characterization techniques include the use of process knowledge, laboratory and field experimentation, literature search, technical judgement, non-destructive examination/assay, and destructive analysis.

This chapter discusses the various regulations including 40 CFR part 191 which drive waste characterization, the ways in which waste characteristics can impact performance assessment (PA), the methods used for characterizing the waste, and the rationale for the waste characterization requirements of the 40 CFR part 194 rule.

4.1.1 Brief History of DOE's TRU Waste Characterization Program

DOE's TRU waste characterization program is based on the requirements developed for the proper handling and disposal of TRU wastes intended for the WIPP. Historically, this characterization has focused on two types of techniques; empirical — laboratory analyses to quantify hazardous and radioactive waste constituents such as metals, volatile organic compounds, Pu-239, etc.; and, informational based — the use of process/acceptable knowledge derived from site operations to classify wastes according to established categories.

This report describes the various facilities at TRU waste generator sites that are dedicated to characterizing TRU wastes via routine or modified chemical and radiochemical analyses.[1] Consistent with the 40 CFR part 194 rule, these aspects relate to *waste components*, as defined above. However, this definition of waste characterization excludes *waste characteristics*, which have historically been addressed under experimental programs, such as the Actinide Source Term Program (ASTP). The definition of *waste characterization* must be expanded accordingly to include these other aspects. As discussed in subsequent sections, the current DOE waste acceptance criteria and waste characterization guidance documents do not address the requirements of 40 CFR part 194 concerning *waste characteristics*.

4.1.1.1 DOE WIPP Waste Acceptance Criteria (WAC)

DOE developed and published tentative criteria for the acceptance of TRU waste produced under the defense related programs (DOE91) in 1980. These criteria were developed to ensure the safety of all operations at the WIPP. The waste acceptance criteria document was intended to provide: 1) criteria for use in project design; 2) technical justification for the WAC; and 3) quantitative guidelines to be used by waste generators for certifying TRU wastes. The criteria do not specifically stipulate whether further waste treatment or processing will be required, but DOE recognized that this decision would have to be made in the future. Revision 4 of the WAC, published in 1991, included additional criteria relevant to waste transportation and regulatory requirements for hazardous waste in order to provide a single, comprehensive document for all parties involved with the shipment and handling of WIPP waste. These criteria are summarized in Table 4-1. Revision 4 of the WAC also describes the relationship among the various DOE guidance documents that address characterization of TRU wastes, including the WIPP TRU Waste Characterization Quality Assurance Program Plan (TRU QAPP) (DOE94b) and the generator and/or storage site Quality Assurance Project Plans (QAPjPs). However, as discussed below, the WAC document is outdated and is not integrated with the TRU QAPP.

The Waste Acceptance Criteria Certification Committee (WACCC) is responsible for developing the WIPP WAC and verifying compliance of TRU waste with the WIPP WAC at the generator/storage facilities. According to DOE, compliance will be demonstrated through audits and surveillances at waste generators (DOE91). It should be noted that WAC

[1] Many standard analytical protocols have been modified to accommodate the analytical and radiological aspects of analyzing materials heavily contaminated with Pu-239.

Table 4-1. Summary of Waste Acceptance Criteria and Requirements[1]

WAC Criterion/ Requirement & Section	CH or RH	WIPP Operations and Safety Criteria	Transportation: Waste Package Requirements: TRAMPAC/RH-Cask[2]	RCRA Requirements	Performance Assessment Criteria
Waste Container Requirements/Criteria					
Waste Containers 3.2.1	CH	*Type A, Noncombustible*	*55-gal drums, SWBs, or SWB Overpack of 55-gal Drums or Test Bin*	No Additional Requirements	Same as Transportation
	RH	*Type A, Noncombustible*	*RH Canister*	No Additional Requirements	None
Waste Package Size 3.2.2	CH	Maximum dimension specified	*55-gal Drums in Two Seven Packs, of Two SWBs*	None	Same as Transportation
	RH	*RH Canister*	RH Canister	None	None
Waste Package Handling 3.2.3	CH	Drum and Box Handling Attachments	*Seven Packs, or SWBs*	None	No Additional Requirements
	RH	*Axial Pintle*	Axial Pintle	None	None
Waste Form Requirements/Criteria					
Immobilization 3.3.1	CH & RH	*≤ 1% Below 10 Microns, ≤ 15% Below 200 Microns*	None	No Additional Requirements	Same as WIPP Operation
Liquids 3.3.2	CH & RH	*Only Residual Liquids (see definitions in Section 3.3.2.1)*	< 1 Volume Percent	No Additional Requirements	< 1 Volume Percent
Pyrophoric Materials 3.3.3	CH & RH	≤ 1% Radionuclides, No Non-Radionuclide Pyrophorics	*≤ 1% Radionuclides, No Non-Radionuclide Pyrophorics*	*See Section 3.3.5.3*	Same as Transportation
Explosives and Compressed Gases 3.3.4	CH & RH	Not Permitted, 49 CFR 173 Subpart C and G	*Explosives and compressed gases are not permitted*	*See Section 3.3.5.3*	No Additional Requirements

Table 4-1. Summary of Waste Acceptance Criteria and Requirements (Continued)

WAC Criterion/ Requirement & Section	CH or RH	WIPP Operations and Safety Criteria	Transportation: Waste Package Requirements: TRAMPAC/RH-Cask[2]	RCRA Requirements	Performance Assessment Criteria
Waste Form Requirements/Criteria (Cont.)					
TRU Mixed Wastes 3.3.5	CH & RH	*Hazardous Waste must be Reported*	*Corrosives are not permitted*	*WIPP RCRA parts A & B Permit Applications, WAP, NMD*	No Additional Requirements
Specific Activity of Waste 3.3.6	CH	*> 100 nCi/g TRU*	Same as WIPP Operations	None	Same as WIPP Operations
	RH	*> 100nCi/g TRU ≤ 23 Ci/liter total*	Same as WIPP Operations	None	Same as WIPP Operations
Waste Package Requirements/Criteria					
Waste Package Weight 3.4.1	CH	< 21,000 lbs	*1000 lbs per drum, 4000 lbs per SWB, 7265 lbs per TRUPACT-II payload, 19,250 lbs per TRUPACT-II, 80,000 lbs GVW (DOT)*	None	None
	RH	*< 8,000 lbs*	RH-Cask TBD	None	None
Nuclear Criticality (Pu-239 FGE) 3.4.2	CH	See List in 3.4.2.1	*< 200 g/drum < 325 g/SWB, or < 325 g/TRUPACT-II*	None	Same as Transportation
	RH	≤ 600 g	*< 325 g/cask*	None	Same as Transportation
Pu-239 Equivalent Activity 3.4.3	CH & RH	*≤ 1000 PE-Ci/ package*	None	None	None
Surface Dose Rate 3.4.4	CH	*≤ 200 mrem/hr*	*≤ 200 mrem/hr, DOT Package Limits, and Shielded Packages per SARP*	None	Same as WIPP Operations
	RH	*95% ≤ 100 rem/hr. 5% ≤ 1000 rem/hr.*	RH-Cask TBD and DOT Package Limits	None	None

Table 4-1. Summary of Waste Acceptance Criteria and Requirements (Continued)

WAC Criterion/ Requirement & Section	CH or RH	WIPP Operations and Safety Criteria	Transportation: Waste Package Requirements: TRAMPAC/RH-Cask[2]	RCRA Requirements	Performance Assessment Criteria
Waste Package Requirements/Criteria (Cont.)					
Removable Surface Contamination 3.4.5	CH & RH	*≤ 50 pCi/100 cm^2 alpha, ≤ 450 pCi/100 cm^2 beta-gamma*	None	None	Same as WIPP
Thermal Power 3.4.6	CH	No Limit Report if > 0.1 watts/ft^3	*Refer to Limits in TRUPACT-II SAR Section 1.2.3.3*	None	Same as Transportation
	RH	*≤ 300 watts/canister*	RH-Cask TBD	None	None
Gas Generation 3.4.7	CH	Vented	*TRAMPAC Limits: See requirements in Section 3.4.7.2, ≤ 500 ppm Flammable VOCs; Chemical compatibility study; all trace chemicals < 5 weight percent*	NMD Requirements Apply	SNL Test Plan
	RH	Vented	RH-Cask TBD	None	Same as CH
Labeling 3.4.8	CH	*Id Number, DOT*	*Id Number and Waste Shipping Category*	Same as DOT	None
	RH	*Id Number, DOT*	RH-Cask TBD	TBD	None
Data Package Requirements/Criteria					
Data Package/ Certification 3.5.1	CH	*Certification, WWIS Information, Data Format*	*Tables 13.1 to 13.3 in Appendix 1.3.7 (TRAMPAC)*	*Hazardous Waste Manifest per 40 CFR part 262 NMD and QAPP Requirements*	*PA Data Package, QAPP Requirements*
	RH	*Certification, WWIS Information, Data Format*	RH-Cask TBD	TBD	None

Table 4-1. Summary of Waste Acceptance Criteria and Requirements (Continued)

WAC Criterion/ Requirement & Section	CH or RH	WIPP Operations and Safety Criteria	Transportation: Waste Package Requirements: TRAMPAC/RH-Cask[2]	RCRA Requirements	Performance Assessment Criteria
Other Requirements/Criteria					
Additional Requirements 3.6.1	CH	None	***One Shipping Category per TRUPACT-II, Authorized TRUCON Content Codes, Waste Aspirated per SARP, Payload Control Procedures***	Regulations or Permit Conditions as Determined by NMED	None
	RH	None	RH-Cask TBD	TBD	None

1 - Limiting parameters are shown in bold italics.
2 - RH Cask limits have been finalized.

Source: Waste Acceptance Criteria for the Waste Isolation Pilot Plant (DOE91)

audits have not been performed at waste generator sites for the last two years. Historically, the WIPP WAC has been disconnected from waste characterization activities at the generator sites, precluding a prospective incorporation of WAC related requirements in generator site's ongoing waste generation practices. DOE plans to integrate the WAC in site waste generation activities in support of its greater reliance on process knowledge as the main waste characterization tool for newly generated wastes (DOE94d). The TRU waste generator sites differ in their individual approaches to the generation and characterization of TRU waste.

4.1.1.2 WIPP TRU QAPP

DOE released Revision B of the TRU QAPP in July, 1994. This document replaced the Waste Characterization Program Plan for WIPP Experimental Waste and the Quality Assurance Program Plan for the WIPP Experimental Waste Characterization Program. In the TRU QAPP, DOE

> identifies the quality of data necessary, and techniques designed to attain and ensure the required quality, to meet the specific objectives associated with the Department of Energy (DOE) Waste Isolation Pilot Plant (WIPP) Transuranic Waste Characterization Program (DOE94b).

This document provides guidance for the TRU waste generator sites in developing their site-specific QAPjPs. The QAPjPs contain detailed information regarding how the site will achieve the data quality objectives (DQOs) for the various waste characterization techniques. It is worth noting that neither this document nor the DOE Carlsbad Area Office's (CAO) guidance on the use of acceptable knowledge provides DQOs for waste characterization performed using acceptable knowledge (DOE94b, DOE95c).

4.2 REGULATORY DRIVERS FOR WASTE CHARACTERIZATION

This section briefly summarizes the various laws, regulations, and agreements which underlie the WIPP WAC and the specific waste characterization requirements which are distilled from these sources. The sources discussed include:

- Agreement for Consultation and Cooperation between DOE and the State of New Mexico
- The WIPP Land Withdrawal Act (LWA)
- NRC regulations for the packaging and transportation of radioactive waste (10 CFR part 71)
- Department of Transportation regulations
- Resource Conservation and Recovery Act and amendments
- The Federal Facilities Compliance Act (FFCA) of 1992
- EPA Toxic Substance Control Act regulations
- EPA 40 CFR part 191
- EPA WIPP compliance criteria (40 CFR part 194)

From the summary it will be clear that waste characterization, in various forms, is required not only to satisfy 40 CFR parts 191 and 194, but a variety of other regulations and agreements as well.

In certain instances, the regulatory framework separates the radioactive waste into two categories: 1) contact-handled transuranic waste (CH-TRU) and 2) remote-handled transuranic waste (RH-TRU). Definitions and restrictions applicable to each type of radioactive waste are presented in the ensuing discussion, where appropriate.

4.2.1 Agreement for Consultation and Cooperation—July 1, 1981

An Agreement for Consultation and Cooperation (the Agreement) between the State of New Mexico and the U.S. Department of Energy was signed by the parties on July 1, 1981. Appendix B to this Agreement is entitled Working Agreement for Consultation and Cooperation (the Working Agreement). Article IV of the Working Agreement provides a basis for the State to comment on waste acceptance criteria as described in IV.E.1.(c):

> DOE has provided this documentation to the State. Any State comments as to public health and safety concerns shall be provided to the DOE WIPP Project Manager within ___[2] calendar days after receipt of documentation from DOE. DOE shall respond to the State comments within ___[2] calendar days after receipt of such comments. Nothing herein shall preclude further discussions of the matter or any updates prepared by DOE. Reasonable time frames for State comments and DOE response to any DOE updates shall be negotiated by the principal representatives of the parties.

The Agreement and the Working Agreement were modified in November 1984 under the First Modification to the July 1, 1981 "Agreement for Consultation and Cooperation" on the WIPP by the State of New Mexico and the U.S. Department of Energy. Article VI.B of the Agreement was revised to set certain limitations on remote-handled transuranic waste including the following maximum values for specified parameters:

- volume — 250,000 cubic feet[3]
- surface dose rate — 1,000 rem/h
- volume with surface dose greater than 100 rem — 12,500 cubic feet
- activity level (averaged over canister volume) — 23 Curies (Ci)/l
- amount of radioactivity — 5.1 million Ci

The First Modification further specified that the concentrations of radionuclides in the RH-TRU canisters would be determined by one or more of the following methods: "(1) materials accountability; (2) classification by source; (3) gross radioactivity measurements; (4) direct measurements of major contributing radionuclides; or (5) such other methods as the parties may agree to."

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[2] To be negotiated in original agreement.

[3] This is 4% of the total waste volume.

A second modification to the Agreement was implemented on August 4, 1987 which included, among other things, amendment of Article VI.E to contain the following paragraph:

> "4. The transportation of radioactive waste to WIPP shall comply with the applicable regulations of the U.S. Department of Transportation and any applicable corresponding regulations of the U.S. Nuclear Regulatory Commission. All waste shipped to the WIPP will be shipped in packages which the Nuclear Regulatory Commission has certified for use."

4.2.2 WIPP LWA

The WIPP LWA was signed into law on October 30, 1992. Several items in the LWA relate to waste characterization including relevant definitions and limitations (particularly those involving RH-TRU waste). The following definitions from Section 2 of the LWA are important to waste characterization:

> "(20) TRANSURANIC WASTE — The term "transuranic waste" means waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes per gram of waste, with half lives greater than 20 years, except for—
>
> > (A) high-level radioactive waste
> >
> > (B) waste that the Secretary has determined with the concurrence of the Administrator, does not need the degree of isolation required by the disposal regulations; or
> >
> > (C) waste that the Nuclear Regulatory Commission has approved for disposal on a case-by-case basis in accordance with part 61 of title 10, Code of Federal Regulations."[4]
>
> "(3) CONTACT-HANDLED TRANSURANIC WASTE — The term "contact-handled transuranic waste" means transuranic waste with a surface dose rate not greater than 200 millirem per hour."

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[4] The apparent intent of exceptions (B) and (C) is to preclude shipment to the WIPP of wastes which meet the transuranic waste definition, but can be properly disposed in other than a geologic repository (e.g., greater than Class C wastes (as defined in §61.55)).

"(4) REMOTE-HANDLED TRANSURANIC WASTE — The term "remote-handled transuranic waste" means transuranic waste with a surface dose rate of 200 millirem per hour or greater."[5]

Section 7 of the LWA imposes the following waste-related limitations:

- Restrictions of remote-handled transuranic waste (RH-TRU)
  - 1,000 rem/h maximum surface dose rate
  - surface dose rate less than 100 rem/h for 95% by volume of all RH-TRU
  - Canister activity limited to 23 Ci/liter (averaged over the canister volume)
  - Total RH-TRU radioactivity is limited to 5.1×10^6 Ci
- Repository capacity — 6.2 million cubic feet of transuranic waste

Most of the waste requirements in Section 7 are also included in the First Modification to the Agreement for Consultation and Cooperation between DOE and the State of New Mexico (Section 4.2.1 above).

In Section 12, Congress made clear its intent that disposal at the WIPP be limited to TRU wastes by prohibiting the shipment and disposal of high-level radioactive waste or spent nuclear fuel.[6] In Section 16, it further specified that the TRU waste must be shipped to the WIPP in containers whose design is certified by NRC and whose QA requirements meet NRC standards.

[5] According to the LWA definitions of CH-TRU and RH-TRU, waste with a surface dose of exactly 200 millirem per hour meets both definitions.

[6] These terms are defined in Section 2 of the Nuclear Waste Policy Act of 1982 as follows:
12. "High-level radioactive waste": (A) The highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such waste that contains fission products in sufficient concentrations; and (B) other highly radioactive material that the Commission, consistent with existing law, determines by rule requires permanent isolation.
23. "Spent nuclear fuel" means fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated for reprocessing.

4.2.3 NRC Regulations for the Packaging and Transportation of Radioactive Waste (10 CFR part 71)

In 10 CFR part 71, the NRC sets "(1) requirements for packaging, preparation for shipment, and transportation of licensed material; and (2) procedures and standards for NRC approval of packaging and shipping procedures for fissile material and for a quantity of other licensed material in excess of a Type A quantity"[7] (§71.0). Under this rule, packages must be approved for each specific use. Subpart D of the rule defines the contents of the application for approval of a transportation package. (In the case of WIPP, the application approval package is the Safety Analysis Report (SAR) for the TRUPACT-II Shipping Package. Revision 0 was issued in February 1989. The latest revision is No. 14 which was issued in October, 1994.) The package description in the approval application must include the following information with regard to the contents of the shipping package (§71.33):

- Identification and maximum radioactivity of the radioactive constituents
- Identification and maximum quantities of fissile constituents
- Chemical and physical form
- Extent of reflection, the amount and identity of nonfissile materials used as neutron absorbers or moderators, and the atomic ratio of moderator to fissile constituents
- Maximum normal operating pressure
- Maximum weight
- Maximum amount of decay heat
- Identification and volumes of any coolants

The DOE shipping package application for the TRUPACT-II Shipping Package has been assigned Docket No. 71-9218 by the NRC who issued a Certificate of Compliance No. 9218

[7] A Type A quantity is an amount of radioactive material which does not exceed certain isotope-specific limits stipulated in Appendix A of 10 CFR Part 71.

(DOE93a) for use of this container to ship CH-TRU.[8] Revision 5 (June 9, 1994) of this certificate specifies the following limitations on the contents of the TRUPACT-II based on the items from §71.33 listed above:

> "Dewatered, solid or solidified transuranic wastes. Waste must be packaged in 55-gallon drums, standard waste boxes (SWB) or bins. Waste must be restricted to prohibit explosives, corrosives, nonradioactive pyrophorics, and pressurized containers. Within a drum, bin, or SWB radioactive pyrophorics must not exceed 1 percent by weight and free liquids must not exceed 1 percent by volume. Flammable organics are limited to 500 ppm in the headspace of any drum, bin, or SWB."
>
> "Contents not to exceed 7,265 pounds including shoring and secondary containers, with no more than 1,000 pounds per 55-gallon drum and 4,000 pounds per SWB."
>
> "Fissile material not to exceed 325 grams Pu-239 equivalent with no more than 200 grams Pu-239 equivalent per 55-gallon drum and 325 grams of Pu-239 equivalent per SWB."
>
> "Decay heat must not exceed values specified in Tables 6.1 through 6.3 of "TRUPACT-II Content Codes," (TRUCON), DOE/WIPP 89-004, Rev. 6."
>
> "Physical form, chemical properties, chemical compatibility, configuration of waste containers and contents, isotopic inventory, fissile content, decay heat, weight and center of gravity, radiation dose rate must be limited in accordance with Appendix 1.3.7 of the application, "TRUPACT-II Authorized Methods for Payload Control," (TRAMPAC)."
>
> "Each drum, bin, or SWB must be assigned to a shipping category in accordance with Table 5, "TRUPACT-II Content Codes," (TRUCON), DOE/WIPP 89-004, Rev. 6, or must be tested for gas generation and meet the acceptance criteria in accordance with Attachment 2.0 of Appendix 1.3.7 of the application."

As noted above, the Certificate of Compliance specifies that waste properties are determined and limited according to the specifications in TRAMPAC. TRAMPAC (Appendix 1.3.7 to the SAR) is the document which provides acceptable methods for the preparation and

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[8] As of the date of publication of this document, the most recent revision to the TRUPACT-II Shipping Package Application is Revision 14 submitted to NRC by Westinghouse (on behalf of DOE) on October 14, 1994. The current revision and revision date for other related documents are as follows:

- TRUPACT-II Content Codes (TRUCON) - Revision 8, October 1994
- TRUPACT-II Safety Analysis Report (SAR) - Revision 14, October 1994
- Certificate of Compliance No. 9218 - Revision 6, March 30, 1995

characterization of payloads for transport in TRUPACT-II. Parameters for which TRAMPAC specifically identifies restrictions are as follows:

- Physical and chemical form of the CH-TRU waste
- Chemicals to ensure chemical compatibility between all constituents in a given shipment
- Maximum pressure in a package during a sixty-day transport period
- Amount of potentially flammable gases that might be present or generated in the payload during a sixty-day transport period
- Layers of confinement (e.g., plastic bagging) in payload containers
- Fissile material content for individual payload containers and the total package
- Decay heat for individual payload containers and the total package
- Weight of the individual payload containers and the loaded TRUPACT-II
- Center of gravity for the payload assembly to be transported in TRUPACT-II
- Dose rate of individual payload containers, the total package, and three loaded packages on a truck trailer

The foregoing discussion is specific to CH-TRU waste. Currently there is no approved shipping container for RH-TRU waste. DOE plans call for RH-TRU to be shipped in the RH-72B, which is a scaled down version (5/8 scale) of the NuPac 125B container certified by NRC and used to ship waste from Three-Mile Island Unit 2 (DOE93a).

The TRAMPAC provides some detail on how various parameters are to be tested. For example, Section 9.4, <u>Methods of Determination and Control of Radionuclides</u>, specifies five allowable methods for the identification and quantification of radionuclides in TRU waste including:

- passive gamma
- radiochemical assay using alpha and gamma spectroscopy
- passive neutron coincidence counting
- passive-active neutron assay
- calorimetry

Attachment 3.0 to the TRAMPAC discusses each of the allowable methods including typical errors, sensitivities, calibration standards, assay procedures, and operator training. These topics are addressed further in the WIPP Transuranic Waste Quality Assurance Program Plan (DOE94b) and the site specific Quality Assurance Project Plans.

4.2.4 U.S. Department of Transportation Regulations: 49 CFR part 173 — Shippers — General Requirements For Shipments and Packaging

The Department of Transportation (DOT) has jurisdiction over hazardous materials shipments affecting intrastate and interstate commerce (DOE93a). This authority is derived from the Hazardous Materials Transportation Act of 1975 as amended by the Hazardous Materials Transportation Uniform Safety Act of 1990. Subpart I of 49 CFR part 173 sets out DOT regulations for the shipment of radioactive materials. Basically, the DOT regulations provide that any package which meets the applicable requirements of NRC regulation 10 CFR part 71 is authorized for shipment (49 CFR 173.416(b)). The DOT regulations add no additional waste characterization requirements beyond those already imposed by the NRC.

4.2.5 Resource Conservation and Recovery Act (RCRA)

The Resource Conservation and Recovery Act of 1976 (RCRA) and the Hazardous and Solid Waste Amendments of 1984 (HSWA) provide the statutory framework for the regulation of hazardous wastes at the WIPP. Under HSWA, certain "listed" and "characteristic hazardous" wastes are prohibited from land disposal unless the wastes meet specified treatment standards or it can be demonstrated to a reasonable degree of certainty that there will be no migration of hazardous constituents from the disposal unit for as long as the wastes remain hazardous. Migration of hazardous constituents outside the unit boundary must not exceed health-based limits (EPA92). The approach being taken by DOE at the WIPP is to seek a no migration variance rather than meet the technology-based treatment standards.

Requirements of a petition to seek a no migration variance are set forth in 40 CFR part 268—Land Disposal Restrictions. Specific requirements (§268.6) which relate to waste characterization are:

> §268.6(a)(2) A waste analysis to fully describe the chemical and physical characteristics of the subject waste [must be provided]

§268.6(b)(1) All waste .... sampling, test, and analysis data must be accurate and reproducible to the extent that state-of-the art techniques allow

§268.6(b)(2) All sampling, testing, and estimation techniques for physical and chemical properties of the waste .... must have been approved by the Administrator

§268.6(b)(3) Simulation models must be calibrated for the specific waste .... conditions and verified for accuracy by comparison with actual measurements.

The No Migration Guidance Manual for Petitioners (EPA92) elaborates on the waste analysis dictated under §268.6(a)(2) noting that "proper management of wastes for as long as they remain hazardous requires that potential incompatibilities and waste transformation mechanisms be assessed." Some additional guidance provided in the Manual regarding details of waste descriptions is summarized below:

- Waste types and sources
  - applicable waste codes (EPA and industrial)
  - waste-generating processes
  - hazardous constituents and their properties
  - quantities of waste to be disposed
  - rate of disposal
  - handling and storage practices

- Waste characteristics
  - potential for leachate formation
  - waste solubilities
  - hazardous-constituent vapor pressures
  - other factors affecting waste mobility
  - analytical testing results for 40 CFR part 261 Appendix VIII hazardous constituents reasonably expected to be present in the waste

- Waste incompatibilities
  - potential chemical interactions
  - identification and characteristics of reaction products

- Waste transformation mechanisms
  - biodegradation
  - photodegradation
  - hydrolysis
  - oxidation/reduction
  - volatilization

In 1990, EPA granted DOE a conditional no migration variance to permit DOE to implement an underground test program with a limited quantity of actual TRU waste at the WIPP (55 FR 47700). DOE subsequently canceled the test program so the no migration variance was never exercised. However, some of the conditions imposed by EPA in this conditional variance are instructive as presaging future EPA requirements when DOE seeks a final no migration variance to dispose of TRU wastes in the repository.[9] It is recognized that the conditional variance was based on short-term no migration considerations over a ten-year test phase with particular focus on air emissions. Thus, some of the conditions specified in granting the variance may not be indicative of requirements for permanent disposal.
In granting the conditional variance, EPA imposed the following requirements relating to waste analysis:

> To ensure that each waste container had no layer of confinement which contains flammable mixtures of gases or mixtures of gases which could become flammable when mixed with air, samples of gas from the head space in each container must be analyzed for hydrogen, methane, and volatile organic compounds. It must also be demonstrated that the headspace gas is representative of the gas within all layers of confinement in a container.
>
> To ensure that the wastes to be emplaced are compositionally similar to the wastes on which the no migration petition was based, representative samples of headspace gas must be analyzed and compared to compositions supplied with the petition. If the results are not comparable, the waste may not be shipped to WIPP (without treatment or modification)

A key finding in the conditional no migration determination was that "if adequate data are not collected, EPA will not be in a position to approve any no-migration petition for the operational or post-closure phase." EPA clearly stated that further characterization of the waste would be required before a final no migration petition could be considered by the Agency. EPA noted that, at a minimum, wastes should be analyzed for 32 organic compounds and six metals (Cd, Cr, Pb, Se, Hg, Ag). Testing should include headspace analysis of all waste types for the organics and analysis of sludges for both organics and metals.

4.2.5.1 RCRA part B Permit Application

Since New Mexico is authorized by EPA to permit facilities which treat, store and dispose of radioactive mixed waste, the RCRA part B Permit Application must be submitted to the New

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[9] DOE submitted a draft petition to EPA for a disposal phase no-migration variance in May, 1995.

Mexico Environment Department (NMED). In February 1991, DOE submitted a RCRA part B Permit Application for the Test Phase and in May 1995 (Revision 5) for the disposal phase.[10]

The draft part B Permit Application contains a Waste Analysis Plan which was prepared in accordance with EPA guidance (EPA94). According to the Permit Application (Revision 5), the following waste is unacceptable for management at the WIPP facility:

- Ignitable, reactive and corrosive waste (Free liquids, explosives, compressed gases, oxidizers, and non-radioactive pyrophorics are prohibited.)
- Headspace gas volatile organic compounds (VOCs) in concentrations resulting in emissions not protective of human health and the environment
- Incompatible wastes (Waste must be compatible with container, cask, and TRUPACT II materials as well as other waste.)
- Compressed gases
- Free liquids (Residual liquids in well-drained containers must be less than 1% by volume.)
- Waste with 50 parts per million or more of polychlorinated biphenyls (PCBs)
- particulate waste not solidified, stabilized, or consolidated
- Wastes with EPA codes not listed in the RCRA part A permit application

The Waste Analysis Plan further specifies all waste containers (for both newly-generated and retrievably-stored wastes) undergo headspace gas analysis for total VOC concentrations. Based on results and trends DOE may propose in the future to reduce the sampling frequency. Homogeneous solids and soil/gravel wastes will be periodically sampled for VOCs, semi-volatile organic compounds, and metals. Debris wastes will be characterized on the basis of acceptable knowledge rather than examination and/or assay. The physical form of all retrievably-stored wastes will be determined by radiography or visual examination.

[10] New Mexico's RCRA regulations (HWMR-7) mirror the Federal RCRA regulations.

4.2.6 Federal Facilities Compliance Act of 1992 (Public Law 102-386)

The FFCA is an amendment to the Solid Waste Disposal Act (SWDA) (42 U.S.C 6981) which, among other things, imposes certain restrictions on DOE regarding the storage of mixed wastes.[11] After October 6, 1995, DOE can continue to store mixed waste without violation of Section 3004(j) of the SWDA only if a plan has been submitted to EPA, or to a state agency authorized by EPA to regulate the hazardous components of the mixed waste, and has been approved by the appropriate agency. An order requiring compliance with the plan must also have been issued. According to Sec. 102 © of the FFCA, the requirement does not apply to facilities subject to existing agreement, permit, administrative, or judicial order. For example, a tri-partite compliance agreement among DOE, EPA Region X, and the State of Washington exists for the Hanford Site which takes precedence (DOE94a). While the FFCA does not, per se, require waste characterization, the compliance plans may.

The FFCA does, however, require that DOE generate an inventory of mixed wastes. Some of the specified elements of this inventory include:

- a description of each type of mixed waste including the name of the waste stream.
- the EPA hazardous waste code for each type of mixed waste that has been characterized at each DOE facility[12]
- an inventory of each type of waste that has not been characterized by sampling and analysis at each DOE facility
- the basis of DOE's determination of the applicable hazardous waste code for each type of mixed waste and a description of whether the determination is based on sampling and analysis or on process knowledge

The FFCA also requires that DOE develop and submit Site Treatment Plans for the development of treatment capacity and technologies for handling mixed waste. Required inventory reports and plans are described in Section 3021 of the FFCA. Mixed waste

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[11] Mixed wastes are wastes which contain a hazardous component regulated under the Resource Conservation and Recovery Act and a radioactive component regulated under the Atomic Energy Act.

[12] EPA Hazardous Waste Codes are found in 40 CFR parts 260 - 270.

inventory reports have been completed (DOE94c) and Draft Site Treatment Plans have been summarized in a recent DOE report (DOE94a). The National Summary Report (DOE94a) noted that about one-third of the existing mixed TRU waste can probably be shipped to the WIPP without further treatment, but the balance will require additional treatment to meet the expected waste acceptance criteria. Thus, at least implicitly, the FFCA requirements will result in increased understanding of the characteristics of the waste destined for the WIPP. Existing and proposed DOE facilities to treat mixed TRU waste are as follows:

- Existing Facilities
    - Idaho National Engineering Laboratory
    - Rocky Flats Environmental Technology Site
    - Argonne National Laboratory - East
    - West Valley Demonstration Project[13]

- New Facilities
    - Hanford Site
    - Argonne National Laboratory - West
    - Idaho National Engineering Laboratory
    - Nevada Test Site
    - Rocky Flats Environmental Technology Site
    - Oak Ridge Reservation
    - Savannah River Site[14]

Comments derived from information contained in the Site Treatment Plans for several of these mixed TRU treatment facilities are noted below.

Rocky Flats Environmental Technology Site (RFETS)

RFETS estimates the following distribution of mixed TRU wastes (RFP94):

- Meets WIPP WAC and TRAMPAC — 52.4%
- Test and possibly repackage for TRAMPAC — 30%
- Immobilize for WIPP WAC — 5.4%

[13] TRU wastes at West Valley are not defense related and therefore are not slated for disposal at the WIPP.

[14] According to DOE94a, Vol II, the Savannah River Site has deferred treatment until more definitive information is available regarding the WIPP WAC.

- Neutralize for WIPP WAC — 4.4%
- Oxidize for WIPP WAC — 1.2%
- Incomplete data — 6.6%

According to the draft site treatment plan, RFETS proposes to construct a facility which will include capabilities for repackaging, immobilization, neutralization, and oxidation. This facility is planned for operation in 2008.

As noted above, approximately 30% of the RFETS waste will require testing to determine whether the gas-generation requirements of TRAMPAC (see Section 4.2.3) will be met.

Nevada Test Site (NTS)

Mixed TRU waste at the Nevada Test Site (NTS) was shipped there from Lawrence Livermore Laboratory between 1974 and 1990 (NTS94). Since this waste is poorly characterized and may be in oversized packaging, NTS is proposing to construct a TRU Waste Certification Building, which, if funded, would be operational in FY 1999. Operations will include breaching, sampling, and repackaging waste, and certifying that the containers meet the WIPP waste acceptance criteria.

Idaho National Engineering Laboratory (INEL)

INEL has identified 52 waste streams, some portion of which will require treatment to meet the WIPP WAC (IDA94). Facilities proposed to handle these projected needs include the Remote Mixed Waste Treatment Facility (RMWTF), the Idaho Waste Processing Facility (IWPF), and several Generator Treatment Plan (GTP) sites to handle small waste volumes. The IWPF is designed to include the following treatment technologies: stabilization, amalgamation, sizing, and incineration. The RMWTF is designed to handle RH- and CH-TRU wastes containing reactive metals.

Argonne National Laboratory - East (ANL-E)

ANL-E has a few cubic meters of acidic waste water which must be treated in a proposed precipitation/filtration unit prior to shipment to WIPP (ANL94). The wastewater will be neutralized, heavy metals will be precipitated, and residual sludge will be stabilized. Other ANL-E waste streams can be shipped without treatment.

Oak Ridge National Laboratory (ORNL)

ORNL is proposing the construction of a Waste Handling and Packaging Plant (WHPP) to handle five of its six waste streams (OAK94). The sixth waste stream is subject to CERCLA action under an existing agreement involving the State of Tennessee. The WHPP would contain a sludge mobilization facility which would fluidize waste from storage tanks and transfer it to the processing facility. In the processing facility, which consists mainly of a bank of hot cells, wastes will be remotely dried, assayed, packaged, and checked for contamination. Hot cell operation is dictated by the fact that a significant fraction of the ORNL wastes are RH-TRU. Start up tests for the WHPP are projected for 2005.

Other DOE Locations

Draft Site Treatment Plans at other TRU waste generator sites such as Lawrence Livermore and Los Alamos National Laboratories, the Savannah River Site, and the Mound Plant are much less specific as to planned actions.

4.2.7 TSCA: 40 CFR part 761— PCB Manufacturing, Processing, Distribution in Commerce and Use Prohibitions

Unlike the RCRA regulations, the TSCA regulations do not provide for the issuance of no migration variances. Thus, waste containing PCBs must be treated to meet TSCA requirements before disposal (IDA94). Generally speaking, §761.60—Disposal requirements—specifies that PCBs at concentrations of 50 ppm or greater must be treated in a licensed incinerator. Alternate methods of disposal which achieve the same level of performance in destroying PCBs as incinerators may be approved by EPA (§761.60(e)).

The draft site treatment plans prepared by INEL and Rocky Flats have noted that PCB-contaminated TRU waste at those facilities must be treated (IDA94 and RFP94). INEL states that wastes "will be treated to meet TSCA requirements" while Rocky Flats says that "PCBs must be destroyed or oxidized to meet WIPP WAC."

As discussed above in Section 4.2.5.1, Revision 5 of the WIPP RCRA part B Permit Application prohibits "waste with equal to or more than 50 parts per million (50 milligrams per liter) polychlorinated biphenyls (PCBs)." The Waste Analysis Plan indicates that transformer oils containing PCBs have been identified in a few waste streams included in the organic sludges summary category and consequently these streams must be examined for PCBs.

Revision 1 of the WIPP Baseline Inventory Report (WTWBIR) states that 13 TSCA waste streams cannot be accepted at the WIPP under the terms of the draft RCRA part B Permit Application and are consequently excluded from the WTWBIR (DOE95a).

4.2.8 Environmental Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes (40 CFR part 191)

Subpart A, Environmental Standards for Management and Storage, of this rule sets annual dose equivalent exposure standards for the maximum off-site individual during facility operation as follows (50 FR 38085):

- whole body — 25 mrem
- thyroid — 75 mrem
- other critical organ — 25 mrem

These standards, coupled with DOE Order 6430.1-General Design Criteria, were used as the basis for setting the upper limit on TRU waste packages received at the WIPP at 1,000 Curies of Pu-239 equivalent activity[15] (DOE87). Inhalation dose calculations are based on particles having a 1 μm Activity Median Aerodynamic Diameter. Assumed accident scenarios set the particle size distribution for drum handling mishaps which, in turn, lead to a particle size specification in the WIPP WAC. Wastes not meeting the particle size specification mat require treatment prior to shipment to the WIPP. Distribution of drums of waste with high curie contents may be important in analyzing releases from drilling intrusions.

Subpart B, Environmental Standards for Disposal, and Subpart C, Environmental Standards for Ground-Water Protection, of the amended rule (58 FR 66414) prescribe the long-term containment requirements which the WIPP must meet and defines performance assessment as the basis for assessing compliance with the cumulative release limits in Subpart B. Performance assessment will establish, through iterative calculations, an envelope of waste acceptance criteria which, if met, should provide a reasonable expectation that the disposal standards can be achieved for the regulatory life of the repository.

[15] Pu-239 equivalent curies are used to normalize the inhalation hazard of various transuranic nuclides to that posed by Pu-239.

4.2.9 Criteria for the Certification and Re-certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR part 191 Disposal Regulations (40 CFR part 194)

The WIPP LWA orders EPA to promulgate, through a formal rulemaking process, the criteria which the Agency would use to assess DOE's compliance with the 40 CFR part 191 disposal standards at the WIPP. §194.24 of the rule deals with waste characterization and requires DOE to identify the chemical, radiological, and physical characteristics of all existing waste, and to the extent practicable, to-be-generated waste, proposed for disposal at the WIPP. DOE can use process knowledge, non-destructive examination/assay, and other methods to provide this waste description.

DOE is further required to substantiate that all waste characteristics which could impact containment of wastes by the disposal system have been identified and their impact assessed. Waste characteristics include, inter alia, radionuclide solubility, ability of radionuclides to exist in stable colloidal suspensions, gas generation potential, and shear strength. DOE must also substantiate that all waste components which influence the critical waste characteristics are identified and their impact assessed. Waste components include, but are not limited to, such items as the activity of each radionuclide, metals, cellulosics, cheating agents, and water and other liquids.

Using this information, DOE is required to set limits on those waste components judged to be important and to show that, when all of these components are set at the designated limits,[16] the disposal system will meet the numeric requirements of §191.34 and §194.55. It is then incumbent on DOE to ensure that the waste actually emplaced in the WIPP falls within these limits.

4.3 IMPACTS OF WASTE CHARACTERISTICS AND COMPONENTS ON PERFORMANCE ASSESSMENT

Generally speaking, waste characteristics are determined through laboratory and fields studies or through literature assessment combined with technical judgement. Waste components tend to be measured on an on-going basis. As discussed in the following paragraphs, both waste characteristics and waste components can affect performance assessment.

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[16] In some cases, the upper limit on a component will produce the more conservative result while in other cases the lower limit will be controlling. For example, solubility of actinide elements generally increases as the pH of the solution is lowered. Thus one would want to specify the minimum quantity of components which would tend to increase pH.

4.3.1 Waste Characteristics

Waste characteristics can be broadly divided into four categories according to what they affect: mobility of actinide elements in solution, strength, fluid flow, and gas generation in the sealed repository (SAN92). These categories are discussed in general terms in this section and in more detail in sections 4.3.5 and 4.3.6.

4.3.1.1 Mobility in Solution

It is expected that under certain conditions the WIPP wastes will be exposed to brines. These brines can be the result of seepage of Salado Formation brines through the repository walls, seepage of brines from the overlying Rustler Formation through poorly sealed shafts or boreholes, or from flow of Castile Formation brines released by an inadvertent borehole (or boreholes) into the waste-filled rooms of the repository. The quantity of brine to which the waste is exposed is dependent on several factors including the stage of the creep closure of the room, the source of the brine, capillary effects, and the gas pressure in the room. The brine can mobilize the actinide elements in the waste by two mechanisms—solubility and formation of stable colloids. Solubility of the actinides is a complex function of brine strength, pH, oxidation state of the actinide species, carbon dioxide levels, and presence of organic ligands which can form soluble complexes with the actinides. Conditions for the formation of various types of stable colloids are still being examined in the laboratory. Once the actinide elements are mobilized, there are several conceptual mechanisms available by which they can be transported to the accessible environment. If the actinide elements are not mobilized in the brine, the only mechanism available for release from the disposal system is via waste-laden material brought to the surface as the result of inadvertent drilling.

4.3.1.2 Waste Strength

Waste strength enters into performance assessment calculations in several ways. The crushing resistance of the waste provides a back stress which opposes the creep closure of the bedded salt surrounding the waste and consequently slows the closure process. Room collapse, which is in part linked to crushing resistance, determines the porosity in the waste as a function of time. This porosity, in turn, is used in equations to calculate the flow of brine through the waste. In addition to the crushing resistance (i.e., volumetric plasticity as a function of pressure), other waste parameters needed for the constitutive equations used to calculate the waste response to stress are shear modulus, bulk modulus, and yield function constants. The constitutive parameters have been assumed based on educated guesses. While SNL believes these parameters are of secondary importance, they have recommended that bounding studies be conducted using extreme values of these parameters to provide an indication of disposal room response (LAB95). The crushing resistance has been obtained from laboratory experiments using simulated waste mixtures. From these experiments, a composite repository-wide curve of mean stress versus volumetric strain was developed based on an assumed waste weight mix of 28% metals (including the container), 28% combustibles, and 44% sludges (LAB95).[17] This curve was used in the 1992 WIPP Performance Assessment (PA) (SAN92, vol. 3, p. 2-71). Conceptually, the waste mix fits the definition of a waste component which influences a waste characteristic—the crushing resistance. Assessment of the response of the room to collapse also requires knowledge of the initial waste porosity. This waste characteristic can also be derived from the densities of the components which make up the waste.

The shear strength of the waste is needed to analyze the amount of waste which might be eroded from the wall of an intruding borehole by the action of the drilling fluid. Depending on the type of analysis performed, the tensile strength of the waste may also be needed to assess the amount of spallation which occurs in a borehole due to gas pressure release within the waste.

4.3.1.3 Gas Generation Within the Waste

Several mechanisms have been identified which can cause significant quantities of gas to be generated by the wastes after emplacement (BRU94). The principal gas generation mechanisms are related to the anoxic corrosion of certain metals and the anaerobic microbial degradation of cellulosics and other organic compounds. (Oxygen initially present when the disposal rooms are sealed is consumed in a reasonably short period producing an oxygen-free environment.) Quantities of gas produced by radiolysis and release of volatile organic compounds are small by comparison.

The anoxic corrosion of ferrous metals requires the presence of water, which is consumed in the reaction while hydrogen is produced. This water can be initially present in the waste,

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[17] Based on information in DOE95a, the current weight fractions are 0.59 solid organics, 0.13 solid inorganics, and 0.28 sludges.

brine which seeps into the disposal room from the surrounding formations, and/or brine which is released by an intruding borehole from a reservoir in the underlying Castile Formation. For gas generation to proceed at a significant rate, the ferrous metals must be inundated by water. The rate is reduced by three to four orders of magnitude when exposure is limited to water vapor. Aluminum and its alloys can be similarly involved in anoxic corrosion also producing hydrogen.

Microbial degradation of cellulosics and, perhaps, plastics and rubber, can produce a variety of gases including hydrogen, methane, hydrogen sulfide, carbon dioxide, and nitrous oxide. For this to happen, the following conditions must all be met:

- the microorganisms are present when the repository is sealed
- the microorganisms persist for a significant fraction of the 10,000-year repository life
- adequate water is present
- sufficient oxidants are present
- sufficient nutrients such as P and N are available

If the gas pressure generated by these mechanisms exceeds the lithostatic pressure of the surrounding rock formation (i.e., about 14.8 MPa or 150 atmospheres), several disposal system responses are possible. The relatively brittle anhydrite interbeds above and below the repository horizon could fracture providing enhanced pathways for transport of radionuclides to the accessible environment, the creep closure process could be reversed, and/or brine could be driven from the disposal rooms causing the gas-producing reactions to cease.

Recent work has shown that gas spallation processes can cause significant quantities of waste to be transported to the surface from an intruding borehole. These processes become significant when the pressure in the waste exceeds the fluid pressure of the drilling mud at the base of the borehole (about 8MPa).

4.3.1.4 Fluid Flow

SNL uses the computer code BRAGFLO to model two-phase flow in various regions of the repository. The mass balance equations in BRAGFLO employ effective permeability k_i which is the product of the intrinsic permeability and the relative permeability of the *i*th phase (i.e., gas or water). In the 1991 and 1992 WIPP performance assessments, the intrinsic permeability of the waste was set at 1×10^{-13} m^2 based on some experimental work with simulated waste (SAN92). The relative permeabilities of the gas and the liquid were derived from empirical composite curves based on measurements in many porous materials such as sand, sandstone, and clay as a function of liquid saturation (i.e., the amount of pore space in the waste occupied by liquid at any point in time). These empirical curves require assumptions as to the residual brine saturation, the residual gas saturation and a pore shape distribution parameter. In addition, the BRAGFLO equations also require specification of the capillary pressure which is assumed, based on an empirical relationship, to be a function of intrinsic permeability and a factor which reflects parametric uncertainty. Since no WIPP waste-specific data exist for capillary pressure or relative permeability, a high degree of parametric uncertainty exists for waste-related flow properties.

4.3.2 Waste Components

Waste components can be generally divided into those which influence certain waste characteristics thus indirectly influencing PA, and those which directly influence performance assessment. The former category would include such items as quantities of gas generating materials, physical waste composition (i.e., waste volume mix), and quantities of constituents affecting waste mobility (e.g, organic ligands). The total quantity of various actinide elements present in the waste will govern whether the amount of the actinide species mobilized in the waste is limited by the solubility of the element in intruding brines or by the total inventory of the element in the waste. Waste components which directly influence performance assessment generally relate to the quantities of radioactivity in the waste (i.e., its curie content).

The curie content of waste enters explicitly into performance assessment calculations in two ways. First, it is used to set the release limits in accordance with Table 1 of 40 CFR part 191. For TRU radionuclides, the release limits in Table 1 are based on one million curies of alpha-emitting transuranic radionuclides with half-lives greater than 20 years. Thus, if the

WIPP repository hypothetically contained 5 million curies of TRU radionuclides, the release limits used in determining compliance with §191.13 would be five times the values listed in Table 1. A feature of 40 CFR part 191 is that the allowable release is linearly proportional to the amount of TRU waste emplaced in the repository. Second, the variability in the curie content from drum to drum may be used to calculate the variability in the quantity of radioactivity released to the land surface from a borehole which inadvertently intercepts the waste. The quantity of radioactivity in the waste also enters into performance assessment indirectly. For example, when coupled with the amount of brine in-flow into a disposal room, the quantity of radioactivity determines whether the concentration of a nuclide in solution is limited by solubility (including colloidal formation) or by the total radionuclide inventory.

At a more fundamental level, the quantity of radioactivity determines whether the waste meets that TRU waste definitional specification of 100 nanocuries per gram of waste. Wastes containing less than 100 nanocuries per gram are classified as low-level wastes and are excluded from disposal at the WIPP.

4.3.3 Current and Projected Waste Inventory at the WIPP

Waste destined for disposal at the WIPP is to be packaged in 55 gallon steel drums, Standard Waste Boxes (which are 1.9 m^3 steel containers designed to fit into a TRUPACT-II shipping package), and cylindrical canisters for RH-TRU. Based on a waste volume of 0.208 m^3 for a 55-gallon drum, the capacity of the repository is 846,000 drum equivalents.[18] Each disposal room within the repository is nominally slated to receive 6,804 drums.

According to Revision 1 of the WIPP Transuranic Waste Baseline Inventory Report (WTWBIR), the DOE TRU waste generator sites currently have in inventory 73,000 m^3 of CH-TRU and 1,200 m^3 of RH-TRU waste (DOE95a). Thus, the current inventory is approximately 41% of CH-TRU capacity and 17% of RH-TRU capacity. The sites expect to generate an additional 51,000 m^3 of CH-TRU waste and 3,600 m^3 of RH-TRU waste in the future. Since the current inventory plus the volumes of waste projected to be generated before repository closure are less than the statutory/regulatory capacity of the repository, DOE, for scoping purposes, scales the projected inventory so that the statutory capacity is

[18] The term drum equivalents is used to reflect the fact that not all the waste is packaged in 55-gallon drums. The drum-equivalent calculation assumes a repository volume of 176,000 m^3.

reflected in total inventory numbers. For example, since the currently anticipated RH-TRU volumes are 4,800 m^3, and the capacity as limited by DOE's agreement with the State of New Mexico is 7,080 m^3, an additional 2,280 m^3 of waste are added to the anticipated RH-TRU quantity to reach the repository limit.[19] CH-TRU is treated similarly. Details are presented in Table 4-2.

Table 4-2. Transuranic Waste Disposal Inventory for WIPP (Cubic Meters)

Waste Matrix Code Groups	Stored Volumes	Projected Volumes	Anticipated Volumes	WIPP Disposal Volumes
Contact Handled Waste				
Combustible	7.1E+03	2.7E+04	3.4E+04	6.2E+04
Filter	4.3E+02	1.1E+03	1.5E+03	2.6E+03
Graphite	6.7E+02	4.3E+01	7.1E+02	7.6E+02
Heterogenous	3.0E+04	4.6E+03	3.5E+04	3.9E+04
Inorganic Non-metal	1.2E+03	3.2E+02	1.5E+03	1.8E+03
Lead/Cadmium Metal Waste	5.6E+01	1.3E+02	1.8E+02	3.1E+02
Salt Waste	3.3E+01	6.0E+01	9.2E+01	1.5E+02
Soils	3.7E+02	4.5E+02	8.3E+02	1.3E+03
Solidified Inorganics	1.7E+04	8.0E+03	2.5E+04	3.4E+04
Solidified Organics	1.5E+03	3.0E+02	1.8E+03	2.1E+03
Uncategorized Metal	1.2E+04	8.6E+03	2.1E+04	3.0E+04
Unknown	1.7E+03	0.0E+00	1.7E+03	1.7E+03
Total CH Volumes	**7.3E+04**	**5.1E+04**	**1.2E+05**	**1.8E+05**
Remote Handled Waste				
Combustible	1.5E+01	3.2E+00	1.8E+01	2.0E+01
Filter	8.9E-01	2.1E+00	3.0E+00	4.3E+00
Heterogenous	4.4E+02	3.3E+03	3.8E+03	5.9E+03
Lead/Cadmium Metal Waste	0.0E+00	6.0E+00	6.0E+00	9.8E+00
Salt Waste	0.0E+00	2.8E+00	2.8E+00	4.6E+00
Solidified Inorganics	6.1E+02	1.7E+02	7.9E+02	9.0E+02
Uncategorized Metal	8.8E+01	8.6E+01	1.7E+02	2.3E+02
Unknown	1.1E+01	2.4E+01	3.5E+01	3.5E+01
Total RH Volumes	**1.2E+03**	**3.6E+03**	**4.8E+03**	**7.1E+03**
Total TRU Waste Volumes	**7.4E+04**	**5.4E+04**	**1.3E+05**	**1.8E+05**

Source: WTWBIR, Revision 1, Table 3-5

[19] In its WTWBIR documentation, Hanford submitted two "suspect" RH-TRU waste streams with a volume of 41,232 m^3. Since no radionuclide information was available on these streams, they were not included in the scale-up in Revision 1 of the WTWBIR, but it should be noted that the volume of these two streams is six times the allowable RH-TRU capacity of the repository.

TRU waste is a complex mixture of sludges, metals, combustibles such as paper and rags, soils, filters, graphite, etc. As discussed above, these waste components can influence actinide solubility, gas generation, and waste strength characteristics. Table 4-3 provides a comparison of the relative compositions of the CH-TRU and RH-TRU wastes based on the data in Table 4-2 (DOE95b).

Table 4-3. Estimated Composition[1] of Waste Disposal Inventory at WIPP Repository Capacity (DOE95b)

Final Waste Form	% Total CH Inventory	% Total RH Inventory	% Total CH-TRU and RH-TRU Inventory
Combustible	34	<1	33
Filter	1.4	<1	2
Graphite	<1	0	1
Heterogeneous Waste	22	83	24
Inorganic Non-Metal Waste	1	0	1
Lead/Cadmium Metal Waste	<1	<1	<1
Salt Waste	<1	<1	<1
Soil	1	0	1
Solidified Inorganics	19	13	19
Solidified Organics	1	0	1
Uncategorized Metals[2]	17	3	16
Unknown[3]	1	1	1

[1] Totals may not add to 100% due to rounding.
[2] Includes all metals/alloys except lead and cadmium.
[3] Waste is presently uncharacterized but will be characterized prior to shipment to WIPP.

In developing the information contained in Tables 4-2 and 4-3, DOE prepared profiles for approximately 360 waste streams at various generating sites. The profiles were then assigned to one of approximately 130 waste matrix codes (WMC) and the WMCs were categorized into one of thirteen Waste Matrix Code Groups (WMCG) (DOE95a). The WMC numbers and the WMCG descriptions are shown in Table 4-4.

Table 4-4. Waste Matrix Code Group Names
(Source: WTWBIR, Revision 1, Table 1-2)

Waste Matrix Code Group	Waste Matrix Codes
Solidified Inorganics	1000[1], 1100[1], 1110[1], 1120[1], 1130[1], 1140[1], 1190[1], 1200[1], 1210[1], 1220[1], 1230[1], 1240[1], 1290[1], 3000[2], 3100, 3110[3], 3111[3], 3112[3], 3113, 3115[3], 3116[3], 3119[3], 3120, 3121, 3122, 3123, 3124, 3125, 3129, 3130, 3131[3], 3132[1], 3139[1 or 3], 3150, 3190, 3900[2], 6100[4], 6120[5], 6130[6], 6140[5], 6190[4], 6200[7], 6210[8], 6230[8], 6290[7], 7300[3], 9100[2], 9200[2]
Salt Waste	3000[2], 3140, 3141, 3142, 3143, 3149, 3900[2]
Solidified Organics	2000[1], 2100[1], 2110[1], 2120[1], 2190[1], 2200[1], 2210[1], 2220[1], 2290[1], 2900[1], 3000[2], 3114, 3200, 3210, 3211, 3212, 3213, 3219, 3220, 3221, 3222, 3223, 3229, 3230, 3290, 3900[2], 6100[4], 6110[5], 6190[4], 6200[7], 6290[7], 9100[2], 9200[2]
Soils	4000, 4100, 4200, 4900
Uncategorized Metal (Metal Waste Other Than Lead and/or Cadmium	5000[9], 5100, 5110, 5190, 6200[7], 6220[8], 7000[10], 7490[11], 9300[10]
Lead/Cadmium Metal	5000[9], 5120, 5130, 6200[7], 6220[8], 7000[10], 7200, 7210, 7220, 7400[11], 7410[11], 7420[11], 9300[10]
Inorganic Non-Metal Waste	5000[9], 5200, 5210, 5220, 5230, 5240, 5290
Combustible	5000[9], 5300, 5310, 5311, 5312, 5313, 5319, 5320, 5330, 5390
Graphite	5000[9], 5340
Heterogenous	5000[9], 5400, 5420, 5430, 5440, 5450, 5490, 6200[7], 6220[8], 6290[7]
Filter	5000[9], 5410
Excluded Waste[12]	5250, 5350, 6300, 6400, 7100
Unknown[13]	8000, 8100, 8200, 8900

[1] Liquid waste streams are assumed to be solidified prior to sending to WIPP.
[2] WMCs 3000, 3900, 9100, and 9200 are placed in "solidified inorganics," "salt waste," or "solidified organics," depending on the information provided by the TRU waste generator/storage site.
[3] particulate waste streams are assumed to be solidified prior to sending to WIPP.
[4] WMCs 6100 and 6190 are placed in "solidified organics," or "solidified inorganics," depending on the information provided by the TRU waste generator/storage site.
[5] Liquid lab pack waste is assumed to be solidified prior to sending to WIPP.
[6] Solid lab packs are assumed to be solidified prior to sending to WIPP.
[7] WMCs 6200 and 6290 are placed in "solidified organics," "solidified inorganics," or "heterogeneous" if the waste stream must be solidified per the generator/storage site. They are placed in "uncategorized metal," or "lead/cadmium metal waste" if they are primarily nonreactive metal contaminated with reactive metal. Reactive waste streams must be treated prior to shipment to WIPP.
[8] Waste stream is assumed to be treated prior to sending to WIPP. Volume change is provided by the TRU waste generator/storage site.

[9] WMC 5000 is placed in "uncategorized metal," "lead/cadmium metal," "inorganic non-metal," "combustible," "graphite," "heterogeneous," or "filter," depending on the information provided by the generator/storage site.
[10] WMC 7000 and 9300 are placed in "uncategorized metal" or "lead/cadmium metal," depending on the information provided by the generator/storage site.
[11] WMCs 7400, 7410, 7420, and 7490 are assumed to be drained of liquid and contain only metal waste.
[12] These waste streams are excluded from disposal in WIPP at this time, e.g., PCB and asbestos wastes (see Table 3-2).
[13] If adequate information is provided by the generator/storage site, these WMCs are changed. If there is not enough information, these waste streams remain as "unknown" and are excluded from disposal in WIPP until characterized.

Because various waste material parameters (i.e., waste components) are important to performance assessment calculations, the WTWBIR provides estimates of the mix of materials expected in the inventory. For example, iron and aluminum are important to assess the amount of hydrogen gas which might be generated by anoxic corrosion if these metals are exposed to brine. The estimated ranges for these material parameters, expressed as material densities, are summarized in Table 4-5 for CH-TRU waste (DOE95a).

Table 4-5. WIPP CH-TRU Waste Material Parameter Disposal Inventory (Table 5-1 from DOE95a)

Category	Materials	Waste Material Density (Kg/m³)		
		Maximum	Average	Minimum
Inorganics	Iron Based	2.1E+03	8.3E+01	0.0E+00
	Aluminum Based	1.0E+03	1.2E+01	0.0E+00
	Other Metals	1.4E+03	2.7E+01	0.0E+00
	Other Inorganic	2.1E+03	3.9E+01	0.0E+00
Organics	Cellulose	9.6E+02	1.7E+02	0.0E+00
	Rubber	6.8E+02	2.1E_01	0.0E+00
	Plastics	8.9E+02	5.3E+01	0.0E+00
Solidified Materials	Inorganic	2.2E+03	1.3E+02	0.0E+00
	Organic	1.4E+03	8.4E+00	0.0E+00
Soils		1.6E+03	5.7E+00	0.0E+00
Container Materials	Steel		1.4E+02	
	Plastic/Liners		3.3E+01	

Using the average values from this table, the waste material density in a drum is 550 kg/m^3. Based on the statutory waste volume, the total weight of waste in the repository would be about 97 million kilograms (210 million pounds). The waste containers will add another 170 kg/m^3 to the inventory or 30 million kilograms (66 million pounds).

4.3.4 Identification of Significant Radionuclides

In addition to information on physical and chemical parameters, the WTWBIR also includes information on the radioactivity associated with the wastes. The estimated radionuclide inventories in the WTWBIR, scaled to statutory capacity, are:

- CH-TRU — 3.60 million curies
- RH-TRU — 2.11 million curies

Details are included in Table 4-6.

Table 4-6. Major Nuclides in Disposal Radionuclide Inventory
(Source: WTWBIR, Revision 1, Table 4-2)

NUCLIDE	TOTAL CH-TRU (Ci)	TOTAL RH-TRU (Ci)
Am-241	2.23E+05	5.30E+02
Ba-137m	5.03E+03	3.10E+05
Cs-137	5.32E+03	3.28E+05
Pu-238	1.89E+06	3.53E+03
Pu-239	3.85E+05	6.41E+03
Pu-240	7.22E+04	1.74E+02
Pu-241	1.01E+06	9.06E+02
Sr-90	4.07E+03	6.68E+05
U-233	1.38E+03	8.57E+02
Y-90	4.07E+03	6.68E+05
TOTAL, major nuclides	3.60E+06	1.99E+06
TOTAL, all nuclides	3.60E+06	2.11E+06

Virtually all (i.e., 99.4%) of the CH-TRU radioactivity is associated with only five nuclides—Am-241, Pu-238, Pu-239, Pu-240, and Pu-241. In the case of RH-TRU, 93.5% of the curie inventory is attributable to four fission products (Cs-137, Sr-90, Y-90, and Ba-137m) with half-lives of 30 years or less. Because most of the RH-TRU inventory is composed of nuclides with short half-lives, DOE has estimated that the contribution of RH-TRU to the total radionuclide inventory in the repository will decline from about 37% initially to about 1% after slightly more than 200 years (DOE95b). Based on the specific activity of the five major CH-TRU nuclides, the total quantity of these radioactive materials in the WIPP is about 7,000 kg or about 0.005% of the total inventory mass. The total quantity of other very long-lived uranium and thorium radionuclides is about 104,000 kg.

Accurate data on the fractional abundance of each radionuclide contained in TRU waste are necessary because differences in solubility, mobility, and half-life determine the extent to which specific radionuclides reach the accessible environment in a given scenario. The behavior of uranium isotopes U-233 and U-234 provides a good example of the importance of understanding the radionuclide composition of TRU wastes in assessing their potential migration to the accessible environment. In the 1992 performance assessment (SAN92), U-233 and U-234 were estimated to comprise approximately 0.06 percent of the initial inventory, yet they accounted for about 21 percent of the projected discharge to the accessible environment (for the E1E2 scenario at 1,000 years with fracture flow, matrix diffusion, and no retardation). Accurate determination of the uranium inventory is thus very important, even though its quantity is minor compared to plutonium and americium radionuclides.

4.3.5 <u>Determination of Actinide Solubility Limits</u>

Actinide solubility in the Castile or Salado brines that come in contact with the waste is generally thought to be one of the most important parameters for calculating releases to the accessible environment (SAN92). Because actinide solubility is not well understood, there is considerable uncertainty in estimating the quantities of plutonium, americium, and uranium in solution. Estimates of the solubilities of actinide species expected in TRU wastes had a range of 13 orders of magnitude in the 1992 performance assessment (SAN92). The mean, median, and range of values used in SAN92 were obtained by expert elicitation.

In addition to pure solubility (where solid material is dissolved in the liquid) which can be affected by brine salinity, pH, Eh, and the presence of chelating agents and other chemical constituents, there are concerns and greater uncertainty about the possible concentrations of colloidal dispersions (very fine particles in the 0.001 to 0.1 μm diameter range that can remain suspended in the liquid). Colloid formation was not considered in the 1992 PA (SAN92).

To provide more defensible information, DOE has been conducting laboratory experiments on actinide solubility and colloid formation under the Actinide Source Term Program (ASTP) (LOS93, NOV94a, NOV94b). The ASTP has been using small-scale laboratory experiments to develop a conceptual model of actinide solubility. DOE intends to verify this model using large-scale tests (the Source Term Test Program-STTP) with TRU wastes. These tests are currently in process at Los Alamos National Laboratory (LANL). Questions remain regarding the extent to which these studies are representative of actinide mobility in TRU wastes under disposal conditions. For the final Compliance Certification Application, DOE is proposing to include a look-up table which will define solubilities in various environments.

The solubility (or dissolved species) model is an "equilibrium thermodynamic model based on the Pitzer formalism for activity coefficients in concentrated electrolytes" (BYN95). The dissolved species model is developing experimental solubility data, in brines of various compositions and ionic strengths, for five actinide elements—americium, neptunium, thorium, uranium and plutonium in four valence states—+III, +IV, +V, and +VI. Ultimately, the dissolved species model is expected to provide to performance assessment the solubility for these five actinide elements as a function of:

- oxidation state
- brine type
- pH
- pCO_2
- organic ligands

The partitioning of the actinide elements between the four possible oxidation states must also be specified for PA. In recent modeling studies, solubility ranges of 1 to 10^{-10} were assigned for all oxidation states with median values ranging from 10^{-7} moles per liter for +IV to 10^{-4} moles per liter in the +VI oxidation (SNL95). Suggested oxidation state distributions in the same study were:

- Americium — all +III
- Thorium — all +IV
- Uranium — 0 to 20% +VI, balance: randomly distributed among +III, +IV and +V
- Neptunium - randomly distributed between +IV and +V
- Plutonium — 0 to 20% +VI, balance: randomly distributed among +III, +IV, and +V

The specification of the oxidation state distribution for each element poses some difficult technical questions. Since the disposal room environment is expected to become anoxic early in the life of the repository, logic would suggest that the actinide elements will exist in their reduced oxidation states (NOV94a). However, research has shown that alpha radiolysis can convert Am+III to Am+V (NOV94a) and the presence of carbonate stabilizes plutonium in the +VI state (REE94). Consequently, DOE chose to use statistical sampling to characterize the mix of oxidation states for the various actinide elements to be included in PA. The STTP may provide additional experimental insight into these distributions (NOV94a).

Based on experimental work under the ASTP currently in progress, DOE plans to refine the data used in the dissolved species model by the end of the first quarter of 1996 and use these data in the final compliance certification application (BYN95).

4.3.6 Determination of Gas Generation Rates

Volatile organic compounds (VOCs) present in TRU waste can vaporize after waste emplacement in the disposal system and create a potential problem for compliance with RCRA regulations. Gases other than VOCs are also expected to be generated in the waste as a result of corrosion, microbial activity, and radiolysis. These processes are expected to produce gases in much greater quantities than from VOCs present in the waste and represent the principal mechanisms of concern in performance assessment.

In PA, it is necessary to evaluate the combined effect of gas generation on waste storage room closure and brine inflow. The pressure resulting from significant gas generation could retard the rates of both room closure and brine inflow. In the absence of any gas generation there would be no retardation of room closure rates or brine inflow. The determination of the rates for room closure and brine inflow requires complex modeling with computer codes where coupling of physical processes is difficult and use of parameters that have not been measured on actual or, in many cases, even simulated waste.

An analysis of the combined effect of room closure and brine inflow requires an assessment of which occurs first. If complete closure occurs before brine inflow, the enclosed space's very low permeability and porosity could effectively minimize any future brine inflow and mixing with waste. The amount of contaminated brine available for release by drilling would thus be minimal. Conversely, if brine inflow occurs before complete room closure, there could be extensive mixing of disposal system contents with brine, creating a significant amount of contaminated brine available for release in a drilling puncture.

Gas generation is also directly related to actinide solubility, discussed in a previous section. Preliminary work under the ASTP indicates that the presence of carbon dioxide gas (CO_2) directly affects the solubility of plutonium, uranium and other actinides under laboratory conditions (SAN93). The applicability of this information to actual TRU wastes under disposal conditions remains to be demonstrated. As previously mentioned, gas generation can also impact the amount of waste spallation associated with drilling events.

Waste components will affect gas generation rates and processes. The amount of gas generated by corrosion is directly related to the quantity and type of metal present in waste and waste containers, the surface area of the waste, and available moisture. The amount of gas generated by microbial activity is related to the amount of available moisture and cellulosic material (e.g., paper, cloth, and wood). Radiolytic gas generation is a function of the amounts of alpha radioactivity, moisture, and cellulosic material present.

The initial liquid content of the waste may be important to its gas generation characteristics (SAN92). Table 3-1 of the WIPP WAC notes that, as a guideline, residual liquid in well-drained containers should be restricted to approximately one volume percent of the internal container, with the aggregate amount of residual liquid less than one volume percent of the external container (DOE91). The residual liquid limit could be checked in three ways:

- Upon assembly of the drum by personnel at the waste generator site;
- By radiography performed on site by waste generators during the drum certification process
- During visual examination of a container, as applicable

While the combination of these three techniques appears adequate to meet the residual liquid criterion, the use of one technique alone may not suffice. For example, radiography has not been demonstrated to be a fail-safe method for detecting containers of liquids within a waste drum. In January 1993, a full 8-ounce can of adhesive was missed by an operator conducting Real-Time Radiography (RTR) at INEL, and later discovered during the visual examination of the drum contents. Radiography detects movement of liquids within a container; therefore a completely full container could be missed.

4.3.6.1 Average Stoichiometry Model

The average stoichiometry model was used to calculate quantities of gas generated in the 1992 performance assessment (SAN92). DOE also plans to use this model for calculations in the final Compliance Certification Application (NOW95). The average stoichiometry model is part of BRAGFLO—a computer code which calculates two-phase flow in the repository. Thus, brine and gas flows into and out of the repository are coupled to gas generation (i.e., pressure). Sufficient gas pressure can also cause fracturing of the nearby anhydrite layers increasing their permeability. In addition, BRAGFLO uses a porosity surface developed by the SANCHO/SANTOS computer codes to simulate room closure. This porosity surface is a function of the amount of gas present at any point in time. In this way, gas generation is also coupled to the geomechanical behavior of the disposal rooms.

The average stoichiometry model considers the anoxic corrosion of ferrous materials and the anaerobic degradation of cellulosics and rubbers, and calculates the quantity of gas generated and the quantity of water consumed. DOE has discussed the fact that aluminum and its alloys could behave in a similar manner to ferrous materials, but have not included aluminum corrosion in the model.[20] The model does not include possible gas consuming reactions nor does it address other possible gas producing mechanisms such as radiolysis.

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[20] Based on the information contained in Table 4-5, it can be estimated, using average values, that the amount of hydrogen produced from ferrous metal corrosion could range from 6.9 to 9.2 x 10^8 moles depending on which corrosion reaction occurs and assuming the presence of sufficient water to consume all the iron. Similarly, the amount of hydrogen produced by the corrosion of all of the aluminum would be 1.2 x 10^8 moles or 11 to 14% of the amount from iron corrosion. However, using the maximum values in Table 4-5, the contribution from aluminum would be more than 50% of the total hydrogen. These calculations assume that 1.5 moles of hydrogen are generated for each mole of aluminum consumed.

Two possible anoxic corrosion mechanisms are considered in the model:

$$Fe + 2H_2O = Fe(OH)_2 + H_2 \qquad (1)$$
$$3Fe + 4H_2O = Fe_3O_4 + 4H_2 \qquad (2)$$

Equation 2 produces 33% more hydrogen per mole of iron consumed than does equation 1. Because uncertainty exists as to which equation prevails, DOE has chosen to treat the stoichiometry of the reaction as an uncertain variable which is sampled over the range of possible values for performance assessment calculations. To do this, the two equations above are combined into an "average" equation as follows:

$$Fe + ((4+2x)/3)H_2O = (4\text{-}x)H_2 + (3x)Fe(OH)_2 = ((1\text{-}x)/3)Fe_3O_4$$

The values of x are assumed to be uniformly distributed between 0 and 1 for Latin Hypercube sampling purposes in PA.

Inundated corrosion rates have been developed from laboratory corrosion studies of mild steels for up to 24 months duration in brine solutions with the pH ranging from an initial value of 6.7 to approximately 8.3 at the end of the tests and a nitrogen overpressure of 10 to 15 atm. The measured hydrogen production rates as a function of time were as follows:

3 months — 0.19 moles H_2 per m^2 steel surface per year
6 months — 0.21 moles H_2 per m^2 steel surface per year
12 months — 0.16 moles H_2 per m^2 steel surface per year
24 months — 0.10 moles H_2 per m^2 steel surface per year

SNL recommended that a value of 0.1 moles/m^2·y (3 x 10^{-9} moles/m^2·sec) be used as the best estimate (i.e., median value) (BRU94).

To obtain an estimate of the maximum inundated corrosion rate, it was assumed that the actual pH of the brines in the WIPP repository could vary from 3 to 12. Based on work by earlier investigators cited in BRU94, SNL assumed that the anoxic corrosion rate was essentially constant between pH 4 and 10. Outside this range the following pH dependent changes were anticipated: at pH 3, the rate was expected to be higher by a factor of 50; at pH 11, it would be lower by a factor of 0.05; and at pH 12, it would be lower by a factor of 0.005. In addition, it was assumed that the corrosion rate would increase with pressure and at lithostatic pressure the rate would be four times higher than under the experimental conditions noted above. Consequently, the maximum rate for inundated corrosion was set at 4 x 50 x 0.1 or 20 moles/m^2·y (BRU94). This is equivalent to a maximum value of 6.35 x 10^{-7} moles/m^2·sec.

Corrosion rate data for humid environments (i.e, where the steel is exposed to water vapor) were also developed. Based on the amount of brine present in a disposal room at any given time as calculated by BRAGFLO, the relative amounts of steel subject to inundated corrosion and humid corrosion are calculated. For PA purposes, it is necessary to convert these corrosion rates to a volumetric gas generation rate (i.e., moles H_2 per m^3 of repository volume per second). This requires information on the surface to volume ratio of the contents of an average drum. To perform this conversion, SNL assumes that a drum of CH-TRU waste has an approximate area of 4 m^2 and the contents of the drum contribute an additional 2 m^2 (BRU94). If one assumes that the drum and its contents have the same surface to volume ratio (as was assumed by SNL in the past) and the surface area of the drum is actually 4.5 m^2, then, from the current average inventory data in Table 4-5, it can be estimated that the surface area of the ferrous contents of a drum is 2.7 m^2 and the total surface area of steel per drum is 7.2 m^2 which is 20% higher than the value being used in the 1992 PA (SAN92). For microbial reactions, the following highly generalized equation is used to calculate gas generation (BRU94):

$$CH_2O + \text{unknowns} + \text{microorganisms} = (5/3)\text{gas} + \text{unknowns} \qquad (3)$$

CH_2O, a simplified formula for glucose, is assumed to represent various organic materials (cellulosics, rubbers, and plastics) present in the waste which may be subject to microbial degradation. The actual reactions which could occur and the extent to which water is produced or consumed are subject to a considerable amount of uncertainty. The quantity of gas produced could vary from 0 to 1.67 moles per mole of glucose consumed depending on which of several possible reactions is assumed to occur. Consequently, the stoichiometric coefficient is assumed for PA to vary uniformly over this range rather than remain fixed as shown in equation (3) (SAN92). Plastics and rubbers are expected to be generally more resistant to microbial degradation than cellulosics (papers and rags), but may be subject to some radiation-related degradation reducing their resistance to microbial attack. The extent to which rubbers and plastics enter into the gas generation reactions is uncertain, but should be addressed in PA. Similar to the treatment of anoxic corrosion, assumptions were made that microbial degradation in humid environments proceeded at some fraction of the inundated rate. This fraction was assumed to vary uniformly from 0 to 0.2.

4.3.6.2 The Reaction Path Model

SNL has also developed a more sophisticated model to analyze gas generation, called the reaction path model. This model includes treatment of oxic and anoxic corrosion of steels including passivation and depassivation reactions, microbial degradation, radiolysis of brine, and consumption of carbon dioxide by calcium-bearing species. Unlike the average stoichiometry model, the reaction path model uses thermodynamic calculations to estimate phase stability at any point in time. For example, at certain CO_2 fugacities, iron carbonate may form which prevents anoxic corrosion of the ferrous materials. If the CO_2 fugacity is reduced sufficiently, the passivating layer can decompose allowing corrosion to proceed.. While SNL has judged this to be the most comprehensive gas generation model (BRU94), DOE decided that the average stoichiometry model will be used for compliance demonstration. This decision is based on the position that PA has shown a low sensitivity to gas generation and the reaction path model is "unnecessarily costly in time and resources for PA calculations" (NOW95). The model will be retained to support calculations related to actinide chemistry.

4.3.7 <u>Establishing the Waste Envelope</u>

For the Compliance Certification Application, DOE will conduct performance assessments using the available information on waste characteristics and waste components, which must demonstrate that the WIPP complies with §191.13 and §194.34. Many of the waste properties will not be precisely known values which can be used for input to PA as constants. Rather, they will be imprecisely known variables for which a range and probability distribution function will be assigned. The PA process will define an acceptable envelope of waste properties which will ensure compliance with the regulations *on a statistical basis*. This is not to say that some individual complementary distribution functions (CCDFs) produced from particular combinations of uncertain parameters may not exceed the limits in §191.13, but it is required that the mean CCDF comply with §194.34(f) (i.e., there is 95% confidence that the mean of the population of CCDFs meets the disposal standards in §191.13).

Once an acceptable waste envelope has been defined through PA calculations, DOE must have procedures in place to ensure that the actual wastes fall within this envelope. It is conceivable that an actual waste component could lie within the range used to develop the waste envelope, but have a different probability distribution function than was assumed in the PA calculations used for compliance determination. Compliance might not then be demonstrable with actual waste. To preclude this possibility, 40 CFR 194.24 contains procedures for showing compliance at the waste envelope limits. These procedures are discussed in Section 4.6.

4.4 METHODS FOR CHARACTERIZING WIPP WASTE INVENTORY

The DOE/CAO Quality Assurance Program Description (QAPD) (DOE95c) is the quality management document that identifies the quality requirements applicable to WIPP waste characterization. The QAPD establishes the minimum requirements for the development of QA programs for the National TRU Programs Office (NTPO) and the generator sites' QAPjPs. The DOE states that the requirements in the CAO QAPD "are based on the QA requirements and criteria contained in 10 CFR §830.120," and that the QAPD is "consistent with applicable Environmental Protection Agency (EPA) requirements" (DOE94d).

As mentioned previously, the controlling document for TRU waste characterization is the TRU QAPP (DOE94b). This document outlines two approaches, one for retrievably stored wastes and one for newly generated wastes. Both approaches are based in large part on the waste classification system presented in the WTWBIR.[21] DOE asserts in the WTWBIR that the Waste Matrix Codes (WMCs) used to categorize wastes have been established based on "grouping wastes with similar physical and chemical properties."[22] In the TRU QAPP, DOE states their rationale for using WMCs to track TRU wastes:

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[21] The waste classification presented in the WTWBIR was initially developed by DOE and was presented in the DOE Waste Treatability Group Guidance (DOE95) which was prepared to meet the requirements of the Federal Facilities Compliance Act (FFCA) of 1993. This approach was used in DOE's Mixed Waste Inventory Report (MWIR) (DOE93).

[22] It should be noted that wastes may be categorized differently depending on the waste management objective, e.g., for purposes of storage, transportation, or treatment. For example, wastes with the same WMC would be stored together due to their similar physical or chemical nature. For transportation, wastes would be grouped according to different requirements, e.g., the requirements of the TRUPACT-II content codes.

> To ensure consistency throughout the DOE complex regarding TRU waste inventory information, TRU waste characterization information will be correlated to the Waste Matrix Codes established by DOE as acceptable to the WIPP facility.[23]

The TRU QAPP states that there are three broad groups of WMCs:

- solid process residues — 3000 series
- soils — 4000 series
- debris wastes — 5000 series

Existing wastes in these three WMCs will be considered retrievably stored wastes and will be characterized directly. Existing wastes in the other WMCs described in Table 4-4 (WMCs 1000, 2000, 6000 and 9000) will require treatment prior to shipment to the WIPP and will then be considered newly generated wastes. Wastes will be characterized for disposal in accordance with the approach outlined below. The Acceptable Knowledge Guidance Manual (DOE95c) states that

> Four broad matrix parameter categories of waste are used to describe the physical form of the waste and to determine TRU waste characterization requirements: homogeneous solids (summary category S3000), soil/gravel (summary category S4000), debris wastes (summary category S5000), and special wastes (summary category S7000).

The Acceptable Knowledge Guidance Manual further states that Series 7000 (special) wastes will be classified as RCRA hazardous in the same manner as the Series 5000 (debris) wastes (DOE94b). For both waste types, the determination of their RCRA hazardous classification will be made using acceptable knowledge alone, without corroborative empirical sampling and/or analysis. A generalized flow diagram for TRU waste characterization is presented in Figure 4-1. The specific approaches for characterizing newly generated and retrievably stored wastes provide statistically derived means to select waste containers from all three WMCs for verification by visual examination, and waste containers from series 3000 and 4000 WMCs for RCRA characterization.

[23] Many wastes will have other identification codes that are no longer used as well as EPA derived hazardous waste codes assigned to them. This creates considerable confusion.

The steps in characterizing newly generated and retrievably stored waste are as follows:

- establish profiles for waste streams
- using process knowledge, assign waste containers to waste streams
- assign a waste matrix code to each waste stream
- test all waste containers using headspace gas analysis, radiography, and radioassay
- select statistically determined number of waste containers for RCRA characterization and/or visual examination, depending on the assigned WMC
- determine if waste is hazardous and develop a WMC description

In addition, for newly generated wastes, it is necessary to verify that the waste generating processes have operated within the profile's established administrative controls.

The information listed above must be coordinated with a consideration of the manner in which the waste stream is defined. The definition applicable to TRU waste is found in DOE's Acceptable Knowledge Guidance Manual (DOE95c), and is of fundamental importance to TRU waste characterization because "waste characterization and DQO activities are performed on a waste stream basis" (DOE95c). For the purposes of characterization, TRU waste streams are distinguished on the basis of three factors:

- the summary category of the waste (WMC, WMCG, etc.)
- the waste's status (newly generated or retrievably stored)
- the waste gensis (continuous process or batch)

The combination of these three factors determines the waste stream's anticipated variability and the extent of verification required. Additionally, waste streams are identified on the basis of their waste characterization objectives as defined by the applicable regulatory requirements, e.g., RCRA, TRUPACT-II, etc.

DOE's TRU Waste Characterization Program currently consists of the following six activities: radiography, radioassay, headspace sampling and analysis, solid process residues and soils sampling and analysis, visual examination, and use of acceptable knowledge/process knowledge. Other aspects of TRU waste characterization typically involve scientific research (actinide solubility, etc.) to define *waste characteristics* (see Section 4.3.1). Radiography,

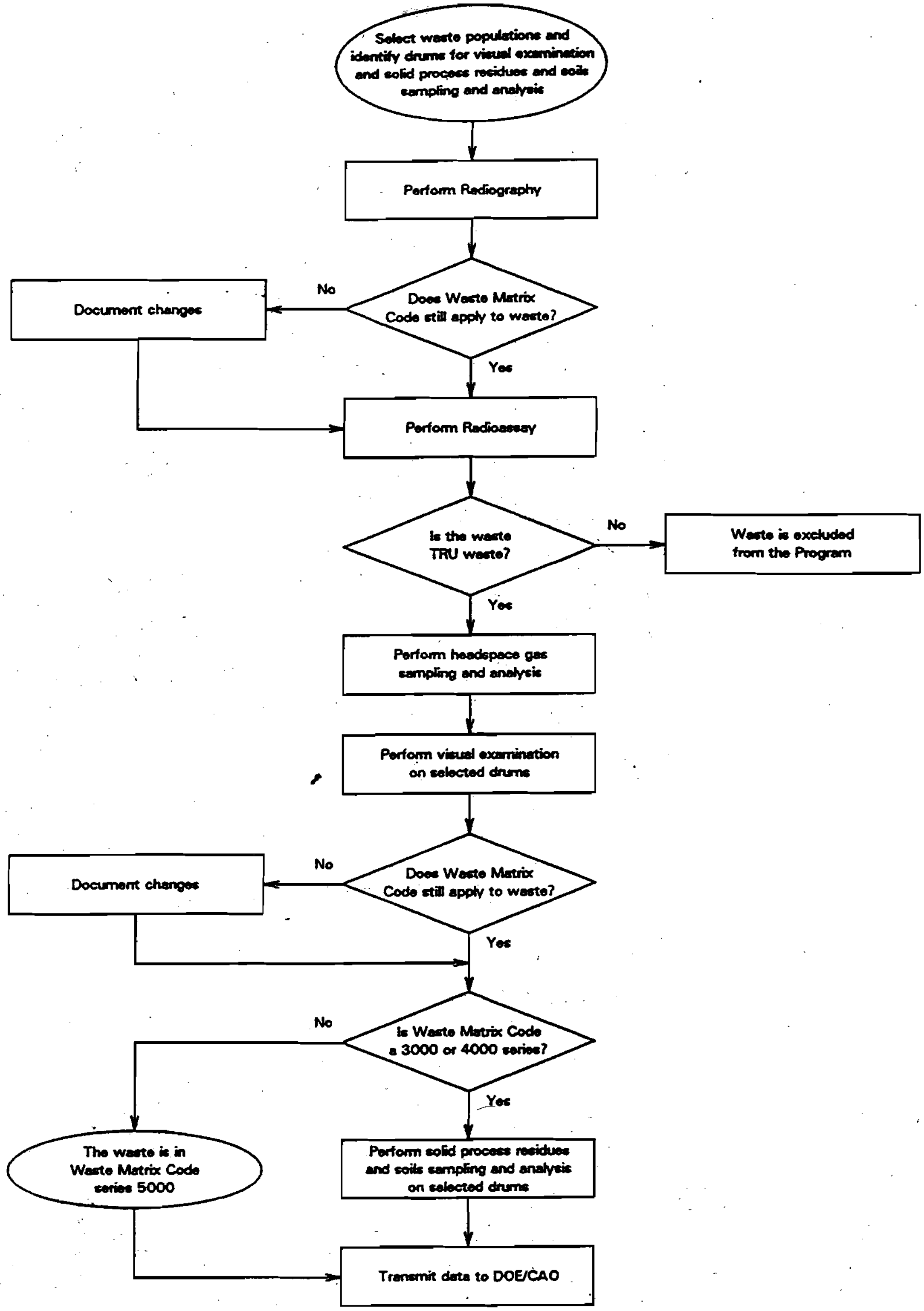

Figure 4-1. Generalized Sequence for TRU Waste Characterization

radioassay, headspace sampling and analysis, solid process residues and soils sampling and analysis, visual examination are summarized in the sections below, and the use of acceptable knowledge/process knowledge is discussed in greater detail in Section 4.6.

All TRU waste generators currently perform some waste characterization activities on site, although their capabilities vary considerably. The major TRU generator facilities are: Idaho National Engineering Laboratory, Oak Ridge National Laboratory, the Rocky Flats Environmental Technology Site, Savannah River Site, Hanford, Los Alamos National Laboratory, the Nevada Test Site, Lawrence Livermore National Laboratory, Argonne National Laboratory-East, Argonne National Laboratory-West and the Mound Plant (DOE94d). Some of these sites have multiple facilities involved with some aspect(s) of TRU waste generation, characterization, and storage. As indicated in Table 4-7, these sites have a mix of equipment required to perform the analytical techniques listed above.

Table 4-7. Waste Characterization Capabilities of Ten Main TRU Waste Generators

TRU Generator Site	Current Waste Characterization Capabilities
Oak Ridge National Laboratory (ORNL)	RT RA VE SA HG[2]
Hanford (HANF)	RT RA VE[3] HG[3] SS[3]
Idaho National Engineering Laboratory (INEL)[1]	RT RA HG VE SA SS
Argonne National Laboratory-East (ANL-E)	RA HG
Savannah River Site (SRS)	RT RA
Rocky Flats Environmental Technology Site (RFETS)	HG RT RA VE SS SA
Los Alamos National Laboratory (LANL)	RT RA HG VE SS SA
Lawrence Livermore National Laboratory (LLNL)	RA VE HG RA
Nevada Test Site (NTS)[4]	--
Mound Plant (MOUND)[5]	--

RT = Radiography
RA = Radioassay
VE = Visual Examination
HG = Headspace Gas Sampling and Analysis
SA = Solid Residue Analysis
SS = Solid Residue Sampling

[1] Includes Argonne National Laboratory-West (ANL-W).
[2] Expected to have this capability by FY 1996.
[3] Expected to have this capability by 2002.
[4] NTS currently plans to use the mobile TRU characterization system being developed by LANL.
[5] Mound's plans for TRU characterization are currently uncertain.

In general, facilities that either have historically produced or currently manage plutonium or plutonium-bearing wastes as part of their routine operations have radioassay facilities for the purpose of nuclear accountability. These facilities can be used for waste characterization purposes. Los Alamos National Laboratory is currently developing a mobile TRU characterization system for use by small-quantity TRU sites (MAR95). While DOE will require all TRU waste generator sites to be fully capable of certifying their own wastes prior to shipment to WIPP, the specific details and logistics regarding characterization are unavailable at this time.

4.4.1 Radioassay

Radioassay involves a variety of measurement techniques used to determine the radionuclide content of a waste container. Typically, TRU waste generators are most interested in certain radionuclides, specifically actinide or transuranic species. However, for purposes of radionuclide inventory, many other radionuclides are quantified predominantly by measurement of their gamma emission. Generally, TRU waste generators use non-destructive techniques based on neutron or gamma measurements to quantify the Physical measurements, i.e., inductively coupled plasma/mass spectrometry (ICPMS), are also used, but less frequently. Passive Active Neutron (PAN) counting and Segmented Gamma Scan (SGS) counting are two examples of systems in common use.[24] PAN is used to identify and quantify the odd- and even-numbered isotopes of plutonium by measuring their neutron emission both spontaneously in the passive mode and in response to bombardment within the detector, the active mode. SGS measures the photon emissions from a waste container using a standard intrinsic germanium type of photon detection system coupled with a transmission source, typically Se-75 for assays of weapons grade Pu-239. A container is divided into a number of segments and each segment is assayed with the transmission source to develop a waste drum specific photon attenuation correction factor by segment. Next the drum is measured without the source and the radionuclides of interest are quantified. Computer enhancement of the data provides a more complete assay of the drum's photon emitting radionuclides (Pu-239, Am-241, etc.).

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[24] There are other radiometric techniques used for radioassay, such as Pulse Neutron Coincidence Counting (PNCC) and gamma determinations using a simple unsegmented intrinsic germanium type photon detection system. Still other methods are currently under development.

Due to the wide variety of assay systems employed by TRU generators, concerns have been expressed regarding the comparability of radioassay data among DOE sites. partially in response to this, DOE recently implemented a performance demonstration program (PDP) for radioassay techniques comparable in principle to the PDP for Headspace Gas Analysis, described in Section 4.4.3. PDP participants receive a "standard" waste drum with a known activity concentration and isotopic distribution. Each participant analyzes the drum and reports the results to the program coordinator for scoring and statistical evaluation. Participants are required to use the same techniques for PDP samples as they use for actual characterization of TRU wastes and are "qualified" for that specific technique or combination thereof. Qualification is mandatory and must be maintained to enable a site to certify and ship TRU waste to WIPP.

4.4.2 Radiography

Radiography is a nondestructive, non-intrusive qualitative technique used to identify the contents of a waste container. Most DOE sites currently employ Real-Time Radiography (RTR), which uses x-rays and a video system to allow an operator to view the container's contents in real-time. RTR's primary use is to examine and verify the physical form of the waste and to ascertain that a container complies with the specifications of a content code or other physical requirements. The Quality Assurance Objectives (QAOs) for radiography do not address precision or include specific Minimum Detectable Levels (MDLs) because this technique is primarily a qualitative determination (DOE94b). A statistically determined subset of the waste containers examined with radiography will be verified independently by visual examination (DOE94b). The overall approach to visual examination of waste is presented in Figure 4-2.

While radiography is generally effective, certain materials, particularly lead liners, are not readily penetrated by x-rays and render radiography ineffective when they are present in a waste container. DOE has acknowledged this and states in their Waste Characterization Methods Manual (DOE95d) that

> Containers with high density waste (e.g., leaded rubber, cemented sludges) can only be examined at their edges. In addition to this limitation, waste containers that are configured with a lead liner cannot be examined with radiography.

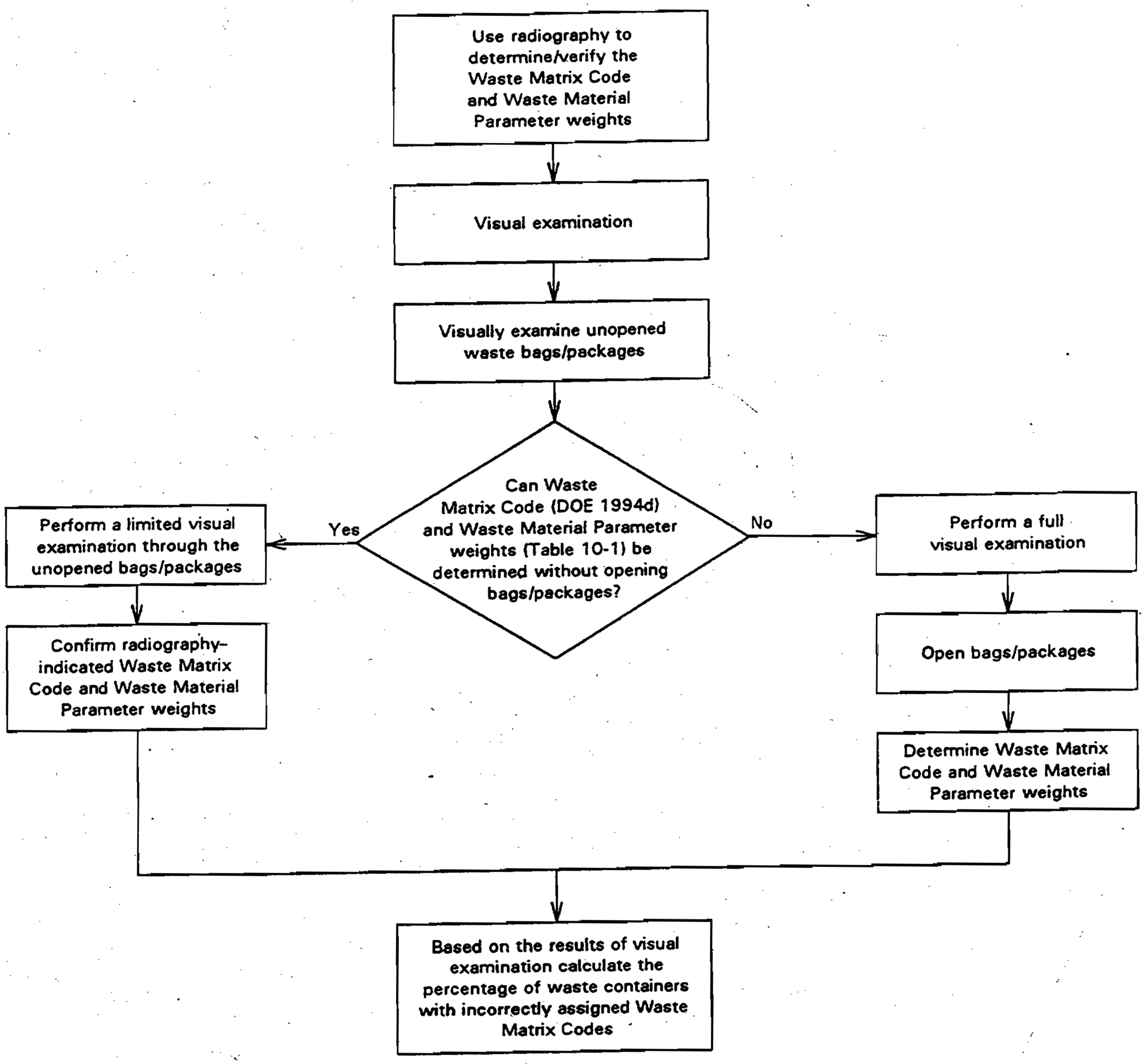

Figure 4-2. Programmatic Approach to Visual Characterization of TRU Waste

As discussed in Section 4.3.6, small containers completely full of liquid intermingled with other waste in a drum can appear to be empty due to the lack of visible fluid movement upon agitation, and may be missed by operators. Radiography has historically been performed manually, which is tedious and labor intensive. However, DOE has been investigating the feasibility of digitizing the current analog information obtained with RTR and hopes to realize sufficient gains in efficiency to allow installation of an automated system at INEL and possibly at other sites. DOE has made the point that there is "no equivalent or associated method found in EPA sampling and analysis guidance documents." There are other industries that use radiography and may have protocols applicable to DOE. DOE further states in their Waste Characterization Methods Manual that:

> Standardized training requirements for radiography operators are based on existing industry standard training requirements and comply with the training and qualification requirements of ASME NQA-1, Element 2, except for Supplement 2S-2 (DOE95d).

There is no DOE-wide formal certification or accreditation process for radiography operators and each site specifies how it will achieve the training requirements and QAOs presented in the TRU QAPP in their QAPjP.

4.4.3 Headspace[25] Sampling and Analysis

Headspace sampling and analysis are the determination of the chemical composition and concentration of flammable gases, volatile organic compounds, and other gases contained in the void volumes of waste containers. These compounds are determined by gas chromatography and/or gas chromatography-mass spectrometry. TRU wastes are typically packaged in 208 liter (55 gallon) drums. The drums contain 90 mil polyethylene liners, and inside each liner is a 208 liter polyethylene bag that may contain many other smaller bags. Sampling within a waste container can occur in three general areas: in the innermost layer of confinement, i.e., any of the small bags within the drum's interior; in the spaces within the drum liner; and under the drum lid, in the space between the drum lid and the sealed drum liner. The 3-year-old WIPP Performance Demonstration Program for Headspace Gas

[25] The term "headspace gas" should be interpreted to mean hydrogen, methane, and the volatile organic compounds that exist within a layer of confinement in a TRU waste container (DOE94b).

Analysis is detailed in DOE92. This program is used to qualify DOE TRU generators to certify TRU waste containers for shipment to WIPP. Once a participant is qualified using a technique(s), the participant may characterize waste containers for shipment to WIPP using only that same analytical technique(s) used to analyze the PDP samples. participation is mandatory and blind samples are distributed to all participants annually.

4.4.4 Solid Process Residues and Soils Sampling and Analysis

Solid process residue and soil sampling and analysis are used to determine the hazardous constituents in TRU wastes classified as solid process residues and soils (Series 3000 and 4000 WMCs). Sampling procedures are based on methods found in EPA's SW-846 (EPA86) and are detailed in the Methods Manual (DOE95d). The analytical procedures to be used are also based on SW-846, but were modified by Los Alamos National Laboratory for this purpose. A facility for these analyses is presently operational at Oak Ridge National Laboratory. The DOE intends to use sampling and analysis primarily to verify characterizations made using process knowledge.

4.4.5 Visual Examination

Visual examination is the characterization of the contents of a waste container by physical removal, inspection, and sorting for the purpose of establishing or verifying that the correct waste codes have been assigned. In this time-consuming, hands-on process, the contents of a drum are unpacked, examined, segregated if necessary, and repackaged. Several TRU generators have modified facilities that can be used for this purpose. However, it is not clear whether DOE will require each TRU waste generator to have this capability on site or if certain sites would be designated to perform this function for others. Argonne National Laboratory-West has a waste characterization chamber designed for visual examination of waste containers. DOE considers visual examination to be a means of verifying assumptions made using process knowledge, e.g., correct waste code assignment and absence of non-conforming items (residual liquids, compressed gases, etc.). For newly generated wastes, DOE intends to use process knowledge and prospective documentation of each waste container's contents to ensure each container's compliance. For <u>all</u> TRU wastes (newly generated and retrievably stored), DOE says that

> As a QC check, a statistically significant portion of the certified waste containers must be opened and visually examined. (DOE94b)

The actual number of containers examined must be empirically derived by each site annually, and DOE asserts that

> The number of waste containers requiring visual examination will ensure that the Program is 80-percent confident that, if the indicated number of waste containers is examined, the UCL_{90} of the miscertification percentage will be less than 14 percent, (i.e., there is only a 10-percent chance that the miscertification rate is greater than 14 percent). (DOE94b)

4.4.6 <u>Use of Acceptable Knowledge/Process Knowledge</u>[26]

Each of the above techniques is intended to complement the waste characterization data generated using process knowledge. DOE intends to rely heavily on process knowledge for most WMCs and to use it as the primary means of waste characterization for newly generated waste and retrievably stored WMC 5000 wastes (DOE94b). DOE anticipates that retrievably stored waste will require more frequent verification by empirical techniques to certify wastes in accordance with all applicable requirements. Because process knowledge is such an important element in waste characterization it is discussed in detail in Section 4.5 below.

4.5 USE OF PROCESS KNOWLEDGE (ACCEPTABLE KNOWLEDGE) TO CHARACTERIZE TRU WASTES

4.5.1 <u>Definition and Regulatory Precedent For the Use of Process Knowledge (Acceptable Knowledge)</u>

The DOE recently released guidance to address the use of acceptable knowledge/process knowledge for the characterization of TRU wastes (DOE95c). This guidance document provides the following:

- definitions for acceptable knowledge and process knowledge
- guidance to distinguish types of waste streams for waste characterization purposes

[26] The term *process knowledge* has historically been used to refer to what DOE currently calls *acceptable knowledge*. As defined by DOE (DOE95e) and discussed in the text, acceptable knowledge is a broad category of types of information that includes process knowledge.

- classes of acceptable knowledge

- Quality Assurance requirements for the use of acceptable knowledge to characterize TRU wastes

- specific requirements for acceptable knowledge documentation

The document summarizes DOE's approach to the use of process knowledge for characterizing TRU wastes that previously was scattered among many DOE and CAO documents (DOE94b, DOE94e, DOE95c). In this document, DOE has followed EPA's approach of defining *process knowledge* as a subset of acceptable knowledge (EPA92). DOE defines acceptable knowledge as follows:

> *Acceptable knowledge* includes process knowledge and results from previous testing, sampling, and analysis associated with the waste. Acceptable knowledge includes information regarding the raw materials used in a process or operation, process description, products produced, and associated wastes. Acceptable knowledge documentation may include the site history and mission, site-specific processes or operations, administrative building controls, and all previous and current activities that generate a specific waste.

DOE also states that-

> Acceptable knowledge refers to information that can be used for waste characterization in lieu of waste sampling and analysis conducted in accordance with the requirements specified in the Transuranic Waste Characterization Quality Assurance Program Plan, and may include process knowledge and the results of previous surrogate waste sampling and analysis.

DOE defines process knowledge as follows:

> *Process knowledge* is a term used by the EPA to refer to detailed information on a waste that is obtained from existing published or documented waste analysis data or studies conducted on hazardous wastes generated by process[s] similar to that which generated the waste. Process knowledge describes the process or operation that generated the waste that is being characterized. Process knowledge is used to identify specific constituents in a waste stream and the method (or process) by which the constituents are used that created the final waste.

The precedent for the use of waste-related information in waste characterization originates in the Resource Conservation and Recovery Act (RCRA). Under RCRA, a waste generator is allowed to use "acceptable knowledge" to determine whether a waste is hazardous (EPA94). As stated above, process knowledge is one form of "acceptable knowledge." DOE has determined that "when used in conjunction with other waste characterization techniques" acceptable knowledge "is appropriate to obtain the required TRU waste characterization information" (DOE95c). This information encompasses many aspects of TRU waste, including WMC, physical form, and assignment of a waste container to a specific waste stream. This information will be required to determine compliance with the acceptance criteria from the WIPP WAC, TRUPACT-II, and the TRU QAPP.

Historical definitions of process knowledge within the EPA-regulated community of RCRA waste generators typically include two important aspects:

- they were used solely for the purpose of determining that a waste is hazardous under RCRA; and
- they focused on engineering assessments of waste streams where waste characterizations were based on computational methodologies that were documented, such as mass balance or process engineering diagrams.

While DOE's definition includes these aspects and others, it is not clear that DOE's use of process knowledge is completely consistent with RCRA. In the TRU QAPP (DOE94b) and the Transuranic Waste Characterization Acceptable Knowledge Guidance Manual (DOE95c), DOE outlines the main purposes for the use of process knowledge, including:

- sorting newly generated and retrievably stored waste containers into waste streams;
- estimating the volume and weight of a waste container's contents;
- determining if WMC Series 3000 & 4000 wastes exhibit toxicity characteristics as specified in 40 CFR part 261, Subpart C, in conjunction with empirical sampling and analysis;
- determining if WMC 5000 Series wastes are RCRA hazardous in the absence of empirical sampling and analysis;
- selecting the appropriate method to quantify a waste drum's radionuclide content; and
- describing waste stream continuous processes and changes over time.

4.5.2 Using Process Knowledge for Waste Characterization

The credibility of using process knowledge ultimately rests upon the user's ability to provide the appropriate support documentation. This documentation must demonstrate that the waste producing process was adequately controlled during waste generation to allow the use of information as opposed to empirical investigation. The DOE has proposed eight classes of acceptable knowledge (DOE95c). These are summarized in Table 4-8.

For newly generated and retrievably stored wastes, DOE plans to assign waste containers to a waste stream based on process knowledge after first developing a profile for each waste stream (DOE94b). DOE describes this approach in the TRU QAPP. Waste stream profiling assumes that the waste-generating process is a well-defined and controlled process that can be supported by sufficient documentation, and that the documentation is available and amenable to direct inspection.

Table 4-8. Classes and Examples of Acceptable Knowledge

Class of Acceptable Knowledge	Examples of Supporting Information
waste generating process information	process flow diagrams, documented inputs/outputs, process controls, operating procedures
engineering and design information	piping and glove box designs, equipment and holding tank specifications
supporting data	surrogate waste sampling and analysis data, comparable waste stream analytical data
supplemental data	data obtained from research and development operations, effluent monitoring data, product quality control data
expert knowledge	personnel interviews, site inspections, test or research plans
standard industry practice information	vendor information, material safety data sheets, common industrial operations or treatment practices
compliance program information	RCRA permits, safety analysis reports, chemical inventory databases
program management information	Quality Assurance Plans, procurement documents, operating procedures, waste certification procedures

Important aspects of waste stream profiling include consideration of the following:

- whether multiple profiles are required for complex waste streams
- profile's responsiveness to changes in the waste producing process(es)
- quantification of the uncertainty associated with each part of the profile
- how each stream's profile would be determined, i.e., using average concentration values of specific constituents, or by establishing a range of acceptable concentrations
- reconciliation of a waste stream's profile with an out-of-specification analysis of a specific drum originating in the stream
- protocol required when a waste stream was found to be outside of the profile

It should be noted that much of the waste for which DOE uses acceptable knowledge/process knowledge as the main waste characterization tool originates from non-routine types of activities that are not typically understood to be controlled processes, with well-defined feed materials, intermediate products and outputs. Example are wastes from unscheduled maintenance and the cleanup of chemical or radioactive spills. Acceptable knowledge/ process knowledge may be a poor choice as a waste characterization tool for these and other similar types of waste.

4.5.3 Use of Acceptable Knowledge/Process Knowledge for TRU Inventory

The use of acceptable knowledge/process knowledge to characterize TRU wastes is advantageous for several reasons:

- to minimize worker radiation exposure;
- the physical nature of many wastes (i.e., WMC Series 5000 and 7000 wastes) does not lend itself to conventional SW 846 type analytical procedures; and
- many historical wastes were generated prior to the establishment of RCRA, and are inadequately characterized according to current standards.

As discussed earlier, DOE currently details its inventory of current and anticipated TRU waste in the WTWBIR. The WTWBIR combines information from the following two documents:

- *Integrated Data Base for 1993: U.S. Spent Fuel and Radioactive Waste Inventories, Projections, and Characteristics*, DOE/RW-0006, Rev. 9, April 1994; and
- *U.S. Department of Energy Distribute of the Phase II Mixed Waste Inventory Report*, May 1994 (MWIR).

The WTWBIR is currently considered the best source for information on DOE's inventory of TRU waste. Process knowledge was used to generate much of the information in this document particularly as the basis for calculating waste volumes and other data. Process knowledge should be used with caution because DOE TRU waste generators exhibit great diversity with respect to waste generation and handling. Additionally, uncertainty estimates associated with process knowledge data and their application are not provided and it is unclear that DOE has sufficiently quantified/evaluated these.

4.5.4 Evaluating the Use of Process Knowledge

The use of process knowledge as a predictive tool for TRU waste characterization has not undergone rigorous regulatory scrutiny. Due to the nature of chemical analyses and the complexity of assigning hazardous waste codes, it is important to assess the appropriateness of comparing waste characterizations made with process knowledge to those made with empirical sampling and analysis.[27] For the purpose of this report, such comparisons have been made and one is discussed below (EPA95).

DOE conducted a 2-year investigation of the correlation between process knowledge and empirical sampling and analysis. This study was completed in 1985 and involved a total of 242 containers of TRU waste, which ranged from new (6 months old) to older waste (12

[27] For example, certain waste streams are classified as hazardous solely by virtue of the presence of a specific chemical(s) within the waste generating process (process knowledge), regardless of concentration. For such *listed wastes*, the inability of a chemical analysis to detect the listed waste does not affect the waste stream's classification as hazardous (EPA94). Waste streams are often assigned waste codes for *characteristics wastes* (D Codes) in a *conservative* manner for the purpose of storage, meaning that if a waste generator thinks there is a reasonable probability the waste could exhibit a specific D Code (process knowledge), it is assigned. However, upon empirical testing, many wastes would not actually test hazardous for all of the D Codes they had been assigned. In both of these examples, the comparison between the waste codes assigned using process knowledge and empirical sampling and analysis is inappropriate.

years old in 1983). Of these, 199 drums and 10 boxes were generated at the Rocky Flats Plant and 33 drums were generated at Los Alamos National Laboratory. All containers were initially shipped to the Idaho National Engineering Laboratory (INEL), where they were assayed nondestructively using RTR. The study's objective was to collect information on gas generation, evaluate various venting devices, examine waste for compliance with the WIPP-WAC and evaluate the adequacy of nondestructive examination as a certification technique. The two-volume document *TRU Sampling Program: Volume I—Waste Sampling and Volume II—Gas Generation Studies* (CLE85) describes the study in detail and provides the investigation's results.

The waste containers had initially been "characterized" at the generator facility (RFP or LANL) by the assignment of a Waste Content Code[28] (see Appendix A to CLE85) prior to shipment to INEL. At INEL, each drum was examined using real-time radiography and radioassay by passive-active neutron counting and the results were recorded. The drums were then shipped to the Rocky Flats Plant, where each drum was completely dismantled within a hot cell for visual examination. The contents were emptied, weighed, and analyzed by radioassay when appropriate, and all results were recorded. This study's main purpose was to determine the adequacy of RTR as a nondestructive characterization technique. However, it also provided an opportunity to evaluate the use of process knowledge as a predictive tool. By comparing the content code assigned by the generator using process knowledge against the "proper" content code assigned after complete hands-on examination of the waste container (the equivalent of sampling and analysis), process knowledge can be evaluated as a tool for assigning the correct content code. Toward this end, the data from this investigation were analyzed statistically and the results are described below.

The Kappa statistic was used to evaluate how well process knowledge was able to classify waste by content code compared to how well the codes would be expected to have been assigned by chance alone (EPA95). In summary, process knowledge assigned content codes much better than would be expected by chance alone, indicating that for these waste containers, process knowledge was effective as a predictive tool for waste classification. It should be noted that DOE's proposed use of process knowledge may not lend itself to this type of verification, in large part because problematic sample matrices do not permit comparisons to be made with sampling and analysis results. DOE has recognized this

[28] The Waste Content Codes used for this study were developed prior to TRUCON Codes. TRUCON Codes were intended to include all aspects of waste covered by the Waste Content Codes.

problem with debris wastes (WMC 5000 series) where process knowledge is the preferred waste characterization technique.

In evaluating the CLE85 study, three caveats should be noted -

1) The waste containers used in the study were not statistically selected and therefore were not necessarily representative of TRU waste, thus limiting the study's applicability.

2) Production and waste handling practices, documentation protocols, assay methods, etc., vary among TRU generators. Because of the lack of established, auditable, uniform criteria for waste characterization by all TRU generators, questions exist regarding this study's applicability. Caution must be exercised in applying conclusions to TRU waste generators or specific waste streams other than those used in this study which originated primarily from Rocky Flats and Los Alamos.

3) This analysis provides information on the ability of process knowledge to assign a content code; no conclusions can be drawn about the ability of process knowledge to provide other important, detailed information (e.g., isotopic distribution, amount of free liquids, gas generation rates). This is particularly true for retrievably stored, older waste, where existing information is sparse.

The study discussed here is the only documented evaluation of the use of process knowledge available at this time. However, additional information exists at INEL, Hanford, Oak Ridge National Laboratory, and the Savannah River Site, where DOE contractors have been attempting to verify waste content codes assigned by process knowledge using other techniques. At INEL alone, DOE has performed radiography and radioassay on approximately 30,000 drums of waste to date, some percentage of which have also been visually examined. The information is not yet available so it is not known what level of documentation exists for these examinations or if other formal comparisons have been made. This information could be very useful to a more comprehensive evaluation of the use of process knowledge as a predictive tool.

4.6 TECHNICAL RATIONALE FOR WASTE CHARACTERIZATION PROVISION OF 40 CFR part 194

4.6.1 General Information on Waste

Section 194.24(a) of the rule requires that DOE provide information on the chemical, radiological, and physical composition of the waste scheduled for disposal at the WIPP including both existing and, to the extent practicable, to-be-generated waste. This description can be based on assays, non-destructive examination, process knowledge and any other appropriate evaluation techniques. This information is needed to anticipate the behavior of the waste in the disposal system.

Description of the radiological composition requires, for each radionuclide present or expected, an estimate of the quantity of radioactivity (curies) at the time of disposal (i.e., when the disposal system is sealed). This could involve setting an upper limit for each nuclide. Demonstration that the waste meets the TRU criterion of 100 nCi/g is also required. In addition, information on the expected drum-to-drum variation in radioactivity levels may be required to model cuttings releases associated with drilling events.

Description of the chemical composition would involve documentation of components which might affect waste containment by affecting waste solubility, colloid formation, gas generation, or gas consumption, inter alia. As has been discussed previously, solubility can be affected by the quantity of organic ligands, the quantity of CO_2-forming constituents, and the quantity of waste constituents which can alter the pH of any intruding brines. To characterize gas generation potential, it is necessary to know the quantities of iron and aluminum alloys, the quantities of combustibles, plastics and rubber, and the quantity of water initially present in the waste.

Description of the physical characteristics of the waste would include information on surface-to-volume ratios of corroding metals, waste density and porosity, waste permeability, weight or volume mix of waste forms such as sludges, metals, paper, rags, etc.

4.6.2 Documentation of Waste Characteristics

§194.24(b)(1) further requires that DOE submit documentation substantiating that all waste characteristics which influence the containment of wastes in the disposal system have been identified and assessed for their impact on disposal system performance. The rule lists, but does not limit the characteristics to such items as solubility, gas generation, ability to form stable colloids, shear strength, and compactability as examples of waste characteristics which must be assessed.

The waste shear strength (shear resistance) used in modeling borehole wall erosion during drilling events was originally deduced by SNL investigators from seabed data, which showed that the shear resistance of such materials was between 1 and 5 Pa, a range quoted to be several orders of magnitude lower than macroscopic soil shear strength (PAR70, BER95). For the 1992 WIPP PA, SNL assigned a range of 0.1 to 10 Pa and a median value of 1 Pa for the shear resistance based on the assumption that the waste would behave similarly to montmorillonite clay (BER95, SAR73). However, this parameter was not sampled over the assigned range in the PA calculations; rather the median value of 1 Pa was used in the CUTTINGS model.

If the flow of the drilling mud between the drill collar and the borehole wall is turbulent rather than laminar, an additional waste characteristic—the surface roughness—is required to calculate the shear stress acting on the waste. In the 1992 PA, the range of expected surface roughness was set at 0.025 to 0.04 m, with a median value of 0.01 m (SAN92). The absolute surface roughness values chosen for PA exceeded those of very rough concrete or riveted steel piping (BER94, STR75).

4.6.3 <u>Documentation of Waste Components</u>

Section 194.24(b)(2) requires DOE to submit documentation substantiating that all waste components which <u>influence</u> the waste characteristics described above in 4.6.2 have been identified, and their impact on disposal system performance assessed. The waste components to be evaluated include, inter alia, metals, cellulosics, chelating agents, water, and total activity (in curies) for each radionuclide present in the waste. Other waste components not specifically listed in the rule which may need evaluation include waste mix (by weight, volume, and/or density), quantities of rubber and plastics, quantities of pH altering constituents, quantities of CO_2-forming and -consuming species, and container-to-container variability in radioactivity level. A summary of waste characteristics likely to be used in performance assessment and the waste components which influence them is presented in Table 4-9. It should be noted that, in many cases, there is no single companion waste component for a waste characteristic. This is because the characteristics are in many cases determined by laboratory experiments which cannot be directly related to on-going measurements of the waste.

Table 4-9. Summary of Waste Characteristics and Waste Components Likely to be Used in WIPP Performance Assessment

Waste Characteristic	Waste Component Influencing Waste Characteristic
ROOM CLOSURE	
Shear modulus	
Bulk unloading modulus	
Yield function constants	
Volumetric strain vs. pressure	Waste mix
Initial waste density	Waste mix
CUTTINGS	
Shear strength	
Absolute surface roughness	
Permeability	
particle diameter	
particle density	
Tensile strength	
BRAGFLO - Flow	
Pore shape distribution parameter(s)	
Residual saturations - liquid and gas	
Threshold displacement pressure	
Intrinsic permeability	
Initial porosity	Waste mix
BRAGFLO - Gas Generation	
Anoxic corrosion rates (humid and inundated)	Quantity of iron (and aluminum)
Microbial degradation rates (humid and inundated)	Quantity of cellulosics
	Quantity of plastics and rubbers
	Quantity of electron acceptors (oxidants) such as SO_4^{2-} and NO_3^{1-}
	Quantities of nutrients (P and N)
Equivalent drum surface area	Surface to volume ratio for iron (and aluminum)
Number of drums per disposal room	
Radiolysis rate	Quantity of alpha emitters
	Initial water content[1]
	Quantity of cellulosics
ACTINIDE MOBILITY	
Solubility - pCO_2	Quantities of CO_2-forming and CO_2-consuming species
Solubility - pH	Quantities of acid and base formers
Solubility - complexing agents	Quantities of complexing agents
Solubility - brine concentration	
Solubility - actinide oxidation states	
Colloid concentration(s)	
SOURCE TERM	
Radioactivity	Quantity of curies for each radionuclide
	Drum-to-drum curie distribution
Actinide concentration	Quantity of each actinide

1 - Influences all gas generation mechanisms.

In addition to identifying and assessing the impact on disposal system performance of all waste components which influence waste characteristics, DOE is required under §194.24(b)(3) to substantiate any decision to exclude consideration of any waste characteristic or waste component because such characteristic or component is not expected to significantly influence the containment of the waste in the disposal system.

4.6.4 Limits on Waste Components

DOE is required to set limits on all significant waste components and show that the WIPP complies with §194.34 and §194.55 based on these limits (§194.24(c)). In doing this, DOE must describe the basis for setting these limits and demonstrate that, when all of these waste component parameters are set at their limit, the mean CCDF obtained will meet the containment requirements of 40 CFR part 191.13 at the 95% confidence limit.

As discussed previously in Sections 4.3.1.1 and 4.3.5, actinide solubility depends on various factors including pH, pCO_2, and presence of organic ligands. If the quantities of pH altering species, CO_2-forming and -consuming species and organic ligands in the waste are determined to be important, DOE is required to set limits on these waste components and demonstrate that the mean CCDF obtained when these components are set at the conservative limits meets the requirements of §194.34. For example, CO_2 tends to stabilize plutonium in the +VI valence state which has high solubility, but CO_2 can be removed from the system by reaction with lime or calcium hydroxide. Thus, the conservative limits would be those quantities of materials which produce the maximum amount of $C0_2$ and result in the least CO_2 removal in this specific example with respect to plutonium.

Once the acceptable limits on the waste components have been set, DOE must establish a system of controls which assures that the waste actually emplaced in the WIPP will fall within these limits. Elements of this system of controls include measurement, sampling, chain of custody, and other documentation. If, as discussed in Section 4.6.1, DOE sets an upper limit on the quantities of each radionuclide, then it will be necessary to show during disposal, that this limit will not be exceeded taking into account uncertainties in the measurements of the curie-content of the waste at the various generator sites.

4.6.5 Quality Assurance

As discussed previously in Section 4.3.7, the components of actual waste may differ significantly from the components that were assumed in developing the waste characteristics for the compliance application. This is especially true, since only about 40% of the total CH-TRU waste has been generated to date. The provisions of §194.24 were developed to ensure that the repository will remain in compliance as long as the waste emplaced is within the established limits. EPA believes that the proposed procedure for bounding the waste characteristics is not overly prescriptive and can be addressed within the sensitivity analysis framework which is an integral part of performance assessment. To enhance confidence in the waste characterization process, all activities and assumptions are subject to the quality assurance requirements of §194.22. Use of process knowledge to quantify waste components is specifically subject to these quality assurance requirements (§194.24(c)). EPA is empowered to use audits and inspections to ensure that the quality assurance requirements are met (§194.24(h)).

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5. Future State Assumptions

5.1 INTRODUCTION

A framework, or set of bounding assumptions, is required in order to limit speculation in performance assessments and compliance assessments about how changes that occur over time may effect the WIPP disposal system. The "Future State Assumptions" are designed to establish that framework by providing guidance on how to treat future uncertainties such as changes in demographics, changes in human physiology, changes in technology, advances in medical science. §194.25 states:

> (a) Unless otherwise specified in this part or in the disposal regulations, performance assessments and compliance assessments conducted pursuant the provisions of this part to demonstrate compliance with §191.13, §191.15 and part 191, subpart C shall assume that characteristics of the future remain what they are at the time the compliance application is prepared, provided that such characteristics are not related to hydrogeologic, geologic or climatic conditions.
>
> (b) In considering future states pursuant to this section, the Department shall document in any compliance application, to the extent practicable, effects of potential future hydrogeologic, geologic and climatic conditions on the disposal system over the regulatory time frame. Such documentation shall be part of the activities undertaken pursuant to § 194.14, Content of compliance certification application; § 194.32, Scope of performance assessments; and § 194.54, Scope of compliance assessments.
>
> (1) In considering the effects of hydrogeologic conditions on the disposal system, the Department shall document in any compliance application, to the extent practicable, the effects of potential changes to hydrogeologic conditions.
> (2) In considering the effects of geologic conditions on the disposal system, the Department shall document in any compliance application, to the extent practicable, the effects of potential changes to geologic conditions, including, but not limited to: dissolution; near surface geomorphic features and processes; and related subsidence in the geologic units of the disposal system.
> (3) In considering the effects of climatic conditions on the disposal system, the Department shall document in any compliance application, to extent practicable, the effects of potential changes to future climate cycles of increased precipitation (as compared to present conditions).

The final rule requires that performance assessments and compliance assessments shall include dynamic analyses of geologic, hydrogeologic and climatic processes and events that will evolve over the 10,000-year regulatory time frame. All other present day conditions will be assumed to exist in their present state for the entire 10,000-year regulatory time frame. These latter requirements apply to the future demographic and physiologic state of mankind, among all other assumptions necessitated by performance assessments and compliance assessments. Predicting the manner in which society will change would necessitate predicting the effect of historical, economic and political forces which typically bring about societal and demographic change. The speculative nature of such predictions precludes the development of an acceptable methodology for inclusion in the final rule that could make reliable predictions of the future state of society, science, languages or other characteristics of future mankind. For example, suppose that we know the current population density around the WIPP and we know that the population has grown at a certain rate over the last three decades (a very short time-frame when compared to the WIPP regulatory time-frame of 10,000 years). In addressing the future, one could extrapolate future population density based on the historical growth rate which might, over a 10,000-year regulatory period, result in unreasonable values, or one could assume that the population density remains constant (i.e., the status quo). The latter approach is to be used for future states. It is inappropriate to make long term predictions based on short term data. As in the population example above, certain activities are influenced by complex and interrelated forces (economics, government policy, etc.) and therefore cannot be predicted with reasonable accuracy.

Effects of climatic change are to be considered because they are reasonably predictable from the geologic record of the last several thousand years. However, there is no need for speculation on the possible secondary effects from climate change (e.g., increased precipitation which could allow irrigated agriculture near the site and change human economic activity and lifestyle) as these would be driven by the complex interrelated forces listed above. A similarly convincing basis exists as well for hydrologic and geologic conditions. This chapter will examine the body of scientific knowledge which may be used to extrapolate hydrologic, geologic and climate conditions into the 10,000 year regulatory time frame.

5.2 LAND USE AROUND THE WIPP SITE

Analyses of the WIPP's long-term performance will have to establish population and land use characteristics. The information provided below demonstrates how certain aspects of present-day demographics can be established and described for use in these analyses.

Population

The 1979 resident population within fifty miles of the WIPP Site is shown in Table 5-1. These data were estimated for the 1980 WIPP Final Environmental Impact Statement (FEIS) (ALA79, DOE80). An examination of the US Census data indicated that the total Eddy County and Lea County population grew from 90,363 to 104,370 between 1970 and 1990 (DOC90). This is an average of about 0.7% per year. The 1990 Census data examined were not detailed enough to determine if there were changes in the population within 10 miles of the WIPP Site since 1979.

Table 5-1. 1979 Resident Population Within 50 Miles of the Site[a,b]

Sector[c]	0-5	5-10	10-20	20-30	30-40	40-50	Total
North	0	0	35	25	175	25	260
North-northeast	0	0	25	5	55	5,610	5,695
Northeast	0	0	0	25	75	8,660	8,760
East-northeast	0	0	15	70	205	33,200	33,490
East	0	0	5	15	3,240	155	3,415
East-Southeast	0	0	5	10	3,035	295	3,345
Southeast	0	0	5	15	25	30	75
South-Southeast	0	0	0	25	10	40	75
South	0	0	5	15	55	15	95*
South-southwest	6	0	5	30	90	15	145
Southwest	0	0	55	30	10	45	140
West-southwest	0	0	1,750	200	50	65	2,065
West	0	0	70	31,780	40	35	31,925
West-northwest	0	10	5	190	55	50	310
Northwest	0	0	30	20	65	12,055	12,170
North-northwest	0	0	15	5	220	10	280*
Radius Total	6	10	2,025	32,460	7,440*	60,305	102,245
Cumulative Total	6	16	2,040	34,500	41,940	102,245	

a Population estimated by Adcock and Associates (1977-1979).
b Figures for all areas beyond the 10 mile radius have been rounded to the nearest five.
c Distance from site (miles).
* The totals for this column and these rows are not in agreement with the numbers shown due to errors in the original data source.

Land Ownership and Use

Land in the vicinity of the WIPP is primarily owned by the Bureau of Land Management (BLM). Figure 5.1, included here from the WIPP FEIS (DOE80), illustrates land ownership for 1980. Since 1980, the following changes occurred in the Township 22 South Range 31 East (where the WIPP site is located): 1) the state-owned sections 16 and 32 were transferred to BLM in exchange for federal land elsewhere, and 2) the 4 by 4-mile area in the southwestern portion of the township was withdrawn for the WIPP site (see attached Figure 5.2 from DOE93).

At the WIPP, within its 16 mi^2 site, DOE presently controls 35 acres around the site's shafts and buildings (see Figure 5.2). Neither trespassing nor non-project uses are permitted in this area. Not shown in the figure is a 300-acre area around which DOE eventually plans to erect a five-strand barbed wire fence to prevent access to the area which overlies the repository footprint. DOE is presently considering extending the no-trespassing area to a total of 1,454 acres (see Figure 5.3), although grazing would be permitted on the newly added 1,154 acres.

Grazing and recreational uses – hunting, trapping, and off-road vehicle use – will be permitted on the remainder of the 16 mi^2 site. No surface or subsurface mining or exploration, nor water well drilling, will be permitted anywhere on the site except for two existing gas leases in section 31 at the southwest corner of the site. Land use immediately off the WIPP site allows for grazing, oil and gas exploration and production, extraction of sand, gravel, and caliche from surface pits, and recreational use. Figure 5.3 from the FEIS shows the location of some of these various activities. There is also extensive potash mining to the west, north, and northwest of the WIPP site. Figure 5.3 illustrates the locations of active potash mines relative to the WIPP site. Non-resident occupational employment within ten miles of the WIPP site is estimated to be 360 potash workers per shift (three mines) and twenty-four workers on cattle leases (ALA79, DOE90). Oil industry employment has not been estimated, but in 1990–1992 there were seventy-five oil and gas wells drilled within two miles of the WIPP site boundary (SIL94). A large agricultural area supported by irrigation is located along the Pecos River, which is 15–20 miles to the west and southwest of the WIPP (see Figure 5.3). Because of a scarcity of water in the fully allocated Pecos River Basin, the irrigated area is not likely to increase significantly.

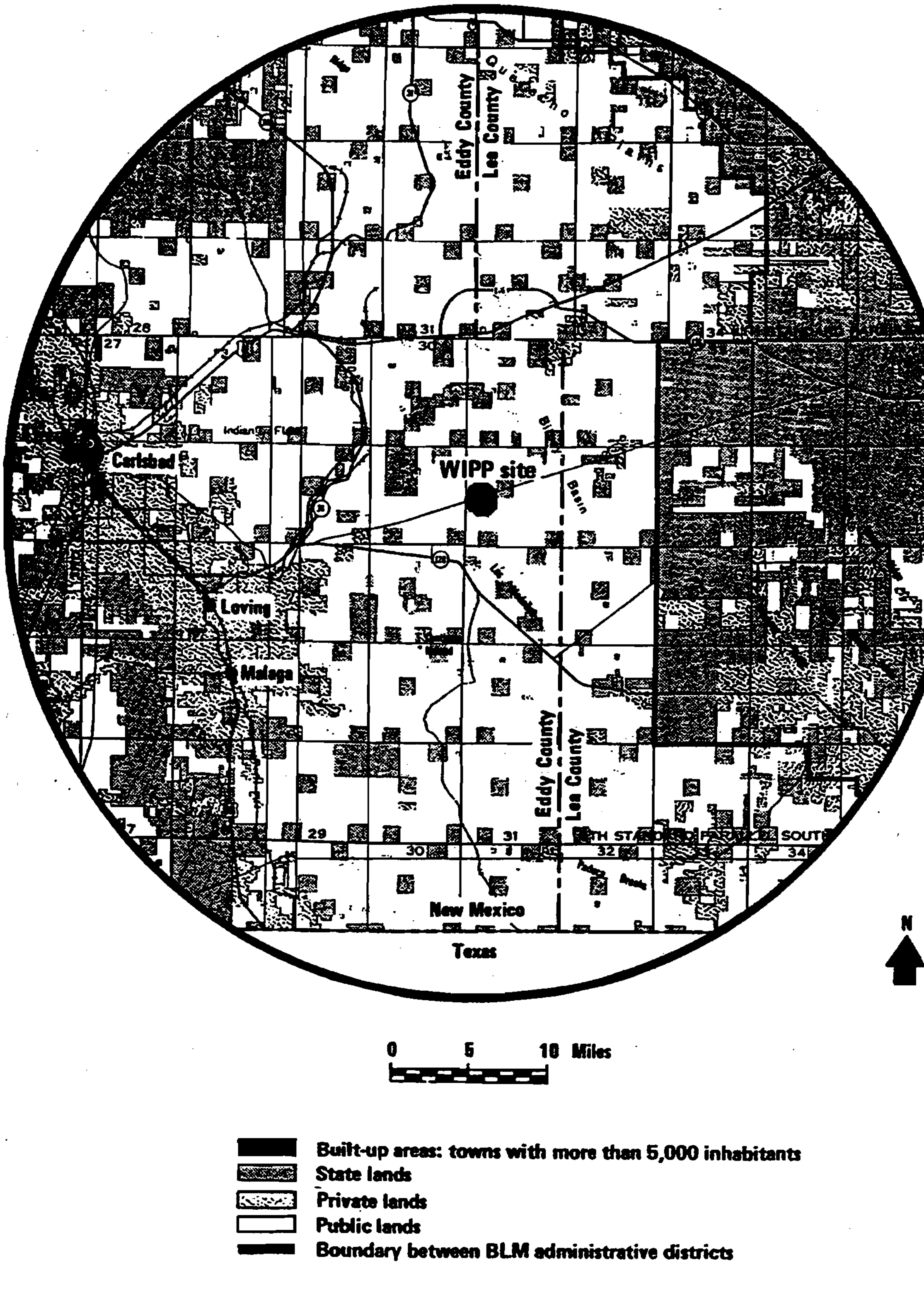
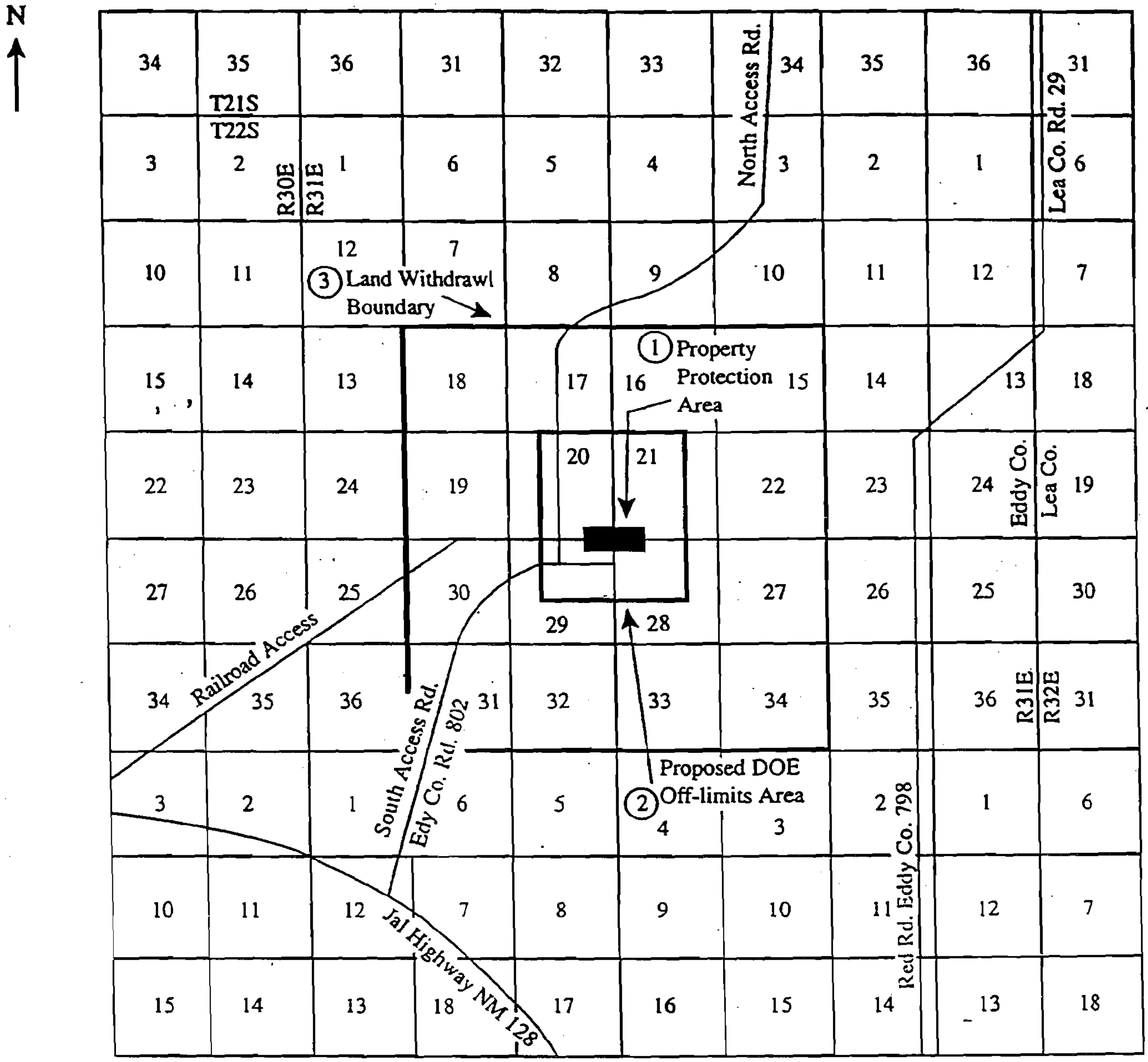
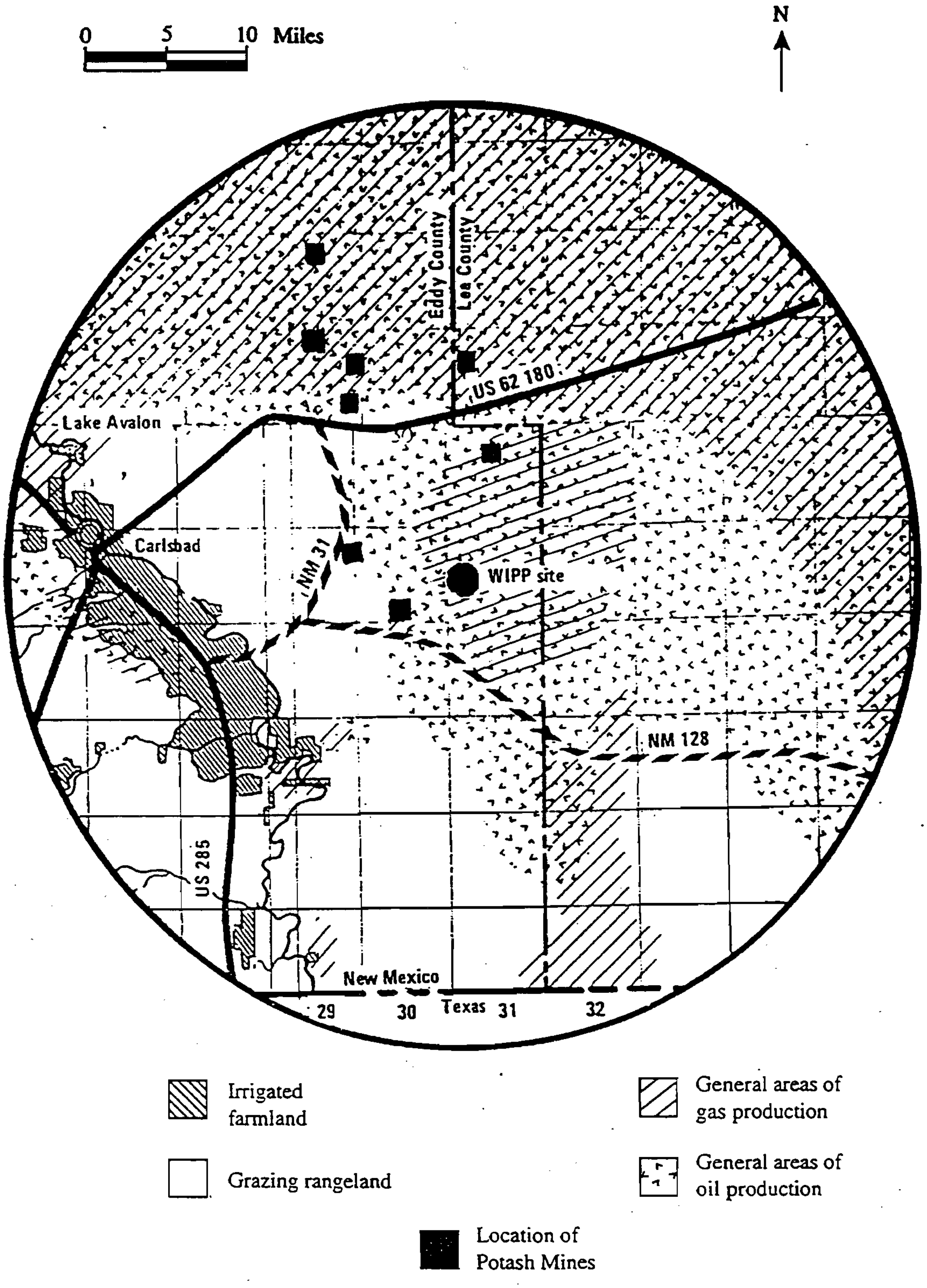


Figure 5.1 Land Ownership Within 30 miles of the WIPP Site



1. Major WIPP facility enclosed by an 8-foot, chain link fence and barbed wire outriggers
2. Can be posted against trespass
3. Will be posted by "Information Signs" only

Figure 5.2 WIPP Land Withdrawal Area and Surroundings



Sources: Bureau of Reclamation Land Use Map, 1968; New Mexico Bureau of Mines and Mineral Resources, New Mexico Energy Resources Map, 1974; Adcock and Associates, field surveys, 1978.

Figure 5.3 Land Use Within 30 Mile Radius of the WIPP Site

There are several highways near the WIPP site. US 62/180, connecting Carlsbad and Hobbs, is a four-lane divided highway located about nine miles north of the site which carries an average daily traffic flow of 1,850 vehicles (this and following averages were recorded in 1978). NM 128, about three miles south of the site, connects Carlsbad to Jal, New Mexico. This two-lane paved road conducts an average daily traffic flow of 220 vehicles. NM 31, about eight miles west of the site, connects NM 128 and US 62/180 and averages 510 vehicles per day. Numerous dirt roads in the area are maintained for ranching, pipeline maintenance, and oil and gas site access. In addition, there are now paved north and south access roads to the WIPP site from US 62/180 and NM 128, respectively. Most daily commuter traffic to the WIPP site uses the South Access Road. Present plans indicate all waste shipments arriving by truck will use the North Access Road. There is also a railroad spur connecting the WIPP site, but there are presently no plans for its use.

5.3 FUTURE STATES OF CLIMATE

Geologic, hydrologic, or climatic conditions are the only assumptions required by §194.25 to be predicted into the future. This section explicates part of the scientific record which can provide a basis for informed prediction of these three categories of events.

General State of Knowledge

Paleoclimatic data from southeastern New Mexico and the surrounding area indicate that the wettest and coolest Quaternary climate at the site can be represented by the last glacial maximum, when mean annual precipitation was approximately twice that of the present (SWI94). These data indicate that the hottest and driest climates have been similar to those of the present. The report also states that "the regularity of global glacial cycles during the late Pleistocene confirms that the climate of the last glacial maximum is suitable for use as a cooler and wetter bound for variability during the next 10,000 years."

Mean annual precipitation at the WIPP has been estimated to be between 28 and 34 cm/yr (HUN85). Geologic data from southeastern New Mexico and the surrounding region show repeated alternations of wetter and drier climates throughout the Pleistocene, corresponding to global cycles of glaciation and deglaciation. Data from plant and animal remains and paleo-lake levels permit quantitative climate reconstructions for the region only for the last glacial cycle, and confirm the interpretation that conditions were coolest and wettest during glacial maximums (SWI93). Mean annual precipitation 22,000 to 18,000 years ago, when the last North American ice sheet reached its southern limit roughly 1500 km north of the WIPP, was approximately twice that of the present (SWI94).

The following text is quoted from SWI94, "Incorporating Long-Term climate Change in Performance Assessment for the Waste Isolation Pilot Plant." It provides a general summary of the investigations which provide the basis for the 1992 WIPP PA assumptions regarding the potential for the range of future climatic extremes (SAN92).

> Glacial periodicities have been stable for the last 800,000 years (MIL41, HAY76, IMB84, IMB85). Barring anthropogenic changes in the Earth's climate, relatively simple modeling of climatic responses to earth's orbital changes suggest that the next glacial maximum will occur in approximately 60,000 years (IMB80). The extent to which unprecedented anthropogenic climate changes may alter this conclusion is uncertain, but presently available models of climatic response to an enhance greenhouse effect (MIT89, HOU90) do not predict changes of a larger magnitude than those of the Pleistocene. Furthermore, published models do not suggest significant increases in precipitation in southeastern New Mexico following global warming (WAS84, WIL87, SCH87, HOU90). Even allowing for anthropogenic change, climate variability at the WIPP can be bounded by Pleistocene extremes (SWI93).

The estimated mean annual precipitation at the WIPP during the late Pleistocene and Holocene is shown on Figure 5.4.

SWI93 draws the following three conclusions regarding climatic trends. First, maximum precipitation in southeastern New Mexico in the past coincided with the maximum advance of the North American ice sheet. (Minimum precipitation occurred after the ice sheet had retreated to its present limits.) Second, past maximum long-term average precipitation levels were roughly twice present levels. Minimum levels may have been 90% of present levels. Third, short-term fluctuations in precipitation have occurred during both the glacial maximum and the present, relatively dry, interglacial period, but fluctuations during the present interglacial period have not exceeded the upper limits of the glacial maximum.

SWI93 also states: "It would be unrealistic to attempt a direct extrapolation of precipitation {a figure is referenced} into the future. Too little is known about the relatively short-term behavior of global circulation patterns, and it is at present impossible to predict the probability of a recurrence of a wetter climate such as that of approximately 1000 years ago.

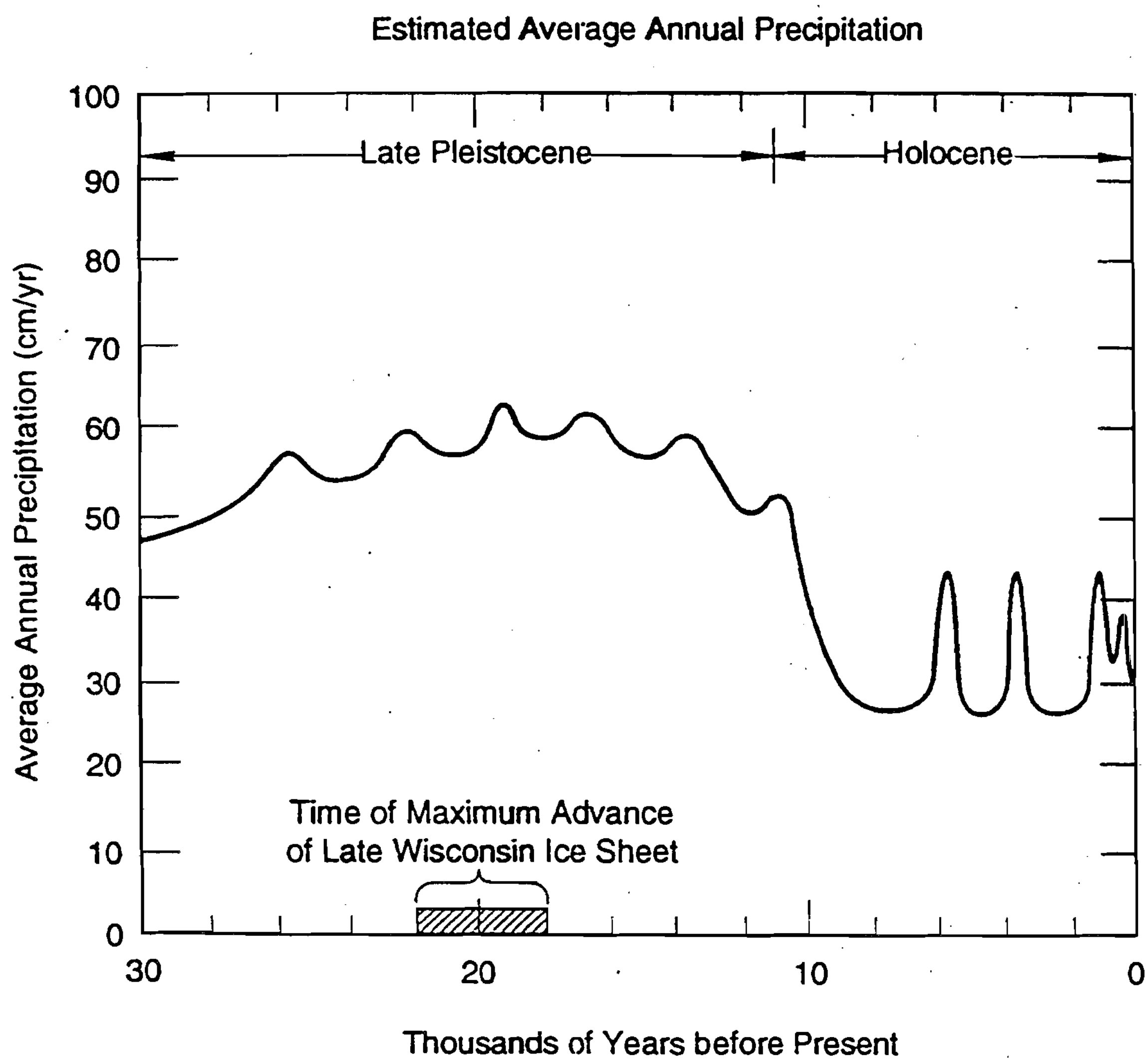


Figure 5.4 Estimated Mean Annual Precipitation Rate at the WIPP During the Late Pleistocene and Holocene (SWI93)

The long-term stability of the patterns of glaciation and deglaciation, however, do permit the conclusion that future climatic extremes are unlikely to exceed those of the late Pleistocene. Furthermore, the periodicity of glacial events suggests that a return to full glacial conditions is highly unlikely within the next 10,000 years."

Glaciation

Southeastern New Mexico is far from any region where extensive Pleistocene continental glaciation occurred. It is highly improbable, even in the event that global "icehouse" conditions developed, that the WIPP site would be affected by continental glaciers. In turn, the probability of glaciers and glacial erosion directly affecting the WIPP site is extremely small. *Alpine* glaciation, however, was quite extensive in northern New Mexico during the Pleistocene (CHR87). Evidence for alpine glaciers extends down to elevations of at least 8000 feet, possibly less. These glaciers, their deposits, and meltwaters affected and continue to influence the regional hydrology and Quaternary stratigraphy of this region. In the event of a major climatic change, alpine glaciation might be possible in the Guadalupe Mountains which have maximum elevations greater than 8000 feet (Guadalupe Peak is 8751 feet high).

5.4 GEOLOGIC FUTURE STATES

Sea-level fluctuations and hurricanes/seiches/tsunamis

The likelihood of sea-level fluctuations and hurricanes/seiches/tsunamis can be considered to be small due to the elevation (~3,300-3,500 feet) and landlocked position of the WIPP site. These conditions ensure that it will neither be inundated in the event of a eustatic sea-level rise (not even a rise of unprecedented scale) nor will it be affected by any catastrophic ocean current.

Regional uplift and subsidence

The Rio Grande Rift, an elongate, fault-bounded, extensional feature that extends roughly north-south across central New Mexico, began to form about 30 million years ago. One segment of the Rio Grande Rift, called the Tularosa Basin, is located within 150 km of the WIPP site. Extension continues within the rift today, as expressed by numerous active fault scarps that cut through Quaternary deposits (BLA76; CHA79; OLD89). There is some suggestion, based on the timing of development of structural features across the region, that extension may be slowly propagating eastward, toward the WIPP site. While long-term, rates of regional uplift/subsidence may not increase drastically over the next 10,000 years, detailed studies of Quaternary seismic activity and co-seismic fault slip should be done in the vicinity of the WIPP site in order to substantiate the claim that episodic, short-term uplift/subsidence will not compromise the integrity of the repository. This will largely entail detailed field mapping and analyses of Quaternary stratigraphy and structural features.

Landslides

The Pecos River, the largest river in the vicinity of the WIPP site, flows within 12-15 miles of the site. The difference in elevation between the Pecos River and the WIPP site is approximately 400 feet. It should be feasible to determine whether inundation of the WIPP site is possible in the event that a landslide dams or diverts the river at any of several different points along the river. A worst-case scenario might involve: 1) a landslide that dams the river where it is narrow, slightly downstream from, yet close to, the WIPP; 2) the landslide occurs during the annual peak discharge of the Pecos River; 3) the landslide and damming of the river occur at the same time as major flooding in southeastern New Mexico; and 4) the landslide occurs at a place along the river where the adjacent topography is such that flood waters are preferentially funneled toward the WIPP. Examination of aerial photographs and land-based studies might allow determination of the frequency of landslide events along the banks of the Pecos River and whether or not the (paleo)Pecos River ever flooded areas far beyond its "historical" flood plain. Furthermore, under pluvial conditions, the Pecos River may not maintain its current course in the future. Cores and/or trenches through Quaternary alluvium also might help with determining the frequency and magnitude of flooding events near the WIPP site.

Seismic activity (and faulting)

The main concerns regarding seismic activity and co-seismic slip or initiation of faults are: 1) whether the fault cuts through the repository and cumulative slip along the fault then brings radioactive waste into physical contact with circulating ground water; or 2) whether seismic events cause permeable faults or fracture zones to develop which lead to hydrologic communication between waste in the repository and circulating ground-water.

Given the tectonic setting of the WIPP site and the proposed depth of the repository, it is highly improbable that cumulative slip on a hypothetical fault that cuts through the repository could bring waste into contact with aquifers that sandwich the repository within 10,000 years. Thus, it seems reasonable to eliminate this from geologic scenarios, although as mentioned above under "Regional uplift and subsidence," detailed studies of the neotectonic activity around the WIPP site seem warranted.

New faults or fractures also could breach the repository and allow circulating ground waters to move through the repository and transport radionuclides to the surface or to shallow aquifers.

<u>Volcanic and magmatic activity</u>

Given the following, however, it seems reasonable that the inception of volcanic or magmatic activity is unlikely over the next 10,000 years and need not be considered in geologic scenarios: 1) the WIPP site is located presently in a relatively tectonically quiescent setting; 2) the WIPP site probably will remain tectonically quiescent over the long-term, based on present and projected vectors of motion for the North American plate and adjacent plates; and 3) volcanic/magmatic activity is typically associated with active, plate-margin settings (either extensional, compressional, or strike-slip settings), while mid-plate volcanism/magmatism is much less common and is related to deep-seated, mantle processes. The studies outlined previously under <u>Regional uplift and subsidence</u> would enhance confidence in the conclusion that volcanic and magmatic activity need not be considered as geologic scenarios.

<u>Earthquakes produced by subsurface fluid injection/removal</u>

Injection or removal of subsurface fluids during recovery of hydrocarbons is known to produce earthquakes. Earthquakes with magnitudes as high as 5.0 on the Richter scale, but generally between 1.0 to 3.0, are known from some areas (HOL68). Earthquakes of this type have been recorded in the Permian Basin (largely anecdotal evidence). Hazard assessment for the WIPP site should include the possibility of human-induced earthquakes as there are productive oil fields near the WIPP site that are currently under waterflood. Even small scale earthquakes could affect the integrity of seals.

5.5 HYDROLOGIC FUTURE STATES

The hydrologic properties of the geologic strata within the disposal system can be changed due to the occurrence of natural processes and events. As an example, dissolution may, in the future, affect the hydrologic properties of the Culebra dolomite layer of the Rustler Formation. The presence and degree of fracturing in the Culebra dolomite is thought to be directly related to the amount of dissolution of halite occurring below the Culebra (SNY85). As the magnitude of fracturing and development of secondary porosity increases, the Culebra transmissivity generally increases (CHA85). Based upon observations of outcrops, core, and detailed shaft mapping, the Culebra can be characterized as a fractured medium, at least locally, at the WIPP site (CHA84; HOL84). Aquifer tests also indicate responses characteristic of a fractured media (BEA87).

Dissolution within the Rustler Formation is observed both at the surface within Nash Draw, and in the subsurface at the WIPP site. Nash Draw, located immediately west of the WIPP site, is a depression resulting from both dissolution and erosion (BAC81). In Nash Draw, members of the Rustler are actively undergoing dissolution and locally contain caves, sinks, and tunnels typical of karst morphology in evaporitic terrain (HAU87).

BAC80 identified three types of dissolution occurring in the Delaware Basin: local dissolution, regional dissolution, and deep-seated dissolution. Local dissolution is the near-surface dissolution where surface or ground waters penetrate soluble strata though joints or fractures, causing local dissolution and possible collapse and fill, as well as dissolution features such as shallow caves above the regional water table. Regional dissolution occurs when chemically unsaturated water penetrates to permeable beds, where it migrates laterally, dissolving the soluble units which it contacts. On a regional scale, the consequence of such dissolution appears to be removal of highly soluble rock types, such as halite, combined with displacement and fracturing of adjacent rocks. Deep-seated dissolution occurs well below the water table, forming caverns within the rock.

At the WIPP site, regional dissolution is thought to have occurred within the Rustler Formation in the past (SNY85). However, there is some controversy as to whether this dissolution front is still active. BAC85 feels that most of the dissolution in the Rustler predates or occurred during a much more humid time in southeastern New Mexico over 500,000 years before present. BAC85 does suggest, however, that dissolution is still active in Nash Draw in areas very close to Livingston Ridge.

In the Rustler Formation at the WIPP site, most investigators feel that a westward increase in regional dissolution is reflected by a decrease in the number and thickness of halite beds and subsequent thinning of the Rustler Formation (HAU87). The stratigraphic level of the first occurrence of salt is in the upper Rustler along the eastern margin of the WIPP site, and progressively moves down-section through the Rustler as one moves west. As the bedded halites are dissolved, insoluble residues remain, forming beds of mudstones, siltstones, and chaotic breccia with a clay matrix (HAU87). Halite beds in the non-dolomitic members tend to be thin and grade westward into the residuum. Although most investigators concur with the premise that a dissolution front exists in the Rustler Formation at the WIPP site (COO71, POW78, MER83, CHA84, SNY85), there are some investigators who oppose this concept and believe that the westward decrease in halite within the Rustler represents depositional limits (LAM83, HOL84). HOL84 reported that, in their detailed mapping of the Rustler in the waste-handling shaft, no post-depositional dissolution features were identified.

Whether or not the dissolution front hypothesis is correct, there are general trends associated with the presence or lack of bedded halite within the Rustler Formation. As the presence of bedded halite within the Rustler increases, so does the thickness of the formation. Generally, as the amount of halite in the Rustler decreases, the transmissivity of the dolomitic members increases (HAU87), presumably from increased fracturing of the units as a result of halite removal and subsequent foundering and collapse of the more competent dolomite beds. In parts of Nash Draw, hydraulic potentials in the Magenta and Culebra are essentially the same (i.e. no vertical movement up or down). As one moves eastward onto the Livingston Ridge surface, the difference in hydraulic potentials between the two units increases. This could represent the increase in the effectiveness of the Tamarisk Member as a confining unit (or aquitard) with decreased halite removal (HAU87).

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6. Use of Expert Judgment

6.1 INTRODUCTION

6.1.1 Background

In 40 CFR part 194, EPA states that expert judgment should only be permitted in situations where data are not reasonably obtainable by collection or experimentation. EPA requires that compliance applications clearly identify all instances in which judgment is used and the experts involved. Documentation must be included which describes the process for expert judgment elicitation, the results of expert elicitation, and the reasoning behind those results. Documentation of interviews used to elicit judgments from experts, deliberations and formal interactions among experts, background information provided to experts, and the questions or issues presented for elicitation of expert judgment are also requested.

Although the Agency has not specified any particular methods for expert judgment elicitation, the Agency has included some restrictions and guidelines for the selection of individuals as experts in the 40 CFR part 194 criteria. These include prohibitions on: selecting individuals who are members of the team of investigators requesting the judgment or the team of investigators who will use the judgment; selecting individuals who maintain a supervisory role or who are supervised by those who will utilize the judgment; and selecting a membership of which less than two-thirds consists of individuals who are not employed directly or indirectly by DOE (unless it can be shown that this is impracticable because of a lack or unavailability of qualified independent experts, in which case at least one-third of the membership must be non-DOE personnel). Compliance certification applications must provide information which demonstrates that the expertise of any individuals and the panel, as a whole, involved in expert judgment is consistent with the level of knowledge required by the questions or issue presented to that individual and the panel.

Additionally, EPA requires that at least five individuals be used in any expert elicitation process, unless a lack or unavailability of experts can be demonstrated and documented. Also, any compliance certification application should include a discussion explaining the relationship between the information presented, the questions asked, the judgment of any expert panel or individual, and the purpose for which the expert judgment is being used.

EPA requires that a minimum of five persons form an expert panel so that the elicited results are representative of diverse viewpoint. This should result in a more informed and objective process. However, an expert elicitation could be conducted with fewer than five individuals in the event that there is a lack or unavailability of potential experts, provided that a rational is stated. §194.26 of the final rule states this restriction:

> At least five individuals shall be used in any expert elicitation process, unless there is a lack or unavailability of experts and a documented rational is provided that explains why fewer than five individuals were selected.

It is essential that any expert panel member should be free from conflict of interest. Accordingly, two-thirds of the members of any panel should not be employed by DOE, directly or indirectly. This restriction does not extend to those persons who receive funding from the Department in those instances in which such funding is for activities not related to WIPP (such as university professors). Expert panels may include persons employed by the State of New Mexico Environmental Evaluation Group assuming that their expertise can be demonstrated to be adequate for the elicitation. Compliance applications must demonstrate this expertise, and EPA's judgment on the adequacy of this demonstration will be used in making the decision on the issuance of certification.

Finally, EPA proposes that the elicitation process provide the public an opportunity for presentation of scientific and technical views to the experts.

The Background Information Document (BID) for the 1993 amendments to 40 CFR part 191 notes that "It is generally accepted that the use of expert judgment is required in the process of evaluating the long-term containment potential of a geologic waste disposal facility" (EPA93). In this context, the term "expert judgment" refers to a very structured, formalized process involving panels of experts. However, expert judgment may also be applied by an individual charged with making a determination on a given situation.

DOE is using both expert panel and individual investigator judgment to support the WIPP performance assessment. In some instances, an expert panel may be convened and opinion elicited using a highly structured, formal approach. In other cases, a single principal investigator may be asked to supply an estimate of a parameter where a limited amount of experimental data is available and also provide an estimated probability distribution function for that parameter. The principal investigator may also be asked to define the probability distribution function for a parameter where considerable experimental data are available, but which still must be interpreted.

6.1.2 NRC Publications on the Expert Judgment Process

NUREG/CR-5424 (NRC91) notes that the process by which expert judgment is elicited will vary depending on the particular situation. NUREG/CR-5424 lists the following factors that may affect how the judgment can best be gathered:

- The type of information needed from the experts (answers only or ancillary expert data)
- The form in which the expert's answers are needed for input into a model
- The number of experts available
- The interaction desired among the experts
- The difficulty of setting up the problems
- The amount of time and study needed by the experts to provide judgments
- The time and resources available to the study
- The methodological preferences of the interviewer or knowledge engineer, analyst, funder, and experts

Among the ways in which elicitation processes may differ include the degree to which the experts interact, the structure imposed on the process, the number of meetings, whether the expert's reasoning is requested or not, whether the expert judgment undergoes some translation in a model and is returned to the experts for the next step, and whether all or some of the elicitation is conducted in person, by mail, or by telephone.

NUREG/CR-5424 states that despite these variations, there are only three basic elicitation situations and a general sequence of steps. The three basic situations are as follows:

> Individual interviews - where one expert is interviewed in a private, usually face-to-face situation, by an interviewer or knowledge engineer (a person who, in addition to interviewing, represents and enters the expert knowledge into a computer system). This situation permits obtaining in-depth data from experts, such as on their means of solving the problem, without distracting or influencing them with other experts.

Interactive groups - where the experts are in a face-to-face situation with both one another and a session moderator when they give their opinion. The degree of structure may vary from totally unstructured to carefully choreographed as to when the experts present their views and when there is open discussion.

Delphi - where the experts give their judgments to a moderator, in isolation from one another. The moderator makes the judgments anonymous, redistributes them to the experts, and allows them to revise their previous judgments. If desired, the iterations can be continued to the point where consensus is achieved. This process is intended to counter some of the biasing effects of interaction.

The general sequence of steps in the elicitation process are described below (NRC91):

1. Selection of the question areas and particular questions
2. Refining of the questions
3. Selection and motivation of the experts.
4. Selection of the components (building blocks) of elicitation
5. Designing and tailoring of the components of elicitation to fit the application
6. Practicing the elicitation and training the in-house personnel
7. Eliciting and documenting expert judgments (answers, and/or ancillary information)

NUREG/CR-5411,"Elicitation and Use of Expert Judgement in Performance Assessment for High-Level Radioactive Waste Repositories" (NRC90b), indicates five areas of performance assessment of high-level waste repositories for which the benefits of a formal expert judgment process may be warranted:

-scenario development and screening
-model development
-parameter estimation
-data collection and experimentation (information gathering)
-strategic repository decisions

40 CFR part 194 does not require that expert judgment be applied to any one area in particular, but leaves this choice up to DOE, subject to the restrictions in the final rule.

A well-documented application of the formal use of expert judgment is the U.S. Nuclear Regulatory Commission's study, NUREG/CR-1150, "Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants" (NRC90). That study was undertaken to provide a risk perspective for the radioactive release resulting from a core meltdown (see section 6.2.1.1 for further discussion of NUREG/CR-1150).

6.2 EXAMPLES OF THE USE OF EXPERT JUDGMENT AT FACILITIES OTHER THAN THE WIPP

Expert judgment has been used in various scientific forums not related to the WIPP. Four reports on use of expert judgment are reviewed in this section: the NRC's application in severe accident risk assessment; the Electric Power Research Institute's use in a probabilistic seismic hazard analysis; the United Kingdom's use in risk assessment of radioactive waste disposal; and the European Space Agency's examination of expert judgment for risk assessment in space programs.

6.2.1 Nuclear Regulatory Commission

6.2.1.1 NUREG/CR-1150

A well-documented use of expert judgment in the area of nuclear reactor safety is presented in NUREG/CR-1150. The report summarizes an assessment of the risks from severe accidents in five commercial nuclear power plants in the U.S. The risks were measured in a number of ways, including: the estimated frequencies of core damage accidents from internally initiated accidents and externally initiated accidents for two of the plants; the performance of containment structures under severe accident loadings; the potential magnitude of radionuclide releases and offsite consequences of such accidents; and the overall risk (the product of accident frequencies and consequences) (NRC90).

The report notes that the risk analysis of severe reactor accidents inherently involves the consideration of parameters for which little or no experiential data exist. Expert judgment was used to supplement and interpret the available data. The principal steps used in the formal elicitation of expert judgment for the NUREG/CR-1150 study are shown schematically in Figure 6-1 and discussed briefly below:

- Selection of issues - The parameters considered were restricted to those with the largest uncertainties, expected to be the most important to risk, and for which widely accepted data were not available.

- Selection of experts - Seven panels of experts were assembled to consider the various sets of principal issues. The experts were selected on the basis of their recognized expertise in the issue areas. Representatives from the nuclear industry, the NRC and its contractors, and academia were assigned to each panel to ensure a balance of perspectives.

- Training in elicitation methods - Both the experts and analysis team members received training from specialists in decision analysis. The team members were trained in elicitation methods so that they would be proficient and consistent in their elicitation. The experts' training included an introduction to the elicitation and analysis methods, to the psychological aspects of probability estimation (e.g., the tendency to be overly confident in the estimation of probabilities), and to probability estimation.

- Presentation and review of issues - Presentations were made to each panel on the set of issues to be considered, the definition of each issue, and relevant data on the issues. Also, for the initial meeting, researchers, plant representatives, and interested parties were invited to present their perspectives on the issues to the experts. NUREG/CR-1150 notes that frequently these presentations took several days.

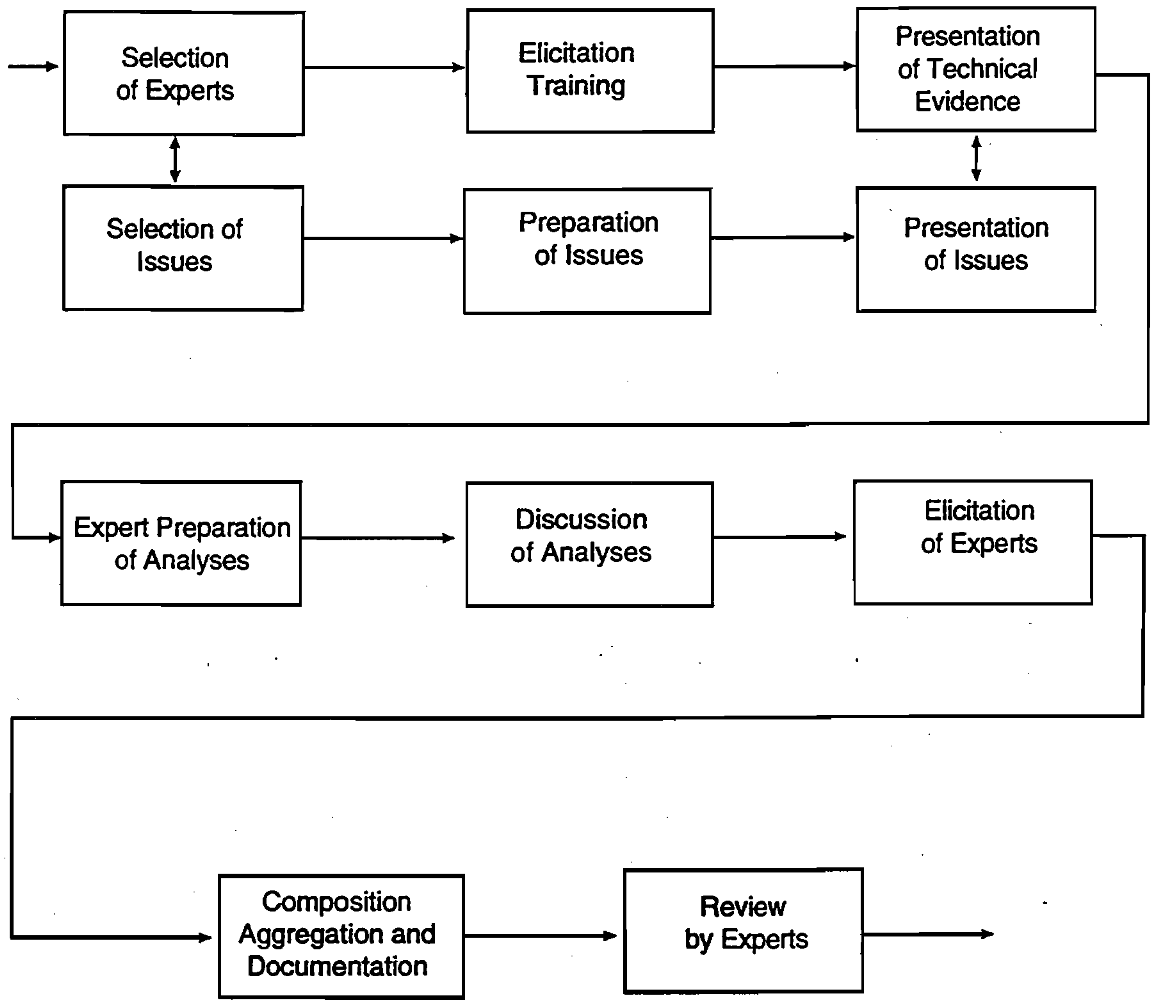
- Preparation of expert analyses - Following the initial meeting in which the issues were presented, the experts were given time (from 1 to 4 months) to prepare their analyses. During this period, several panels met to exchange information and ideas. In some cases, panels were briefed by the project staff on the results from other panels to provide the most current data.

- Expert review and discussion - After the experts had completed their analyses a final meeting was held in which each expert discussed the methods he or she used to analyze the issue. NUREG/CR-1150 states that while these discussions frequently led to modifications of the preliminary judgments of individual experts, the experts' actual judgments were not discussed in the meeting because group dynamics can cause people to unconsciously alter their judgments in the desire to conform.

- Elicitation of experts - Following the panel discussions, each expert's judgments were solicited. The elicitations were done privately with one expert at a time so that the discussions could be performed in depth and so that an expert's judgments would not be adversely influenced by the others.

- Composition and aggregation of judgments - The analysis staff composed probability distributions for each expert's judgments, and then aggregated the individual judgments to provide a single composite judgment for each issue. NUREG/CR-1150 notes that each expert's opinion was weighted equally in the aggregation, based on findings in previous studies that this method performs best.

- Review by experts - Each expert's probability distribution and associated documentation developed by the analysis staff were reviewed by that expert. The purpose of this review was to ensure that potential misunderstandings were identified and corrected and that the issue documentation properly reflected the judgments of the expert.



From NRC90

Figure 6-1. Principal Steps in NUREG/CR-1150 Expert Elicitation Process

Results of the elicitation are presented in NUREG/CR-1150, and documented in detail in two separate reports (NRC89, NRC90a). While members of each panel are identified in NUREG/CR-1150, specific judgments are presented anonymously (e.g., the members are identified only as Expert A or Expert B).

6.2.1.2 Yucca Mountain Climate Study

More recently, the use of expert judgment elicitation was examined in a study to predict future climate in the vicinity of Yucca Mountain, Nevada, the site currently undergoing characterization for DOE's high-level waste repository. A report documenting that study was presented at the Fifth Annual International Conference on High-Level Radioactive Waste Management in Las Vegas, Nevada, in May 1994 (DeW94).

The expert elicitation procedure used consisted of the following 11 steps, adapted from NUREG/CR-5411 (NRC90b):

1. Determine the objectives and goals of the study
2. Recruit the specialists (experts)
3. Identify the issues and information needs
4. Provide initial data to the specialists
5. Conduct the elicitation training session
6. Discuss and refine the issues
7. Provide a multi-week study period
8. Conduct the elicitation
9. Provide post-elicitation feedback
10. Aggregate the experts' judgments (if required)
11. Document the process

The elicitation team (those persons who would be responsible for conducting the elicitation) and the expert panel were recruited concurrently with the development of the issue statement. Nominations for expert panelists were formally requested from climatology/geography associated societies and organizations. A formal peer-ranking based selection process resulted in five final panel members, drawn from 42 nominees.

An initial meeting was held, with three goals: (1) to orient the experts; (2) to refine the initial issue statement; and (3) to conduct elicitation training. The experts received background information on the proposed repository system, the current and past climate in the Yucca Mountain vicinity, and the NRC's performance assessment program. Extensive training was provided on probability elicitation, including the interpretation of subjective probabilities, methods for generating subjective probabilities, and possible biases in the judgment process. The experts refined the initial issue statement and generated a list of factors and assumptions that would be considered by the group.

The experts had one month between the initial meeting and the individual elicitation to review any relevant literature, run models, or otherwise prepare for the elicitation, including providing a position paper. The experts had access to each other for consultation to exchange data or clarify information, but they prepared their positions independently. The actual elicitations were conducted individually to obtain the independent judgment of each expert.

DeW94 concluded that while each of the steps used in the elicitation process influences the outcome, four points are critical:

(1) the process of recruiting the experts should be formal and as unbiased as possible;

(2) the credentials of the experts enhance the credibility of the elicitation, and their ability to communicate their reasoning is a primary determinant of the quality of the results;

(3) the conduct of the elicitation sessions themselves is extremely important and should be well-planned and practiced ahead of time;

(4) concise and thorough documentation of the process including recording of the elicitation sessions, as well as the results, differentiates between most informal and formal expert judgment efforts and is essential in any formal expert elicitation project.

6.2.2 Electric Power Research Institute

Expert judgment was used in a 1983 effort by the Electric Power Research Institute (EPRI) and the 42 utilities in the Seismicity Owners Group (SOG) to develop a methodology for assessing the seismic hazard at nuclear power plant sites. The results are documented in the report *Seismic Hazard Methodology for the Central and Eastern United States* (EPR88).

In the EPRI study, earth science expertise was provided by teams formed specifically to promote interaction among different disciplines (geology, geophysics, seismology) and thus avoid an overly narrow disciplinary focus. Work was conducted through a series of workshops. Participating Earth Science Teams were required to identify and document specific factors that could be used to evaluate the activity of tectonic features. For each feature, each team was also required to assess the extent to which those factors were exhibited. This established a distinction between scientific uncertainty (uncertainty in the relationship between tectonic activity and physical characteristics) and information uncertainty (the extent to which any particular feature exhibits any given characteristics).

Six Earth Science Teams were formed to prepare and interpret input to the seismic hazard analysis. EPRI used the team approach to achieve the interdisciplinary expertise needed to evaluate various data sets and tectonic processes on a national scale. Team personnel were chosen to strike a balance between, first, academic and applied experience, and second, regional expertise. The stated overall aim was to minimize interpretation bias.

This study was accomplished through a series of seven workshops. The first workshop defined data needs for the program. Workshops 2 through 7 were structured in pairs to accomplish interpretations of tectonic stress regime, tectonic framework and seismic sources and source seismicity parameters. Procedures were explored in depth during each workshop to establish a common understanding among participants of the state of knowledge about processes and the relative value of available data for making interpretations.

The Earth Science Teams proceeded with this information and their personal expertise to develop their individual interpretations. Interpretations were shared among program participants at the second workshop of each pair. Each team shared the rationale and the strength of theory and data supporting its interpretations. EPRI notes that although this team-to-team interaction was desired, no effort was made to force a consensus interpretation among teams on any element. Teams were asked to reach internal consensus on all interpretations within a team.

EPRI stated that, with this approach, "..it is believed that uncertainty resulting from incomplete understanding of tectonic processes has been captured. The estimated uncertainty in hazard results ... reflects the state of the scientific community's uncertainty about earthquakes causes and processes in the central and eastern United States." (EPR88)

6.2.3 Other Countries

6.2.3.1 United Kingdom

A 1992 report commissioned in the United Kingdom by Her Majesty's Inspectorate of Pollution, Department of the Environment (DoE) examined procedures for the elicitation of expert judgments in probabilistic risk analysis of radioactive waste repositories (WAT92). The report concluded that "Expert judgment is necessary for the measurement of uncertainty about input parameters, since for many such parameters no frequency data are available."

WAT92 described several sources of bias that can influence judgments. The first noted was that of *availability*. This is based on the observation that people are often influenced by the ease with which they can remember the occurrence of similar events. An example was cited in which a group of well educated people in the United States were told that about 50,000 people a year die in traffic accidents in the United States. They were then asked how many people die from a long list of other causes, including common ailments such as heart disease and rare ones such as smallpox vaccination. It was found that rare causes were overestimated while common causes were underestimated. The explanation was that deaths from a rare cause such as botulism are widely reported, but people commonly hear about deaths from common causes such as stroke only when someone known to them dies in this way. Because all cases of rare causes are available, but not all cases of common causes, rare causes are overestimated.

A second possible source of bias is *representativeness*. This is based on the premise that, for example, when people attempt to assess the probability that an individual belongs to a particular class, on the basis of limited information, they judge the extent to which that information suggests the individual is typical of the class, ignoring the underlying frequency. In terms of a repository, an expert asked for the probability that the porosity of a rock formation was greater than a certain figure might base his judgment on the extent to which observable characteristics of the rock samples suggested that it was of a particular type of known porosity, independent of the known distribution of different types of rock in the area. This emphasizes the need for a published account of the reasons supporting a probability judgment.

The third potential source of bias presented was due to *anchoring and adjustment*. This recognizes that a natural starting point for making a judgment may be chosen and the judgment modified away from the initial position, but typically not far enough. Again using the example of estimating the porosity of a rock, an expert might base judgment on a different rock, for which the porosity was well known, but fail to adjust the estimate away from this properly.

WAT92 also examined protocols for eliciting probabilities. It noted that the protocol developed at the Stanford Research Institute, and referred to as the SRI protocol, has been widely accepted. The SRI protocol has five stages.

> In the first stage, the analyst *motivates* the person whose probabilities are to be elicited. The first step in this process is to ensure that the expert understands the nature and purpose of the analysis, and how the probabilities elicited will be used in the analysis. In the second step, the analyst helps the expert to explore for possible motivational biases, e.g., if the expert desires a low value of a variable, either because he thinks that this would be consistent with what his superior is expecting him to say, or because he wishes it were true, then such views should be discovered, if possible, and the expert encouraged to account for them in the elicitation task.
>
> The next stage in the protocol is the *structuring* phase. In this phase, the goal is to make absolutely clear the definition of the variable for which the probability distribution is being elicited. This should also include the exploration of assumptions about the state of the world (e.g., in eliciting probability distributions for the porosity of rock, assumptions made about physical variables such as temperature and pressure which could affect porosity should be clearly defined).
>
> The *conditioning* phase in the protocol is used to establish the data and arguments which the expert is going to use to make judgments, and to cope with any identified biases. Once the available data sets are listed, the expert is encouraged to consider other possible ways of thinking about the variable, for example, focusing on scenarios that might lead to extreme outcomes.
>
> Numerical representation begins in the fourth, or *encoding*, phase. The techniques for encoding can be categorized according to whether the probabilities are inferred indirectly from the expert's judgments, or directly by asking the expert to respond with a probability for a given event, or, in the case of continuous variables, for a value such that the cumulative probability is equal to a given value. WAT92 notes that there is no consensus that any one method is better than another, but that there is a tendency for experts to be overconfident, i.e., they fail to spread their uncertainty sufficiently.

The final stage involves *verifying* that the numerical representations of uncertainty properly support the expert's opinions. Assuming that no recognized protocols were identified, the analyst must determine how best to conduct this process.

WAT92 does not reach a conclusion that any one protocol is superior, but it notes several important considerations. First, the most important requirement for success is to devote adequate time and effort to the process. Second, the experts should receive some general introduction on the nature of elicitation, and what is known from psychology about measuring perceptions of uncertainty. Third, the subject matter about which the judgments are sought should be at the heart of the process. The analyst should have some knowledge of the subject matter, and the experts should be encouraged to produce carefully reasoned arguments to support his judgments. Fourth, throughout the process care must be taken to ensure clarity and investigate unstated assumptions. Fifth, the encoding process should follow a generally accepted technique.

6.2.3.2 European Space Agency

In February 1990 the European Space Agency (ESA) released a report entitled *The Use of Expert Judgment in Risk Assessment* (COO90). The report provides the results of an examination of expert judgment application. The examination included (1) a survey identifying and studying the different and most important methods for the use of expert judgment; (2) a survey of application of expert judgment data in industries, research institutes and other organizations; and (3) development and evaluation of methodologies for expert judgment application.

The major conclusion of the ESA research was that "The introduction of valid and effective procedures for the use of expert judgment in risk assessment is a non-trivial, but worthwhile task."

Nine phases in the procedures for using expert judgment were identified:

1. Problem identification phase
2. Expert identification phase
3. Expert choice phase
4. Question formulation phase
5. Seed variable choice
6. Elicitation phase.

7. Combination phase
8. Discrepancy analysis and feedback to experts
9. Documentation and communication phase

While the order and format may be somewhat different, these phases are approximately equivalent in content to the steps previously described in section 6.1.3, with the exception of step five, seed variable choice. The ESA study attempted to assess the quality of the experts' judgments before their use, and establish a basis for calibrating the judgments. This was done by eliciting the experts' judgment for quantities, known as seed or calibration variables, that were known to the analyst but not to the experts.

One conclusion of the ESA study was that elicitation should be conducted individually, i.e., not in a group setting. The report notes "The advantage of group meetings is that experts can discuss together with the analyst the interpretation of all the questions so encouraging a shared understanding of their meaning. The disadvantage is that group processes naturally suppress the spread of opinion and lead to underestimating uncertainty. The balance lies we feel with the group not meeting." The report states that, if it is decided that the group should meet, they meet to discuss the questions to be answered and separate before any elicitation of the likelihoods takes place. This is consistent with the techniques used in the NUREG/CR-1150 study, where groups met for presentation and discussion of the issues, but the individual elicitations were conducted in private.

The ESA report also identified the need for the generation of an audit trail in the use of expert judgment data to permit other analysts to repeat and check the information. The report considered the issue of whether the experts should be protected with anonymity, and if so, to what extent. Opinions were divided, but the report concluded the audit trail should be such that "in circumstances of sufficient gravity" the ESA (as the client soliciting the expert judgments) could identify all experts and their judgments.

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7. Peer Review Procedures

7.1 INTRODUCTION

To operate the WIPP as a repository for transuranic radioactive waste, the DOE must demonstrate that applicable health, safety, and environmental requirements have been satisfied. Peer reviews may be employed as part of a comprehensive quality assurance program. These peer reviews will give confidence that work completed, underway, or planned was, is, or will be properly performed. The ASME "Quality Assurance Program Requirements for the Collection of Scientific and Technical Information for Site Characterization of High-Level Nuclear Waste Repositories," ASME-NQA-3-1989 Edition (NQA-3), includes peer review among those activities affecting quality associated with the collection of scientific and technical information, when other established methods cannot be used to establish the adequacy of information.

Additional peer review is also necessary to establish the validity of procedures, methods, or interpretations which may not be addressed by a quality assurance program. Because of the nature of the assessments at the WIPP, in particular the potential uncertainties associated with geotechnical data and their analyses, and the need to project performance over thousands of years, peer reviews are essential to assure that all important factors are considered in assessing the performance of the WIPP.

7.1.1 Background

The 40 CFR part 194 compliance criteria for the WIPP provide the following requirements for peer review, at §194.27 of the final rule:

> (a) Any compliance application shall include documentation of peer review that has been conducted for, in a manner required by this section, for:
>
> (1) Conceptual models selected and developed by the Department;
> (2) Waste characterization analysis as required in §194.24(b); and
> (3) Engineered barrier evaluation as required in §194.44.
>
> (b) Peer review processes required in paragraph (a) of this section, and conducted subsequent to the promulgation of this part, shall be conducted in a manner that is compatible with NUREG-1297 "Peer Review for High-Level Nuclear Waste Repositories."
>
> (c) Any compliance application shall:

(1) Include information that demonstrates that peer review processes required in paragraph (a), and conducted prior to the implementation of the promulgation of this part, were conducted in accordance with an alternate process substantially equivalent in effect to NUREG-1297 and approved by the Administrator or the Administrator's authorized representative; and

(2) Document any peer review processes conducted in addition to those required pursuant to paragraph (a) of this section. Such documentation shall include formal requests, from the Department to outside review groups or individuals, to review or comment on any information used to support compliance applications, and the responses from such groups or individuals.

The EPA must be satisfied that peer review processes at the WIPP are sufficient to assess the scientific premises properly on which the performance assessments are based.

7.2 OTHER PEER REVIEW PROGRAMS

7.2.1 Definition and Use of Peer Review

Peer review has a well-established role in controlling various aspects of scientific research, engineering research, scientific and engineering applications, and educational processes. Editors and publishers of technical journals use peer review to ascertain the quality and suitability of a manuscript submitted for publication. Funding agencies use peer review to seek advice concerning the quality and promise of proposals for research support. Some research institutions use peer review as another check on research in certain sensitive fields such as human experimentation.[1] Some universities use peer review for promotions of faculty (STE93).

Peer review serves a second objective of ensuring integrity in scientific research. Recent spectacular cases of fraud in scientific research have led to federal regulations that require

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[1] At the University of Michigan, potential researchers must complete a questionnaire that addresses certain key areas of concern, prior to submitting their project funding request. If the applicant indicates that the research will involve, for example, the use of human subjects, vertebrate animals, or radioactive materials, the University subjects the project funding request to one or more peer review committees for approval. These committees review the application for compliance with specific laws and regulations, why the research must be conducted in the manner proposed, and how the research will be supervised (UMI90).

At the University of Michigan, proposals for research on human subjects can be reviewed by as many as twelve peer review committees. The proposer must provide the rationale for and justify the use of each subject. This peer review process is designed by the University to compel the would-be researcher to think about their responsibilities, and to discuss these responsibilities with their colleagues (STE93).

peer review as a measure to detect and prevent continuation of these frauds (NAT93). The same pressures to enforce rules regarding misconduct in science have led to the inclusion of mandatory peer review for ongoing scientific and engineering research and development by government agencies.[2] For example, one study reported that in 1987, five cases of fraud and misconduct in science, primarily in biomedical research, were widely publicized. These cases galvanized the U.S. Congress to renew its earlier interest in regulating certain aspects of scientific research. In subsequent years, various federal agencies such as the Department of Health and Human Services (DHHS), and within DHHS, the Public Health Service and the National Institutes of Health (NIH), adopted rules to address these instances of fraud. One rule was specifically related to improving the performance of peer review (GOL93).

Many Federal agencies use some form of peer review to evaluate the technical merit of proposed research projects.[3] Similarly, private institutions frequently use peer review to evaluate research projects. Often the focus of these peer reviews is to determine which of several proposed research projects will be funded. Those projects which, through the peer review process, are deemed most promising are chosen for funding. Peer review is also used to determine if a particular project merits continued funding. Some Federal agencies use peer review to evaluate the technical adequacy of proposed or ongoing projects. This use of peer review most closely parallels the peer review process required by 40 CFR part 194.

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[2] See *e.g.*, 10 CFR Part 60

[3] The National Science Foundation (NSF) uses a merit review system to make major awards in support of important research facilities, centers, and other large-scale research-related activities. At the NSF, the entire process of determining which research projects are to be publicly funded is called the merit review system. The most important aspect of this merit review system is the technical peer review each potential research project receives. The merit review system encompasses the administrative procedures for conducting this peer review and the procedures for publicizing results (NSF94, 93, 92, 77; NSB67). Merit review also encompasses criteria that the NSF considers necessary to augment technical quality and competence. These criteria include immediate practical relevance, and the development of science and engineering capacity in all regions of the country (NSF94). The purpose of the review process is to ensure that the most meritorious projects are chosen for support, that the selection process is fair in practice and perception, and that the results in each case are clearly and publicly explained (NSF94; NAS93, 92). Officials at the NSF concluded that one of the reasons that the United States has the most successful research system in the world is because of the extensive use of peer review to identify the best ideas for financial support. According to NSF94, "Peer review-based procedures such as those in use at NSF, the National Institutes of Health, and other federal research agencies remain the best procedures known for ensuring the technical excellence of research projects that deserve public support. Motivating this process is clearly a true scientific interest in seeing that only technically feasible projects get funded (NSF94). However, fiscal realities, and a growing occurrence of dishonesty in the research process has focused even more attention on the adequacy of merit, or peer review at the National Science Foundation (NSF94).

7.2.2 Peer Review at the Department of Health and Human Services

7.2.2.1 Public Health Service

In the 1980s, the U.S. Congress began hearings on misconduct in scientific research because of highly publicized cases of outright fraud. These problems seemed to have occurred to a large degree in the biomedical research arena (GOL93). Congressional interest in this problem led to several attempts to reform control of research at government agencies staffed by the Public Health Service (PHS) (GOL93) and to require institutions receiving funding from U.S. government agencies to put in place measures to detect and correct misconduct in science (GOL93). In 1989, PHS promulgated a final rule which required any institution applying for funds from the PHS to certify that it had adopted satisfactory misconduct procedures. One element in this set of procedures was a strong peer review procedure (GOL93).

7.2.2.2 National Institutes of Health

Scientific research at the NIH is organized around Intramural and External projects, and the peer review process differs somewhat according to project designation.

NIH Peer Review of Intramural Research. Scientists in the Intramural Research Program of the NIH are generally responsible for conducting original research consonant with the goals of their individual Institutes, Centers, and Divisions. Senior NIH officials have expressed concern regarding the rigor of scientific research conducted by NIH scientists (NAT93). One of such research is peer review. In its 1990 "Guidelines for Conduct of Scientific Research at the National Institutes of Health," NIH officials define peer review and stress its importance as:

> [an] expert critique of either a scientific treatise, such as an article prepared or submitted for publication, a research grant proposal, a clinical research protocol, or of an investigator's research program, as in a site visit. Peer review is an essential component of the conduct of science. Decisions on the funding of research proposals and on the publication of experimental results must be based on thorough, fair, and objective evaluations by recognized experts.[4]

[4] See NAS93 quoting from "Guidelines for the Conduct of Research at the National Institutes of Health" NIH, 1990.

The guidelines go on to state the essential elements of the peer review process:

- the reviewer must be expert in the subject matter under review

- the reviewers should avoid any real or perceived conflict of interest that might arise because of a direct competitive, collaborative, or other close relationship with one or more of the authors of the material under review

- the review must be based solely on scientific evaluation of the material under review within the context of published information and should not be influenced by scientific information not publicly available

- the material being reviewed is privileged and should not be used to benefit the reviewer unless the information has previously been made public

Peer review is used at the NIH at all stages of research carried on under the control, direction, or funding of the organization. These stages are:

- idea/issue generation
- program formulation
- project proposal evaluation and selection
- final reports/other products review
- on-going program/project review

Peer review is performed to some extent in all these stages. There are, however, significant variations both in the extent and nature of the peer review, depending on the stage of research, and whether or not the activities are carried out by NIH employees, or if the activities are NIH-funded.

At the NIH, peer review is mandated by law. Peer review policy and practice are generally consistent throughout NIH with only limited variations among the institutes.

NIH Peer Review of External Research. Each institute of the NIH has a statutory peer review panel, called a National Advisory Council (NAC, or variation) that conducts analyses of projects. The NAC is usually composed of 16 to 18 senior level personnel, including a mix of scientific disciplines as well as mandatory representation by ex officio federal officials and public (i.e., nonscientific) members. The NACs have a broad charter to address any matter affecting the performance of their respective institute. All NACs prepare an annual report assessing broad issues related to their institute, including future directions and general policy. These reports are then forwarded to the Director of NIH.

NACs participate in peer reviews at many stages of a project. The first stage is generally one involving the initial determination of project funding. Many different individuals and activities compete for funding from the various institutes. NAC participation is generally strong at this point in a potential project's life because the determination as to which projects are funded bears heavily upon the direction the institute will take in the future. NIH personnel need, and are statutorily required, to evaluate projects to ensure that only the most promising ones are funded. The early stages of a project in which the NACs are involved include:

- Idea/Issue Generation Stage — This is likely to be an initial policy determination or a determination to proceed along a certain avenue of research. Specific projects need not be addressed.

- Program Formulation Stage — This stage receives peer review similar to that in the Idea Generation stage. One aspect of the peer review process at this stage is to consider whether resource requirements related to long range goals are reflected in the peer advice described under the Idea Generation stage.

- Project Design — For external research activities, the peer review is generally limited. Following participation in the formulation of research programs, the NACs do not ordinarily play a part in the design of projects. According to one NIH official, this is in part because of time constraints on participation of council members. The limited review is also due to inadequate scientific expertise (in specialized areas of research) of NAC members, which as mentioned, include senior officials and members of the public, generally better qualified to provide broad ethical or legal reviews.

- Project Proposal Evaluation, Selection, and Award Stage — At this point a dual process of peer reviews takes place, looking at both technical merit and cost issues.

7.2.3 Peer Review at the National Aeronautics and Space Administration

The National Aeronautics and Space Administration (NASA) uses peer review primarily to evaluate the merit of research and development proposals, and to allocate funding (NAS87, 94). NASA also uses peer review to decide if certain projects warrant renewal or continued funding (NAS94). Organizationally, NASA includes three science offices and two engineering offices,[5] each of which employs some form of peer review, particularly in regards to evaluating proposals for research and development. However, NASA's science offices use peer review to a much greater extent than do the engineering offices (NAS94). The explanation for this difference in use of peer review centers on the nature of work performed by the two types of offices. The engineering offices are more likely to engage in straight procurement actions, such as purchasing rocket engines, whereas the science offices have, as a goal, promoting specific types of research (NAS94). The discussion that follows primarily describes the peer review process followed by the science offices. The NASA engineering offices follow a similar, if somewhat truncated, version of the same process.

NASA uses two types of solicitations to obtain research proposals: an Announcement of Opportunity (AO); and a NASA Research Announcement (NRA). NASA uses Announcements of Opportunity for large research procurements such as designing an instrument for installation on a satellite. NASA uses Research Announcements for more narrowly focused scientific investigation, such as using data collected during the Magellan spacecraft voyage (NAS94).

Either solicitation is written to address certain hardware, policy, or scientific needs as envisioned by NASA. This narrow drafting of the solicitation eliminates the need to consider policy during subsequent peer reviews of the proposals (NAS94). NASA has relied primarily on panels convened under the auspices of the National Academy of Sciences (NAS) to advise the administration on scientific goals and priorities. The panels report to various boards. NAS creates these boards, excluding NASA scientists in order to avoid any possible conflict of interest. However, some panel members may be drawn from NASA offices (NAS94).

NASA takes the long-term science goals and priorities from the NAS and, through committees, translates these goals and priorities into programmatic goals and strategies. The committees are established by NASA under the auspices of an Advisory Council that is composed of about 20 distinguished individuals, including corporate executives, university

[5] The three science offices are:

Office of Life and Microgravity Sciences and Applications
Office of Mission to Planet Earth
Office of Space Science

The two engineering offices are:

Office of Aeronautics
Office of Advanced Concepts and Technology

scientists, historians, and others. NASA selects the members of the Advisory Council. Within the Advisory Council are a number of standing committees. These committees use the NAS goals and priorities to develop recommendations for major programs such as the Hubble space telescope (NAS94). These committees are, in effect, peer review panels.

When a NASA science office issues a research proposal (either an AO or a NRA), NASA scientists compete for proposal acceptance on the same grounds as outside, or external, scientists and external research entities such as universities. This intramural versus extramural competition does not exist for Announcements of Opportunity issued by one of the two NASA engineering offices, but may exist for NASA Research Announcements issued by the engineering office.

Once the NASA standing committees have recommended programs, NASA officials in the engineering and science offices translate them into specific program plans or projects, including budget proposals. Each program or project is assigned to a program office within the engineering or science office. At this point, the size of the program or project budget partly determines whether an Announcement of Opportunity or a NASA Research Announcement is made. The nature of the solicitation determines the following peer review process (NAS94).

NASA uses Announcements of Opportunity to solicit proposals from scientists in the United States and abroad. The AOs are typically used for larger budget items, about 100 million dollars (NAS94). In response to an AO, NASA may receive up to 100 proposals. The designated program scientist within a NASA science office establishes one or more peer review panels to review each proposal, and selects the members for each panel. Approximately 50 to 75% of the peer review panel members are university scientists, with the remaining members from NASA or other government agencies. The proposals are mailed to the panel members for initial review. Some additional co-readers may also review the proposals and can add comments, but do not participate further in the evaluation process. After the initial review, the peer panel meets to discuss the proposals and reach consensus on the evaluations. At the conclusion of the panel deliberations, the peer panel submits its recommendations to the NASA program office. The recommendations are reviewed by

NASA staff, and a NASA Associate Administrator makes the final determination as to which proposals to fund (NAS94).[6]

NASA Research Announcements (NRAs) are usually for smaller-budget items and concern more narrowly focused scientific research. The NASA Program Manager determines the level of peer review to be conducted. Just as in an AO, the proposals are usually mailed to the members of the peer review panel. A follow-up panel meeting is often used to discuss the proposals and to make recommendations to the NASA program office. An award under an NRA will usually not call for a deliverable; rather, the expectation is that the results of the research will be published. In this manner, NASA officials feel they are advancing the boundaries of science (NAS94). Grants under the NRAs are typically for three years and the awards are in the $100,000 range.

During the three-year period that an NRA is in effect, NASA conducts periodic (e.g., annual or mid-term) reviews of progress. This review is typically performed by the NASA Program Manager, and could result in termination of the NRA award. If the scientific research must extend beyond the original grant time period, the grantee submits a new proposal that is reviewed using the same process as followed for initial selection.

Periodic review of projects funded under an AO follows a somewhat different course. The initial peer panel that recommended particular grants will establish a Science Working Group composed, essentially, of all the principal investigators of the winning organizations. This Science Working Group is chaired by a NASA scientist. The Science Working Group meets periodically to review progress and the final deliverables.

7.2.4 Peer Review at the U.S. Environmental Protection Agency

The EPA uses various panels such as Science Advisory Boards (SABs) (see Section 7.2.4.3) and the National Advisory Council on Environmental Policy and Technology (NACEPT) to advise the agency on scientific, technical, and policy matters. NACEPT activities are authorized under Public Law 92-563, the Federal Advisory Committee Act (FACA), and are

[6] Note that a single AO could result in numerous contracts, each concerned with a specific aspect of the work described in the AO (NAS94). NASA awards under AOs typically call for production of specific hardware such as scientific instruments to emplace on a research satellite. As such, the award is controlled through a contract and the selection process is in many respects similar to a regular government procurement (NAS94).

designed to provide recommendations and advice to the EPA Administrator. Review and critique of documents and reports is a precursor to formulating sound advice.

The NACEPT is composed of several committees covering diverse technical areas. The EPA established the WIPP Subcommittee under the aegis of the Environmental Measurements and Chemical Accidents Committee to advise the Administrator in implementation of the WIPP Land Withdrawal Act (PL 102-579) (EPA93). Members of the WIPP Subcommittee include representatives from academia, an environmental activist organization, the New Mexico Environmental Evaluation Group, the State of New Mexico Environment Department, and various technical consulting companies. To date, the WIPP Subcommittee of the NACEPT has provided advice to EPA in three general areas:

- criteria to be used in evaluating DOE Test Phase Plan and Waste Retrieval Plan for WIPP
- criteria to be used in determining compliance with 40 CFR part 191
- selected issues related to 40 CFR part 194

The EPA uses SABs to provide advice concerning on-going scientific studies within the Agency. These SABs function in much the same manner as does the NACEPT. SAB members include personnel from inside and outside the agency.

Finally, EPA makes use of external peer review groups. These groups can be constituted as special panels formed by the agency, or can come from other government agencies. Examples of these reviews are provided in sections 7.2.4.1 through 7.2.4.3.

7.2.4.1 Peer Review of Proposed Sewage Sludge Disposal Regulations

One particular EPA peer review effort concerned draft standards for the disposal of sewage sludge, U.S. EPA Proposed Rule 40 CFR parts 257 and 503. The proposed rule was reviewed by a peer review committee (PRC) created by an element of the U.S. Department of Agriculture (USDA).

The EPA, under authority of the Clean Water Act,[7] proposed regulations to protect the public health and the environment from any reasonably anticipated adverse effects of certain

[7] 33 U.S.C.A. 1251, *et. seq.*

pollutants that might be present in sewage sludge. The proposed regulations were published in 1989, and included standards for the final use or disposal of sewage sludge applied to both agricultural and non-agricultural land, distributed or marketed, placed in disposal sites, or incinerated. Part of the proposed regulation asked the USDA to review the scientific and technical basis of the proposed rule. The review was conducted by a peer review committee created by USDA's Cooperative States Research Service (CSRS), Regional Research Technical Committee (W-170).[8] Dr. A.L. Page of the University of California, Riverside and Dr. T.J. Logan of Ohio State University were the co-chairs of the peer review committee. The rest of the peer review committee consisted of 33 experts from academia, government and private industry (USD89).[9]

The PRC met in Washington, D.C. for four days. The PRC broke into smaller workgroups centered around specific aspects of the proposed regulation. For example, workgroups analyzed those portions of the proposed regulations that dealt with monofills, with surface disposal, with agricultural land application, etc. Each workgroup reviewed the proposed regulations and prepared draft reports. During the four-day period, the entire 35-person PRC would meet to discuss progress and to identify common areas. After the four-day session, each workgroup reviewed and edited their section, and then the entire document was reviewed and edited by each of the PRC members. The two PRC co-chairs, along with the chairmen of each work group, met over a five-day period to revise and edit the complete draft report (USD89).

The PRC draft report is organized as a series of workgroup reports, with an overall summary and set of recommendations. The sections of the report prepared by the individual workgroups list the workgroup members, but do not show which workgroup member prepared any particular comment. The PRC draft report does not contain any information regarding the background or qualifications of individual PRC members, nor does it include

[8] The W-170 committee and its predecessors, W-124 and NC-118, are CSRS committees formulated for the purpose of conducting regional research. These regional research projects are developed by researchers from land grant universities, agricultural experiment stations, and USDA laboratories within four regions in the U.S. (USDA89). As is obvious by the peer review of 40 CFR Parts 257 and 503, the W-170 Committee engages in activities other than pure agricultural research.

[9] Four members of the PRC were from the EPA, the agency whose work was being reviewed (USD89). The PRC draft report does not explain how it avoided conflict of interest problems by having EPA personnel on the PRC staff. However, the breadth and detailed nature of the comments prepared by the PRC tend to indicate that the review was completely objective.

any documentation regarding possible conflict of interest. In short, there is no way to know from reading the PRC report if there was any conflict of interest.[10]

7.2.4.2 Ecological Risk Assessment Peer Review

In 1984, EPA organized the Risk Assessment Guidelines program to ensure scientific quality and technical consistency in the Agency's risk assessments. The first group of guidelines was issued in 1986, and focused on evaluating risks to human health. In 1991, EPA issued an agency-wide draft statement of general principles to guide ecological risk assessment. This guide was titled "Framework for Ecological Risk Assessment."

To improve the technical basis for ecological risk assessment guidelines, EPA requested an independent peer review of the draft "Framework for Ecological Risk Assessment." A panel of twenty experts participated in the review (EPA92).[11]

The peer review of the draft framework consisted of three steps. First, the draft framework document was mailed to each of the twenty members participating in the review. Each reviewer prepared comments that were in turn distributed to all other reviewers. Next, a peer review workshop was held to obtain an independent review of the logic, scientific validity, and utility of the principles that were proposed in the draft framework document. Workshop participants reached a consensus on the acceptability of some parts of the draft framework, and made recommendations for changes to other parts. Finally, a written report was prepared, summarizing the results of the workshop, and presenting the panel's recommendations to EPA (EPA92).

To help frame the discussion and focus attention on certain critical issues, each workshop participant was provided a set of "pre-meeting issue papers." These papers stated general issues and then requested that the participants comment on specific aspects of the risk

[10] One other point that should be noted is that there is no indication of follow-up on any of the PRC draft report comments. While EPA may very well have incorporated all of the PRC comments into the proposed regulation, that fact was not evaluated in this analysis.

[11] Of the twenty participants, none were from the EPA, including its regional offices. Participants included members of state and federal agencies, private industry and (primarily) public and private universities (EPA92). Some of the entities represented had, however, done work for the EPA in the past. The EPA was represented by about 30 "observers" (EPA92).

assessment guidelines. For example, under the topic "Ecorisk Paradigm," each participant was presented with the following statement and question to consider: "The proposed paradigm for risk assessment is modeled after the National Research Council paradigm for human health risk [reference omitted]. Is the modified paradigm presented in the framework document appropriate for ecorisk assessments, or is another approach preferable?" (EPA92). This general issue was followed by several sub-issues and questions that addressed specific aspects of the proposed process for assessing risk.

The peer review described above did not indicate to what extent conflict of interest issues were considered, although as previously noted, the report did state that the peer review was "independent." The report also did not describe in detail the procedural steps followed throughout the peer review process. For example, there is no discussion about how the peer review members were selected, the process for incorporating comments, follow-up action if the authors of the draft framework document disagreed with any comments of the peer review team, etc.

7.2.4.3 The Science Advisory Board

The EPA uses a number of advisory councils, often known as Science Advisory Boards (SABs), to provide guidance on a wide range of topics potentially affecting the environment (EPA92a). These boards are part of EPA's advisory committee program, and operate under the Federal Advisory Committee Act.[12] The EPA constitutes and terminates SABs as the need arises. For example, from 1992 to 1993, EPA formed eight new committees for topics as diverse as wood furniture manufacturing and local government policy, and terminated five committees (EPA93a).

The composition of some SABs indicate that their function extends beyond the technical arena. For example, the Clean Air Act Advisory committee comprises "50 senior representatives from state and local government, academic institutions, unions, environmental and public interest groups, industries and service groups." (EPA92a). The four workgroups formed from this committee addressed topics such as: effective communication/outreach methods for implementing reductions in airborne emissions; regulatory reform options; and

[12] Public Law 92-463, October 6, 1972. Further guidance on the functioning of federal advisory committees can be found in General Services Administration Final Rule Subpart 101-6.10, "Federal Advisory Committee Management," August 1989.

alternative programs that would assist and encourage states to promote energy efficiency (EPA92a). On the other hand, the Federal Insecticide, Fungicide, and Rodenticide Act Scientific Advisory Panel is comprised entirely of experts in the field of pesticides and the impact of their use on human health and the environment (EPA92a).

Each of the committees or SABs formed under EPA's advisory committee program develops or is issued a charter stating the purpose, objective and scope of activity, functions, and conduct of meetings (EPA92a). Committee members may or may not be compensated for their services depending on the individual committee. The EPA may pay travel and per diem expenses for all committee members. Some committee members may be government employees. All members are subject to conflict-of-interest restrictions (EPA92a).[13]

The various committees meet periodically throughout the year, at times established in their individual charters. The chair of each panel or committee submits a written report of the meeting. This report includes the panel's recommendations and conclusions. Transcripts are made and retained for the entire meeting (EPA92a).

7.2.5 Nuclear Regulatory Commission Peer Review Guidance

Compliance criteria in 40 CFR part 194 require peer review at the WIPP to be performed in a manner compatible with NUREG-1297. NUREG-1297 contains a generic technical position for peer review at high-level nuclear waste repositories (NRC88). NUREG-1297 provides guidance on the definition of peer reviews, the areas where a peer review is appropriate, the acceptability of peers, and the conduct and documentation of a peer review.

The NUREG document defines the following peer review-related terms:

- Peer — a person having technical expertise in the subject matter, or a critical subset of the subject matter, at least equivalent to that needed for the original work.
- Peer review group — an assembly of peers representing an appropriate spectrum of knowledge and experience in the subject matter. The group should vary in size based on the subject matter and the importance of that subject matter to safety or waste isolation.

[13] See 40 CFR Part 3, Subpart F - standards of Conduct for Special Government Employees. This regulation includes rules regarding conflict-of-interest. The rules require nominees to committees such as EPA's, to submit a Confidential Statement of Employment and Financial Interests (EPA Form 3120-1), that fully discloses any outside sources of financial support.

- Peer review — a documented, critical review performed by peers who are independent of the work being reviewed. The review is an in-depth critique of the assumptions, calculations, extrapolations, alternate interpretations, methodology, and acceptance criteria employed, and of conclusions drawn from the original work.

- Peer independence — a peer was not involved as a participant, supervisor, technical reviewer, or advisor in the work being reviewed and, to the extent feasible, has sufficient freedom from funding considerations to assure the work is impartially reviewed.[14]

The NUREG document describes the circumstances under which a peer review is warranted. These circumstances occur when the suitability of procedures and methods essential to showing that the repository system meets or exceeds its performance requirements cannot otherwise be established through: 1) testing; 2) alternative calculations; or 3) reference to previously established standards and practices. (These circumstances are the same as those listed in ASME NQA-3, previously described in section 7.1.) NUREG-1297 provides examples of these situations, including when:

- critical interpretations or decisions will be made in the face of significant uncertainty,

- decisions or interpretations having significant impact on PA conclusions will be made, or

- novel or beyond state-of-the-art testing, plans and procedures, or analyses are or will be utilized.

The composition of the peer review group depends on: the complexity of the work to be reviewed; its importance in establishing compliance with safety or performance goals; the degree of uncertainty in data or the technical approach; and the extent to which differing viewpoints exist. The peer review group should include individuals representing major schools of scientific thought. The actual number of peer reviewers is not as important as the technical qualifications of the reviewers. The group should be structured to avoid a bias toward particular theories, methods of analysis, or institutional practices (NRC88).

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[14] NUREG-1297 states that, because of the DOE's pervasive effort in the waste management area, most persons who would be acceptable from a technical perspective are likely to have had some connection to DOE in the past. As such, the NUREG document concludes that "[I]t may not be possible to exclude all DOE or DOE contractor personnel from participating in a peer review." (NRC88). The NUREG document suggests that in these cases, a documented rationale as to why someone of equivalent technical qualifications and greater independence was not selected should be filed with the peer review report (NRC88).

Each peer review group should be led by a chairman. In meetings and correspondence, the peer review group should evaluate and report on:

- validity of assumptions
- alternate interpretations
- uncertainty of results and consequences if wrong
- appropriateness and limitations of methodology and procedures
- adequacy of application
- accuracy of calculations
- validity of conclusions
- adequacy of requirements and criteria

NUREG-1297 states that full and frank discussions are essential between the peer reviewers and the persons who performed the work being reviewed (NRC88).

The peer review process should include written minutes of any proceedings, deliberations, and activities of the peer review group. After the peer review group completes its analysis, the agency responsible for quality assurance should produce a written report, under the direction of the peer review group chairman, and signed by each member of the group. The report should include statements by individual members stating any dissenting views or additional comments as appropriate. The report should also include information concerning the qualifications of individual peer review group members and their organizational affiliations (NRC88).

7.2.6 Peer Review at the Department of Energy

The Office of Program Analysis (OPA) conducts peer review assessments of DOE research and development. "Procedures for Peer Review Assessments," DOE/ER-0491P, dated April 1991, describes general processes for conducting these peer reviews (DOE91). The peer review procedures are intended to provide the basis for implementing the methodology developed by OPA. The reviews are performed by examining individual projects which comprise a program and by assessing the quality of the research, quality of the research team, productivity, probability of success, and mission relevance for each project reviewed.

This OPA peer review is intended as a funding screening method, not a thorough scientific analysis of the project, or project report. In fact, this peer review procedure is also limited—the review is limited to 65 minutes, and of that period, 30 minutes are allocated to the "Principal Investigator" to present the project's hypothesis, scientific approach, and results. After the peer review panel has completed all evaluations of all projects assigned to it for review, the panel members make their recommendations considering two basic criteria: the highest payoff research needs or opportunities, and their order of priority.

7.2.6.1 Methodology

The DOE assembles peer review panels, as required, in its primary functional areas of research. Project reviews take place in panel sessions lasting from two to four days. Prior to the panel session, each principal investigator submits a package of documents which is distributed to the panel members to assist in evaluating the principal investigator's project at the panel session.

7.2.6.2 Peer Review at the Yucca Mountain Site

Yucca Mountain is being considered as a site for long-term deposition of high-level radioactive waste. As such, many of the detailed geologic, hydrologic, and other scientific investigations being performed at the WIPP are or were also performed at Yucca Mountain. This section examines peer review of one of these proposed studies and one of the investigation reports.

Peer review panel members were provided advance copies of the draft documents to be considered. In one case, this was a copy of two proposals for in-situ study of radionuclide migration (NVO81). In the other case, the document was a report of an investigation of hydrology and geology in the Yucca Mountain area (NVO81a). Panel members were given a "charge," that is, they were asked by the Technical Project Officer to review the documents with certain criteria in mind. Following the panel session, each individual peer reviewer sent comments to the Technical Project Office. The technical project officer then prepared responses to these comments, and submitted the responses to NTS management.

Peer Review of Radionuclide Migration in Tuff and Granite, NVO 196-23. This review concerned two proposals for future in situ investigations of radionuclide migration in tuffaceous and granitic rock. The proposed radionuclide migration work was to be conducted by scientists from Los Alamos National Laboratory, Sandia National Laboratories, and Argonne National Laboratory for the tuffaceous rock and the Lawrence Livermore National Laboratory for the granitic rock (NVO81).

Comments in the radionuclide migration peer review report were compiled from a peer review panel meeting conducted August 18-19, 1980 in Las Vegas, Nevada, as well as individual comments submitted by each of the peer review panel members. Individual comments were submitted after the panel meeting concluded, typically within one month (NVO81).

The need for a peer review panel was determined the Office of Nuclear Waste Isolation (ONWI) and the Nevada Nuclear Waste Storage Investigations (NNWSI).[15] Reviewers representing appropriate fields of expertise were invited to attend the review sessions. Nationally known, as well as prominent state and local, scientists were selected to participate in the peer review process. At the peer review meetings, the NNWSI Technical Project Officers, Principal Investigators from the laboratories, and NTS technical staff members involved in the radionuclide migration studies made detailed presentations and answered questions about their investigative actions and findings, as well as the proposed study efforts. The peer review panel consisted of eight scientists from universities, private industry, and a government agency other than DOE.[16]

The peer review report contains summarized comments from the panel sessions as well as individual comments from reviewers. Some summarized comments lack scientific precision. For example, in discussing the use of tracers, the peer review panel noted that "Tracers mentioned for cold experiment (except for U-235) will sorb like crazy and never be observed at the collection point...." (NVO81).

A section of the peer review report is a reply to the peer review comments prepared by the Technical Project Officer. The reply indicated that some of the panel's comments will be incorporated; however, the panel provided no mandatory comments, and there was no opportunity for the panel to concur with the reply prepared by the Technical Project Officer.

[15] The NNWSI were a part of the National Waste Terminal (NWTS) Program of the DOE. The NNWSI were formally organized in 1977 and managed by the Waste Management Project Office of DOE's Nevada Operations Office. The NNWSI existed to develop or improve the technology for high-level nuclear waste handling, containment, and isolation, and determining whether suitable rock units on or adjacent to the Nevada Test Site (NTS) were technically acceptable for a licensed permanent nuclear waste repository (NVO81, NVO81a).

[16] The one government panel member was from the U.S. Geologic Survey.

Peer Review of Geologic and Hydrologic Investigation of Yucca Mountain Peer Review Documentation, NVO-196-22. This peer review was conducted in a somewhat different manner than the previously described review. Peer review panel members were provided the basic report ahead of time, and then met to discuss its technical merit. The panel session included a site visit to a portion of the Nevada Test Site. Following the panel session, individual members submitted written comments to the Technical Project Officer.

One reviewer felt that the panel meeting was not long enough to complete all required discussions. The same reviewer was dissatisfied with breaking the panel review into several different workshops. He felt that there was too much interrelationship between, for example, the hydrology and geology sections for them to be discussed separately.

Several panel members commented that, although the peer review panel presentations were generally useful, the panel members did not receive a handout of the material from the individual speakers prior to their discussions. One of these reviewers went on to note that "Most of us were not that familiar with the geologic formations, their positions in the geologic column, or the details that characterize them." (NVO81a).

The lone representative (out of ten) from industry noted that a certain difference existed between the academicians on the panel and himself.[17] Because of what he perceived as the "urgency of the problem" (i.e., finding a repository for high level radioactive waste), this reviewer felt that "more forward, goal oriented (industrial) approach to the depository siting should be considered." He urged inclusion of more industry representatives on future peer review panels. (NVO81a).

Summary of NVO Peer Reviews. These two peer review documents might seem, on cursory inspection, to be similar. However, NVO 196-23 appears to be related to a research/investigation funding decision while NVO 196-22 is more of a technical review that is intended to verify the adequacy of the investigation. However, the peer review comments in NVO 196-23 are primarily technical in nature, and contain no specific recommendations as to whether or not the two projects should be funded. The comments for NVO 196-22, on the other hand, address several programmatic issues in addition to technical comments.

[17] According to this reviewer, "The university - industry differences in approach to applied research investigations is well known." (NVO81a).

The format for submitting comments, a general set of comments from the peer review panel followed by written comments from individual panel members, appears to have posed a dilemma for the NNWIS staff and the Technical Project Officer. Some individual comments were diametrically opposed, while other comments reflected the views of only one or a few members. One reason for this situation may have been the apparent lack of a panel chairman. Instead of the panel evaluating and concurring in the work, in effect several different (eight to ten) peer reviewers commented. The project staff was thus put in the position of having to respond to more comments than if a unified set of comments had been forwarded by a panel chairman, and the project staff had to respond to comments that did not always agree as to the direction the research should follow.

In addition, post-panel submission of written comments meant that any potential interactions between panel members and the project staff was necessarily limited or non-existent. This problem was apparent from several project staff replies. For example, several panel members referred to the need to access "open-file reports" and to have project documentation provided to the panel members in advance of the peer review panel meeting. The project team responded that they were uncertain as to what reviewers mean by higher profile reports. Misunderstandings like this might be resolved if the comments had been provided during the panel session, or if some mechanism existed for the panel members and the project staff to interact after submission of peer review comments.

7.3 SUMMARY OF PEER REVIEW

Peer review, as practiced at other government agencies and at private institutions such as universities, varies from an informal process in which reviewers are mailed a document and after review, simply send back a set of comments, to a more formal process with specific agendas, scheduled panel meetings, specific forms to use for recording comments, feedback mechanisms between panel members and project staff, etc. Based on the different processes used by various agencies for conducting peer reviews, the most effective peer reviews occur when:

- sufficient advance notice is given;
- adequate numbers of reviewers are selected so that all aspects of the project are represented;

- for large projects, a panel session lasts several days and includes site visits, if necessary;
- the panel has a chairman, and the chairman seeks to gain consensus on the peer review comments and presents a unified list of conclusions to the Principal Investigator;
- any strong disagreements among panel members are be highlighted;
- reviewers have a charter, or a check list of items or evaluation criteria, to consider in the review;
- members are not discouraged from voicing opinions in any area related to the subject being reviewed;
- a process is in place wherein responses to peer review comments are reviewed by at least the panel chairman;
- any major differences between panel and project staff are resolved;
- the agency forming the peer review panel strives for a balance of expertise, and of scientific views, on the panel.

Thus, use of peer review to establish the accuracy or adequacy of scientific procedures, methods, scope of examination, or data is best accomplished when peer reviewers are selected based on depth and area of expertise (and considering possible conflict of interest), and when the process and results are thoroughly documented and responded to by principle investigators.

After evaluating a variety of peer review programs for different purposes, EPA has identified important criteria for conducting and documenting peer review, as described above. The Agency determined that these criteria are clearly articulated in NUREG-1297, which provides appropriate guidance for implementing such procedures. Thus, the final rule provides that peer reviews required for the WIPP must be conducted in a manner that is compatible with NUREG-1297.

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8. Uncertainty and "Reasonable Expectation"

8.1. INTRODUCTION

8.1.1 Background

The final rule places statistical requirements on the results of performance assessments in order to consider the quantitative uncertainty inherent in long-term predictions. As stated in EPA's 40 CFR part 191 disposal standards, "Because of the long time period involved and the nature of the processes and events of interest, there will inevitably be substantial uncertainties in projecting disposal system performance. Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word in situations that deal with much shorter time frames."

Several physical processes take place over the design life of the WIPP. Because of uncertainty propagation, a calculation based on worst case values for each input parameter across all processes would yield results that would not be likely to portray disposal system performance. This is only one dimension of the uncertainty issue. A paper presented by Zuidema of Switzerland's National Cooperative for the Storage of Radioactive Waste (NAGRA) at a 1991 NEA workshop on criteria for HLW disposal identified four sources of uncertainty in disposal system safety analysis:

- uncertainty in scenarios;
- uncertainty in conceptual models;
- parameter uncertainty; and
- parameter variability.

Recognizing these uncertainties, the disposal standards state that there should be "a reasonable expectation ... that compliance ... will be achieved." This phrase represents a general principal for due consideration of (1) the uncertainties involved in projecting disposal system performance for 10,000 years, and (2) the entire record submitted to the Administrator.

The goal of the WIPP performance assessment is to develop predictions of the distributions of the cumulative release, doses to individuals, and radionuclide concentrations in ground water over 10,000 years at the WIPP disposal site (SNL92, HEL93a). These distributions are functions that indicate the probability of exceeding various levels of three parameters: cumulative releases, doses to individuals and ground-water concentrations. Ideally, a single function for each parameter would be formed by combining distributions resulting from all possible scenarios, after considering all uncertainties in scenarios, in conceptual models, in parameter uncertainty, and in parameter variability over the 10,000-year regulatory horizon mandated in 40 CFR part 191.

Certain physical parameters may remain unchanged over 10,000 years, but changes, for example, in geology and climate, must be forecast "to the extent practicable" (§194.25(b)). Among the scenarios of interest is the number of times humans will inadvertently intrude into the disposal system in search of resources. DOE has developed a human intrusion scenario (SNL93, HEL93b) with sub-scenarios including two different intrusions: the first is a penetration of the disposal system and a brine pocket below the disposal system which allows brine to enter the disposal system; the second is the interception of the disposal system without hitting a brine pocket. Both events result in the release of the radionuclides to the accessible environment from the cuttings associated with drilling operations and can result in release to the accessible environment by lateral transport in ground water associated with overlying geologic formations.

The predictions generated by the WIPP performance assessment model for a variety of human intrusion scenarios are made conditionally: if scenario A occurs and the model parameters are assigned certain values, then the model predicts the distribution of releases under a specific set of assumptions. The predictions are made using very elaborate computer codes requiring many input parameters to define the scenarios and their implications. These input parameters may be based on actual data or on expert judgments.

8.1.2 General Approach to Evaluating Compliance

This section discusses the statistical concepts which are relevant to regulatory decision-making. The random variable R denotes the cumulative release of radionuclides from a disposal system, while a fixed numerical limit (L) is selected as the maximum allowable release for the disposal system. Unless there is a strict upper bound on its distribution, the random release cannot be proved to satisfy a specific mathematical constraint of the form "R is less than L." At best, if the probability distribution of the release is known exactly, then the probability that the release is less than the regulatory limit may be calculated from the distribution. This probability is denoted by the notation $Pr\{ R < L \}$, which is read as the "probability that R is less than L."

For most regulatory applications, it is sufficient to require that the probability of the release being less than the regulatory limit is high. Probability values near 100 percent would be necessary to ensure that compliance is almost always obtained. If one uses the symbol P denote this high level of probability, the regulatory requirement would be written as

$$Pr\{ R < L \} > P$$

An equivalent statement of the regulatory requirement is that the P^{th} percentile of the distribution of R be less than the regulatory limit L. Let R_P denote the P^{th} percentile of the distribution of R. Using percentiles, the regulatory requirement may be written as

$$R_P < L$$

Under either of these equivalent interpretations of the requirements in §191.13(a), there would be at least a probability P that the random release is less than the regulatory limit. In this case of a known distribution for the release, all that remains is to select the appropriate value of the required probability (P), and the appropriate value for the release limit (L).

If this were an enforcement problem for a hypothetical nuclear plant, the distribution of the release could be determined by going to the site and measuring radionuclide releases from the stack. From these observations, collected over time, the distribution of the random release could be estimated, leading to a compliance determination based on data and standard statistical procedures.

In this example, the need to estimate the distribution of the release from sample values results in a sampling error for the estimated probability that the release is less than the regulatory limit. If the percentile interpretation is used, there will be sampling error in estimating the P^{th} percentile of the distribution. These sampling errors should be considered when comparing the estimated probability or percentile to the requirement. A 90 or 95 percent confidence interval is often used for sample-based estimates of the probability or percentile. If the confidence interval lies entirely below the required value, the power plant is determined to be in compliance at the appropriate level of confidence. If the resulting confidence interval was too broad to reach a clear determination of compliance, more observations could be collected to reduce the confidence interval.

Confidence interval procedures are designed to be applied to samples of observations on the random variable of interest. As more and more observations are collected, more and more information is gained about the distribution of the random variable, and the resulting confidence intervals on the estimated probabilities and percentiles become smaller and smaller.

There is a fundamental difference between this well-known procedure of collecting actual <u>observations</u> on a random variable and the process of making <u>predictions</u> of a random variable. As more and more predictions of a random variable are generated, there is no guarantee that more information is generated about the true distribution for a future realization of the random variable.

Unlike the simple nuclear plant example above, the subject of analysis for the WIPP disposal system is the distribution of cumulative releases of radionuclides to the accessible environment over a 10,000-year time frame. Because the cumulative release for this site is a future realization of a random variable, its prediction involves considerable uncertainty. <u>Estimates</u> of the probabilities and/or percentiles are required to verify compliance. Due to the uncertainty intervals surrounding these estimates, there can be no absolute assurance that the probability statements contained in the regulations are satisfied. At best, compliance can be determined only to within a certain level of confidence.

Estimates derived from the WIPP performance assessment modeling system will have errors of prediction associated with each estimate produced by the model. However, unlike the sampling problem referred to earlier, the "confidence intervals" for the estimates are not necessarily reduced by running the model repeatedly, generating more and more predictions based on the same assumptions. Rather, the WIPP performance assessment has attempted to reduce the "confidence intervals" or, more generally, the uncertainty interval surrounding the estimated probabilities and percentiles by running the model under a wide variety of assumptions.

The current WIPP performance assessment process addresses two sets of uncertainties:

1) the uncertainties surrounding probability distributions selected for values of parameters used as WIPP performance assessment model inputs; and

2) the uncertainties surrounding the definition, screening, and quantification of possible future scenarios and their probabilities.

DOE has expanded its efforts to quantify uncertainty distributions for the input parameters, thus reducing uncertainty due to the first type of assumptions. Panels of experts have addressed the probabilities of future scenarios in an attempt to reduce uncertainty regarding the second type of assumptions.

In the nuclear plant example, there was a possibility of reducing the size of the confidence intervals of estimates by collecting more observations at the site. In the prediction problem, only one method is available for reducing the uncertainty of the resulting estimates. This method involves quantifying the uncertainty associated with the assumptions on which the forecast is based. The uncertainty surrounding model input parameters may be estimated by specifying probability distributions for these parameters based on the best knowledge of the disposal system. If the uncertainty distributions are developed based on observations of the variability of physical parameters measured at the WIPP site, then uncertainty intervals surrounding these physical parameters can be reduced further by collecting more information about the site, waste characteristics, and their interactions. This leads to a greater reduction in uncertainty concerning the estimated probabilities and percentiles for the total release. Thus, uncertainty due to the first set of assumptions may be reduced by collecting more information about the model input parameters.

The selection of possible future scenarios and the probabilities assigned to these scenarios in the second set of assumptions involve a different type of uncertainty.

8.1.3 Outline of Chapter 8

The following section presents a formalized concept of the probability of compliance. Applications of the probability of compliance concept to a variety of compliance criteria are discussed. Alternate criteria for compliance are compared and the advantages and disadvantages of each noted in Section 8.3. Section 8.4 reviews other regulatory examples of concepts related to reasonable expectation. Conclusions and recommendations are presented in Section 8.5.

8.2 PROBABILITY OF COMPLIANCE

8.2.1 Review of the Probabilistic Requirements of 40 CFR Part 191

§191.13(a) contains the following regulatory requirements:

> Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a *reasonable expectation*, based upon performance assessments, that cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all *significant* processes and events that may affect the disposal system shall:
>
> > (1) Have a likelihood of *less than one chance in 10* of exceeding the quantities calculated according to Table 1 (Appendix A); and
> >
> > (2) Have a likelihood of *less than one chance in 1,000* of exceeding *ten times* the quantities calculated according to Table 1 (Appendix A). [*Italics added for emphasis.*]

Table 1 of Appendix A of 40 CFR part 191 defines a set of permissible release limits for the isotopes of concern. In instructions accompanying this table, guidelines are suggested for the appropriate use of Table 1 quantities in conducting a performance assessment. For each isotope, the ratio of the predicted cumulative release to the accessible environment over 10,000 years to the permissible release limit listed in the table is to be calculated. The ratio thus obtained is often referred to as the "normalized release" for each isotope. The normalized releases for all isotopes in the table are then added together to form the sum of the normalized releases. For example, the limit given in Table 1 for cumulative releases of each listed plutonium isotope to the accessible environment for 10,000 years after disposal is 100 curies per unit of waste disposed of at the site. If the estimated cumulative release over 10,000 years for the isotope is 70 curies per unit of waste, the normalized release for this isotope is calculated as 70/100 = 0.70. The normalized release is to be calculated in this fashion for each isotope in Table 1.

The sum of the normalized releases for all isotopes disposed of at the site is used for evaluating the probabilistic requirements 1 and 2 in §191.13(a) given above. To satisfy §191.13(a)(1), there must be a reasonable expectation that the probability of the sum exceeding 1 is less than 10 percent. To satisfy §191.13(a)(2), there must be a reasonable expectation that the probability of the sum exceeding 10 is less than 0.1 percent. In terms of percentiles, the 90^{th} percentile of the distribution of the summed normalized releases must be less than 1, and the 99.9^{th} percentile must be less than 10. §191.13(a) requires that estimates be made for two upper percentiles of the distribution of releases and specifies upper limits on these percentiles.

To construct this distribution predicting the disposal system's performance requires calculation of the summed normalized release (termed simply the "release" in this discussion) and its probability of occurrence for each intrusion sub-scenario. The cumulative probability distribution for the release is obtained by sorting the estimated releases for each sub-scenario in increasing order. The ordered releases and their associated probability values are then used to construct the cumulative probability distribution, which is a step function defined over the range of release values which are called the arguments of the function. The step function starts at zero for a release value of zero. At each estimated value of the release, the function steps up by an amount equal to the associated probability of the release. The cumulative distribution function so defined is a non-decreasing function which cannot exceed the value of unity (1). The value of the function is equal to the probability that the release is <u>less than or equal to</u> the value of the argument of the function.

The Complementary Cumulative Distribution Function (CCDF) is defined as the difference between the cumulative distribution function and the value 1. The probability and percentile limits set forth in §191.13(a)(1) and (2) and the reasonable expectation of compliance concepts are described in terms of the CCDF of the summed normalized release variable. The value of the CCDF function gives the probability that the release is <u>greater than</u> the value of the argument. The CCDF for the random variable R is denoted by the function

$$F(r) = \Pr\{ R > r \}.$$

The function F(r) is always between 0 and 1, and can never increase as r increases. Using the CCDF function, §191.13(a)(1) and (2) are commonly written in statistical terminology as:

(1) $F(1) < 0.1$; and
(2) $F(10) < 0.001$.

An equivalent statement of the regulatory requirements written in terms of the 90th percentile (denoted by $R_{.9}$) and the 99.9th percentile (denoted by $R_{.999}$) as

(1) $R_{.9} < 1$; and
(2) $R_{.999} < 10$.

Because the summed normalized release is not only a random variable, but a random variable with a distribution that can be predicted only with a considerable degree of uncertainty, only estimates of the probabilities and percentiles (i.e., the quantities written on the left side of the four inequalities above) can be developed. Each estimated probability and percentile will have an error of estimation. One interpretation of the concept of reasonable expectation is that there must be reasonable evidence that all or most of the uncertainty intervals for the estimated percentiles and probabilities will fall below the designated regulatory requirements.

8.2.2 Statistical Interpretation of the Requirements of 40 CFR Part 191

As noted in the introduction, a random variable with no strict upper bound cannot be "proved" to satisfy a specific mathematical constraint of the form $R < L$, where the limit L is a specified number. This situation is encountered often in the application of statistical methods to environmental problems. The random variable R denotes a random level of emissions and the fixed numerical limit L is the maximum allowable emission for the substance under consideration. If the probability distribution of the emission R is known exactly, then an exact estimate of a percentile or a probability may be derived by calculus. If this probability is large (i.e., near 100 percent), then it would be "almost always" true that the emissions are less than the regulatory requirement.

The order of the inequality inside the probability statement may be reversed. In this case, the probability that R exceeds L would be required to have a small value. The requirement then would be stated as

$$\Pr\{R > L\} < Q,$$

where Q is a small probability value. Using the CCDF function notation, the regulatory requirement is stated as

$$F(L) < Q.$$

The values $Q_1 = 0.1$ (10 percent) or $Q_2 = 0.001$ (0.1 percent) are used in 40 CFR section 191.13(a) at two different values of the radioactivity release, $L_1 = 1$ and $L_2 = 10$, respectively.

The required estimate of a probability or percentile can be calculated from the known distribution and compared directly to the proscribed probability level. This procedure provides a simple "Yes" or "No" answer for determining compliance with the probabilistic requirements of 40 CFR part 191.

If the distribution of R is not known exactly, then the above approach is not sufficient to define compliance with the regulatory requirements in a statistical framework. The estimated probabilities or percentiles will have an associated uncertainty interval because the exact distribution of R is unknown. Hence, there will be uncertainty in determining if the estimated probability is less than the target probability. This uncertainty in determining compliance could be addressed in two ways. Careful review of the modeling procedures and the record before the Agency by panels of expert reviewers could be used to increase the level of confidence in the reported results. Or, a statistical determination of compliance could be made from the reported results by conducting a hypothesis test at a specified level of confidence. These two approaches are discussed in more detail in the following sections.

8.2.3 Use of Expert and Peer Review for Determining Level of Confidence

The use of statistical methods alone cannot assure that predicted releases of radionuclides to the accessible environment from the WIPP disposal site will comply with the regulatory requirements of 40 CFR part 191.

A compliance determination would be based on the entire record before the Agency, including both qualitative and quantitative evaluations. For each of the quantitative requirements in the regulations, the determination of reasonable expectation may be based on quantitative analyses as specified in the regulations, supported by qualitative judgment of the degree of confidence in the reported WIPP performance assessment and compliance assessment results.

A qualitative assessment of the degree of confidence may be derived from the formal review process. The review process would comprise, in part, empirical testing of the model components, a complete review of the documentation of the model, evaluation of all significant uncertainties, and peer review where required by 40 CFR part 194 and involving assessment of the assumptions and findings reported in the WIPP compliance application.

The testing of model components would include evaluation of the physical basis for the model, verification of the numerical accuracy of the calculations performed by the model, validation of approximations made in the calculations, and review of the probability distributions assigned to uncertain input variables.

The peer review process of the conceptual models provides an additional level of confidence for the reported numerical results of the performance assessment process. However, the quantitative nature of the requirements of 40 CFR section 191.13(a) implies that qualitative evaluation alone is not sufficient for determining compliance. In the following sections, quantitative measures of the degree of confidence obtained by statistical procedures are reviewed.

8.2.4 Use of Statistical Methods for Determining Compliance

Many statistical methods can test hypotheses about the distribution of R when the underlying distribution is not known exactly but must be estimated. The methods primarily differ according to the assumptions made concerning the form of the unknown distribution. These methods generally are classified as parametric or non-parametric.

Parametric methods contain specific assumptions concerning the form of the probability distribution for the variable to be tested. A particular family of probability distributions, indexed by one or more parameters, is selected as a general model for the observed data. Estimates of the parameters are made from the data to select from the family a specific distribution to use for the hypothesis test. A typical parametric example is the use of the family of normal or Gaussian distributions parameterized by a population mean and a population variance which is the square of the standard deviation. The normal distribution has the familiar "bell-curve" shape, being symmetric about the mean of the distribution. Furthermore, the mean, median (or simply stated the middle value), and mode (that is, the most likely value) are represented by the same point of the distribution. Parametric methods begin by estimating the unknown mean and variance parameters of the distribution using the available data, denoted by X_1, X_2, ... X_N. A typical estimator for the population mean (M) of the normal distribution is the simple average:

$$M = \Sigma X_j / N$$

A typical estimator for the population variance (V) is the mean squared variation of each data point X_j from the estimated mean:

$$V = \Sigma (X_j - M)^2 / (N - 1)$$

The population standard deviation is estimated as the square root of the variance of the data samples.

Each of the estimated parameters has an associated measure of sampling error. In the case of the estimated mean, its sampling variance (V_M) is estimated by dividing the population variance by the sample size N: $V_M = V / N$. The standard error of the mean SE(M) is calculated as the square root of V_M. Thus, the standard error of the mean is smaller than the population standard deviation by a factor equal to the square root of sample size N. As the number of observations increases, the standard error of the estimated mean is reduced by a predictable amount. Estimates of the sample size required to reduce the standard error of the mean to specified levels may be derived based on this relationship.

Parametric models such as the normal distribution also are used for testing hypotheses. A typical parametric hypothesis test for the mean of the normal distribution would begin by estimating the mean and the standard error of the mean using the procedures above. If it is necessary to determine if the mean is below a specified upper limit (L), then the hypothesis test is conducted by comparing the estimated mean to the limit L. Because there is sampling error associated with the estimated mean, the actual comparison is made using the upper bound of the confidence interval for the estimated mean:

$$M + k_a SE(M) < L,$$

where k_a is selected to provide the appropriate a% confidence level for the test.

The lognormal distribution is often used as a parametric model for environmental quantities. This distribution, which is defined for positive variables only, is not symmetric, but highly skewed to the right or left (If there is a long tail on the right side of the distribution which extends up to large values of the variable then it is referred to as positively skewed). The lognormal probability distribution is obtained by an exponential transformation from a normal variable. If the variable X has a normal distribution, then the transformed variable $Y = e^X$ is said to have the lognormal distribution, because the (natural) logarithms of Y values have a normal distribution. Applying the exponential transformation to the mean of the normal distribution, which is also the median, with probability of 0.5 below the median and 0.5 above the median, yields an estimate of the median of the lognormal distribution.

Parameter estimates for the lognormal distribution are typically derived by taking logarithms of the lognormal observations (Y_1, Y_2, ..., Y_N), then applying the estimators defined above for the mean and variance of the normal distribution. For example, the simple average of the logarithms of the Y_j values is an estimate of the mean (and median) of the transformed normal distribution. The exponential function is then applied to the average of the logarithms to calculate an estimate of the median of the associated lognormal distribution. This procedure often is described as calculating the geometric mean of the lognormal observations, which provides the same estimate for the median of the lognormal distribution. Furthermore, if experts provide judgments on the upper and lower percentiles of the distribution, an estimate can be made for the variance of the lognormal distribution. Knowledge of these two parameters (the mean and variance) completely defines the distribution.

Parametric hypothesis tests for the lognormal follow the same general procedures as for the normal distribution. Tests for the median of the lognormal distribution are simpler than for the mean of the lognormal and follow the same procedure as the test for the mean of a normal distribution. The mean of the logarithms of the observations (plus a multiple of the standard error) is compared to the logarithm of the regulatory limit L. Tests for the mean of the lognormal require more detailed calculations to determine the standard error of the estimated mean.

The use of parametric methods is based on several assumptions. The most important of these is the selection of a particular family of distributions as a probability model for the data. Generally, a large number of observations is required to determine if this assumption is correct. However, even with a small number of observations, it may be obvious that certain families of distributions may not be applicable.

Non-parametric statistical tests, by comparison, make minimal assumptions concerning the specific probability distribution for the observed random variable. The usual assumption that the variable has a probability distribution with a defined mean and variance is very general. In terms of modern statistics, non-parametric statistical tests of hypotheses are considered "robust" with respect to assumptions made concerning the form of the distribution of R. The results of a robust statistical test will be affected less than a non-robust test if the actual distribution of the data departs from the assumed distribution.

Specifically for the case when the distribution of the normalized release is <u>not</u> known exactly, 40 CFR sections 191.13(a)(1) and (2) may be written as two statistical hypotheses (H_1 and H_2) to be accepted or rejected by applying a statistical test. Using the CCDF approach, these hypotheses can be stated as:

(1) H_1: $F(1) < 0.1$; and
(2) H_2: $F(10) < 0.001$.

Or, in terms of percentiles, the regulatory requirements may be expressed as:

(1) H_1: $R_{.9} < 1$; and
(2) H_2: $R_{.999} < 10$.

More generally, a single hypothesis referred to as the "joint null hypothesis" may be written in terms of the CCDFs as

H_o: $F(L_i) < Q_i$, for $i = 1, 2$;

or, in terms of percentiles as

H_o: $R_{Pi} < L_i$, for $i = 1, 2$;

with P_i, Q_i and L_i defined as above. The joint null hypothesis is to be tested against all alternatives. If there is no sufficient statistical evidence to reject the null hypothesis, then the null hypothesis is said to be "accepted." Note that the statistical hypothesis testing procedure does not "prove" that the null hypothesis is true; it states only that no sufficient statistical evidence could be found to reject the null hypothesis.

Hypothesis tests concerning probability statements such as H_o: $F(L_i) < Q_i$ or H_o: $R_{Pi} < L_i$ when the distribution is not known with certainty are generally based on samples obtained from the distribution of the random variable. The degree of "truth" obtained by applying these hypothesis tests for probabilities or percentiles of predicted future realizations of the random variable R is more difficult to quantify. In this case, the "truth" of the results can be assessed only probabilistically. The probability of compliance with 40 CFR part 191 may be estimated using simulation results to characterize the uncertainties involved in estimating the future distribution of the random release.

8.2.5 Use of Sampling Methods

The performance assessment modeling process contains two stages of analysis. In the first stage, a set of scenarios is selected for evaluation. Subjective probabilities are assigned to the scenarios. In the 1992 performance assessment (SNL92), scenario probabilities are generated based on the results of expert panels, which addressed the likelihood of human-intrusion processes and the deterrent effect of markers. In the second stage of the analysis, the performance assessment model evaluates the summed normalized release for each scenario. At this stage, specific values for the physical parameters of the model must be selected. Rather than being assigned a single value, each important input parameter has been assigned a probability distribution that reflects the uncertainty in the value of the parameter. (These distributions have been assigned independently for each parameter.) The model is run repeatedly, using a Monte Carlo simulation approach to generate a distribution of possible values for the summed normalized release.

This approach is widely accepted, and is currently being followed by DOE for the WIPP performance assessment and both DOE and NRC for the Yucca Mountain performance assessments. However, other sampling strategies, generally known as "importance sampling" (WU93) have non-equal probabilities in order to concentrate the samples in the region of parameter space where the models have the greatest sensitivities to parameter variations. The purpose of importance sampling is to increase sampling efficiency in order to reduce the computational workload while minimizing the need for model oversimplification or reduced coverage of the parameter space. Furthermore, 40 CFR part 191 requires only the determination of two points on the CCDF at probabilities of 0.1 and 0.001. The rest of the CCDF is not significant to determine these compliance points. (That is not to say that only two points are considered in the compliance determination; other information is not discarded. It is only after all information has been organized into a CCDF that it reduces to this two point test. Because the CCDF algorithm orders the scenarios by calculated release, the approach to the release limits is closest at these two points.) Techniques such as importance sampling might be able to develop the compliance points with far fewer samples than the Latin Hypercube Sampling (LHS) Monte Carlo technique selected by DOE for WIPP performance assessment (SNL85).

In the general Monte Carlo approach, a single value for each input parameter would be sampled independently from the appropriate distribution for the variable within each run of the model. The LHS method is based on dividing the parameter distribution into strata which are intervals of equal probability. An interval is selected, then a random sample is drawn from the selected interval of the distribution. The effect of the LHS procedure is to ensure a more uniform spread of sampled values over the entire range of the parameter distribution than might be obtained by simple Monte Carlo sampling. The LHS procedure would be unnecessary if large sample sizes could be used for the Monte Carlo simulation. Due to the complexity and sometimes costs of the computer models, only a relatively small number of samples are used currently. For small sample sizes, the LHS procedure provides a more efficient sampling technique in comparison to alternatives.

Many types of probability distributions are used to describe the uncertainty in the WIPP performance assessment model input parameters. Physical parameters used in the model are assigned distributions based either on available data or the subjective opinion of experts. Some distributions, based on actual data, do not belong to a known family of distributions. These distributions are constructed directly from the observed data by forming the cumulative distribution function. Other families of distributions selected for the model input parameters typically include the beta, gamma, exponential, normal, lognormal, uniform, loguniform, discrete uniform, binomial, and Poisson distributions. The beta, uniform, and loguniform distributions are appropriate for parameters that are assumed to lie in an interval between two known endpoints. The gamma, exponential, and lognormal distributions are appropriate for positive parameters with distributions which are skewed to the right, with a long tail extending to higher values of the parameter. The first six families of probability distributions are defined for variables that can take a continuous range of values. The discrete uniform, binomial, and Poisson distributions are appropriate for parameters that have only integer values.

In summary, the performance assessment modeling process may be described as a two-step procedure:

1. A complete set of possible future scenarios, denoted by the set $\{S_j, j = 1, \ldots, J\}$, is developed conceptually with the understanding that all possible outcomes have been included. The scenarios are then assigned probability distributions, which must sum to 1 over all scenarios.

2. At this stage, a specified number of independent samples are selected by the LHS procedure, for example, from the subjective uncertainty distributions assigned to the input parameters of the model. Specified pair-wise correlations can be contained in the analysis. The model is then run for each LHS sample S, generating N CCDFs for all scenario S_j. Using all scenarios j, and each list (or vector) of subjective distributions on model input parameters, N distribution functions are computationally generated (where N = number of sample vectors taken using the LHS procedure.) For the scenarios analyzed, each LHS model run generates a different CCDF F_n for the distribution of the summed normalized release.

8.2.6 Conditional Probabilities of Compliance

It may be possible to reduce the set of N LHS CCDFs for each scenario to a single probability distribution. This reduction may be accomplished in two steps. First, the set of LHS curves for each scenario can be reduced to a single distribution for the normalized release. The resulting distribution would be conditional in the sense that the scenario would be assumed to occur with a probability of 100 percent. Second, the conditional distributions for each scenario would then be weighted by the scenario probabilities and combined into a single (unconditional) curve for the WIPP site. This approach was not applied since single probability estimates were not used. Instead, probability distributions were assumed by DOE for the scenarios and a mean CCDF was calculated for the collection of scenarios using a sampling based approach.

Several methods have been proposed to reduce the set of LHS CCDFs to a single curve involving all scenarios (SNL92, ESL92). The methods for reducing to a single CCDF include using these aspects of the LHS CCDF values:

1. the mean which is the simple arithmetic average (i.e. a vertical averaging of the generated CCDF curves;
2. the median which is the 50^{th} percentile;
3. selected upper percentiles (those higher than the median); or
4. selected order (or rank) statistics (e.g., the maximum which is the highest of the ordered observations, the second highest, etc.)

As stated, 40 CFR sections 191.13(a)(1) and (2) require that estimated releases be evaluated at the two values of the summed normalized release: $R = L_1 = 1$ and $R = L_2 = 10$. However, it is informative to generate the entire CCDF for the scenario in graphic form. An example of the reduction of 10 LHS CCDFs to a single curve using the maximum of the set of LHS CCDFs is shown in Figure 8-1. The maximum curve (an example of alternative 4 above) is the solid line labeled A in the figure. The maximum curve, defined as a function of the normalized release R,is also defined to have the highest value of the set of LHS CCDF probabilities at each value of the release.

Figure 8-1 also includes a graphic representation of the requirements of §191.13(a)(1) and (2) indicated at the corners (1 and 2, respectively) of the step function (line B) in the upper right corner of the figure. The regulations proscribe probabilities of release in the region above and to the right of this step function. In this example, the maximum curve complies with §191.13(a)(1) at $R = 1 = 10^0$, while it slightly exceeds §191.13(a)(2) at $R = 10 = 10^1$.

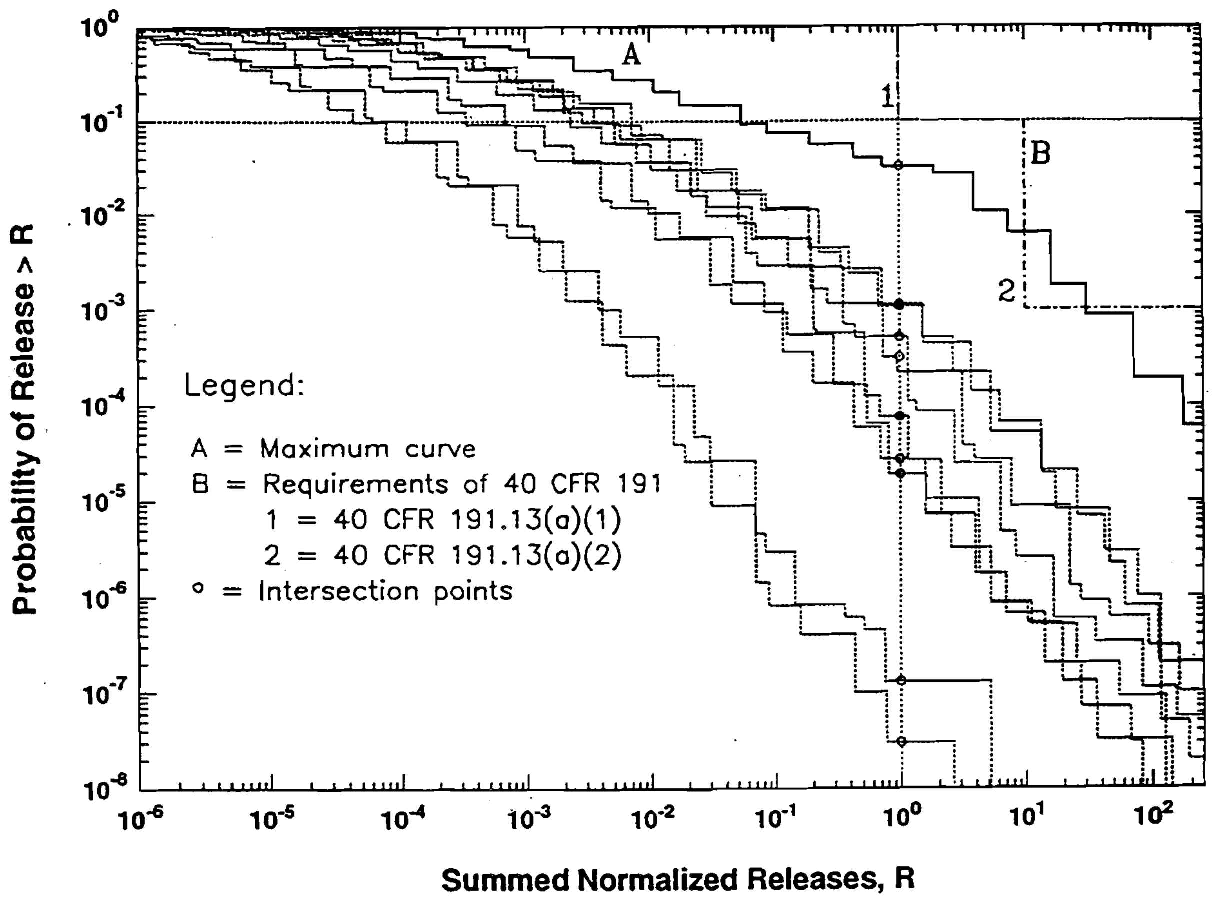

Figure 8-1. Ten Hypothetical LHS CCDFs, with Maximum

Although graphic representation of the entire curve helps in visualizing the curve reduction procedures, the entire curve need not be calculated to determine compliance in the strict statistical interpretation of the regulations. Returning to the discussion of Figure 8-1, the dotted line C marks the value of $R = 1 = 10^0$. To complete the requirement in §191.13(a)(1) a similar line could be drawn to mark the value of $R = 10 = 10^1$. The equivalent of reduction to a "single curve" is obtained by applying one of the four methods of curve reduction noted above to the set of point estimates shown by the large dots along line C. The set of 10 points along line C represent 10 independent estimates of the probability that the normalized release exceeds 1. Although equivalent calculations may be performed for the entire CCDF, only points on the curve noted in the figure and along a similar line $R = 10 = 10^1$ need to be considered in determining compliance. Both sets of point must be considered for the 40 CFR part 191.13(a) compliance test.

Figure 8-2 shows the mean (A), 90th percentile (B), and median (C). of a set of LHS CCDFs. The use of the mean was considered as the first alternative method for reducing the set of LHS CCDFs to a single CCDF, while the median was the second alternative, and the 90th percentile is an arbitrarily selected example of the third alternative. In Figure 8-2, all three reduced curves indicate compliance with both §§191.13(a)(1) and (2). Note, however, that the mean is below the median for small values of R, indicating an asymmetric (non-normal) distribution. Also, it exceeds the 90th percentile at higher values of R. At very high values of R, the mean lies close to the maximum curve shown in Figure 8-1. Calculation of the unconditional probability of compliance for all scenarios is based on the conditional distribution of intersection point values for each scenario. The range of the distribution of these values reflects the range of uncertainty due to the model parameters for the scenario at hand. The mean, median, and percentiles of this distribution, and the maximum, second highest, etc., of the intersection point values, are all possible methods for reducing the set of N intersection points to a single point estimate.

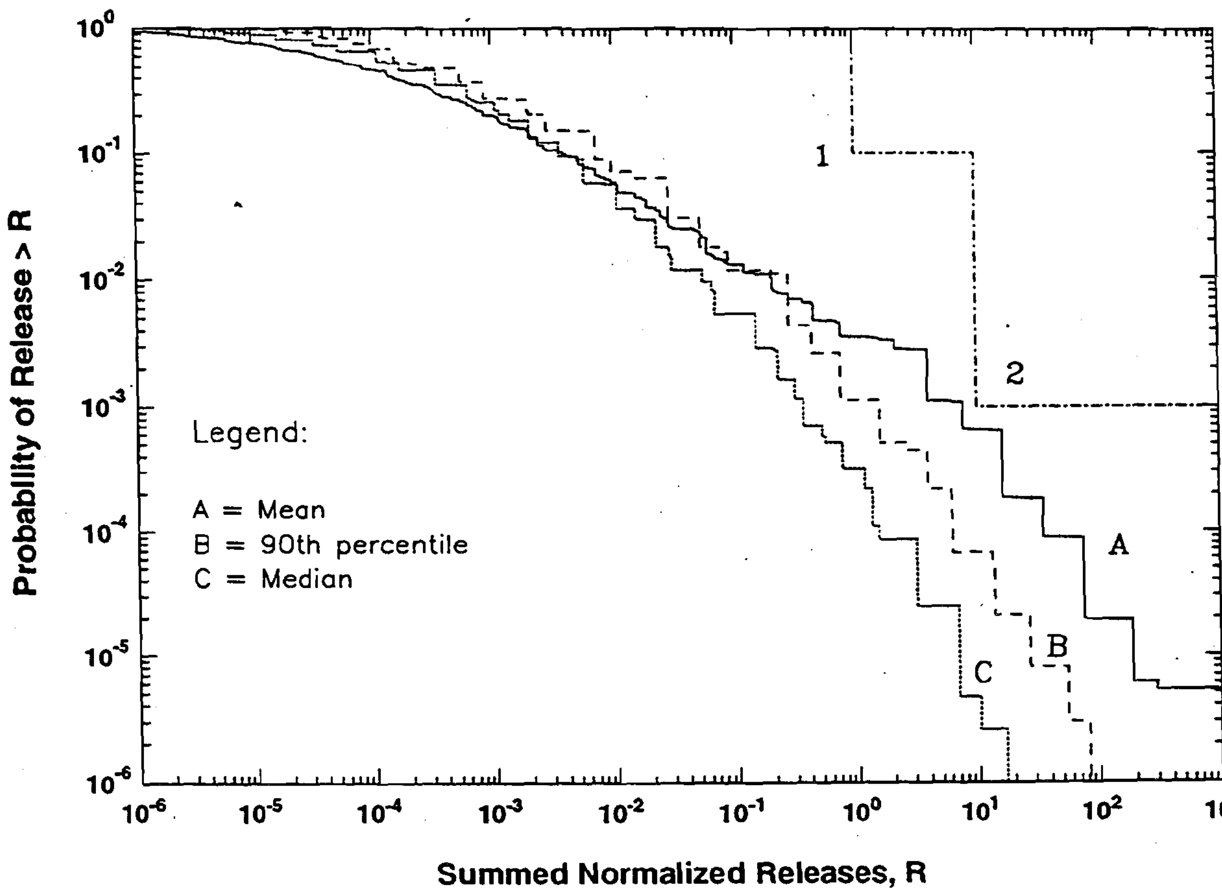

Figure 8-2. Mean, 90th Percentile, and Median Curves from Set of 10 LHS CCDFs

Uncertainty in these point estimates should be considered in the assessment. Hence, the spread of the distribution of intersection points must also be quantified. The combination of the selected point estimate and an estimate of the spread of the distribution is required to characterize the degree of confidence for the determination of compliance.

The following section addresses the derivation of the unconditional probability of compliance from the collection of probabilities for all scenarios and subjective uncertainties on input parameter values. The advantages and disadvantages of the alternative criteria for determining compliance are related to the advantages and disadvantages of each form of curve reduction. The advantages and disadvantages of each form of curve reduction are discussed in more detail in Section 8.3.

8.2.7 Unconditional Probability of Compliance with the Containment Requirements

The probability of compliance may be estimated using one of the four curve reduction methods noted in the preceding section. The uncertainty reflected in the multiple LHS simulations performed for each scenario and uncertain model parameter results in a distribution of point estimates for each release magnitude.

Derivation of the unconditional probability of compliance requires use of the scenario probabilities and simulation of the uncertainty in the scenario probabilities. The use of subjective methods to resolve scenario probabilities and their uncertainty has only just begun. Recently, several expert panels were convened and assigned the task of estimating human intrusion scenario probabilities. The unconditional probability of compliance cannot be estimated using the computational approach until uncertainty ranges have been assigned to the scenario probabilities.

The uncertainty distribution for the scenario probabilities, when available, may be used to simulate a set of N scenario-weighted estimates of the probability of exceeding the various compliance release limits. Again, this set of estimates will need to be reduced to a single point estimate for the probability of compliance, and a measure of the uncertainty interval will be needed for this estimate. Formally, this would require a second application of the four curve reduction methods discussed above. However, it may be sufficient simply to display the resulting distribution of estimates of the probability of compliance graphically to determine if the uncertainty interval is sufficiently high (or low).

8.3 COMPARISON OF ALTERNATIVE CRITERIA FOR COMPLIANCE

8.3.1 Advantages and Disadvantages of Alternative Compliance Criteria Using a Central Point Measure

In section 8.2, a set of N point estimates for each scenario with parameter uncertainty was developed for the probability or percentiles contained in the regulations by determining the intersection of the N LHS CCDFs with the appropriate set of regulatory requirements. This set of N independent estimates for the percentiles R_{Pi} and/or probabilities F(L_i) used in the regulatory requirements determines the uncertainty distribution for each measure of compliance. These estimates must then be compared to the appropriate limiting value (L_i and/or Q_i, respectively) stated in §191.13(a). Because a distribution of estimates is produced by this procedure, it is desirable to reduce this set of estimates to a single test statistic for determining compliance.

After observing N independent samples from the LHS simulations, the probability of compliance may be determined by a variety of methods. The simplest method is to estimate a central point from the distribution of estimates. Alternative methods for determining a central point are listed in Table 8-1, with a summary discussion of the merits and disadvantages of each. The methods include the simple arithmetic mean (or "center of gravity",) the weighted mean, and the median.

Alternative 1 in the list of curve reduction methods presented in the previous section suggests taking the arithmetic average of the appropriate point estimates to use as the test statistic for comparing to the limit in requirement i. The use of a weighted mean is not necessary for conditional analysis due to the equally likely nature of LHS samples.

Alternative 2 is a variation of alternative 1 to account for unequally weighted scenarios.

Alternative 3 uses the median $f_{i,j}(.5)$ as the central point estimate for the test statistic. The median is a more robust point estimate, but this point estimate will be smaller than the true expected value (mean) if the distribution is skewed to the right (e.g., large values are expected to be more common than small values).

Table 8-1. Measures of the Central Point

	Measure	Pros	Cons
1	Arithmetic Mean = M	• The true expected value if probabilities are equal • Easy to calculate • Fair weight to low probability but catastrophic failures	• Inappropriate for distributions highly skewed to right • Low robustness; one "outlier" can dramatically change result • If used as criterion, level of confidence is unknown
2	Probability - Weighted Mean = M_{wt}	• The true expected value if probabilities are not equal • Easy to calculate and explain • Fair weight to low probability but catastrophic failures	• Inappropriate for distributions highly skewed to right • Low robustness; one "outlier" can dramatically change result • If used as criterion, level of confidence is unknown
3	Median = MED = $f_{.50}$	• A true center: there are 50% above and 50% below the median • Non-parametric: no distribution shape is assumed • Known to be very robust; not affected by "outliers" • Easy to calculate for reasonably large sample sizes	• Lower than expected value for distributions skewed to right • If used as criterion, level of confidence is unknown • Discounts low probability catastrophic failures, information is lost

Regardless of the decision to use the mean or median as a central point individually, neither test statistic for determining compliance would reflect the uncertainty indicated by the spread of the distribution of estimates. If the concept of reasonable expectation is interpreted to indicate due consideration of uncertainty, then single point test statistics that are measures of the central point of the distribution of estimates are not adequate for determining compliance. If the median is used as the central point, and the median is barely below the required limit, then there is almost a 50% chance that the regulatory limit would be exceeded. In this case, evidence from the spread of the distribution dictates that the probability of compliance can be no larger than 50%. Furthermore, the level of assurance or confidence at which this rather weak statement of compliance can be made is unknown because the uncertainty in the estimate of the median has not been considered.

To reflect the uncertainty in the distribution of estimates, appropriate measures of the spread of the distribution are required. Alternative estimators for the spread of the distribution of estimates are listed in Table 8-2, with a summary of the advantages and disadvantages of each estimator. Estimates of the spread of the distribution include the population standard deviation, the mean absolute deviation from the median (MAD), and the interquartile range (IQR) which is the difference between the 75^{th} and 25^{th} percentiles. The population standard deviation, based on sums of squared deviations from the mean, is less robust than the mean. Small changes in values far from the median can have a large influence on this estimator. The mean absolute deviation from the mean is more robust but is only appropriate for symmetric distributions. The interquartile range is more robust and appropriate for asymmetric distributions.

Possible numerical measures of compliance which can be used to reflect uncertainty in reduced data sets are summarized in Table 8-3. One test statistic for determining compliance is based on the mean and its standard error of estimation. The test statistic is defined as the upper end of the 95% confidence interval for the estimated mean. Use of the upper confidence bound for the sample mean is one of the statistical compliance criteria suggested by EPA for evaluating the attainment of soil clean-up standards (EPA89). The Nuclear Regulatory Commission (NRC) has adopted EPA clean-up criterion in the guidance for determining compliance with the requirements for license termination (NRC92). In these regulatory applications, actual measurements of residual contamination after site clean-up are used for computing the sample mean and standard error of the sample mean.

Note that the "confidence interval" found by this procedure provides an uncertainty range for the estimate of the mean, not for the spread of the population values. The mean plus a multiple of the standard error of the mean can be used to form this uncertainty interval. The advantages and disadvantages of this test statistic are shown in the first row of Table 8-3. Determination of the appropriate value of the multiplier "k" to yield the desired confidence level is based on the assumption of a Student-t distribution. This assumption may be inappropriate for asymmetric distributions.

Table 8-2. Measures of Spread or Dispersion

	Measure	Pros	Cons
1	Population Standard Deviation = Sigma	• Maximum likelihood estimate for variance of normal distribution • Easy to calculate, even for weighted samples	• Low robustness; one "outlier" can dramatically change result • Inappropriate for skew distributions
2	Mean Absolute Deviation from Median = MAD	• Non-parametric: no distribution is assumed • Provides robust estimate of population Sigma • Provides robust estimate of Standard Error (SE) of estimates of means and percentiles obtained by simulation method • Known to be very robust; insensitive to "outliers" • Easy to calculate for reasonably large sample sizes	• Link to sample variance depends on distribution • Inappropriate for skew distributions
3	Interquartile Range = IQR = $f_{.75} - f_{.25}$	• Non-parametric: no distribution is assumed • Provides robust estimate of population Sigma • Provides robust estimate of Standard Error (SE) of estimates of means and percentiles obtained by simulation method • Known to be very robust; insensitive to "outliers" • Easy to calculate for reasonably large sample sizes	• Link to sample variance depends on distribution

Table 8-3. Numerical Measures of Compliance

	Measure	Pros	Cons
1	Classical Confidence Limit on Weighted Mean $UCL = M_{wt} + k \bullet SE(M_{wt})$	• Classical upper bound for the expected value • Standard Error (SE) reflects uncertainty in estimate of mean • k can be adjusted for desired level of confidence • Easy to calculate, even for weighted samples	• May be inappropriate for skewed distributions • Low robustness; one "outlier" can change result dramatically • Uncertainty in the estimate of SE is not addressed • Level of confidence is based on the t-distribution assumption
2	p^{th} Percentile = f_p (Includes Median = $f_{.50}$)	• Percentile p reflects dispersion due to uncertainty in parameters and probabilities • Non-parametric: no distribution is assumed • p can be adjusted to desired probability point • Easy to calculate, even for weighted samples	• Extreme upper percentiles require large sample sizes • Uncertainty in the estimate of f_p is not addressed
3	Classical Confidence Limit on Upper Percentile $UCL_p = f_p +$ $k \bullet Sigma(f_p)$	• Classical upper bound for an upper percentile of the population distribution • Percentile p reflects dispersion due to uncertainty in parameters and probabilities • p can be adjusted to desired probability point • Standard Error (SE) reflects uncertainty in estimate of percentile • k can be adjusted for desired level of confidence	• Extreme upper percentiles require large sample sizes • Uncertainty in SE(f_p) estimate is not addressed • Level of confidence is based on the t-distribution assumption

Table 8-3. Numerical Measures of Compliance (Continued)

	Measure	Pros	Cons
4	Classical Tolerance Limit on Upper Percentile $t = M_{wt} + k_p \bullet \text{Sigma}$	• Tolerance limit addresses uncertainty in estimation of UCL • To account for uncertainty in SE, k is adjusted higher • k_p can be found for desired level of assurance for percentile p • Relatively easy to calculate, even for weighted samples	• Inappropriate for skewed distributions • Low robustness; one "outlier" can dramatically change result • Level of confidence is based on the t-distribution assumption
5	Non-parametric Tolerance Limit on Upper Percentile $f_{Max} = f_{[1:N]} =$ Maximum of N samples	• Non-parametric: no distribution is assumed • Use of order statistics reflects uncertainty in parameters and probabilities • Level of assurance requires no distribution assumption • Maximum out of N provides a non-parametric upper tolerance limit for upper percentiles • Easy to calculate	• Low robustness; one "outlier" can dramatically change result • Moderately large sample size for acceptable tolerance levels • Difficult to define tolerance limit if samples have unequal weights
6	Non-parametric Tolerance Limit on Upper Percentile $f_{[j:N]} = j^{th}$ highest of N samples	• Non-parametric: no distribution is assumed • Use of order statistics reflects uncertainty in parameters and probabilities • Level of assurance requires no distribution assumption • j^{th} highest out of N provides a robust non-parametric upper tolerance limit for upper percentiles • Higher robustness against "outliers" as j increases to median • Easy to calculate	• Larger sample size for acceptable tolerance values as j increases • Difficult to define tolerance limit if samples have unequal weights

A similar central point test statistic can be constructed for the median, i.e., the estimated median plus a multiple of the standard error of the median. Given that k is selected for 95% confidence, if the upper bound of the confidence interval on the median is less than the limit in the requirement, there will be 95% confidence that the conditional probability of compliance is at least 50%. This is a weak statement concerning compliance, but the probability of compliance can be improved by increasing the percentile from the median at 0.50 to a higher level. Thus, the median is a special case of the family of percentile estimators and their associated test statistics, which are the subject of rows 2 through 6 of Table 8-3. This family of test statistics is discussed in the following section.

8.3.2 Advantages and Disadvantages of Alternative Compliance Criteria Using Percentiles

A simple way to determine if the higher values of the distribution of intersection point values exceeds the regulatory requirements is to count the number of conditional LHS values which are higher than the limiting value. The ratio of this number to N is an estimate of the proportion of LHS runs that are not in compliance. Hence, the probability of compliance is 1 minus this ratio. For example, if there are 100 LHS samples and 10 values exceed the limit, then an approximate estimate of the proportion of samples exceeding the limit is 10 percent. This indicates that the probability of compliance is near 90 percent (if 100 points are adequate to describe the uncertainty distribution in the mean CCDFs.)

A more formal way to do this comparison is to specify that the p^{th} percentile of the distribution of intersection point values is below the regulatory limit. This value, denoted by f_p in row 2 of Table 8-3 was discussed under alternative 3 of Section 8.2. The following statement may be made concerning this percentile: If f_p is less than the limit in the requirement, then the probability of compliance will be at least as large as p. The level of confidence for making this statement is unknown, since the sampling error for the estimated percentile has not been addressed. Additional advantages and disadvantages of the percentile estimator are presented in row 2 of Table 8-3.

The test statistics in rows 3 through 6 of Table 8-3 are designed to provide a known level of confidence that the estimated percentile is less than the limit in the requirement. In row 3 of Table 8-3, the classic 95% confidence interval for the p^{th} percentile is formed by adding a multiple of the standard error to the percentile estimate. As for the confidence interval on the mean in row 1, the multiplier k can be adjusted to provide a 95% confidence interval. The level of confidence thus obtained is based on the assumption of a t-distribution.

The classic tolerance interval test statistic shown in row 4 of Table 8-3 is related conceptually to the confidence interval on the upper percentile discussed in row 3. Although this test statistic utilizes the estimated mean and standard deviation of the population of intersection points, it is applied as an upper tolerance limit for percentiles of the distribution. Due to the asymmetry of the distributions encountered here, the tabulated values for k_p provide only a rough approximation of the true level of tolerance for the test.

The order statistics of the sample of intersection points may be used to provide non-parametric upper tolerance bounds for the percentiles of a distribution (GLI78). The use of the maximum as a test statistic is discussed in row 5 of Table 8-3. For example, it may be demonstrated that the maximum value in a sample of 90 independent values from the same distribution has at least a 99% chance of being larger than the 95^{th} percentile of the distribution. Thus, the maximum in a random sample of at least 90 observations is said to provide a 99% upper tolerance limit for the 95^{th} percentile. A simple proof proceeds as follows.

By definition, the probability of exceeding the 95^{th} percentile is 5%. If observations are made independently, each has a 5% chance of exceeding the 95^{th} percentile. As more and more observations are collected, the chance that at least one of them will exceed the 95^{th} percentile increases with the number of observations. For a sufficiently large sample, there will be a high probability that the maximum in the sample exceeds the 95^{th} percentile. For example, this probability is calculated for N=90 observations by the formula

$$1 - .95^N = 1 - .95^{90} = 0.9901.$$

Thus there is over a 99% chance that the maximum of 90 independent observations will exceed the 95^{th} percentile, <u>regardless of the distribution.</u> If the maximum of the sample is lower than the requirement of §191.13(a), then there is at least a 99% chance that the 95^{th} percentile of the distribution lies below the regulatory requirement. In statistical terms, the maximum value in a random sample of size 90 provides a robust 99% upper tolerance bound for the 95^{th} percentile of the distribution.

By a similar argument, the second highest value in a random sample of at least 76 observations has at least a 90% chance of exceeding the 95^{th} percentile. And, the third highest in a sample of at least 75 has a 75% probability of exceeding the 95th percentile of the distribution. These test statistics based on the higher order statistics are discussed in row 6 of Table 8-3.

The advantage of using the order statistics of the estimates obtained from the intersection points of the LHS CCDFs with the regulatory requirements is that no assumptions are required concerning the specific form for the distribution. The distribution need not be symmetric. Appropriate tolerance bounds for any percentile may be found using the order statistics of the intersection points. Non-parametric tolerance limits for the upper percentiles of the distribution do not require specification of the adjustable multiplier k; hence, no reliance on tables based on the t-distribution assumption are necessary. For this test, the sample size itself is the adjustable parameter.

8.4 OTHER REGULATORY CONSIDERATIONS

This section examines both national and international regulatory requirements for parallels to the concept of "reasonable expectation."

8.4.1 Environmental Protection Agency

8.4.1.1 40 CFR Part 268, Land Disposal Restrictions.

The Land Disposal Restrictions identify hazardous waste that is restricted from land disposal and define those limited circumstances under which an otherwise prohibited waste may continue to be land disposed. §268.6 sets out requirements for exemption petitions which if granted allow land disposal of a prohibited waste. These petitions are generally referred to as "no migration petitions."

The regulations require that the demonstration include the following components:

(1) An identification of the specific waste and the specific unit for which the demonstration will be made;

(2) A waste analysis to describe chemical and physical characteristics of the subject waste;

(3) A comprehensive characterization of the disposal unit site including an analysis of background air, soil, and water quality;

(4) A monitoring plan to detect migration at the earliest practicable time; and

(5) Sufficient information to assure the (EPA) Administrator that the owner or operator of a land disposal unit receiving restricted waste(s) will comply with other applicable Federal, State, and local laws.

Treatment of uncertainty is addressed in Section 268.6(b)(5), which states:

> "An analysis must be performed to identify and quantify any aspects of the demonstration that contribute significantly to uncertainty. This analysis must include an evaluation of the consequences of predictable future events, including, but not limited to, earthquakes, floods, severe storm events, droughts, or other natural phenomena."

The EPA guidance manual offers further instruction on dealing with uncertainty (EPA92). The manual states that a petitioner must identify and evaluate the impacts of predictable future events that could contribute to or result in inadequate waste isolation, such as earthquakes and resulting ground motion, floods and droughts, severe storm events, climatic fluctuations, geologic activity, and likely human-induced processes and events which may affect the isolation capability of the unit, such as disturbance of the hydrologic regime and future land uses.

The manual notes that the level of detail required in individual petitions will depend on site-specific factors. Neither the manual nor the regulations provide limits or assumed values for any specific parameters such as future populations, land use, or climatic changes.

8.4.1.2 40 CFR Part 148, Hazardous Waste Injection Restrictions (Underground Injection Control)

40 CFR part 148 codifies EPA's regulatory framework for implementing the 40 CFR part 268 land disposal restrictions for hazardous waste that is disposed in Class I injection wells. Subpart C, Petition Standards and Procedures, sets out the requirements for seeking a "no migration" petition under these regulations. §148.20 requires that the petitioner demonstrate, with a reasonable degree of certainty, that hazardous constituents will not migrate as long as the waste remains hazardous, by demonstrating either (1) that the injected fluids will not

migrate within 10,000 years, or (2) that before the injected fluids migrate, they will no longer be hazardous because of attenuation, transformation, or immobilization within the injection zone.

§148.21 lists the information that must be submitted in support of a "no migration" petition. It states:

> An analysis shall be performed to identify and assess aspects of the demonstration that contribute significantly to uncertainty. The petitioner shall conduct a sensitivity analysis to determine the effect that significant uncertainty may contribute to the demonstration. The demonstration shall then be based on conservative assumptions identified in the analysis.

8.4.2 Nuclear Regulatory Commission

U.S. Nuclear Regulatory Commission regulations for the disposal of high-level waste in geologic repositories (10 CFR part 60) also address long-term uncertainty issues. These regulations require a finding that issuance of a license for such a geologic disposal system will not constitute an unreasonable risk to the health and safety of the public. Subpart E of the regulation provides performance objectives, site criteria, and design criteria.

The general standard in 10 CFR part 60 for judging whether the performance objectives and criteria are met is "reasonable assurance." §60.101 (a)(2) of Subpart E characterizes this general standard as follows:

> While these performance objectives and criteria are generally stated in unqualified terms, it is not expected that complete assurance that they will be met can be presented. A reasonable assurance, on the basis of the record before the Commission, that the objectives and criteria will be met is the general standard that is required. For 60.112, and other portions of this subpart that impose objectives and criteria for disposal system performance over long times into the future, there will inevitably be greater uncertainties. Proof of the future performance of engineered barrier systems and the geologic setting over time periods of many hundreds or many thousands of years is not to be had in the ordinary sense of the word. For such long-term objectives and criteria, what is required is reasonable assurance, making allowance for the time period, hazards, and uncertainties involved, that the outcome will be in conformance with those objectives and criteria. Demonstration of compliance with such objectives and criteria will involve the use of data from accelerated tests and predictive models that are supported by such measures as field and laboratory tests, monitoring data, and natural analog studies.

§60.112 requires that the disposal system be designed to assure that releases of radioactivity to the accessible environment conform to generally applicable EPA standards.

In 10 CFR part 60, the general standard for judging whether the performance objectives and criteria are met is "reasonable assurance," while 40 CFR part 191 uses the term "reasonable expectation." In its comments to EPA on the Advance Notice of Proposed Rulemaking (ANPR) on compliance criteria for 40 CFR part 191, NRC urged the Agency to reexamine a position taken in 1985 in 50 FR 38071 that "reasonable expectation" was different from "reasonable assurance" (NRC93a).[1] It was NRC's view that the terms were similar, and the Commission suggested that EPA explain any differences in the rulemaking process.

In its comments on the ANPR, the NRC also noted the difficulty in attempting to apply numerical standards (such as a specified confidence level) where data are insufficient to draw rigorous statistical conclusions. The NRC went on to say, "Because a specific statistical test cannot be applied, a more general qualitative 'level of confidence' should be the required measure of compliance. DOE should be required to demonstrate (by a preponderance of the evidence) the required level of level of confidence -- e.g., 'reasonable assurance' -- in future performance of the disposal facility."

In the development of a manual for determining compliance with license termination requirements, NRC has suggested methods for comparing soil and surface measurements of residual contamination to mandated clean-up standards (NRC92). One suggested method is a comparison of the upper bound on the 95% confidence interval to the regulatory standard. NRC notes that the comparison may have three possible outcomes:

(1) If the sample mean exceeds the standard for clean-up, then the site is not in compliance and further cleaning is required.

(2) If the sample mean is lower than the clean-up standard, but the upper limit of the 95% confidence interval for the mean is not below the standard, NRC offers two choices: the site operator may make more measurements to reduce the width of the confidence interval; or the operator may decide to re-clean the site.

[1] A similar standard -- "reasonable degree of certainty" -- exists in the RCRA regulations. DOE recently requested that EPA consider documenting in the 40 CFR part 194 rulemaking that the terms were equivalent for demonstrating regulatory compliance for geologic repositories. This standard requires the Agency to consider only future events that could reasonably be predicted; proof beyond a reasonable doubt is not required.

(3) If the upper limit of the 95% confidence interval for the mean is below the standard, then the site is considered to be in compliance at the 95% confidence level.

8.4.3 Department of Energy

DOE also commented on the 40 CFR part 191 Compliance Criteria ANPR (DOE93). While the Department advocated retaining the concept of "reasonable expectation," it took the position "that additional attempts to specify a numerical or statistical test of compliance would not be productive." Rather, DOE argued that the degree of confidence should not be predetermined; instead, it should be based on all considerations reflected in the record. DOE position was similar to that taken by the NRC. Because, in DOE's view, there are no statistical tests appropriate to the kinds of information contained in the performance assessment, EPA should choose a "more general level of confidence" based on a substantial understanding of the disposal system and the surrounding environment and on peer review of the WIPP performance assessments.

8.4.4 Non-U.S. Disposal Systems

Substantial work on performance assessment and treatment of uncertainty has been undertaken in several countries. These are primarily "total systems" studies, addressing more than just numerical techniques. For example, site selection issues are considered; i.e., one way of reducing uncertainty is to consider sites that are easy to characterize as opposed to sites that look good but are difficult to characterize.

However, finding useful parallels addressing the issue of "reasonable expectation" in programs involving non-U.S. geologic repositories has not been possible because these programs are not nearly as close to actual disposal as those in this country. In 1990, Pacific Northwest Laboratory (PNL) investigators compared programs on repositories for high-level waste[2] and spent fuel in eight countries including Belgium, Canada, France, Germany, Japan, Sweden, Switzerland, and the United Kingdom (PNL90). Conclusions reached by the PNL team include:

- The United States has one of the most developed disposal system concepts and one of the earliest scheduled disposal system startup dates.

[2] It should be emphasized that this report focused on high-level wastes, not TRU wastes.

- The United States has the most prescriptive regulations and performance requirements for the disposal system and its components.

- Most countries have established only general performance requirements for repositories.

- Some countries do not believe that detailed performance requirements and regulations are required and do not plan to develop them.

- No disposal system is scheduled for operation for at least 20 years.

- Only three countries have selected the host rock for their disposal system.

Regulatory status and approach to safety in each country surveyed by PNL are summarized in Table 8-4.

Table 8-4. Regulatory Status and Approach to Safety in Foreign Geologic Repositories

Country	Disposal System Performance Requirements	Status of Regulations	Approach to Proving Safety
Belgium	General only	Details to be developed	Deterministic & stochastic
Canada	General only	Under development	Deterministic & stochastic
France	General only	Under development	Deterministic
Germany	General for total system	Regulations complete	Deterministic, conservative
Japan	Not yet established	Not yet established	Stochastic
Sweden	General for total system	Regulations complete	Conservative, deterministic, some stochastic
Switzerland	Total system objectives	Regulations complete	Conservative, deterministic
United Kingdom	General only	Deferred for disposal system	Conservative, deterministic & stochastic, time-dependent simulation modeling

Outside the United States, Germany has the most advanced program. A candidate site for a high-level waste disposal system has been chosen at Gorleben in Lower Saxony. The disposal system will be situated in a salt dome at a depth of about 800 m. Safety must be demonstrated for 10,000 years, and the maximum allowable dose to the most exposed member of the general public is limited to 30 mrem/y for unavoidable occurrences before and after closure. The assessments to demonstrate compliance are deterministic and are characterized by PNL as conservative and bounding. Conservative is taken to mean that errors would be on the side of protectiveness of people and the environment.

8.4.4.1 Organization for Economic Co-operation and Development (OECD) Nuclear Energy Agency

Several studies have been conducted in the last few years at the international level on assessing the performance of high-level radioactive waste repositories and treating uncertainty in performance assessment. For example, the status of performance assessment methodology development was reviewed at a Symposium on Safety Assessment of Radioactive Waste Repositories, convened by the OECD Nuclear Energy Agency (NEA) in Paris in October 1989. NEA also held a 1987 symposium on "Uncertainty Analysis for Performance Assessment of Radioactive Waste Disposal Systems" (Seattle, February 1987), and published a methodology for scenario development ("Systematic Approaches to Scenario Development") in 1992. The various NEA working groups continue to focus much attention on uncertainty of long-term modeling of disposal system behavior.

8.4.4.2 Canada

The Atomic Energy Control Board (AECB) issued a regulatory policy statement concerning long-term aspects of radioactive waste disposal in 1987, which provides, *inter alia*, that individual risk from a waste disposal facility must not exceed 10^{-6} fatal cancers and serious genetic effects per year (AEC87). The policy statement includes guidance on how to account for the probabilities of various exposure scenarios when applying the basic regulatory requirements, stating that such probabilities "should be assigned numerical values either on the basis of relative frequency of occurrence or through best estimates and engineering judgements." Specifically, it indicates that low-probability exposure scenarios should be assigned values through best estimates and engineering judgments, and that:

> the assignment should be made using quantitative analytical techniques to assess as broad a base of expert opinion as reasonably possible. The use of subjective probability is appropriate as long as the quantitative values assigned through best estimates and engineering judgements are consistent with the quantitative values of the actual relative frequencies in situations where more information is available. The uncertainty of the probability assigned should also be estimated.

Furthermore, the AECB policy statement indicates that calculations of individual risks should be made by either of the following methods:

- using deterministic pathway analysis to calculate annual individual dose, and applying a risk conversion factor of 2×10^{-2} per sievert; or

- using probabilistic analysis to determine a distribution of annual individual doses, calculating the arithmetic mean value of these doses, and applying a risk conversion factor of 2×10^{-2} per sievert.

In the case of deterministic analysis, the AECB urges that analysts not be excessively conservative, but instead make a balanced choice of assumptions to ensure that the assessment describes reasonable situations covering the spectrum of exposure pathways and assesses their impacts rationally. In either the deterministic or probabilistic approach, the AECB indicates that sensitivity analyses should be conducted to investigate the effect of changes in input assumptions and model parameters on the magnitude of the single dose estimate (deterministic) or mean value of dose (probabilistic).

Since the arithmetic mean of a dose distribution could potentially hide the significance of values at the high end of the distribution, the AECB states that "it is judged acceptable to allow 5% of the estimated doses to exceed a dose of 1 mSv (100 mrem) per year to take account of normal statistical variations which are inherent in the probabilistic assessment process," and that the general risk requirement of 10^{-6} fatal cancers per year (which corresponds to a dose of 0.05 mSv/year (5 mrem/year)) takes account of this since a 5% chance of a dose of 1 mSv (100 mrem) corresponds to an average dose of 0.05 mSv (5 mrem).

8.4.4.3 France

In June 1991, France's Directorate for the Safety of Nuclear Installations (DSIN) issued Fundamental Safety Rule No. III.2.f on high-level and alpha waste disposal (FRE91). According to a summary presented by Raimbault et al. (RAI92), the rule provides that demonstration of safety be based on "deterministic evaluations of the radiological impact for two types of envisaged situations:

- a reference situation which corresponds to the occurrence of very probable or certain events.

- hypothetical situations corresponding to occurrence of low probability events that may lead to preferential transfers."

Under the reference situation, individual doses should be $\leq$ 0.25 mSv/year (25 mrem/year) for long exposures associated with very probable or certain events.

The DSIN rule details procedures for conducting performance assessment. The rule requires validation of numerical models; sensitivity analysis with respect to scenarios, models, phenomena, and parameters; and results expressed in terms of radiation exposures, with associated uncertainty bounds.

Based on the DSIN guidance, the Agence National pour la Gestion des Dechets Radioatifs (ANDRA) has developed an iterative procedure consisting of the following principal steps in the safety evaluation:

- identify all applicable radiological criteria
- select scenarios to be considered, with detailed radiological impact analysis and associated sensitivity and uncertainty analysis
- develop a first generation of global safety models corresponding to the selected scenarios
- develop specific detailed models to consider, e.g., glass corrosion
- test and utilize sensitivity and uncertainty analysis techniques
- develop information on consequence uncertainties and identify the most important scenarios, phenomena, geosphere data, or concept parameters
- draw conclusions on concept constraints, and define the most important site data acquisition work.

Input from architectural engineers and site investigators will be provided to the safety assessment team, and vice versa. According to Raimbault et al., at the end of ANDRA's planned underground laboratory phase, this procedure should facilitate "a complete and validated compliance assessment of the disposal system with maximum confidence" and "an optimized and justified design and program of operation for the underground facility" (RAI92).

8.4.4.4 Sweden.

The Swedish Nuclear Power Inspectorate (SKI) has indicated that it has not established a specific policy on how uncertainty should be treated but instead has analyzed the question on a case-by-case basis (AND93). However, SKI indicated that it will need to reach more definite conclusions about how to treat uncertainty at the time of licensing. SKI considers over-reliance on probabilistic assessments to be inappropriate. The Swedish agency wants all countries to agree on performance assessment and uncertainty analysis methodologies. SKI's principal focus in reducing uncertainty is to gain as great an understanding as possible of the physics and chemistry involved in the disposal system and to conduct research in key areas of remaining uncertainty.

The Swedish Nuclear Fuel and Waste Management Co. (SKB) addressed some of these issues, including ambitious probabilistic assessments of ground-water flow in a 1991 report. The report (SKB91) used stochastic modeling for hydrology, bringing in uncertainties in conductivities and other parameters and treating them statistically. However, other types of uncertainties are not treated statistically, but rather by variation analysis and special runs of the statistical model, e.g. with respect to fracture zones. SKB does not want to choose a performance assessment method now but recognizes that when the time comes for evaluating an actual site, the company will have to choose an approach and defend its selection (PAP93).

8.4.4.5 Switzerland

The Swiss, along with the Swedes and Finns, are skeptical of fully probabilistic treatment of uncertainty. Although they do use probabilistic codes, which accept distributions of values for various parameters, they do not assign probabilities to different values and instead randomly select numbers assuming a flat distribution. They emphasize that they do not necessarily try to predict disposal system performance as close to the truth as possible, but rather to predict that repositories are safe; tools that are known to be wrong but that are known to over-predict risks are considered acceptable (McC93).

A paper presented by Zuidema of Switzerland's National Cooperative for the Storage of Radioactive Waste (NAGRA) at a 1991 NEA workshop on criteria for HLW disposal identified four sources of uncertainty in disposal system safety analysis:

- uncertainty in scenarios;
- uncertainty in conceptual models;
- parameter uncertainty; and
- parameter variability.

Zuidema indicated that performance assessment tools can be used to quantify different types of uncertainty: for scenario uncertainty, several alternative future evolutions must be analyzed; for conceptual uncertainties, several alternative conceptualizations must be considered; and for parameter uncertainty, both probabilistic and deterministic models can be used.

Zuidema also identifies disposal system siting and design considerations that are important in reducing uncertainty. Factors to consider are the ease of exploring the geological environment and predicting the evolution of the geological environment over time; and the robustness of the disposal system, including simplicity of physical and chemical properties, availability of large safety margins, and maximum redundancy of barriers.

8.5 CONCLUSIONS

8.5.1 Essential Role of Peer Review

The criteria for evaluating compliance of the WIPP disposal site with the requirements of 40 CFR part 191 include both a qualitative evaluation of the performance assessment and a statistical approach based on evaluation of the multiple CCDFs generated by the performance assessment model using the random-sampling procedure. Each portion of the determination of compliance must evaluate the degree of uncertainty in the results of the performance assessment process. Uncertainties that must be addressed include the selection of a conceptual model for evaluating the likelihood of releases to the accessible environment over 10,000 years, the selection of specific scenarios for evaluation, and uncertainties in the assignment of numerical values for the probabilities of each scenario considered and the physical parameters required by the models.

Although the uncertainty surrounding the selection of values for the physical parameters in the models is significant, it is equally likely that the subjective uncertainties surrounding the selection of conceptual models and scenarios and their probabilities are also a source of uncertainty in the final estimates of cumulative releases generated by the performance assessment model. These subjective sources of uncertainty are not addressed as completely in the random-sampling procedures as are the physical parameters of the model. Hence, a determination based solely on statistical analysis of the performance assessment model LHS results would not address all uncertainties. Peer review of the conceptual models is essential in assessing compliance. However, statistical methods also may be required to evaluate the uncertainties addressed by the LHS procedures.

8.5.2 Selection of a Statistical Criterion for Compliance

Statistical procedures for evaluating compliance with 40 CFR part 191 are expected to add few costs to the WIPP performance assessment program. Compared to the existing software, the additional resources to develop software to perform the calculations required for evaluating compliance using any of the alternate statistical compliance criteria will be minor.

The use of the upper 90% or 95% confidence limit for the sample mean as a test criterion was introduced in Section 8.3.1. Use of the upper bound of the 95% confidence interval for the sample mean has been suggested (EPA89, NRC92) as an appropriate method for determining compliance with soil clean-up standards at decommissioned sites. The hypothesis test for this alternative is defined by the inequality

$$UCL = M + k\,SE(M) < L$$

where the symbol UCL denotes the upper limit for the confidence interval for the sample mean (M), and the symbol SE(M) denotes the standard error of the sample mean, and L is the appropriate regulatory limit specified in §191.13(a). The multiplier k may be selected appropriately to provide a 90% or 95% confidence level by reference to standard statistical tables on the t-distribution. If the upper confidence limit for the mean is less than the value required limit, a determination of compliance would be made.

The advantages and disadvantages of the upper confidence limit for the sample mean were summarized in row 1 of Table 8-3. The advantages of this criterion are repeated here:

- The mean CCDF yields the true expected value.
- Use of the upper bound for the confidence interval is a standard statistical method.
- Use of the standard error of the mean reflects uncertainty in the estimate of the mean.
- The multiplier k can be adjusted to obtain the desired level of confidence.
- The mean is easy to calculate, even for large samples.

For distributions on positive variables which are skewed toward higher values, the mean will often lie above the median of the distribution. Use of the mean in this case is comparable to using a higher percentile than the median for determining compliance. For highly skewed distributions, the mean may exceed the 90^{th} percentile of the distribution. This results in a test which is protective of the environment by increasing the likelihood of a non-compliance test result. Furthermore, the upper confidence limit for the mean will exceed the mean itself, thus adding to the conservativeness of the test procedure. For small sample sizes, the standard error of the mean will be larger, thus making the test even more protective.

The low robustness of the test also results in a more protective test for compliance. If very high "outliers" occur in the sample values, the estimated value for the mean will be very sensitive to these high sample values. The estimated value for the standard error of the mean may also be inflated by outliers. The increases in the estimate of the mean and its standard error due to outliers tend to make the test more protective. Larger sample sizes would reduce the impact of uncertainty due to the t-distribution assumption for selecting the multiplier k. For smaller sample sizes, the value of k indicated by the t-distribution may provide only an approximation for the proper value of the multiplier to obtain a true 90% or 95% confidence interval for the mean.

It appears that the relatively lower robustness of the probability-weighted mean relative to the median is a fundamental characteristic of the uncertainties of performance assessment rather than a flaw of that statistical method. Outliers which lower the robustness of the statistical test represent valid possibilities for large releases from the disposal system. These outliers are the mathematical representation of the recurring theme that "Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word..."

In 40 CFR part 194, EPA decided that the statistical portion of the determination of compliance with 40 CFR part 191 will be based on the sample mean. The LHS sample sizes should be demonstrated operationally (approximately 300 when 50 variables are considered) to improve (reduce the size of) the confidence interval for the estimated mean. The underlying principle is to show convergence of the mean.

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9. Consideration of Human Intrusion

9.1 INTRODUCTION

The containment requirements (§191.13) of 40 CFR part 191 specify that waste disposal systems must be capable of constraining movement of waste to the accessible environment for 10,000 years. To demonstrate this capability, DOE must show that there is a "reasonable expectation" of not exceeding specified release limits "from all significant events and processes that may affect the disposal system." Significant events and processes include those that are both natural and human-initiated. The final rule, 40 CFR part 194, includes specific requirements on human intrusion. These criteria are based on the assumption that inadvertent and intermittent drilling for resources is the most severe scenario to be considered when addressing human intrusion for performance assessment calculations because it provides a direct intersection with the waste and a pathway to the surface. Mining of resources is a very important, though less direct form of a human-initiated process or event.

Under the provisions of the WIPP LWA, no surface or sub-surface mining or oil or gas production, including slant drilling from outside the boundaries of the sixteen square mile withdrawn area, is permitted with one exception. Directional (slant) drilling is permitted from outside the land withdrawal boundary into oil and gas leases in the extreme southwestern corner of the WIPP site, but only at depths below 6,000 feet. This depth is well below the repository horizon at 2,150 feet. EPA can make a determination after consulting with DOE and the Secretary of the Interior that DOE should acquire these leases to assure compliance with the disposal regulations.

The 40 CFR part 194 rule defines two types of human intrusion which must be considered in addition to mining:

- deep drilling events that reach or penetrate the level of waste in the disposal system
- shallow drilling events that do not reach the level of waste in the disposal system.

A variety of drilling events can be envisioned as occurring in the vicinity of the WIPP site. These include exploration and development drilling for oil and gas, exploration drilling for potash, drilling of water wells, and exploration drilling for other minerals. For example, water well drilling around WIPP is currently limited to geologic strata which lie substantially above the WIPP repository horizon—this would be defined as shallow drilling. Even though the wells are located in strata above the repository, if those strata became contaminated with radioactivity from the repository, water extraction could accelerate movement of radionuclides laterally to the boundary of the accessible environment or could directly transport contaminated water to the land surface which is also defined as part of the accessible environment.

This chapter provides background information related to possible human intrusion by drilling and by underground mining. The regional geology relevant to understanding human intrusion issues is described in more detail in the following section. Subsequent sections discuss specific drilling and mining issues.

9.2 GEOLOGIC SETTING

Understanding the regional geology is an essential step in developing a defensible description of human intrusion which might impact the WIPP repository. The WIPP is located in the northern part of the Delaware Basin, which is a large sedimentary basin in Southeastern New Mexico and West Texas. This deep oval-shaped structural depression, which is about 135 miles long and 75 miles wide (COO71), was an embayment covered by a deep sea (i.e., 305 to 245 million years before present [Ma]). Sedimentation within the basin resulted in formation of thick marine strata. Organic activity at the margins of the basin produced carbonate reefs -- the present day Capitan Reef -- that separated the deep-water sediments from the shallow-water shelf deposits which developed landward from the reefs (SAN92). The depositional process, as described by Cooper and Glanzman (COO71), is summarized as follows:

> The irregular floor of the sea was characterized by structural basins, platforms and broad shelves. Fine sand and limestone accumulated in the basins; reefs formed on the margins of the shelves and platforms; limestone and sand accumulated immediately behind the landward side of the reefs; and gypsum, anhydrite, and other evaporite rocks, and silt and clay accumulated in the shallow waters of the shelves. Eventually, the reef growth was halted by increasing the salinity of the sea water and evaporite sediments (Castile, Salado, and Rustler Formations) were deposited in the Delaware Basin. Evaporite deposition was interrupted during two intervals of time, during

> which the water was less saline and limestone was deposited. Toward the end of Permian time, deposition of the evaporite rocks ceased and deposition of terrestrial red beds (Dewey Lake Redbeds) began. Terrestrial deposition continued during parts of Triassic time. Additional thin deposits of sediments accumulated in Quaternary time. A total of 18,500 feet of sedimentary rocks were deposited in places in the Delaware Basin.

The region surrounding the WIPP may be characterized in terms of the geologic composition of the sub-surface features, the hydrologic properties and the history of hydrocarbon (i.e. oil and natural gas) accumulation. The horse-shoe shaped Capitan Reef was formed by the deposition of organic material which differs from the non-organic material which developed into the evaporite salt formations which lie along the interior. King noted this distinction when concluding that the Capitan Reef was separate from the Delaware Basin.

> The rocks of the Guadalupe Mountain region were deposited near the edge of a feature of Permian time known as the Delaware Basin, along whose margin they show complex changes in facies. The rocks laid down outside the basin, in what is here termed the shelf area, are thus very different from contemporaneous basin deposits. (KIN42)

The "complex changes in facies" referred to by King result from the geologic dissimilarities of the carbonate Capitan Reef from its contemporary, the evaporite Bell Canyon formation which adjoins the Capitan Reef on the interior side. (The WIPP is located within the Salado Formation, which is a sequence of evaporite rocks deposited in the Late Permian Epoch (258-245 Ma). A portion of the stratigraphic column that represents this depositional sequence is shown in Figure 9-1 (WEI77).) The Guadalupe Mountains or shelf area, noted by King, in fact contain a portion of the Capitan Reef. Other authors, including Cooper and Glanzman, quoted earlier, have remarked as well upon this distinction: "This structural [Delaware] basin is generally considered to be the area surrounded by the Capitan Limestone [i.e. the Capitan Reef]."

Subsequent to its formation, the hydrologic properties of the Capitan Reef were enhanced by fracturing and dissolution such that the effective porosity of the Capitan Reef increased. Partially as a result of this, the Capitan Reef is today a significant aquifer in the region and is a major source of water for the City of Carlsbad. In contrast, the salt formation which

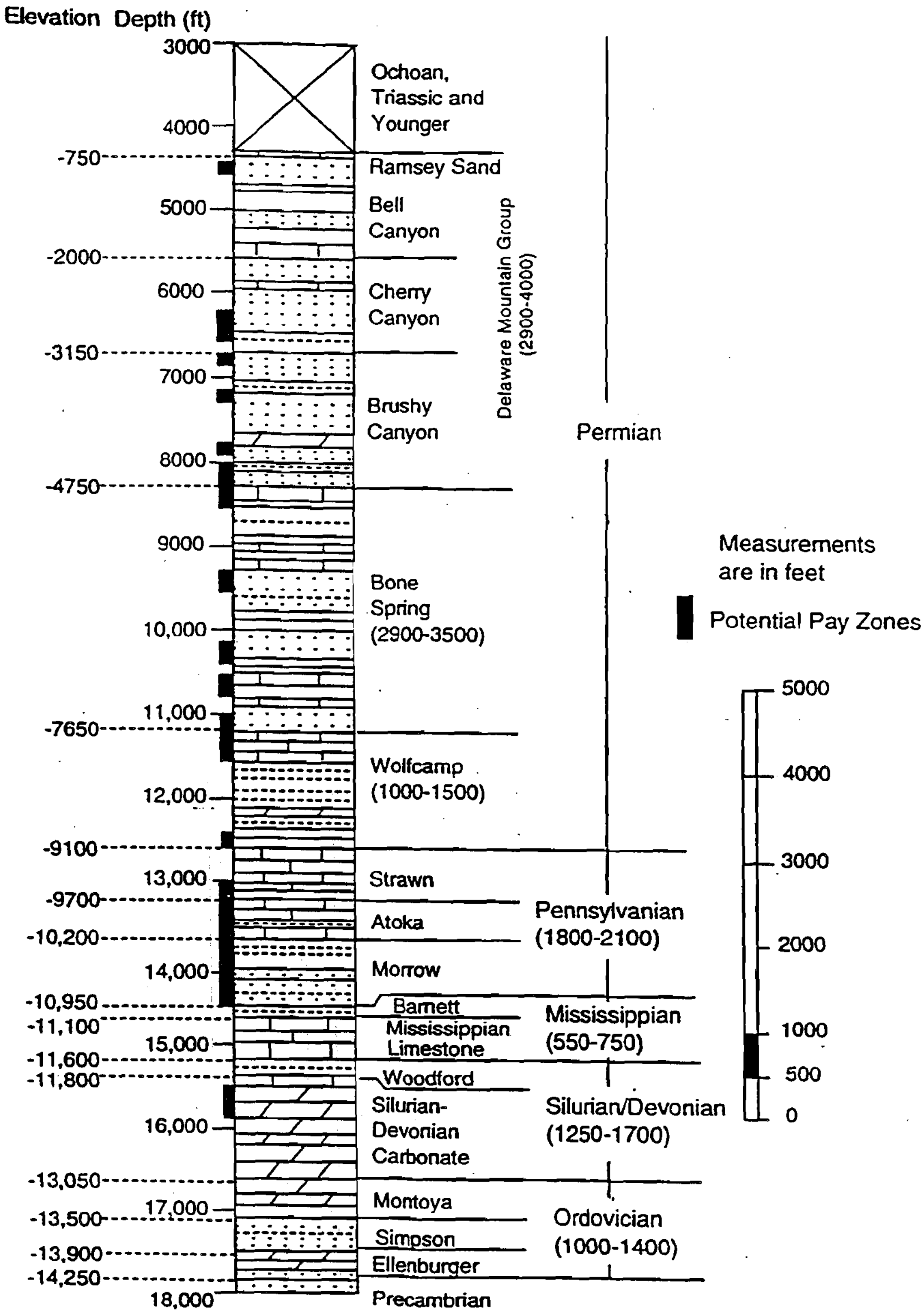

Figure 9-1. Stratigraphic Column and Potential Hydrocarbon Pay Zones (Source: POW78)

contains the WIPP, known as the Salado, has a small primary porosity combined with a lack of transmissive fractures, and thus groundwater flow through the Salado is not significant. The interior regions as a whole are noteworthy for the relative scarcity of potable groundwater.

Over the geologic history of the Delaware Basin, oil and natural gas have accumulated underneath the Capitan Reef. Although formed in the interior portions from organic material, the hydrocarbons preferentially migrated outward until being trapped by the cap-like profile of the underside of the Capitan Reef. Organic material which generates hydrocarbons did, in fact, exist in the interior portions and was deposited during the middle and late Permian era, but as Hills describes (HIL84), the ultimate fate of the hydrocarbons lay elsewhere: "The hydrocarbons contained in the source beds [in the regions within the Capitan Reef] migrated primarily to interbedded sandstone reservoirs within the [Delaware] basin and later to the porous carbonate reservoirs on the margins." This "trapping mechanism" possessed by the Capitan Reef does not have a parallel in the interior portions, such as the Salado and Bell Canyon formations. Hills described this difference: "no large Upper Permian structural traps were formed in the [Delaware] basin, and most hydrocarbons migrated to the surrounding shelves [i.e. the Capitan Reef]."

Various estimates of the area of the Delaware Basin have been cited by different authors. In most cases, neither the basis for the estimate nor whether the cited area includes or excludes the Capitan Reef is mentioned. For example, Hills (HIL84) said the area is about 13,000 square miles (33,500 km^2) while Richey et al. mention that the area (which presumably includes the Capitan Reef) is about 12,000 square miles (31,000 km^2). This same area is cited without attribution by Powers et al. (POW78; v. 1, pp. 3-59). An earlier site selection report had noted that "the area of the Delaware Basin was assumed to be about 30,000 km^2 (CLA74). These differences are not surprising since the boundaries of the Basin mostly lie below the surface and the estimates were intended for descriptive purposes rather than quantitative analysis.

To obtain better quantitative values for the Basin area, the area on several maps was measured using standard software designed for operation with geographic information systems. The areas of the Delaware Basin as depicted in Figure 1 in HIL84, in Figure 3.4-1 of POW78, and Figure 6.3-8 of POW78 were calculated with results as follows:

- HIL84, Figure 1 — 28,000 km^2
- POW78, Figure 3.4-1 — 30,200 km^2
- POW78, Figure 6.3-8 — 25,200 km^2

POW78, Figure 6.3-8 indicates more detailed mapping of the basin boundary and the surrounding Capitan Reef. Various versions of this figure are widely used in the technical publications prepared by Sandia National Laboratories for the WIPP project. This representation of the Delaware Basin embracing 25,200 km^2 is reproduced in Figure 2-2 and is appropriate for estimating intrusion rates.

9.3 INTRUSION BY DRILLING

9.3.1 Oil and Gas Drilling

Drilling for oil and gas has been conducted in the Delaware Basin since the turn of the century. Over the past decade, drilling for oil and gas in the vicinity of the WIPP site has increased significantly (SIL94). Typical oil drilling targets within the Delaware Basin around the WIPP site include Permian age rocks such as the Cherry Canyon and Brushy Canyon Members of the Delaware Mountain Group and the Bone Springs Formation. The tops of these geologic formations lie about 5,700 feet and 8,300 feet below the land surface (GUZ91a). These formations were not generally recognized as exploration and development targets until the late 1980s because their reservoir production characteristics were not well understood (NBM95). However, recent improvements in borehole logging procedures have allowed petroleum geologists to determine which Delaware Mountain Group sediments have a high potential for fluid hydrocarbons.

Gas drilling targets reside in the Pennsylvanian age Strawn, Atoka, and Morrow formations at depths of about 12,700 feet, 13,200 feet, and 13,700 feet below the surface, respectively. All current oil and gas targets are below the WIPP repository horizon and would be defined as deep drilling under 40 CFR part 194.

Data on oil and gas drilling are available from a variety of sources. In New Mexico, the U.S. Bureau of Land Management and State of New Mexico Oil Conservation Division keep records on wells that have been issued permits. In Texas, this information resides with the Texas Railroad Commission. Borehole information is also obtainable from commercial data

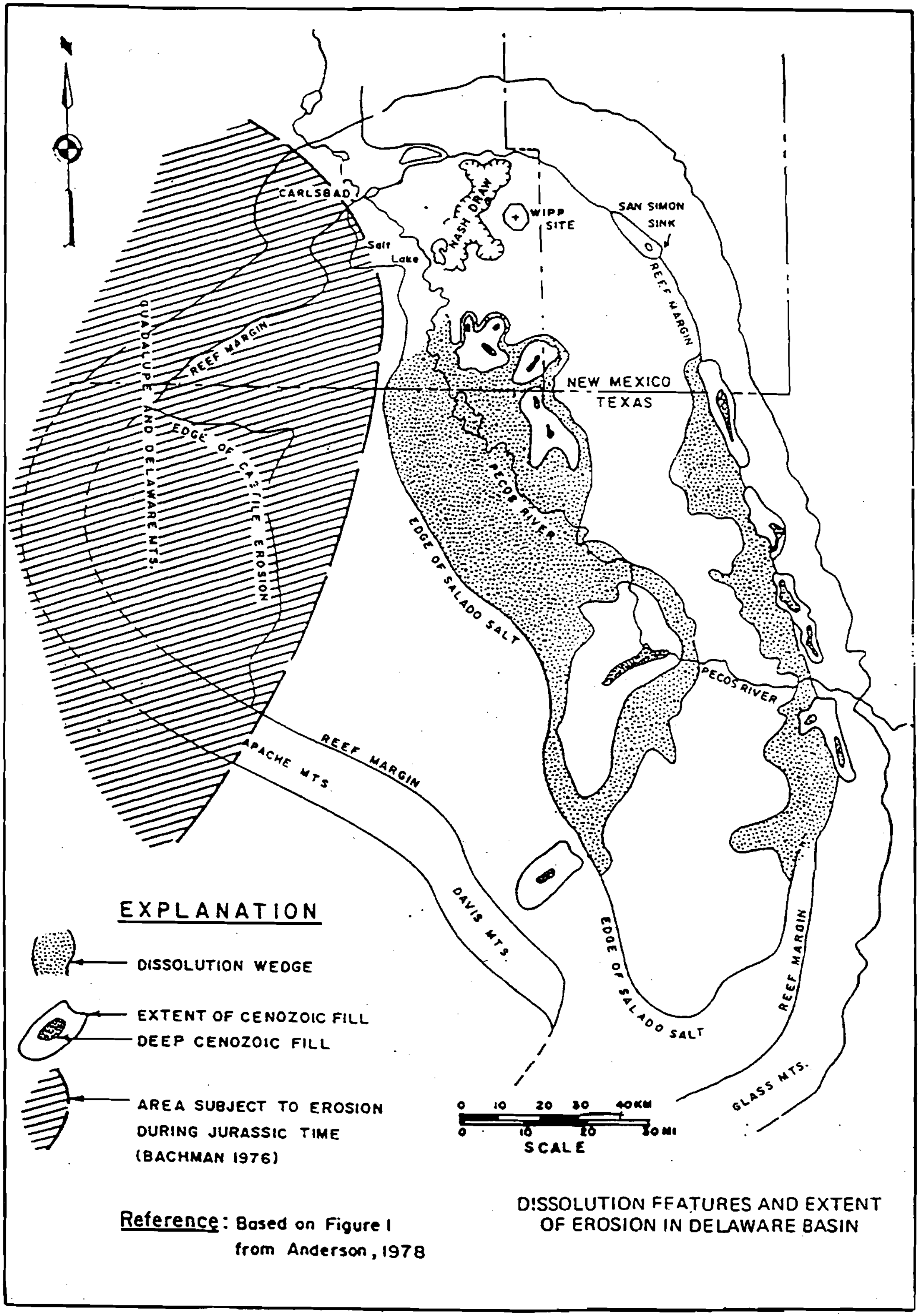

Figure 9-2. Outline of the Delaware Basin (Source: POW78, Figure 6.3-8)

bases such as that managed by the Petroleum Information (PI) Corporation in Denver, Colorado. The earliest Delaware Basin information in the PI data base indicates that five holes were drilled between 1909 and 1914. Four of these holes were in Texas and one was in New Mexico.

9.3.1.1 Permitting Practices

In order to conduct oil and gas drilling, a permit must be obtained either from the U.S. Department of the Interior, Bureau of Land Management (BLM)—if Federal lands are involved—or the Oil Conservation Division (OCD) of the State of New Mexico Energy, Minerals, and Natural Resources Department—if state or private lands are involved. Drilling activity on Federal lands is regulated under 40 CFR part 3160 (Onshore Oil and Gas Operations; Federal and Indian Oil and Gas Lease: Drilling Operations: Final Rule, November 18, 1988). The regulation prescribes minimum levels of performance and enforcement action when rules are violated. Procedural requirements are not included. OCD Rules and Regulations are more specific than those of 40 CFR part 3160 and BLM often follows specific OCD practices. Many detailed procedures—including well casing practices, well completion, and methods of borehole sealing—requiring BLM or OCD approval are area specific, not included in regulations, and not always in writing.

OCD Rule 104 specifies the maximum density for oil and gas wells. Wildcat (i.e., exploration) gas wells in Eddy and Lea Counties of New Mexico are granted a minimum spacing of 160 acres for drilling depths of less than 11,000 feet, or 320 acres if drilled to greater than 11,000 feet. Development (i.e., production) gas wells are also limited to one per 160 or 320 acre tract.

The minimum spacing for wildcat and development oil wells in these two counties is 40 acres. There is also a limit of four development wells per tract when special pool rules apply. However, more wells are allowed if the tract is permitted for active secondary recovery. In each case, oil and gas wells must also conform to boundary offset distances, placing each well within a specified area within a tract. In the absence of secondary recovery operations or special pool rules, the spacing requirements thus allow up to 6.2 oil wells/km^2 or up to 1.5 gas wells/km^2 for each potentially productive formation. BLM follows OCD well spacing rules although they are not legally required to do so. BLM also requires an environmental assessment before a permit is granted.

9.3.1.2 Well Drilling and Casing

After the permit is granted, the drilling contractor will set up equipment at the drill site. For deep holes drilled around WIPP, about 7-10 days are typically required to prepare the site, set up the drill rig, construct the mud pits, and set the surface conductor casing to secure surface sediments before drilling commences.

The drilling of a gas or oil well usually requires a program involving two or more bit sizes to complete a borehole and one to four bit changes per borehole (BER94) to change worn or damaged drill bits. A typical gas or oil well starts with a large diameter hole at the surface into which a conductor pipe is placed. A smaller size drill bit which can pass through the conductor is used to drill a hole to accommodate the surface casing, through which a still smaller bit passes to drill for the production casing. Should bottom hole conditions warrant, a liner may be inserted in the lower portion of the production casing. The bottom hole is usually a minimum of 2 to 3 inches in diameter and telescopes outward to the larger diameters required to accommodate uphole conditions.

The OCD has specified for the past decade or more that all gas and oil wells on New Mexico state and private lands (with minor exceptions) be drilled in the $17^{1/2}$, $12^{1/4}$, and $7^{7/8}$-inch diameter size sequence. As each step in the drilling sequence is completed, the drill string is removed from the borehole and the hole is lined with tubular steel casing which is set in place with cement. The larger diameter surface casing is set from the surface to the top of the Rustler Formation at a depth of about 500-600 feet. The next drilling sequence is initiated which involves penetration of the salt section (the Salado and Castile formations). When the hole reaches the bottom of the Castile at a depth of about 4,000 feet, the drill string is again removed from the borehole and the intermediate casing is set. After the intermediate casing is set, drilling is reinitiated and continues until the target horizon, for example, the Cherry Canyon Formation of Delaware Mountain Group, is reached and the production casing is then set. This size sequence appears also to be the current common practice for drilling on Federal lands administered by the BLM.

OCD records indicate that a two casing program was used during the 1970s and earlier, in which smaller bits and casings were common. A frequent practice in a two-casing run was to combine the surface and intermediate casing intervals into one extending from the surface to a depth of 2,000 to 4,000 feet above the production zone before a smaller bit was used.

A drilling sequence of $10^{3/4}$ or $12^{1/4}$-inch bit followed by a $7^{7/8}$-inch bit was most common for this practice, though no count has been made as to the number of such wells. Gas wells have been completed at depths ranging from 10,000 to 16,000 feet deep and oil wells have been completed at 5,200 to 8,200 feet deep. Drilling and completion of the well typically take about 100 days. Virtually all gas and oil wells in the area are drilled to depths which would penetrate the WIPP horizon.

OCD Rule 107 imposes a number of requirements concerning casing, tubing, cementing, etc., for wells being drilled and completed. Section III8 of 43 CFR part 3160 establishes similar requirements for Federal lands. However, in all cases the detailed procedures for specific locations are not in the regulations and are specified by the appropriate District Offices. OCD states that they inspect 100% of new wells being drilled, cased, and completed. BLM inspects wells under its jurisdiction on a random, less than 100%, basis.

If the WIPP site were to be penetrated by inadvertent human intrusion, such an event would occur during drilling through the salt section before the intermediate casing is set. Once the intermediate casing is set in place and the annulus between the casing and the borehole wall is sealed with cement, then the possibility of radionuclide contamination reaching the surface will be prevented as long as the casing remains intact. Typically, casing integrity is demonstrated by pressure testing and ultrasonic logging of the cemented section for bonding between the casing and the cement and between the cement and the formation. It is estimated that this critical section of a borehole would remain uncased for no more than three days during drilling. While there is no solid data base which describes the frequency of occurrence of improperly cased holes or holes with casing failures, such failures have been reported (KIR94).

9.3.1.3 Detection of the Repository During Drilling

A key question when developing the possible range of human intrusion rates to which the WIPP repository might be subjected, is whether the drilling contractor is likely to detect the presence of the WIPP repository during drilling for oil or gas. The drilling operator could penetrate the WIPP and not realize he had done so. Assuming his drill hole was successful and the anticipated oil pool or gas reservoir was reached, he might drill additional development wells to exploit the resource. These additional holes might also penetrate the waste and be undetected.

Because of the nature of drilling practices employed in the Delaware Basin, the existence of the WIPP may not be revealed by a borehole which intersects the repository. Drilling is typically done by independent drilling contractors whose main goal is to "make hole" and efficiently meet the contract requirements. Drilling through the salt section is typically at a rate of 50 to 100 feet per hour, so only about 8 to 15 minutes would be required to penetrate the repository (based on room height prior to creep collapse of the repository). J. W. Berglund of the New Mexico Engineering Research Institute states, "While in the salt section, drilling mud (brine) is supplied from a large, plastic lined reserve pit dug in the ground with a surface area of about 4,000 ft^2. Drilling mud is pumped from the reserve pit down through the drill pipe and drill bit and up the annulus formed by the drill string and drilled hole. The drilling mud and the drill cuttings are returned directly to the reserve pit where the cuttings settle out. While drilling in the salt section, no formal attempt is made to monitor the character of the cuttings or the fluid volume of the reserve pit. A gas analyzer is not attached to the returns until the hole is much deeper than the depth of the WIPP repository" (BER95).

Even if gas flows were generated when the drill bit intersected the WIPP, this event would more likely be interpreted as a release from naturally occurring gas pockets. If the drill bit encountered brine from the WIPP, this too might be interpreted as a naturally occurring phenomenon. Naturally occurring gas and brine pockets are commonly found in the sedimentary rocks above and below the WIPP horizon in the Delaware Basin. Brine pockets are encountered during drilling of deep boreholes into the Castile Formation below the repository, and to a lesser extent into the Salado Formation above the WIPP horizon. For example, records available at the OCD office in Artesia, NM, reveal that a brine flow blowout (back pressure in the drill stream sufficient to cause actuation of over-pressure relief valves to protect piping from damage) occurred for a recently drilled well (API no. 30-015-27406) (S2, T18S, R30E) at a depth of 898 feet below the surface which is a few feet into the McNutt potash zone of the Salado Formation. Drilling was temporarily halted for four hours during which the flow rate was estimated at 40 to 50 barrels per minute (1,680 to 2,100 gpm). The hole was shut in and allowed to pressurize to 350 psi. Drilling of the $12^{1/4}$-inch diameter hole resumed to a depth of 1,555 feet. Casing was set and cemented. As the brine inflow was similar in characteristics to the brine water drilling fluid being used, no apparent effect was seen except for the break in drilling.

Gas kicks (blowouts) also occur in the Salado Formation in which the WIPP is located. When these are encountered, drillers routinely let the drilling mud blow from the hole—this appears as a cut brine solution when drilling through the salt section—with no effort to retard the blowouts by closing blow-out preventers on the drill rigs. These kicks are of short duration and when completed, drillers restart mud circulation and adjust the drilling mud to the desired weight. Presence of these small pockets of water or nitrogen has been detected both by mining and drilling (COO71). The largest cavity found through 1971 was about 176 m^3 and was not pressurized—at least when discovered by mining (CLA74). There are at least seven reported incidents of pressurized gas blowouts in potash mines. Two of these resulted in fatalities (CHA84).

Brine inflows from Castile Formation brine reservoirs are well documented for two wells—ERDA-6 (S35, T21S, R32E) and WIPP-12 (S17, T22S, R32E)—in which the initial inflow was 20 gallons per minute (gpm) and 350 gpm, respectively. The brine reservoirs were estimated at 26.5 million gallons total for ERDA-6, with 69,000 gallons flowing to the surface during testing, and 714 million gallons total for WIPP-12, with 3.3 million gallons to the surface (POP83). Although historic information is vague and incomplete, similar-sized brine reservoirs were observed in: 1) Mascho-1 (S20, T22S, R33E) drilled in 1937 which had a reported initial flow of 230 gpm, 2) Belco (S25, T23S, R30E) drilled in 1974 with an initial inflow of 350 gpm while flowing for 26 hours, and 3) Shell (S36, T22S, R32E) drilled in 1964 with an initial inflow of 580 gpm. Brief commentary on these wells (POP83) describes stopping of drilling operations until artesian flow is completed, followed by a resumption in drilling. Recent interviews with drillers substantiated this practice. Brine pocket blowouts are like gas kicks, in that they cause no problems beyond drilling breaks. In one well, Pogo (S26, T21S, R31E), a moderate weight drilling mud (15 pounds per gallon - ppg) was applied after four days of flow. Whether the flow was really stopped by this weight of mud or whether the reservoir pressure was exhausted is unknown. A similar weighted mud of 12 ppg did not stop the inflow at another well drilled in 1962.

9.3.1.4 Borehole Plugging and Abandonment

When a borehole is no longer useful it must be plugged and abandoned according to specified procedures. One mechanism identified for releasing wastes from the WIPP repository is the escape of waste-generated gas or contaminated brine through an unsealed or improperly sealed borehole. In some scenarios used to assess the performance of the WIPP, boreholes, plugs, or seals are assumed to remain intact for the full regulatory period, and in some cases the seals are assumed to degrade. Effectiveness of borehole seals is important to maintaining the integrity of the WIPP repository. Borehole permeability was identified in the 1992 WIPP PA as one of two critically important parameters (SAN92).

The New Mexico OCD Rules and Regulations (OCD93) pertaining to sealing off geologic strata and notification are covered in Rule 106, which requires protection of oil- and gas-producing strata from each other and from overlying water strata. Also, "All fresh waters and waters of present or probable value for domestic, commercial or stock purposes shall be confined to their respective strata and shall be adequately protected by methods approved by the Division." OCD Rule 202 (Plugging and Permanent Abandonment) requires prevention of the contamination of fresh waters. The Rules and Regulations define fresh water as less than 10,000 mg/l total dissolved solids (TDS). An underground source of drinking water is defined as an aquifer having less than 10,000 mg/l TDS and containing a sufficient quantity of water to supply a public water system, unless it has been exempted. The Federal regulations also require protection of usable water which means generally those waters containing up to 10,000 ppm of total dissolved solids.

OCD Rule 101 requires a surety bond, payable to the State of New Mexico, before new wells can be drilled. The purpose of this bond is to pay for the proper plugging, sealing, and abandonment of the well if the owner is financially unable to do so in the future. In Eddy and Lea County, the amount of this bond varies from $5,000 to $10,000 per well, depending on well depth. Alternatively, a blanket plugging bond of $50,000 can be obtained to cover all wells drilled by an operator. The BLM also has bonding requirements for new wells, although the adequacy of this program has been questioned by the Department's Inspector General (DOI92). Large numbers of older wells on both Federal and non-Federal lands do not have adequate plugging bonds, and the State and Federal Government's financial obligation to seal and abandon these wells properly may be significant.

OCD Rule 201 requires a well be either properly plugged and abandoned or temporarily abandoned within 90 days after: (1) a 60-day period following suspension of drilling operations, (2) a determination that a well is no longer usable for beneficial purpose, or (3) a period of one year in which a well has been continuously inactive. Despite these requirements, the current status of a large number of wells under OCD regulations is unknown (OCD94). Audits by DOI Office of Inspector General reveal a significant unknown well status problem also exists on BLM lands (DOI89, DOI92).

OCD Rule 202 requires written notice on Form C-103 at least 24 hours in advance of commencing any plugging operations. Verbal approval of the method of plugging and time to begin is permissible for a newly drilled dry hole. The well operator is required to notify the OCD after plugging and site clean-up operations for an inspection of the well and location. However, the operator has up to one year after completion of plugging operations to complete the site clean-up. The Federal Abandonment Requirements, contained in 43 CFR part 3160 III G, specify details of cementing, plugging, and capping boreholes, but do not identify any procedural requirements. Field interviews suggest that 100% of all holes under OCD aegis are inspected, and less than 100% of holes drilled under BLM aegis are inspected for compliance with plugging regulations.

OCD Rule 203 describes conditions under which a well may be temporarily (rather than permanently) abandoned. Temporary abandonment can be for a period of up to 5 years and the operator can apply for renewal at the end of this period. In seeking renewal, the operator is required to test the integrity of the casing with a specified procedure and provide evidence that there will not be migration of water or hydrocarbons between strata.

BLM proposed procedures for reviewing the status of non-producing wells following findings in a 1989 Inspector General Audit Report (DOI89) that large numbers of wells had been inactive for years without meeting BLM's procedures or requirements for temporary abandonment. The 1992 follow up audit report did not consider implementation of these procedures to be adequate. After the 1989 audit, BLM had proposed procedures for reviewing the status of non-producing wells. These proposed procedures would require that BLM field offices review the status of non-producing wells listed monthly and determine whether each well was usable for further oil and gas production. The procedures would also require that the field offices request the operators to either submit a justification for shut-in status, obtain temporary abandonment approval, plug and abandon the well, or resume production. If implemented, the Inspector General felt that its 1989 recommendation would be satisfied (DOI92). However, the Inspector General advised the Secretary of the Interior on March 20, 1992 that BLM did not agree with the Inspector General's recommendation to devote resources and management oversight to improve the Inspection and Enforcement Program.

Gas and oil wells are usually plugged in two ways. Plugs are either placed inside the production casing or inside the intermediate casing when the upper portion of the production casing is removed. In either situation, plugging is performed within a cased hole. As noted previously, in gas and oil wells in the Delaware Basin, surface casing extends from the surface to the bottom of the Rustler Formation and is cemented in place, thereby rendering it permanently fixed. The intermediate casing which is placed inside the surface casing extends from the surface through the salt section and terminates at the bottom of the Castile Formation (a depth of approximately 3,600 feet at the WIPP). This intermediate casing is cemented from bottom to surface and is likewise permanently fixed in place. The production casing which extends from the surface to the Delaware Mountain Group strata for oil or deeper to the Morrow or Strawn Formations for gas may either be cemented inside the intermediate casing from bottom at 6,000 to 8,000 feet deep to the surface, or it may only be cemented for the lower 3,900 feet, thereby allowing the removal of several thousand feet of the inner casing string when the well is abandoned. At least one, and sometimes two, cement-shrouded casing strings separate the WIPP horizon rock from the open hole. A four-part casing is unlikely in the vicinity of the WIPP since four casing strings extending from the surface are required by the OCD only over the Capitan Reef. For deep gas wells incorporating a liner, the fourth inner string is hung from the lower portion of the production casing and does not extend into the intermediate casing.

All downhole tools and fluids are removed from a typical gas and oil well prior to abandonment. A class "C" type cement plug is placed at intervals throughout the hole starting at the guide shoe of the inner casing string (usually the production casing) which has not been drilled out but was previously cemented in place when the inner casing string was set. The inner casing is usually set to the bottom or below the producing zone and perforations are made in the casing for a length of up to 100 feet above the guide shoe. Plugs are placed at the top of each producing formation followed by intermediate plugs, plugs at the bottom and top of the salt section, and a surface plug. Each plug is about 35 feet thick and is placed at intervals no greater than 2,000 feet as specified by OCD. Drilling fluid is placed between each plug.

The position of each plug is carefully monitored because the plug can slip before it sets. Cement plugs are more dense than the fluid upon which they rest and can possibly move or disintegrate into the fluid before hardening. An OCD field representative certifies the placement of each plug for holes on state and private lands before the next interval of fluid is placed.

Field investigations failed to uncover any long-term monitoring of borehole seal integrity. Neither the BLM nor OCD conducts follow-up studies after borehole seals have been installed. The American Petroleum Institute, recognizing that "an unknown but large number of abandoned wells exist that are unplugged or inadequately plugged by today's standards," conducted an analysis of whether abandoned wells could act as conduits to move saline water from deep underground to more shallow-lying underground drinking water sources (WAR90). The studies focused on brine flow from the Lower Tuscaloosa Sand, a mature oil-producing trend in Mississippi and Louisiana at a depth of about 10,500 feet, to the Sparta sands and shales, the drinking water source which bottoms at about 3,100 feet. A nearby injection well in the Lower Tuscaloosa was assumed to provide the driving force for flow in the abandoned well. Two scenarios were examined, viz.:

- Uncased well scenario — The upper 1,500 feet of the well are cased and cemented, but the balance of the borehole remains open. In time, overlying shale sloughs into the hole to form a 154.5 foot column of shale with a porosity of 3% and a permeability of 0.0001 Darcy. Above this is a 4,620 foot column of settled solids from the drilling mud having a porosity of 84% and a permeability of 0.001 Darcy.

- Cased well scenario — The well is cased from top to bottom and the lower 2,000 foot production casing is cemented. The annulus between the balance of the casing and the borehole is left filled with drilling mud. It is assumed that a corroded interval develops in the casing at a depth of 6,000 feet.

The two scenarios modeled using the SWIFT III computer code indicated that—over the range of injection rates considered (20 to 600 barrels per day)—there was no flow into the underground drinking water source. Thus, for the conditions examined, unplugged or poorly plugged boreholes were not a problem. One should also note that the permeabilities used in the API study are about four orders of magnitude lower than used by SNL in the 1992 WIPP PA (SAN92, Volume 3).

Currently, all dry holes from gas and oil exploration are plugged per federal and state standards. Producing wells are not monitored, nor are abandoned formerly-producing wells certified as plugged. Whereas OCD conducts an active program of institutional control for all new wells on state and private lands, BLM performs only random and infrequent checks on new wells located on Federal land. The number of unplugged boreholes drilled prior to the more stringent institutional controls now employed is unknown, but has been characterized as "many" by OCD field personnel.

The 40 CFR part 194 rule assumes that natural processes will degrade or otherwise affect the permeability of boreholes over the regulatory time frame. The issue of unsealed or improperly sealed boreholes must also be factored into analysis of the repository integrity.

9.3.1.5 Human Intrusion Scenarios

In addition to the radioactivity release scenarios involving direct transfer of waste to the surface by a borehole which penetrates the repository, several other scenarios involving human intrusion can be theorized. For example, SNL developed a family of scenarios involving boreholes which penetrate the waste and are then plugged above the overlying transmissive Culebra Member of the Rustler Formation. Solubilized waste then moves up the borehole by brines found in underlying formations and then, due to the borehole seal, laterally through the relatively transmissive Culebra toward the WIPP site boundary (SAN92). The assumption of borehole sealing depth is consistent with the sealing practices in the area and the regulatory requirements. The assumption is also reasonably analogous to the other geologic systems that were analyzed so that DOE should be able to defend the above scenario.

Conceivably some boreholes would miss the waste, but be drilled sufficiently near the disposal region to encounter contaminated brine and rock in, for example, Marker Bed 139, a brittle, fractured anhydrite layer, which immediately underlies the repository.

9.3.2 Exploratory Drilling for Potash

Potash is the generic name for various potassium salts often formed by the evaporation of natural brines whose potassium content is normally expressed in terms of equivalent K_2O. Additional background information on potash mining is included in Sections 9.4.1.

The potash reserves and resources[1] at WIPP lie within the McNutt potash zone of the Salado Formation. The depth of the 11 identified ore zones in the McNutt, based on the ERDA-9 borehole, ranges from about 1,372 feet to 1,741 feet near the WIPP site (POW78) and the McNutt dips generally to the east (CHE78). As noted above, the WIPP repository is located

[1] According to GUZ91b, reserves are those resources that are currently economically recoverable with currently available technology, and resources are mineral deposits that are not currently economical or have not been discovered.

in the Salado at a depth of 2,150 feet. The deepest potash resources are thus about 400 feet above the waste repository. These ore zones vary widely in thickness and mineralization. The zones are not continuous across the Delaware Basin, and certain ore zones are not present in some of the boreholes evaluated. Even when mineralization is present in an ore zone, it may not be sufficient to be of commercial interest. In some cases, mineralization is absent altogether.

The potash resources of the Designated Potash Area (so designated by the Secretary of the Interior, see 9.4.1) lie roughly in an alignment extending from northwest to southeast. Early potash mining started along the northern and western fringe of the district and moved in southerly and easterly directions into the Delaware Basin. Exploratory boreholes have preceded the underground workings, thereby delineating the reserves for further exploitation. Potash boreholes tend to cluster around these mines with occasional boreholes located far-afield.

Exploration drilling is conducted in the area to delineate additional ore reserves. Since this drilling is generally to depths of less than 2,150 feet (except to the east where the ore zones dip downward), this event would be characterized as shallow drilling by 40 CFR part 194. Drilling for potash is significantly different from drilling for oil and gas. In addition to being more shallow, the holes are also smaller in diameter. Approximately 1,892 potash coreholes have been drilled in the Delaware Basin (per BLM estimate), mostly within the designated boundary of the Known Potash Leasing Area. Potash boreholes typically have been drilled either into an undesignated competent stratum of the upper Salado Formation or into the Vaca Triste Sandstone member, which forms the upper contact with the McNutt. The size distribution for all holes examined can be grouped into Rustler Formation drill bit sizes of $5^{1/2}$ inches to $8^{3/4}$ inches in diameter and Salado Formation core bit sizes of $3^{1/2}$ inches to $5^{3/16}$ inches in diameter. After a surface casing is set through the Rustler Formation—sometimes extending into the upper Salado Formation—core bits are used to drill through eleven ore zones in the McNutt potash zone. The cored section of the hole is not cased. The bit size distribution is as follows:

Bit Diameter Distribution

Rock Bit Dia.:	$8^{3/4''}$	$8''$	$7^{7/8''}$	$6^{11/16''}$	$6^{1/2''}$	$6^{1/4''}$	$5^{5/8''}$	$5^{1/2''}$
Percentage:	6%	2%	8%	2%	6%	57%	17%	2%

Core Bit Dia.:	$5^{3/16''}$	$4^{3/4''}$	$3^{15/16''}$	$3^{7/8''}$	$3^{1/2''}$
Percentage:	1%	3%	12%	54%	30%

Most of the potash holes are terminated at or near the lower contact of the McNutt. Three test holes drilled by the U.S. Geological Survey (USGS) were about 2,000 feet deep (JON78) near the WIPP site. Holes as deep as 2,800 feet have been logged in contiguous townships.

Based on discussions with BLM personnel, potash drilling has occurred over a period of about 70 years. (This is consistent with the fact that the U.S. Bureau of Mines (SEA94) has reported saleable potash production from New Mexico since 1933 and records ore grades as early as 1930.)

BLM has a permitting procedure similar to oil and gas for exploratory potash coreholes on Federal lands. The State Engineer requires approval for drilling of potash coreholes on non-Federal lands if the drilling is through artesian aquifers or other water zones that require protection. This requirement may not affect all locations around the WIPP site since the Rustler Formation is not considered artesian.

Under a scenario that includes drilling for potash, all potash boreholes would pass through the Culebra Member of the Rustler Formation. If a borehole contacted a contaminated plume of Culebra water resulting from a prior human intrusion into the repository, it would bring at least as much contaminated fluid to the surface as was in the volume of the Culebra rock intercepted by the borehole. Furthermore, any radionuclides adsorbed on the solid material would also be brought to the surface. For a 7.0 m thick Culebra aquifer with 0.16 porosity, a 6 inch (15 cm) borehole would bring a bulk volume of 0.128 m^3 to the surface. This volume would contain 0.021 m^3 of fluid. Assuming solubilities of 10^{-6} M for plutonium and americium and 10^{-4} M for uranium results in a concentration of about 0.9 Ci/m^3.

Considerably greater quantities of radionuclides could be present in the solid material brought to the surface if surface adsorption in the Culebra is considered. The concentration (C_s) of an element (e.g., Pu, Am, U) in the solids can be shown to be:

$$C_s(g/cm^3) = r_s(g/cm^3)*Kd(cm^3/g)*C_{brine}(g/cm^3)$$

where r_s is bulk density of the solids (about 2.0 g/cm^3) and Kd is the solute distribution coefficient.

In the 1992 PA (SAN92), SNL sampled on a matrix Kd value for plutonium from zero to 100,000 cm^3/g with a median value of 261 cm^3/g. Thus, for the median Kd value the concentration of plutonium in a cubic centimeter of rock is 522 times that in a cubic centimeter of fluid. Since there is only 0.16 as much fluid volume as rock volume in the Culebra (i.e., the porosity is = 0.16), there would be 3,262 times the plutonium in the rock phase as in the liquid phase, resulting in a 59 Ci release to the surface.

If a potash corehole was not properly plugged and were to become a conduit for surface water inflow, it could become a significant source of recharge to the Culebra. If located upgradient from the repository, this recharge could increase the gradient which would shorten water flow time to the accessible environment. Also, the larger water flow rates could increase the quantity of radionuclides being transported if Culebra solubility is limiting or it could decrease the amount being adsorbed in the solid matrix if the larger flow decreases the radionuclide concentration. If the borehole is located down gradient from the repository, recharge might be beneficial because it would decrease the gradient between the repository and the recharge point. However, this inflow of fresher water would increase the gradient between that point and the accessible environment and could also desorb previously adsorbed radionuclides.

9.3.3 Water Well Drilling

Only limited water well drilling occurs around the WIPP site, since most of the water in the area is too high in solids content to be suitable for drinking. Water wells may be used to support oil and gas drilling, mining operations, or stock watering. An application to drill a water well within the boundaries of a declared underground water basin, such as the Carlsbad Underground Water Basin, must be made to the State Engineer. The State Engineer requires a prospective water well driller to publish his application weekly for three weeks in a local newspaper before a permit will be granted.

Based on information obtained from the New Mexico State Engineer's Roswell District Office and various groundwater reports (HEN51, NIC61), the following observations can be made about water well drilling activities around the WIPP:

(1) Water wells are drilled for a variety of purposes. About 20% of the deeper wells (i.e., wells in the Santa Rosa sandstone and lower-lying formations) drilled since 1952 were for oil and gas applications such as drilling muds or mining purposes. About 20% were drilled for stock watering. Several percent were listed as domestic and observation use. Over 40% of these new wells are presently listed as unused and there is no indication of why they were drilled.

(2) There are essentially no data on well pumping rates. Two Rustler Formation wells in Nash Draw (in T22S, R30E) had reported pumping rates of 260 and 700 gpm. A Rustler Formation well in T23S, R30E measured 3 gpm. Two wells in the Triassic strata (in T23S, R31E and T23S, R32E) had yields of 10 gpm.

(3) No assessment has been made of water quality in these wells.

(4) There are very few data available on how extensively these wells are used. In the wells listed as not being used it is not known whether these were dry holes, whether they were ever used, or if they are likely to be used in the future.

(5) Within a given township, new wells are periodically being drilled at the same time existing wells are classified as unused.

No water well drilling in the Carlsbad Underground Water Basin reached repository depths. Therefore, water well drilling would be considered shallow drilling. A pumping water well could, depending on its location, either increase or decrease the gradient in the Culebra between the repository and the accessible environment. A borehole drilled into a contaminated plume of Culebra water would bring some contaminated fluid and solid material containing adsorbed radionuclides to the surface during drilling. For an average borehole diameter of 12.5 inches (32 cm), based on 14 wells near the WIPP site, the area of the hole is 0.079 m^2. For a 7.0 m thick Culebra aquifer with 0.16 porosity this would bring 0.089m^3 fluid in the 0.553 m^3 of solids (bulk volume) brought to the surface. For assumed solubilities of 10^{-6} M for plutonium and americium and 10^{-4} M for uranium, only 0.080 Ci would be transferred to the surface in the fluid. Radionuclide quantities adsorbed on the solids brought to the surface would be somewhat greater if some adsorption of radionuclides on the dolomitic Culebra rocks occurs.

The largest potential consequence would come from an on-site well pumping from a contaminated aquifer. The testing of a well could have significant consequences. For example, some wells on the WIPP site have been pumped at 3 gallons per minute (0.19 l/s) or greater for extended periods. Pumping of a well at this rate for 72 hours would bring 49 m^3 of water to the surface. This volume would carry about 43 Ci to the surface (accessible environment) at 1,000 years (for 10^{-6} M plutonium and americium and 10^{-4} M uranium solubilities). Greater quantities of radionuclides could be brought to the surface if a well were placed in regular production. However, the number of curies brought to the surface could be much less than suggested by this calculation if the actinide concentrations in the plume were lower (because of lower solubility limits or because most radionuclides had been removed by chemical adsorption), or if much of the water being pumped was not from the contaminated plume.

9.3.4 Other Exploratory Drilling

Limited exploratory drilling for other resources has occurred around the WIPP site and could occur in the future. For example, drilling for uranium in shallow lying sediments has been conducted in the past. No evidence of uranium was found in the gamma logs from 36 boreholes near the WIPP site which penetrated the near surface Dewey Lake Redbeds, the Santa Rosa sandstone, or the Gatuna Formation. Although uranium could occur in these types of sediments, no significant occurrence has been found in the Delaware Basin (POW78).

Sulfur is found in the Castile Formation in the Central Delaware Basin mainly in Culberson County, Texas about 50 miles south of the WIPP site (SIE78, POW78). The sulfur appears to be associated with portions of the Castile which lack halite either due to removal by dissolution or to absence during deposition. These controls predominate in the southern and western portion of the Delaware Basin. Since the WIPP site lies east of the edge of the Castile halite, occurrence of economic sulfur deposits is unlikely there.

Quantities of lithium are found dissolved in the brine reservoirs in the Castile Formation which underlies the Salado Formation containing the WIPP repository. Average lithium concentrations of 240, 280 and 360 mg/l, respectively, were reported for the ERDA-6, WIPP-12, and Union wells (DOE83). The reservoir intersected by the WIPP-12 well lies within the LWA boundary and has a "representative" estimated volume of 2.7 x 10^6 m^3 or about 17 x 10^6 bbl (DOE83). Based on the estimated reservoir volume and measured brine chemistry, the reservoir would contain about 0.75 x 10^6 kg of Li. This is equivalent to only about two or three months of domestic production at current rates (BOM94c). In an area of about 775 km^2 around the WIPP site, 12 of 92 boreholes penetrating the Castile Formation intercepted brine (SAN92, Vol. 3), but only a few of these holes were assayed for lithium.

A variety of other minerals are present around the WIPP site, including salt, caliche, and gypsum. However, these minerals are generally sub-economic, and no significant drilling is currently involved in their discovery and exploitation (SIE78). Depending on the depth of the drilling target, exploration for these other minerals could be classified as either shallow drilling or deep drilling as defined in 40 CFR part 194.

9.4 INTRUSION BY MINING

9.4.1 Introduction

EPA requires that consideration of mining-related scenarios should be included in assessing the performance of the WIPP repository (§194.32). This requirement applies to mining of all minerals, although the major commodity currently extracted in the Delaware Basin by underground mining is potash. Economic deposits of this mineral are confined to the northern portion of the Basin in Eddy and Lea Counties, New Mexico near the WIPP site. No other significant underground mining occurs in the Delaware Basin, although some sulfur is extracted via Frasch process wells (in the Castile Formation) in Culberson County, Texas.

As previously noted, potash is a general term for a variety of potassium bearing minerals for which the chemical compound K_2O is often used as a surrogate to characterize the potassium content. About 95% of U.S. potash sales are to the fertilizer industry with the balance primarily to the chemical industry. Historical sources of potash include kelp, wood ashes, lake brines, alunite, cement dust, sugar beet waste, blast furnace dust, and various potassium-rich minerals. Today, U.S. potash production is principally from the rock sylvinite - a mixture of the minerals sylvite (KCl) and halite (NaCl) - and from langbeinite - a potassium magnesium sulfate ($K_2SO_4 \bullet 2MgSO_4$). Potash is typically recovered either by underground excavation mining or by solution mining where water is injected into a mineralized zone and saturated brine is extracted and recrystallized in evaporation ponds. In the Delaware Basin, potash is recovered only by excavation mining.

Extensive underground potash mining is currently being conducted in the vicinity of the WIPP site. During 1992, southeastern New Mexico supplied 81% of U.S. production (DUP94). Mining operations occur in the McNutt potash zone of the Salado Formation. A generalized stratigraphic column showing these Upper Permian potash-bearing rocks and younger strata is included as Figure 9-3 (CHE78). Eleven ore zones have been identified within the McNutt. Primary current mining targets are the 10th ore zone for sylvite and the 4th ore zone for langbeinite. Some mineralization has been identified in ore zones 2, 3, 5, 8, 9, and 11 in the WIPP vicinity[2](NMB95). These mineralized zones extend within the WIPP Land Withdrawal Boundary as shown in Figure 9-4 which plots the boundaries of the current Bureau of Land Management (BLM) Lease Grade criteria[3] as estimated by Griswold (GRI95). Reserve and resource estimates inside the WIPP boundary are summarized in Table 9-1 (NMB95). When the WIPP site was selected in 1976, most of the site lay outside the boundary of the Known Potash Leasing Area (KPLA) (i.e., the area which contains lease grade reserves). However, subsequent site evaluation by DOE (then ERDA) included drilling and coring 21 exploratory holes for potash (POW78). This drilling program indicated that potash mineralization was more extensive than expected. As a consequence, the U.S. Geological Survey used these drill hole data to extend the KPLA. The KPLA now embraces all of the WIPP site although most of the southwestern quadrant of the site is barren of mineralization, as is the repository location.

The WIPP site also lies within what is called the Designated Potash Area. This area, which is defined by Order of Secretary of Interior (51 FR 39425) under the authority of two mineral leasing acts, is slightly larger than the KPLA. It should be noted that the northern most townships within the Designated Potash Area lie outside the northern boundary of the Delaware Basin[4]. According to the Secretarial Order, potash enclaves are delineated within the Designated Potash Area as regions containing currently economically minable ore

[2] The New Mexico Bureau of Mines and Mineral Resources reserve and resource estimates are based on 40 drill holes in and around the WIPP site. Other drill holes exist in the area, but the data are proprietary. These 40 drill holes cover the WIPP Land Withdrawal area and an area extending about 1 mile outside the boundary except for the southwest quadrant of this perimeter area (GRI95).

[3] The current BLM leasing criteria for potash reserves specify ore seams containing at least 4 feet of 4% K_2O (a grade-thickness product of 16) for langbeinite and 4 feet of 10% K_2O for sylvite (a grade-thickness product of 40). These criteria have been in effect since 1969. According to BLM, sylvite is being mined below the 10% K_2O minimum cutoff grade and langbeinite is being mined below the 4% minimum (CON95).

[4] About 50% of the KPLA lies outside the Delaware Basin.

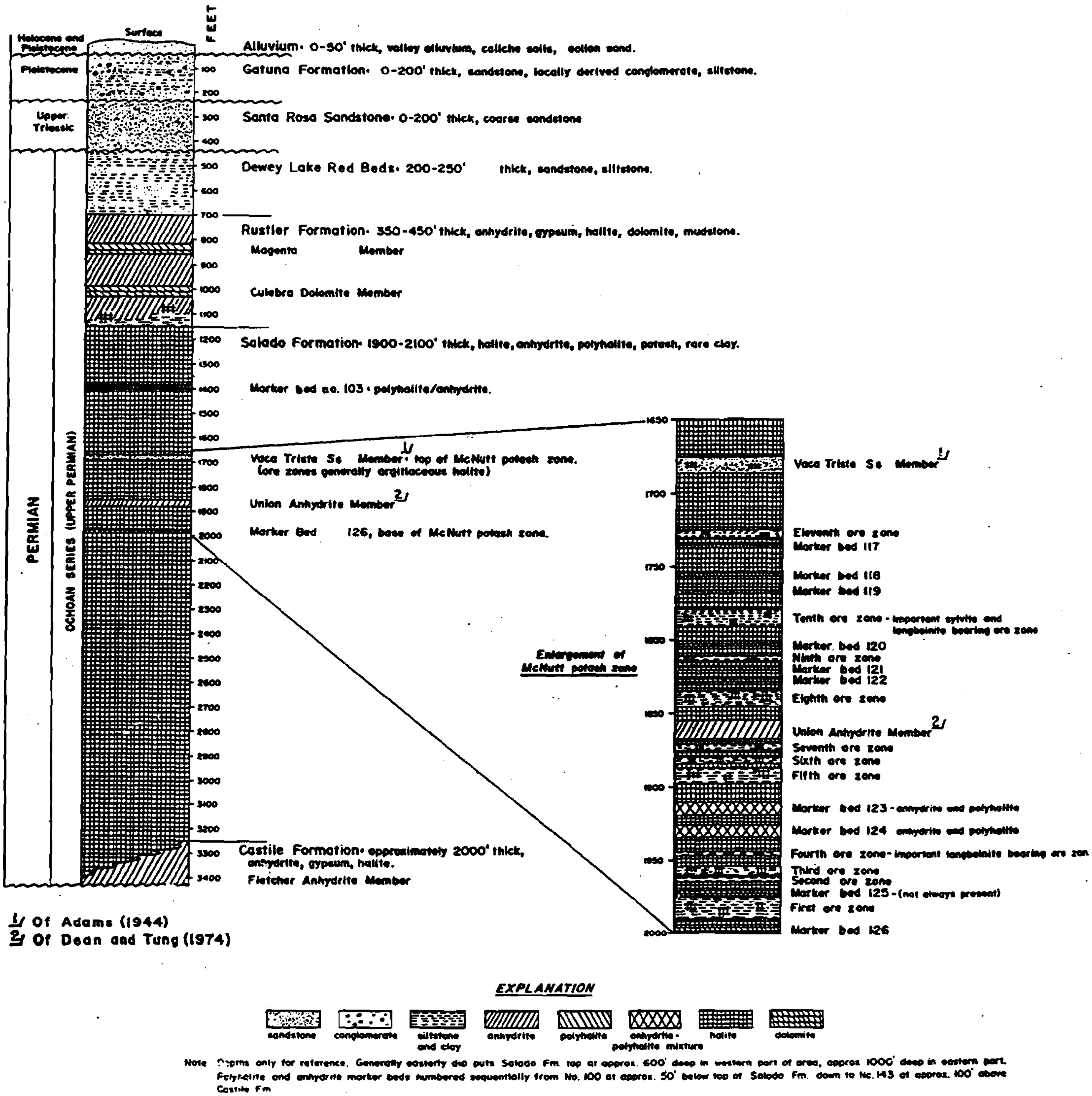

Figure 9-3. Generalized Stratigraphic Column of Permian and Younger Strata, Eddy County, New Mexico (CHE78)

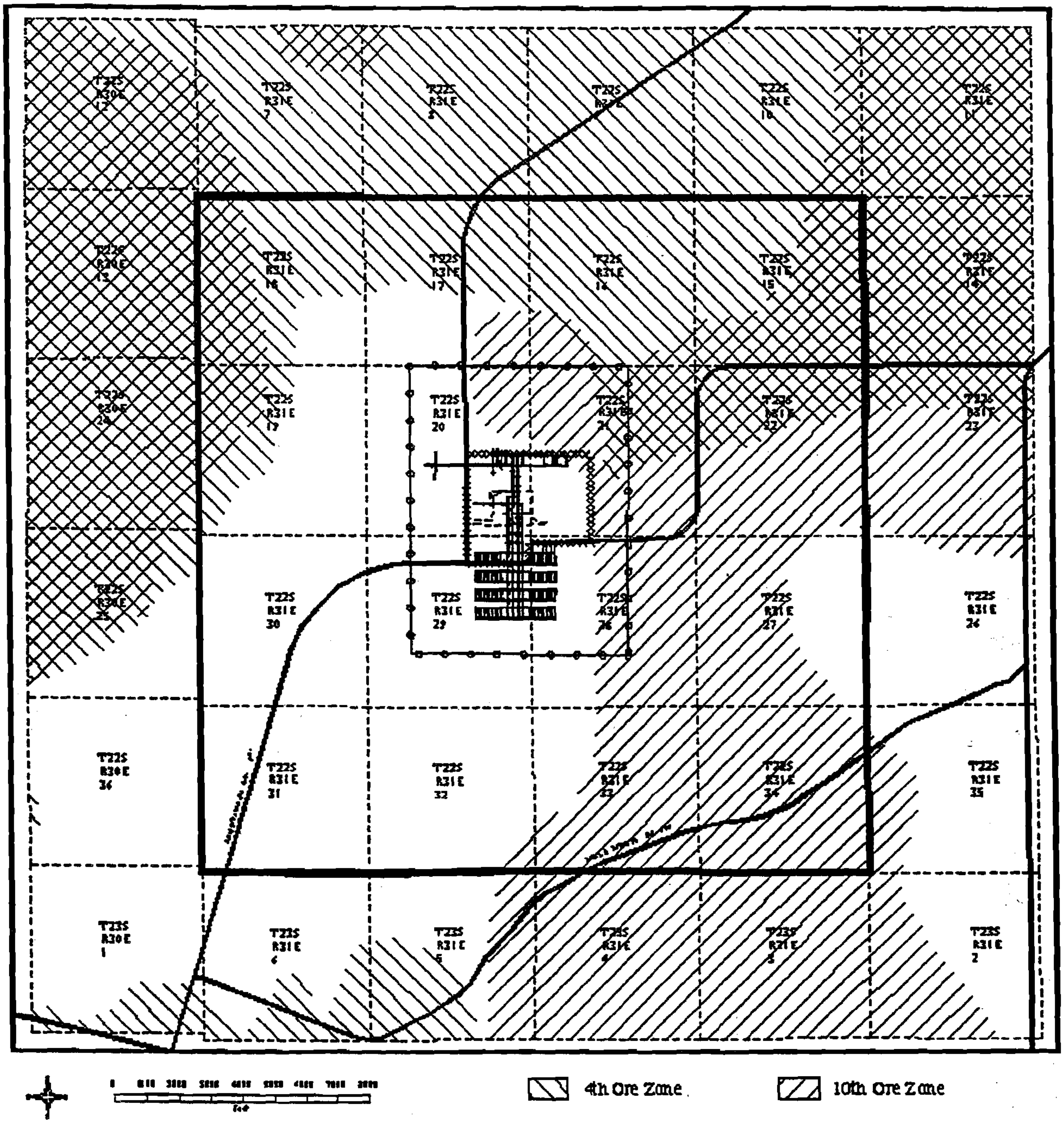

Figure 9-4. Location of BLM Lease Grade Mineralization Within the WIPP Site

Table 9-1. Potash Reserves and Resources Within WIPP Site Boundary (GRI95)

AREA	TYPE OF RESOURCE	MILLION SHORT TONS	K_2O (%)
4th Ore Zone (Langbeinite)	In-place resource (>4% K_2O and actual thickness)	47.0	7.12
	BLM Lease Grade reserve (>4% K_2O and 4-foot mining height)	40.5	6.99
	Minable reserve (>6.25% K_2O and 6-foot mining height)	18.0	7.59
10th Ore Zone (Sylvite)	In-place resource (>10% K_2O and actual thickness)	53.7	14.26
	BLM Lease Grade reserve (>10% K_2O and 4-foot mining height)	52.3	13.99
	Minable reserve (>12.25% K_2O and 4.5 foot mining height)	30.6	15.00
Other Ore Zones	In-place resources[a]	18.4	5.74-15.71

a - Generally do not meet lease grade standards. According to GRI95, these resources could only be minable if advanced thin-seam mining techniques are developed in the future.

reserves. Inside these enclaves, it is Department of Interior policy to deny approval of most oil and gas drilling permit applications from surface locations with two exceptions (51 FR 39425):

"a. Drilling of vertical or directional holes shall be allowed from barren areas within the potash enclaves when the authorized officer determines that such operations will not adversely affect active mining operations in the vicinity of the proposed drillsite.

b. Drilling of vertical or directional holes shall be permitted from a drilling island located within a potash enclave when: (1) There are no barren areas within the enclave or drilling is not permitted within on the established barren area(s) within the enclave because of interference with mining operations; (2) the objective oil and gas formation cannot be reached by a well which is vertically or directionally drilled from a permitted location within the barren area(s); or (3) in the opinion of the authorized officer, the target formation beneath a remote interior lease cannot be reached by a well directionally drilled from a surface location outside the potash enclave."

For perspective, the Designated Potash Area, as of October 1986, occupied 497,002 acres as compared to the area of the WIPP site which is 10,240 acres.

Drilling on state and private lands is controlled by the New Mexico Oil Conservation Division (OCD). Because of problems in implementing then existing OCD regulations, a revised order (No. R-111-P) was approved by the State Oil Conservation Commission on April 21, 1988 (OCC88). Under the terms of R-111-P, the New Mexico "Potash Area" is coterminous with the KPLA. Within the Potash Area, drilling for oil and gas cannot be conducted at any location containing life-of-mine potash reserves (LMR) except by mutual agreement of the lessor and lessee of both the potash and oil and gas interests. Outside the LMR, drilling of shallow wells can be no closer than 0.25 miles of the LMR boundary or 110% of the ore depth, whichever is greater. (Shallow wells are defined as those in all formations above the base of the Delaware Mountain Group or less than 5,000 feet deep, whichever is less.) Deep wells must be at least 0.5 miles from the LMR boundary. One of the objectives of R-111-P was to eliminate the need for drilling islands and three-year mining plans required by the Secretarial Order on Federal lands.

Potash ore reserves in the Carlsbad KPLA were estimated to be about 100 million short tons (90.7 million metric tons) of recoverable K_2O based on 1973 prices (WEI79)[5]. At current production rates of about 1.4 million metric tons per year (DUP92), this reserve would be exhausted in about 65 years (about 15 years after projected completion of the WIPP disposal phase, but during the period of active institutional controls)[6]. In the 1993 WIPP Resource Disincentive Report, DOE commented on the finite nature of the langbeinite supply noting that langbeinite operations would continue for another 28 years if only current reserves are considered and the production period would be extended to 46 years if resources were also included (DOE93). In 1993, the New Mexico Bureau of Mines and Mineral Resources provided a breakdown of the expected operational life of each mine in the area. As shown in Table 9-2, life of the Mississippi Chemical operations is projected to be 125 years while the other five mines should wind down in 33 years or less (BAR93). It should be noted that the mine life estimates are based on published information. Data on actual mining reserves are regarded as proprietary information by the potash mining companies and actual mine life may be longer than projected here.

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[5] In a 1978 study, AIM Inc. estimated potash reserves for the Carlsbad District including those within the WIPP site to contain 109 million tons of recoverable products - a total very similar to the 1973 Bureau of Mines estimate (SEE78).

[6] In 1973, the U.S. Geological Survey stated that, based on then current production levels, crystalline deposits and brines in the U.S. would last for at least 100 years (SMI73). Nearby Canadian resources are adequate for thousands of years.

Table 9-2. Active Potash Mines in New Mexico Showing Estimated Capacity, Average Ore Grade, and Mine Life at the Average 1992 Price of $81.14/st product

Operator	County	Product Capacity (st/yr[1])	Ore Grade (% K_2O)	Mine Life (yrs)
Eddy Potash Inc.[2]	Eddy	550,000	18	4
Horizon Potash Co.	Eddy	450,000	12	6
IMC Fertilizer, Inc.	Eddy	1,000,000[3]	11[3]	33
Mississippi Chemical	Eddy	300,000	15	125
New Mexico Potash[2]	Eddy	450,000	14	25
Western Ag-Minerals[4]	Eddy	400,000	8[5]	30

Data from J.P. Searls, U.S. Bureau of Mines, oral communication, 1993.
[1] May not be operating at full capacity.
[2] Owned by Trans-Resource, Inc.
[3] Muriate, langbeinite, and sulfate combined.
[4] Owned by Rayrock Resources of Canada.
[5] Langbeinite only.

Current mining operations can be economically extended to the WIPP site boundary and it is likely that this will occur (GRI95). Although economic mineralization also lies within the WIPP site, the WIPP Land Withdrawal Act (LWA) (Public 102-579) precludes mining within the withdrawn area. However, at some future time, when active institutional controls no longer exist and if passive institutional controls are ineffective, mining of the potash inside the boundary is a conceptual possibility. The economics would, of course, be different and exploitation would probably require creation of a new infrastructure to transport ore to the surface and beneficiate it since existing facilities would have been abandoned. GRI95 estimates of <u>minable</u> reserves within the site boundary assume that new mine and plant facilities would not be needed if the reserves were exploited now. As noted in Table 9-1, minable reserve estimates are based on higher grades and greater ore seam thicknesses than for Lease Grade reserves.

Potash was first produced from the Delaware Basin in 1931 (BAR93). Measured potash reserves cover an area of approximately 200 mi^2 in the Delaware Basin with the remainder of the reserves located over the Capitan Reef or outside of the Delaware Basin. Since 1931, mining of the different potash ore zones has covered an area (in the Delaware Basin south of T20S) of over 40 mi^2 as estimated from a 1993 map of the potash resources (BLM93). Using 9700 mi^2 as the approximate area of the Delaware Basin, it can be estimated that about 0.4% of the Delaware Basin has been mined over the past 62 years (1993-1931). This produces a conservative estimate of the rate of mining of 1% of the Delaware Basin area over the past 100 years. Any mining of potash or other minerals of current interest elsewhere in the Delaware Basin would raise this percentage.

The following sections discuss potential impacts of mining on the anticipated long-term performance of the WIPP repository and elaborate on the position taken by EPA in the 40 CFR part 194 rule (§194.32(a)) that performance assessment shall consider the effects of mining on the disposal system and these effects can be limited to changes in the hydraulic conductivity of the disposal system induced by mining.

9.4.2 Mining Scenarios

Consideration of mining effects on PA involves scenarios where mining occurs up to the land withdrawal boundary and where mining occurs within the withdrawn area up to the limits of economic mineralization. Mining outside the site boundary could occur at anytime until available resources are exploited. Mining activities inside the boundary should not occur until sometime after active institutional controls are no longer practicable. The types of scenarios will generally be the same regardless of the assumed location of the mining operations and will, in the main, involve events which alter the rate and volume of radionuclide movement through groundwater to the boundary of the accessible environment. It does not appear that mining can seriously impact repository performance unless boreholes, which intrude the waste panels, are also present. Without the presence of an intruding borehole, there is no obvious way to connect the waste with the overlying water-bearing formations which can then provide a lateral transport path.

The most common mining scenario assumes that subsidence of overburden into the excavated region can alter the hydraulic conductivity of the overlying water-bearing strata (e.g., the Culebra Dolomite Member of the Rustler Formation), possibly increasing transport velocities and/or radionuclide mass-fluxes to the accessible environment. SNL summarized the situation as follows (AXN94):

> "Although the land surface in subsiding areas is lowered and there may be local changes in drainage patterns, the overall topographic features that have the primary effect on the water table will remain similar to those of the present. However, subsidence may have impacts other than lowering of the land surface, including possible fracturing of units that overlie the potash zone. This fracturing could lead to an increase in conductivity for those units. The degree of increase and the relative change in conductivity from unit to unit could have an effect on the long-term groundwater flow behavior for Rustler units.

Because the Tamarisk and Forty-niner members presently have very low conductivities, fracturing may cause larger [percentage] increases in conductivity in those units than in the Culebra and Magenta. The effect on flow would be similar to that described for boreholes that do not intrude the repository [ref. omitted] for the same fundamental reasons. That effect would be a change in the direction of the hydraulic gradients in the land withdrawal area. Currently they direct flow in the Culebra from north to south. If the scenario were to occur, they would direct flow in the Culebra towards the southwest."

Detrimental mining-related scenarios might include:

- Increased hydraulic conductivity of water-bearing formations above the mining horizons due to subsidence (Section 9.4.4)

- Change in flow directions within water-bearing members if a vertical hydraulic connection is created by subsidence (Section 9.4.5.2)

- Formation of subsidence-related surface depressions where water could accumulate and alter local recharge characteristics (Section 9.4.5.3)

- Increased hydraulic gradient if significant flow from water-bearing strata into the mine workings occurs (Section 9.4.5.4)

- Damage to borehole or shaft seals by subsidence effects (Section 9.4.5.1)

- Problems created by solution mining (Section 9.4.5.1)

- Increased hydraulic conductivity of the Salado due to excavation induced stresses (Section 9.4.5.6)

Depending on the location of the mining operations, some of these same scenarios may actually be beneficial. Depending on the location, for example, flow of water into underground mine workings might also reduce the hydraulic gradient in the currently envisioned flow path. Of the potentially detrimental scenarios, the only one expected to be of concern is hydraulic conductivity increases in certain strata above the mining location.

The detrimental aspects of these scenarios will be discussed in more detail subsequently, but a review of relevant technical literature will be presented first to establish a framework for that discussion.

9.4.3 Literature Review

9.4.3.1 WIPP Related Studies

Final Environmental Impact Statement

In the WIPP Final Environmental Impact Statement (FEIS) published in 1980, DOE summarized, without comment, prior studies on potash mine subsidence in the area as reported by the BLM in 1975 (DOE80). At that time, it was estimated that subsidence was likely to have occurred over an area of 14 square miles and was expected over an additional 40 square-mile area. The nearest subsidence to the WIPP site occurred at a distance of 3.5 miles. Observed maximum surface subsidence varied from 2.7 to 5.3 feet. This is about two-thirds the height of the mined ore zone.

D'Appolonia Studies

The impact on the WIPP of neighboring potash mines was examined in greater detail by D'Appolonia in 1982 (DAP82). They observed that, even when subsidence occurs, the integrity of the overlying salt section is not jeopardized as demonstrated by the absence of water flow into the potash mines from units higher in the stratigraphic section.

However, D'Appolonia noted that "the opening of entries for underground potash mining causes a redistribution of stresses within the surrounding rock that can lead to opening of fissures and/or increase the hydraulic conductivity of the surrounding rock. Mining can also lead to the more gross effects of surface subsidence and subsidence-induced fracturing above the mined level." Both empirical and simple analytical techniques were used to characterize the extent of such disturbances.

Using a secondary creep law for the salt, they calculated the zone of influence in a horizontal plane around a hypothetical potash mine (at depth of 2000 ft) and a repository room to be 1,900 and 200 feet, respectively. Thus, if the horizontal separation is 2,100 feet, there would be no stress-induced interaction between the two mined regions. D'Appolonia believes this calculation to be conservative because the WIPP also has a vertical separation from the McNutt of about 400 feet.

Estimates were also made of the impact on the hydraulic conductivity of the salt from reducing the confining stress in the salt. This occurs due to stress relief around an excavation. Based on an empirical relationship between salt permeability, octahedral shear stress, and mean confining stress, D'Appolonia calculated the increase in hydraulic conductivity to be less than one order of magnitude. At a distance into the salt of six times the width of mine opening the calculated hydraulic conductivity was only about twice the conductivity of the undisturbed salt.

D'Appolonia suggested that a generalized subsidence equation developed for coal mines in the Appalachian region could be used for making preliminary estimates of the magnitude of surface subsidence as follows:

$$S = sHbe \quad (1)$$

where

- S = maximum subsidence (ft)
- s = subsidence factor (dimensionless)
- H = cavity height (ft)
- e = extraction ratio (dimensionless)
- b = fraction of cavity remaining after backfill (dimensionless)

The subsidence factor is the ratio of the actual vertical displacement to cavity height which in the Carlsbad area is about 0.67. From the equation, assuming no backfill ($b=1$), a mining height of 6 feet, and an extraction ratio of 90%[7] the maximum subsidence would be about 3.6 feet (1.1 m).

As noted previously, potash is sometimes recovered by solution mining although this technique is not being used in the vicinity of the WIPP. According to D'Appolonia, solution mining of langbeinite is not technically feasible because the ore is less soluble than the surrounding evaporite minerals. Solution mining of sylvite was unsuccessfully attempted in the past. Failure of solution mining was attributed to low ore grade, thinness of the ore beds, and problems with heating and pumping injection water. Unavailability of water in the area would also impede implementation of this technique. For these reasons, solution mining is not currently used in the KPLA.

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[7] According to BAR93, 60 to 75% of the ore is extracted during initial mining, but subsequent removal of the remaining pillars results in extraction ratios exceeding 90%.

IT Corporation Backfill Engineering Analysis

In 1994, IT Corporation reported the results of analytical and empirical subsidence studies of the WIPP repository (ITC94). The thrust of these studies was to evaluate the effects of various backfill options on repository subsidence. The effects of potash mines in the vicinity on repository integrity were not addressed, per se. Never-the-less, some generally applicable subsidence information was developed. IT used four techniques to analyze subsidence caused by excavation of the repository:

- Mass conservation method
- Influence function method
- National Coal Board method
- Two-dimensional numerical modeling (with the Fast Lagrangian Analysis of Continua [FLAC] computer code)

As shown in Table 9-3, reasonable agreement was obtained among the four techniques with maximum subsidence at the surface calculated to vary from 0.55 to 0.95 meters for the empty waste area.

Using the FLAC two dimensional, finite element code, the maximum vertical tensile strain in the Culebra Dolomite due to projected WIPP subsidence was calculated to be 0.0034%.

Using the influence function method,[8] ITC developed contour plots showing the areal extent of surface subsidence caused by repository excavation. The limit of subsidence area was about 850 feet beyond the southern edge of the repository footprint. From this analysis, ITC concluded that, since the maximum subsidence was about 0.4 m and since local surface topography varied by more than 3 meters, a subsidence basin would not be created and repository subsidence should not be visible.

[8] The influence function method assumes that each point in an excavation has an identical circular area of influence on surface subsidence. These influence areas are superimposed to obtain the cumulative effect of all extraction elements.

Table 9-3. Summary of IT Corp. Subsidence Prediction Results for WIPP Repository (ITC94)

Underground Area	Contents of Excavation	Subsidence				
		Mass Conservation (m)	Influence Function Method (m)	NCB Method (m)	FLAC Single-Room Model (m)	FLAC Full-Panel Model (m)
Waste Emplacement Area[a]	Empty	0.86	0.56	0.73	0.95	0.55
	Waste Only	0.62	0.40	0.53	NA	NA
	Waste plus loose backfill	0.55	0.36	0.47	0.33	NA
	Waste plus compacted backfill	0.52	0.34	0.44	0.30	NA
Shaft Pillar Area	Empty	0.28	0.10	0.04	NA	0.13[b]
	Loose backfill	0.12	0.04	0.02	NA	NA
	Compacted backfill	0.06	0.02	0.01	NA	NA
Northern Experimental Area	Empty	0.24	0.08	0.02	NA	NA
	Loose backfill	0.11	0.04	0.01	NA	NA
	Compacted backfill	0.05	0.02	0.01	NA	NA

[a] Waste emplacement area includes Panels 1 through 8; 2 through 8 are not yet excavated.
[b] At the Waste Shaft
NCB National Coal Board
FLAC Fast Lagrangian Analysis of Continua
NA Not Available.
m Meters.

Sandia Studies of Subsidence

Sandia has explored the possible impact of WIPP subsidence on performance assessment (PA). In a 1989 study to select events and processes which should be considered in forming possible scenarios, SNL considered three possible processes related to repository-induced subsidence (HUN89):

- Increased hydraulic conductivity of the Salado Formation
- Fracturing
- Disruption of surface drainage

Based on the fact that repository excavation would produce a maximum of a 0.2% increase in the volume of the overlying Salado salt, they concluded that increased Salado hydraulic conductivity would be insignificant. They further concluded that fracturing of the Salado could also be neglected. This conclusion was based on the expectation that the repository would adjust to excavation by creep rather than fracturing. This position was supported by observations in local potash mines where mining was conducted with two levels of extraction. The observed response of the rock in the upper horizons was flexure rather than fracture. However, SNL stated that effects on the Culebra were unknown. With regard to surface drainage, SNL concluded that this would not be a factor because, with a maximum expected surface subsidence of 2 feet, there was no integrated drainage which would be disrupted.

As noted in Section 9.4.2 above, SNL revisited the subsidence issue in 1994 concluding that subsidence could cause fracturing in the more brittle overlying units which could result in increased hydraulic conductivity and possible redirection of flow in the Culebra from a generally north to south direction to a more southwesterly direction (AXN94). Surface subsidence effects were not expected to be of sufficient magnitude to significantly alter the position of the water table.

9.4.3.2 Other Relevant Studies

IT Corporation summarized subsidence observations made at potash mines in southeastern New Mexico (ITC94). Observed angles of draw, measured from vertical edge of the mine workings to the point where surface subsidence ceased, varied from 25 to 58 degrees. ITC noted that the maximum observed subsidence over four potash mines in the area varied from

0.4 to 1.5 m which was between 16 to 66% of an assumed excavation height of 2.6 m (8.5 ft)[9]. ITC felt that the maximum observed subsidence was less than that which will ultimately occur over the excavated area.

A large body of subsidence literature has been developed based on coal mining in the United States and the United Kingdom. In a number of studies, subsidence-induced increases in transmissivity are described. Some examples are provided here.

The U.S. Geological Survey described the effects of subsidence associated with longwall mining of coal in Marshall County, West Virginia (USG88). Three tests were recounted where the transmissivity of a perched aquifer was measured before and after mining a coal seam. In each case, the overburden was about 800 feet thick and the tested aquifer was between 25 and 150 feet below the surface. In two tests, the transmissivity was found to increase significantly, from 3.7 to 160 ft^2/day in one case and from less than 0.001 to 36 ft^2/day in the other. In the third test, only a slight increase between pre- and post-mining transmissivity was observed (from 0.20 to 0.31 ft^2/day). This small change was attributed to the fact that significant subsidence fracturing had not occurred.

Booth discussed to similar studies related to longwall coal mining in the Illinois Basin (BOO92). One series of tests was conducted at a site in Jefferson County, Illinois where coal seams 9 to 10 feet thick were mined at a depth of about 725 feet. The overburden consisted primarily of low permeability shales, siltstones and limestones. An aquifer in sandstone exists about 75 feet below the surface which is confined by an overlying shale unit. Subsidence produced visible surface tension cracks. Subsurface strain measurements and borehole examination indicated fractures and bedding plane separation. In three presubsidence tests, the measured values of hydraulic conductivity in the Mt. Carmel sandstone were 2×10^{-6}, 2×10^{-5}, and 3×10^{-6} cm/s. After subsidence, measured values were 5×10^{-5}, 3×10^{-5}, and 4×10^{-5} cm/s. In another paper discussing the same site, it was reported that post-subsidence values of the hydraulic conductivity in the shale were increased by two to three orders of magnitude (KEL91).

At a second site in Saline County, IL, investigations involved subsidence related to mining a five- to six-foot coal seam at a depth of about 400 feet (BOO92). The Trivoli sandstone

[9] The maximum observation period varied from one week to more than one year.

aquifer lies above the seam and about 180 feet below the surface. Initial conductivities in the Trivoli were less than 10^{-8} cm/s and these increased to about 5×10^{-6} cm/s after mining. Booth attributed this increased conductivity to the supposition "that subsidence had probably improved the interconnectedness of permeable fractures."

The U.S. Bureau of Mines described hydrologic changes associated with longwall mining of coal in Cambria County, Pennsylvania (MAT92). The coal seams studied were at a depth of 740 to 845 feet and were overlain by fine-grained sedimentary rocks and thin coal beds. Only small changes in hydraulic conductivity of the overburden due to mining were measured. Increases were a factor of 2 to 4 and in some cases an unexplainable decrease was noted. The increased conductivity was attributed to excavation-induced creation of new passages for groundwater flow.

Elsworth and Liu used non-linear finite element modeling to estimate changes in hydraulic conductivity associated with longwall mining (ELS95). In their modeling, a 140-foot thick zone of increased horizontal conductivity caused by vertical strains was defined immediately above a 5-foot thick coal seam. The estimated conductivity increase was about an order of magnitude.

Bai and Elsworth described modeling studies involving the interrelationship between subsidence and stress dependent hydraulic conductivity (BAI94). In concept, the rock mechanics approach was similar to that taken here and described in Section 9.4.4.2 below. In the Bai and Elsworth studies, finite element analyses over representative stratigraphy were used to calculate changes in hydraulic conductivity for various fracture spacings.

9.4.4 Impact of Mining on Hydraulic Conductivity

9.4.4.1 Background Information

Based on the available site information, it appears that one of the potential detrimental results of mining near the repository could be increased hydraulic conductivity[10] in the brittle

[10] The terms hydraulic conductivity and transmissivity are sometimes used interchangeably in the text as indicators of altered flow path resistance. Transmissivity is the product of the hydraulic conductivity and aquifer thickness. In the examples presented here, the Culebra thickness is assumed to be constant so the transmissivity is a constant factor of 7.7 higher than the hydraulic conductivity (in metric units).

water-bearing strata above the mining horizons. In the analysis discussed here, the focus is on the Culebra Member of the Rustler Formation which is the most transmissive unit. The Culebra can potentially provide a lateral conduit to the accessible environment if contamination from the repository 1440 feet below reaches the transmissive horizon. According to SNL, the Culebra is a "finely crystalline, locally argillaceous (containing clay) and arenaceous (containing sand), vuggy dolomite ranging in thickness near the WIPP from about 7 m (23 ft) .... to 14 m (46 ft) ....." (SAN92). In its 1992 performance assessment (PA), SNL chose 7.7 meters as the reference thickness. Using information from 41 boreholes, SNL has calculated that the transmissivity of the Culebra varies by about six orders of magnitude depending on the degree of fracturing which exists. In the 1992 PA (SAN92), the median fracture spacing was assumed to be 0.4 m and range between 0.062 and 8 m. Thus, the median number of horizontal fractures through the Culebra thickness would be 19 and the range would lie between 1 and 124.

If subsidence occurs, it may create a network of both vertical and horizontal strains in the Culebra. Vertical tensile strains can increase the aperture of existing horizontal fractures; whereas, horizontal tensile strains can increase the aperture of existing vertical fractures. Compressive strains would have the opposite effect. Increase in fracture aperture increases hydraulic conductivity. This increased hydraulic conductivity can reduce lateral travel time of radionuclides to the accessible environment at the vertical subsurface extension of the site boundary.

As noted above, the 1992 PA assumed that flow and transport through the Culebra is through fractures. In light of this 1992 PA assumption, the following discussion focuses on one potential theory describing groundwater flow through fractures. The subsequent section discusses how the fracture aperture increases can be estimated.

Darcy's law relates the movement of water in a porous medium to the hydraulic gradient and the hydraulic conductivity. The hydraulic conductivity is a measure of the transmissive capacity of the medium coupled with the density and viscosity of the fluid (water in this case). The hydraulic gradient is simply the slope of the water table (unconfined aquifers) or the potentiometric surface for a confined system. The equation for Darcy's law is

$$q = K\frac{dh}{dl}$$

where q is the Darcy velocity (m/yr), K is the hydraulic conductivity (m/yr) and dh/dl is the hydraulic gradient (dimensionless - m/m). Hydraulic conductivity is actually a property of both the physical media (the aquifer) and the fluid. Darcy's law may also be written using intrinsic permeability (k) which is a property of the medium alone, as shown below:

$$q = \frac{k \rho g}{\mu} \frac{dh}{dl}$$

where:

k = intrinsic permeability (m^2)
ρ = fluid density (kg/m^3)
μ = viscosity (Pa·s)
g = gravitational constant (m/s^2)

The advective flow rate for a conservative contaminant (i.e., non-sorbing and nonreactive) migrating through a porous medium is computed by dividing the Darcy velocity (given above), by the effective porosity. The effective porosity for a porous medium is the ratio of the connected void space divided by the total volume of the medium.

In a fractured medium, Darcy's law still applies, however, the hydraulic conductivity of the fracture (K_f) is more difficult to determine. If the fractures are conceptualized as a series of parallel plates (with the fractures being the gaps between adjacent plates), mathematical equations can be derived to determine the equivalent hydraulic conductivity that would be used in Darcy's law.

The porosity of the fracture system actually should be viewed as two components, fracture porosity and matrix porosity. Using the parallel plate analogy, the fracture porosity is the number of fractures times the fracture aperture (gap thickness) divided by the thickness of the aquifer. The matrix porosity is the porosity of the blocks of rock between the fractures. In a fractured system such as granitic rock, the matrix porosity may be effectively zero because there is no intergranular void space. However, there is some measurable porosity space within the Culebra matrix (SAN92).

The hydraulic conductivity of a system of horizontal fractures is determined by the fracture aperture and the spacing between fractures. Given an equivalent hydraulic conductivity of the aquifer (i.e., determined through aquifer testing) and fracture spacing, it is possible to compute the fracture hydraulic conductivity. The calculation is based upon moving the same flux of groundwater through the fracture system as through a porous medium. The derivation of this equation is developed below.

The fracture conductivity equation is derived in two steps. First, the hydraulic conductivity for a single fracture is defined and then this is related to the flow rate through the fracture. The hydraulic conductivity of a single fracture is given as:

$$K_f = \frac{b^2 \rho g}{3\mu} \tag{1}$$

where:

b = half-fracture aperture (m)

K_f = fracture hydraulic conductivity (m/yr)

This equation is presented in a number of papers by Snow (SNO69) and by Gale (GAL82). The equation is often rewritten in terms of the full fracture aperture, as follows:

$$K_f = \frac{w^2 \rho g}{12\mu} \tag{2}$$

where:

w = full fracture aperture ($b^2 = w^2/4$) (m)

The second step in computing the aperture from an equivalent porous medium K value is to equate the flow rates through the porous and fractured systems. The flow through a set of N horizontal fractures of identical aperture is:

$$Q_f = \left[\frac{w^2 \rho g}{12\mu}\right] N w L \frac{dh}{dl} \tag{3}$$

where:

Q_f = flow rate through the fractures (m^3/yr)

L = length of fractures perpendicular to flow (m)

N = number of fractures

The term (NwL) is the area term in a traditional Darcy's law equation. The equation for flow through an equivalent porous medium would be:

$$Q=K_{\epsilon}DL\frac{dh}{dl} \tag{4}$$

where:

- K_{ϵ} = equivalent porous medium hydraulic conductivity (m/yr)
- D = aquifer thickness (m)
- L = length perpendicular to flow direction (m)

As mentioned above, equation 4 may also be written in terms of intrinsic permeability (k) and fluid properties, as show below:

$$Q=\frac{k\rho g}{\mu}DL\frac{dh}{dl} \tag{4b}$$

To compute an equivalent K for the porous medium, the flow rates through the two systems (porous and fractured) must be equal. Setting equation 3 equal to equation 4 yields:

$$K_{\epsilon}D=\frac{w^3\rho gN}{12\mu} \tag{5}$$

with common terms canceling from the equations. This equation can then be rearranged to give an equation of fracture aperture in terms of an equivalent porous medium hydraulic conductivity:

$$w=\left[\frac{12K_{\epsilon}\mu D}{\rho gN}\right]^{\frac{1}{3}} \tag{6}$$

Finally, to get the equation in terms of spacing between fractures (D_f = D/N), the equation becomes:

$$w=\left[\frac{12K_{\epsilon}\mu D_f}{\rho g}\right]^{\frac{1}{3}} \tag{7}$$

After computing the fracture aperture for a given porous medium hydraulic conductivity (equation 7), the fracture hydraulic conductivity is computed from equation 2 above. It can be seen from equation 2 that the fracture hydraulic conductivity (K_f) varies as the square of the aperture (w) while the equivalent porous medium conductivity (K_ϵ) varies as the cube of the aperture.

The following example provides an indication of the magnitude of changes which might be expected in the Culebra hydraulic conductivity resulting from subsidence induced fractures. For these calculations, it is assumed that the vertical tensile strain produced by subsidence results in the opening of existing horizontal fractures rather than the creation of new fractures. The total strain is accommodated by increasing the fracture aperture. Thus, if, for discussion purposes, there is a single horizontal fracture in the Culebra and subsidence from potash mining causes 0.03% vertical tensile strain (which is about 10 times the value calculated in ITC94 for the Culebra from repository subsidence, see Section 9.4.3.1 above), the total displacement is 2.3×10^{-3} m (7.7 m x 0.0003). If 10 horizontal fractures were present, then the increase in each aperture would be 2.3×10^{-4} m.

The effect of subsidence on changes in fracture aperture and hydraulic conductivity of the Culebra for the case of 10 fractures across the aquifer thickness is calculated using the following assumptions:

aquifer thickness (D)	= 7.7m
viscosity(μ)	= 0.001 Pa•s
density (ρ)	= 1000 Kg/m^3
gravitational constant (g)	= 9.79 m/s^2
equivalent hydraulic conductivity (K_ϵ)	= 7.0 m/y = 2.24×10^{-7} m/s
tensile strain	= 0.03% = 0.0003 m/m
total displacement	= 7.7m x 0.0003 strain = 2.3×10^{-3}m

The attendant fracture aperture from equation (6) is:

$$w = \left[\frac{K_\epsilon 12 \mu D}{\rho g N}\right]^{\frac{1}{3}} \tag{8}$$

K_ϵ = equivalent hydraulic conductivity
w = fracture aperture
ρ = density
g = gravitational constant
N = number of fractures
μ = viscosity
D = aquifer thickness

$$w = \left[\frac{2.24x10^{-7}\ x\ 12\ x\ 0.001\ x\ 7.7}{1000\ x\ 9.79x10}\right]^{\frac{1}{3}}$$

$w = 5.96 \times 10^{-5}$ m

For a total displacement of 2.3×10^{-3} m, the displacement per fracture is 2.3×10^{-4} m and the expanded fracture aperture resulting from the tensile strain (w_{strain}) is

$$w_{strain} = 5.96\ x\ 10^{-5} + 2.3\ x\ 10^{-4} = 2.9\ x\ 10^{-4}\ \text{m}$$

To calculate the strain-altered equivalent hydraulic conductivity, $K_{\epsilon S}$,

$$K_{\epsilon s} = \frac{w^3 \rho g N}{12 \mu D} \quad where\ w = w_{strain} = 2.9x10^{-4}$$

$$= \frac{(2.9x10^{-4})^3\ x\ 1000\ x\ 9.79\ x\ 10}{12\ x\ 0.001\ x\ 7.7} \tag{9}$$

$$K_{\epsilon s} = 2.6x10^{-5}\ m/s = 8.2x10^2\ m/y$$

Values of the equivalent hydraulic conductivity for various assumed values of N within the range used in the 1992 PA are summarized below based on 0.03% vertical tensile strain:

N (fractures)	Hydraulic Conductivity (m/y)
1	14.8×10^4
10	8.2×10^2
100	4.4×10^1

From this hypothetical example, it can be seem that the change in hydraulic conductivity is nearly four orders of magnitude for a single fracture and only a factor of six for 100 horizontal fractures through the thickness of the Culebra.

In order to provide a more detailed view of the impact of subsidence on repository performance, a series of modeling simulations were made. First, the strain distribution in the Culebra as a function of distance from the face of a potash mine was calculated using a two-dimensional finite element model (the UTAH2 computer code). Then, this strain distribution was assumed to be accommodated as increases in the aperture of existing fractures. Details of these analyses are presented in subsequent sections.

9.4.4.2 Strain Analysis

A preliminary analysis was conducted to estimate the effects of simulated mining of potash near the WIPP site on the hydraulic conductivity of the Culebra Member of the Rustler Formation. Simulation of longwall mining of potash was done using a two-dimensional finite element computer program, UTAH2. This program has been in use for many years and is considered quite reliable (PAR78, PAR91). In response to mining, the adjacent rock mass moves to a new equilibrium position. Maximum surface subsidence occurs above the center of a mined panel, but diminishes with distance from the panel center. However, as will be shown, maximum strains do not occur at the same location as maximum subsidence. Tensile strains may open existing joints or fractures and fracture opening is assumed to increase hydraulic conductivity. If tensile strain between existing fractures is assumed to be absorbed entirely by fractures, then the change in fracture aperture can be calculated. With the assumption of an initial aperture, the change in hydraulic conductivity can then be estimated as shown in Section 9.4.4.1.

Finite Element Analysis

The UTAH2 finite element program is a small strain, elastic-plastic computer program that uses associated flow rules in conjunction with a pressure-dependent yield criterion. Elastic and strength anisotropy may be independently specified, but one material axis is tacitly assumed to be normal to the plane of analysis. The form of the yield criterion is $J_2+I_1=1$, where J_2 is an anisotropic form of the second invariant of deviatoric stress and I_1 is an anisotropic form of the first invariant of stress. The isotropic form is a paraboloid of revolution about the hydrostatic axis in principal stress space. Essential input data include the elastic moduli as well as the strength parameters, geologic column, mining geometry, boundary conditions and the premining stress state.

<u>Material Properties</u>

For the isotropic case analyzed here, the strength parameters required are the unconfined compressive (C_o) and tensile (T_o) strengths of each material represented in the finite element mesh. The elastic parameters are Young's modulus (E) and Poisson's ratio (ν) for each material. Specific weights (γ) of the various rock types present in the model region are also needed. The data for the four rock types assumed in the model are given in Table 9-4.

Sandstone, anhydrite and halite elastic properties were obtained from a subsidence analysis of the WIPP repository conducted by the IT Corporation (ITC94). Strengths, with the exception of halite were also obtained from (ITC94). Dolomite properties and halite strength are averages of about 20 results obtained from a standard handbook (LAM78).

Table 9-4. Rock Properties By Type

Rock Type	E(10^6 psi)	ν	C_o(10^3 psi)	T_o(10^3 psi)	γ (pcf)
Sandstone	3.8	0.21	15.0	5.0	144
Anhydrite	10.9	0.35	13.3	4.6	144
Dolomite	9.4	0.30	13.3	1.2	144
Halite	4.5	0.25	5.2	3.1	144

Consideration of strength and elastic modulus properties for the Culebra shows that the strain at failure under uniaxial compression is 0.14%. Under tension the strain at failure is 0.013%. Rock strength is strongly affected by confining stress, so under multiaxial compressive stress, the strain at failure should be greater than in the uniaxial case. Tensile strength is not considered sensitive to confining stress, so tensile strain at failure would also be insensitive to confining stress. These estimates of failure strain are based on the laboratory test data summarized in Table 9-4. The rock mass would have different properties depending on fractures that are present in the field, but absent in the laboratory test samples. Strains calculated using laboratory data will be lower than strains calculated using field-scale properties.

Geologic Column

The geologic column used in the analysis was adapted from the ERDA 9 borehole near the center of the WIPP site (POW78). Table 9-5 gives the depth, formation, and thickness of the different strata represented in the finite element model.

Table 9-5. Strata Depth and Thickness

Formation	Depth (ft)	Thickness (ft)
1. Dewey Lake	0	550
2. Rustler	550	58
3. Magenta	608	24
4. Rustler	632	82
5. Culebra	714	26
6. Rustler	740	120
7. Upper Salado	860	507
8. McNutt	1,367	176
9. Potash Seam	1,543	10
10. McNutt	1,553	188
11. Lower Salado	1,741	333
12. Storage Zone	2,074	104
13. Lower Salado	2,178	442
14. Storage Zone	2,620	110
15. Lower Salado	2,730	106
16. Castile	2,836	1,664[11]

As can be seen from Table 9-5, the base of the mesh includes a portion of the Castile to a depth of 4,500 ft (2836+1664). All strata below the Rustler formation were assigned halite properties from Table 9-4. The Rustler Formation was assigned anhydrite properties (except for the Culebra and Magenta which were assigned dolomite properties) and the Dewey Lake Formation was assigned sandstone properties. This assignment is the same as used in ITC94.

[11] The thickness assigned to the Castile does not include the entire unit, rather it is based on assumptions regarding the necessary modeling depth required to minimize boundary effects.

Mining Geometry

The mining panel was assumed to be 10 ft thick[12], 3,000 ft long and located near the middle of the McNutt. However, the center of the panel is assumed to be a line of symmetry, so only 1,500 ft is explicitly represented in the mesh. As a rule of thumb, the influence of an excavation extends "one diameter" from the excavation walls. At one diameter, the stress concentration about a circular hole decreases to within about 15% of the initial stress state. The "diameter" that characterizes non-circular holes is the long dimension of the hole. In this case, the "1-D" guideline suggests that panel excavation may noticeably influence the state of stress 3,000 ft away. Thus, about 3,000 ft was added to the panel depth (1,543 ft) to obtain a vertical mesh dimension of 4,500 ft. The horizontal dimension of the mesh extends 5,250 ft beyond the panel edge and is thus 6,750 ft. The mesh and panel are shown in Figures 9-5 and 9-6 where the scale is 900 ft per inch. There are 4,050 elements and 4,216 nodes in the mesh. The element aspect ratio is 5 or less.

Premining Stress State

The premining stress state was attributed to gravity alone; no tectonic stresses were assumed. The vertical stress is then simply the average unit weight of rock times depth. Under complete lateral restraint, the horizontal premining stress is a constant, K_o, times the vertical stress. The constant depends on Poisson's ratio, ν, and is therefore different for each rock type. In fact, $K_o = \nu/(1-\nu)$, which ranges from about 0.2 to 0.5 based on the values in Table 9-4.

Boundary Conditions

The centerline of a panel was a line of symmetry; no displacement was allowed normal to this line. Zero displacement boundary conditions were also specified normal to the mesh bottom and far side. A zero normal displacement is often represented by a roller. The top of the mesh coincided with the ground surface and was unrestricted except at the sides.

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[12] This thickness was selected as a conservative value based on mine workings in the area (Section 9.4.3.2) and to reflect the possibility of mining on multiple levels.

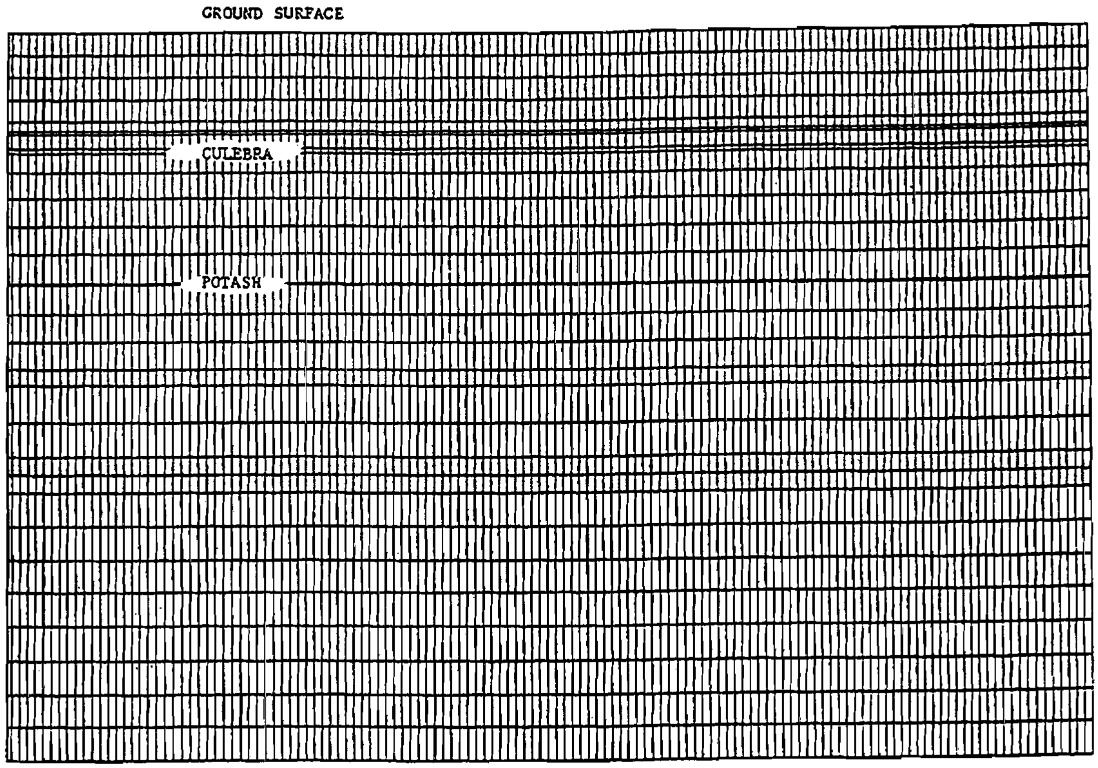

Figure 9-5. Finite Element Mesh Used for Strain Analysis Mesh 4,500 ft by 6,750 ft. Scale: 1 inch = 900 ft.

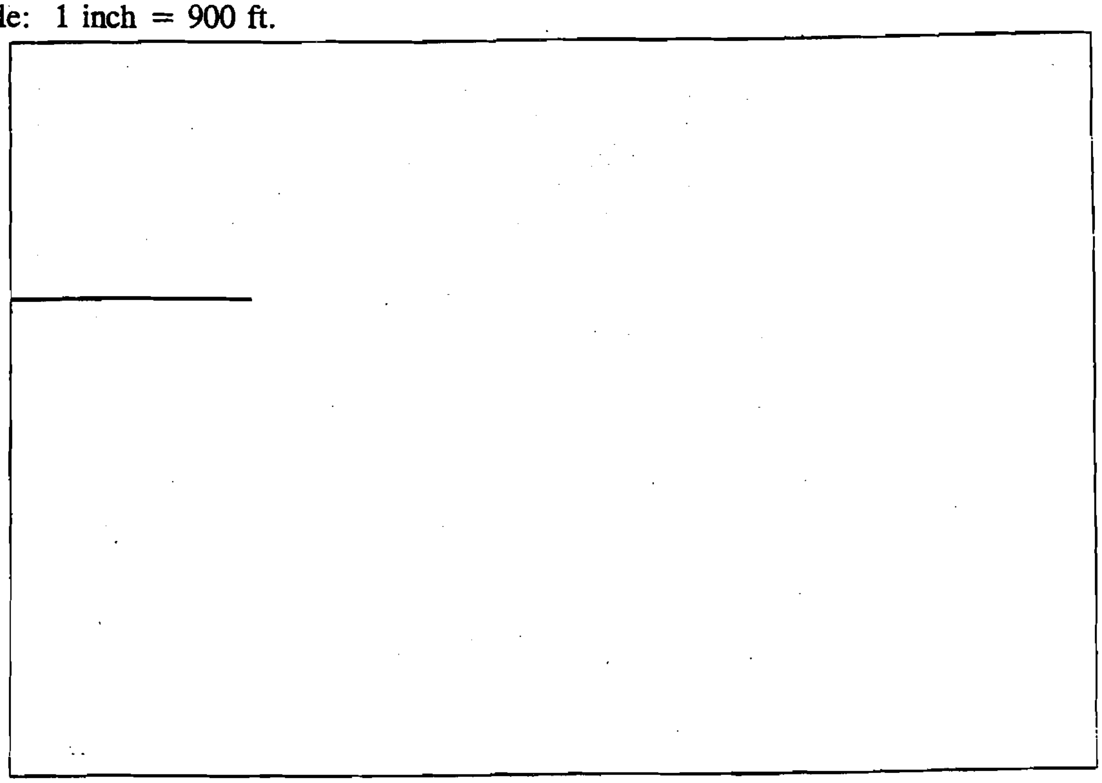

Figure 9-6. Half Width (1,500 ft) of Mined Panel. Scale: 1 inch = 900 ft.

Displacement boundary conditions were also specified on the excavation surface. The panel roof was specified to "sag" 9 inches per load step; the floor was specified to "heave" 3 inches per load step. Thus, 1 foot of closure occurred during each load step at every pair of nodes along the panel except at the panel edge where traction boundary conditions, equal but opposite in sense to the premining stresses, were applied. The amount of seam level closure is controlled by the number of load steps specified, but is physically limited to a maximum of 100% of the mined thickness (10ft).

A second physical constraint on seam closure is the amount of subsidence observed at the surface. The number of load steps was adjusted to meet these constraints. Specifically, seam level closure (relative displacement between roof and floor) is 70% when 7 load steps are applied. The corresponding surface subsidence calculated at the panel centerline is 52.5% of the seam thickness. When 9 load steps are applied, seam level closure is 90%, while surface subsidence is 67.5% of seam thickness. This range of surface subsidence is considered reasonable for full-extraction potash mining.

Fracture Conductivity Change

As described above in Section 9.4.4.1, the parallel plate model for fracture flow states that average flow velocity is proportional to the square of the width (aperture) of the fracture; the volume flow rate (discharge) is proportional to the cube of the aperture (equation 3). Fracture hydraulic conductivity, K_f, is used here to relate flow velocity to hydraulic gradient and is thus proportional to the square of fracture aperture (equation 2). The relative change in hydraulic conductivity is $(K_f - K_{fo})/K_{fo}$ where K_{fo} is the premining fracture hydraulic conductivity. A purely geometrical calculation gives the relative change. Thus, the relative change in fracture hydraulic conductivity is $(w^2-w_o^2)/w_o^2$, where w is the fracture aperture after mining (i.e. w_{strain}) and w_o is premining fracture aperture. This ratio is independent of the units used for hydraulic conductivity such as feet or meters per year.
The post-mining aperture is simply the premining aperture plus the change in aperture, Δw, induced by mining. This change is the strain, ϵ, integrated over fracture spacing, D_f, that is, $\Delta w = D_f\epsilon$. Fracture spacing was assumed to vary between 3 and 300 inches (ca. 0.08 m and 8 m); initial aperture was assumed to vary from 10^{-4} to 10^{-2} inches[13]. Strains are obtained from the finite element simulation of longwall potash mining.

[13] In metric units these apertures are equivalent to 2.5×10^{-6} to 2.5×10^{-4} m. This range of apertures would be associated with equivalent hydraulic conductivities varying from about 6 m/y to about 60,000 m/y. In SAN92, reported hydraulic conductivities (converted from transmissivities using an aquifer thickness of 7.7 m) within the WIPP Land Withdrawal Area ranged from 0.026 to 4,400 m/y.

Results

Two simulations were done. The first case was associated with a subsidence factor (S) of 52.5% (maximum surface subsidence as a percentage of mined panel height); the second case was associated with a subsidence factor of 67.5%. The results are similar in trend, but differ quantitatively.

Case 1.

Horizontal and vertical strains in the Culebra formation are shown in Figure 9-7 for this case (S = 52.5%). The data are strains which are calculated at the centroid of the model elements in the Culebra. Tensile strain is positive in Figure 9-7. The horizontal axis begins at the left edge of the finite element mesh, that is, at the center of the mined panel. Mining extends 3,000 ft, 1,500 ft of which is incorporated into the mesh. Figure 9-7 shows tensile strain in the vertical direction over the mined panel (between 0 and 1500 ft) and horizontal tensile strain beyond the edge of the panel (beyond 1500 ft). The peak vertical tension is about 0.055% (550 micro-in./in) and occurs 1,075 ft from the panel center (i.e., 425 ft inside the panel edge). The peak horizontal tensile strain occurs 175 ft outside the panel edge and is 0.0085% (85 micro-in/in). The horizontal tensile strain initially decreases with distance from this peak and then rises to a broad secondary maximum of about 0.0047% (47 micro-in/in) at 4,275 ft from the panel center after which it decays slowly with increasing distance.

The horizontal strain changes from tension outside the mined panel to compression inside as seen in Figure 9-7. The peak horizontal compression occurs inside the panel and gradually decreases to a minimum at the panel center where the slope of the plot is zero. This trend is indicative of a panel that is sufficiently wide relative to depth to cause maximum subsidence. The panel has super-critical width in subsidence terminology. Critical width is usually given in terms of the angle of draw: $W_c = (2H)\tan(\delta)$. If the angle of draw is 35°, e.g., then critical width is 1.4H where H is the overburden thickness.

Vertical tensile strains would tend to open horizontal fractures, while horizontal tensile strains would tend to open vertical fractures. Compressive strains would tend to close fractures. The magnitude of the vertical tensile strain near the center of the mining panel is about the same as the horizontal compressive strain outside the mining panel and away from

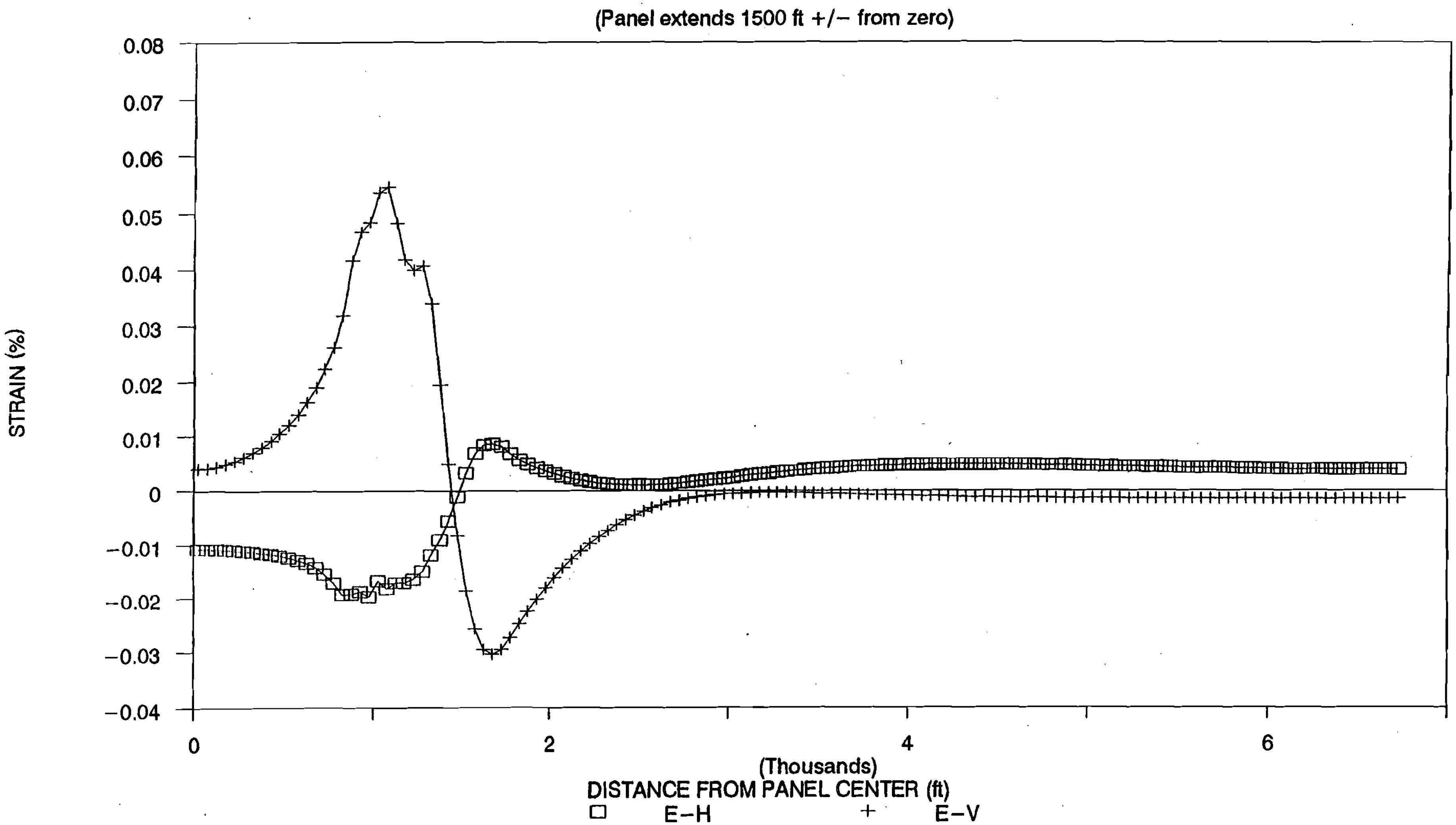

Figure 9-7. Subsidence-induced Culebra strains for subsidence factor of 52.5%. (Panel extends +/-1,500 ft from origin)

the rib. So the change in hydraulic conductivity of horizontal joints over the panel is about the same as the change in vertical joint conductivity for a substantial distance outside the mining panel (neglecting peaks near the rib).

Figure 9-8 shows the change in *vertical* fracture apertures (opening or closing) in the Culebra as a function of distance from the panel center for three assumed joint spacings (3, 30 and 300 inches). Because vertical fractures or joints respond to horizontal strain, joint closure occurs over the mined panel where the horizontal strain is compressive. Vertical joints tend to open outside the mined panel. The magnitude of aperture change increases significantly with joint spacing. Vertical joint opening which occurs outside the mined panel ranges from nil to almost 0.03 inches near the rib.

Figure 9-9 shows the aperture change for horizontal joints (which respond to vertical strain). The peak aperture changes at a 300-inch joint spacing are cut off in the plot. Horizontal joint opening which occurs above the mined panel ranges from nil to well over 0.04 inches.

Figure 9-10 is a semilog plot of the relative increase in hydraulic conductivity of vertical fractures, spaced 3 inches apart, that is induced by horizontal tensile strain outside the mined panel. The relative change depends on the initial fracture aperture; 3 apertures ranging from 10^{-4} to 10^{-2} inches are assumed in the construction of Figure 9-10. Only fractional increases occur below the x-axis in Figure 9-10 (i.e., changes are less than an order of magnitude), while orders of magnitude increase are shown above the x-axis. Figures 9-10b and 9-10c present similar results at joint spacings of 30 and 300 inches. Generally, the relative increase is greater for smaller, more widely spaced joints or fractures.

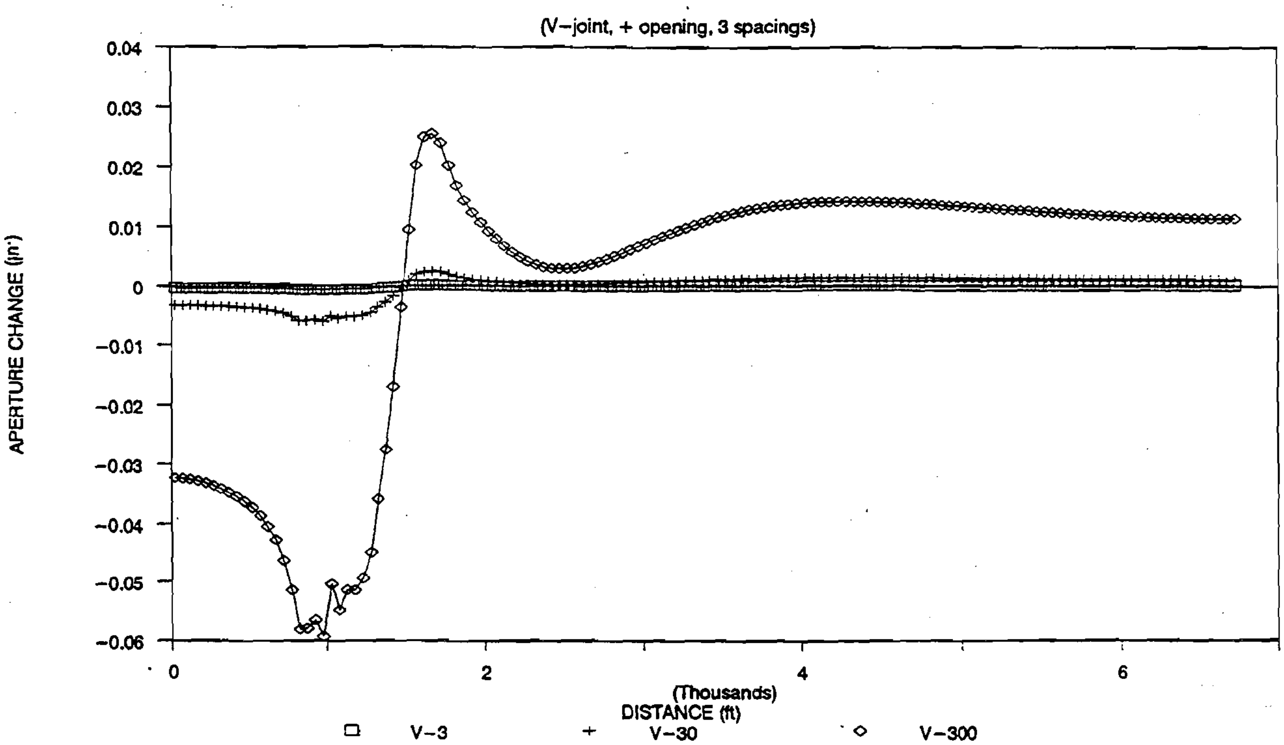

Figure 9-8. Aperture Change in Vertical Joints for Fracture Spacings of 3, 30, and 300 inches and Subsidence Factor of 52.5%

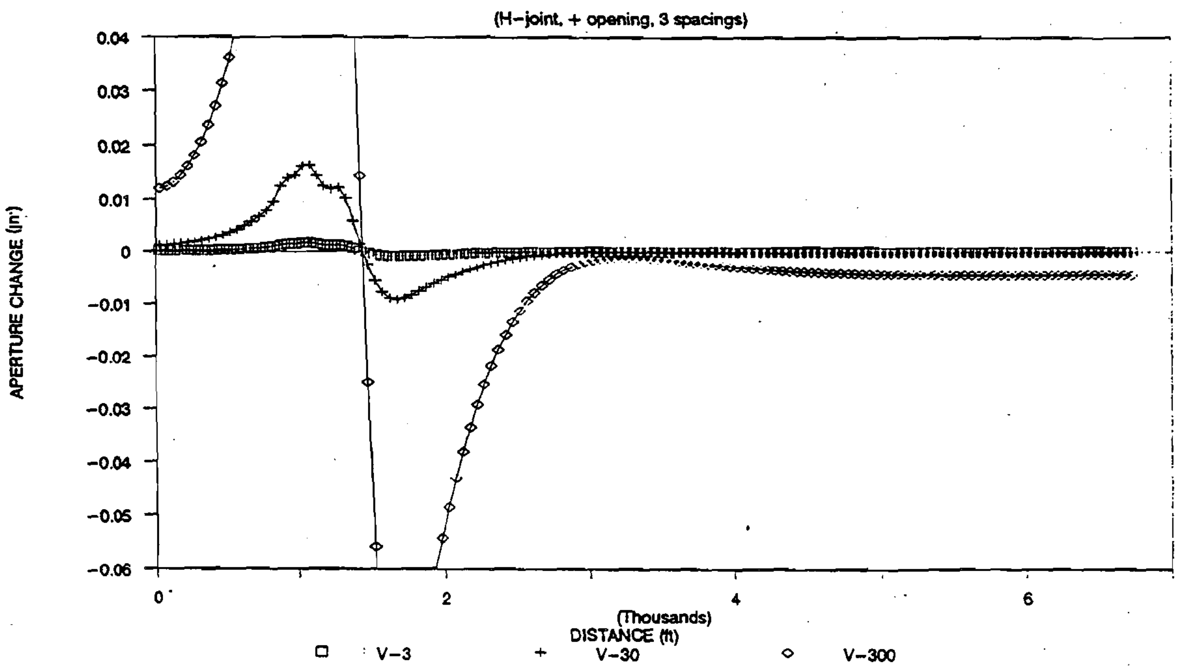

Figure 9-9. Aperture Change in Horizontal Joints for Fracture Spacings of 3, 30, and 300 inches and a Subsidence Factor of 52.5%

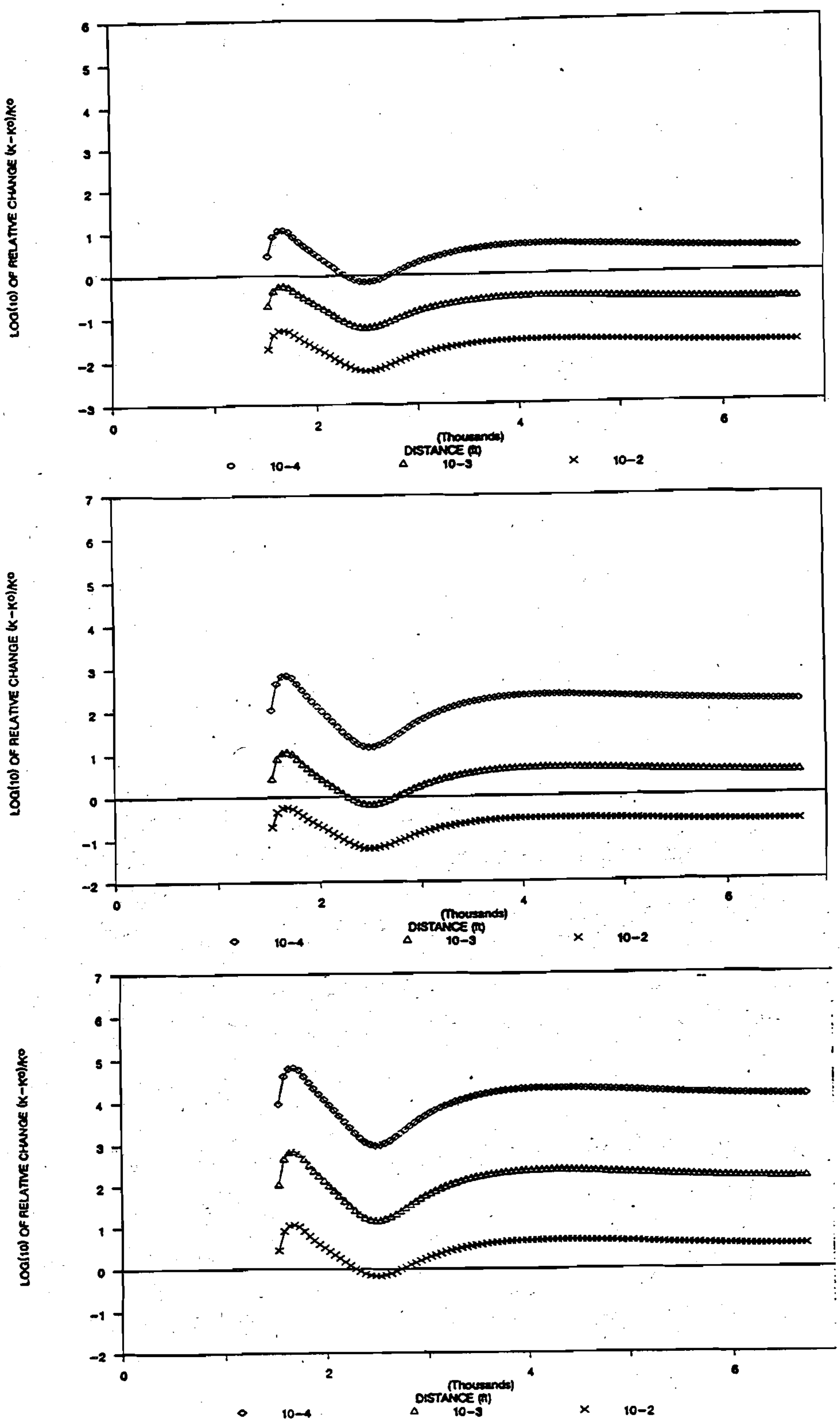

Figure 9-10. Relative Change in Fracture Hydraulic Conductivity for Vertical Joints with various Fracture Spacings, Subsidence Factor of 52.5%, and Fracture Apertures of 10^{-4}, 10^{-3}, and 10^{-2} in. a) 3 inch b) 30 inch c) 300 inch

Figures 9-11a, b, and c show the relative increase in hydraulic conductivity of horizontal joints over the mined panel. Joint spacings of 3, 30 and 300 inches were used for Figures 9-11a, b and c, respectively.

Case 2.

Horizontal and vertical strains in the Culebra formation are shown in Figure 9-12 for this case (S = 67.5%). The peak vertical tension is about 0.071% (710 micro-in/in) and occurs inside the panel as seen in this figure. The peak horizontal tensile strain is about 0.0053% (53 micro-in/in) and occurs 225 feet beyond the panel edge. With distance, the horizontal strain becomes compressive, then reverses to tensile, and reaches a secondary maximum of 0.0053% (53 micro-in/in) at 4,375 ft from the panel center. A gradual decrease occurs thereafter. The trends in vertical and horizontal strain are similar to Case 1. However, increasing the subsidence factor increased the peak vertical tension over the mined panel but decreased the peak horizontal tension outside the mined region. The secondary peaks outside the mined region changed very little.

Since the horizontal tensile strain did not decay with distance as much as expected (see Figure 9-12), the strain analysis was repeated with a larger mesh 9,000 ft by 13,500 ft. As shown in Figure 9-13, with the larger mesh, the horizontal tensile strain decayed to 7 micro-in/in at 7,025 feet from the panel center.

Figure 9-14 shows the change in *vertical* fracture aperture (opening or closing) in the Culebra formation as a function of distance from the panel center for three assumed joint spacings (3, 30 and 300 inches). Vertical joint opening which occurs outside the mined panel ranges from nil to about 0.015 inches which is a smaller range than in Case 1 because of the smaller peak horizontal tensile strain.

Figure 9-15 shows the results for horizontal joints which respond to vertical strain. The peak aperture changes at a 300 inch joint spacing are cut off in the plot. Horizontal joint opening which occurs above the mined panel ranges from nil to well over 0.04 inches.

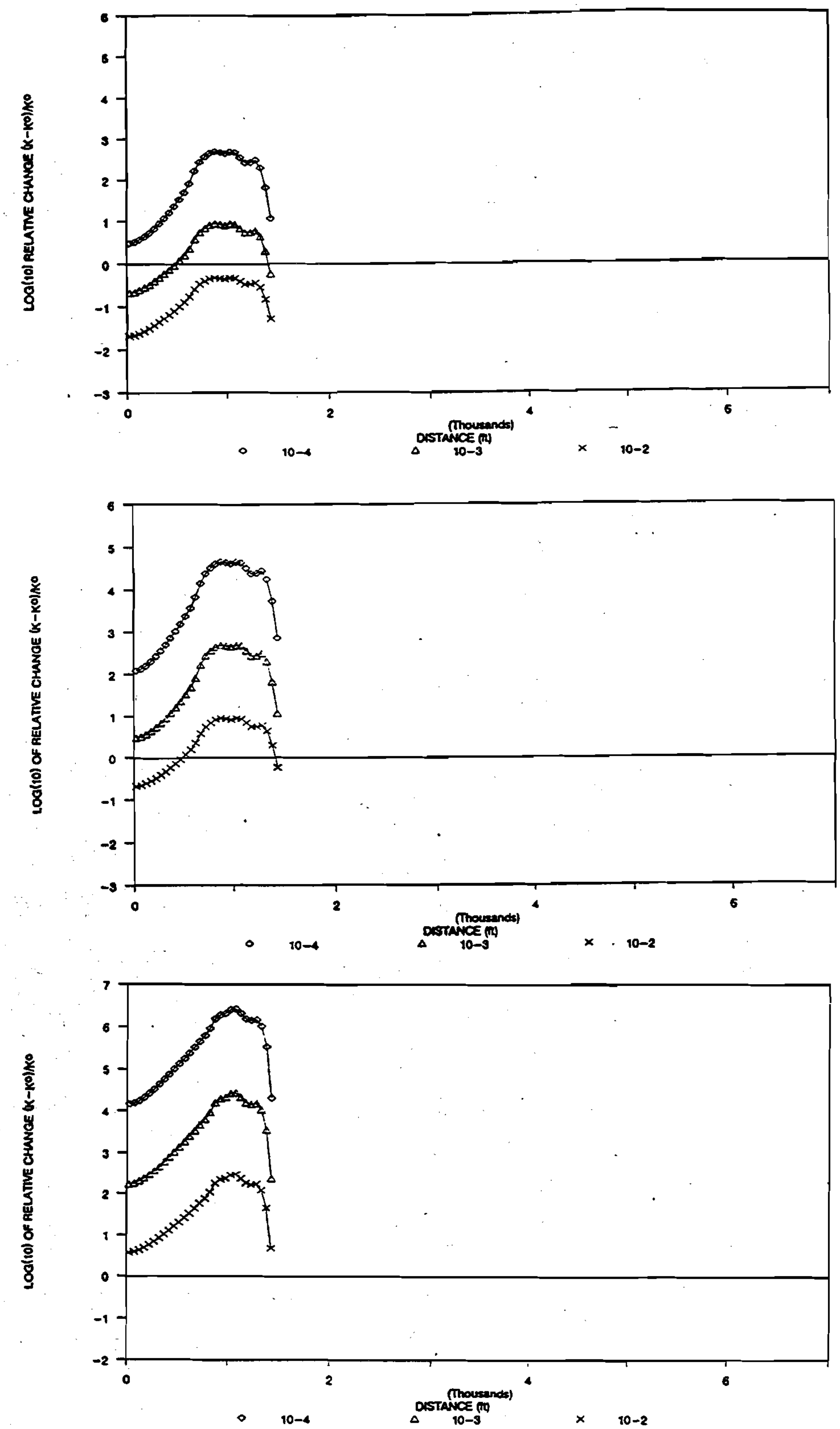

Figure 9-11. Relative Change in Fracture Hydraulic Conductivity for Horizontal Joints with various Fracture Spacings, Subsidence Factor of 52.5%, and Fracture Apertures of 10^{-4}, 10^{-3}, and 10^{-2} in. a) 3 inch b) 30 inch c) 300 inch

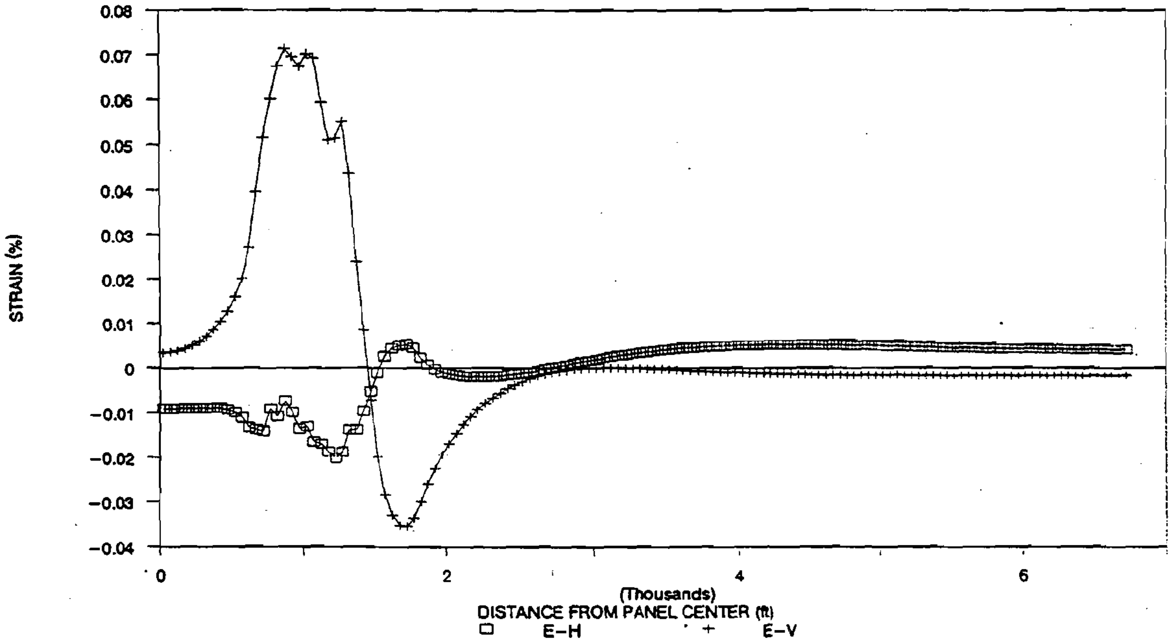

Figure 9-12. Subsidence-induced Culebra Strains for Subsidence Factor of 67.5%
(Panel extends +/-1,500 ft from origin)

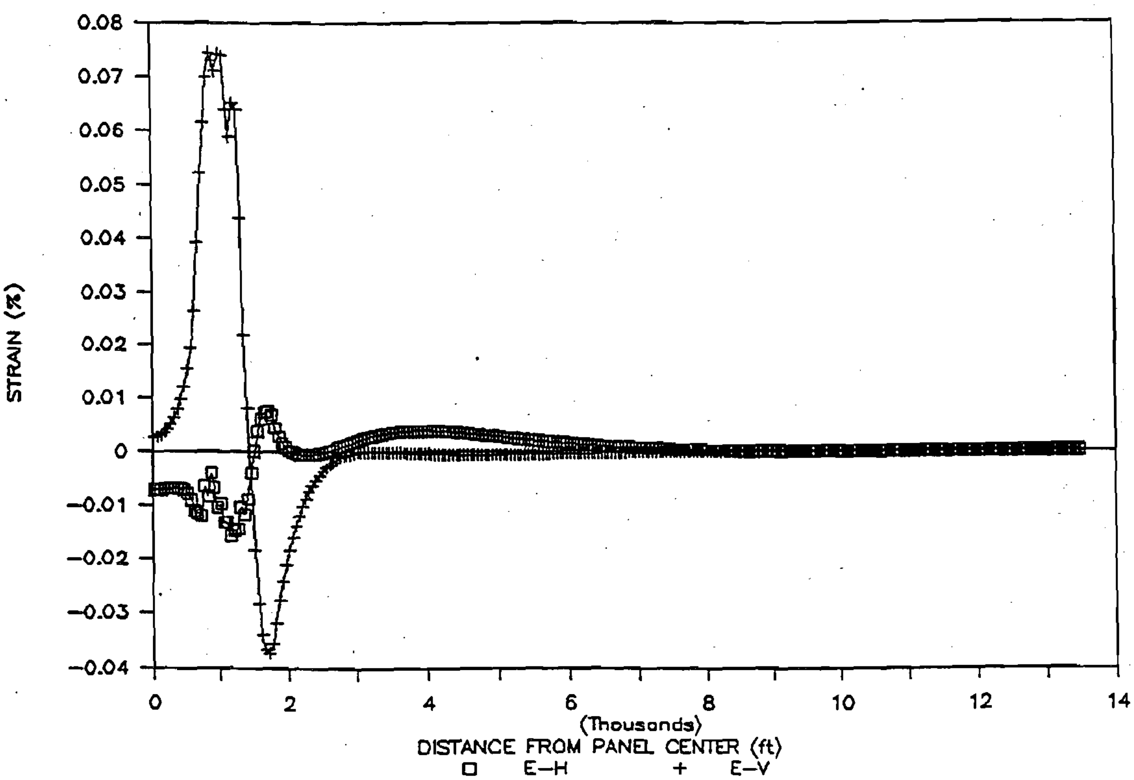

Figure 9-13. Subsidence-induced Culebra Strains for Subsidence Factor of 67.5%. (Panel extends +/-1,500 ft from origin.) Horizontal Mesh Extended to 13,500 ft.

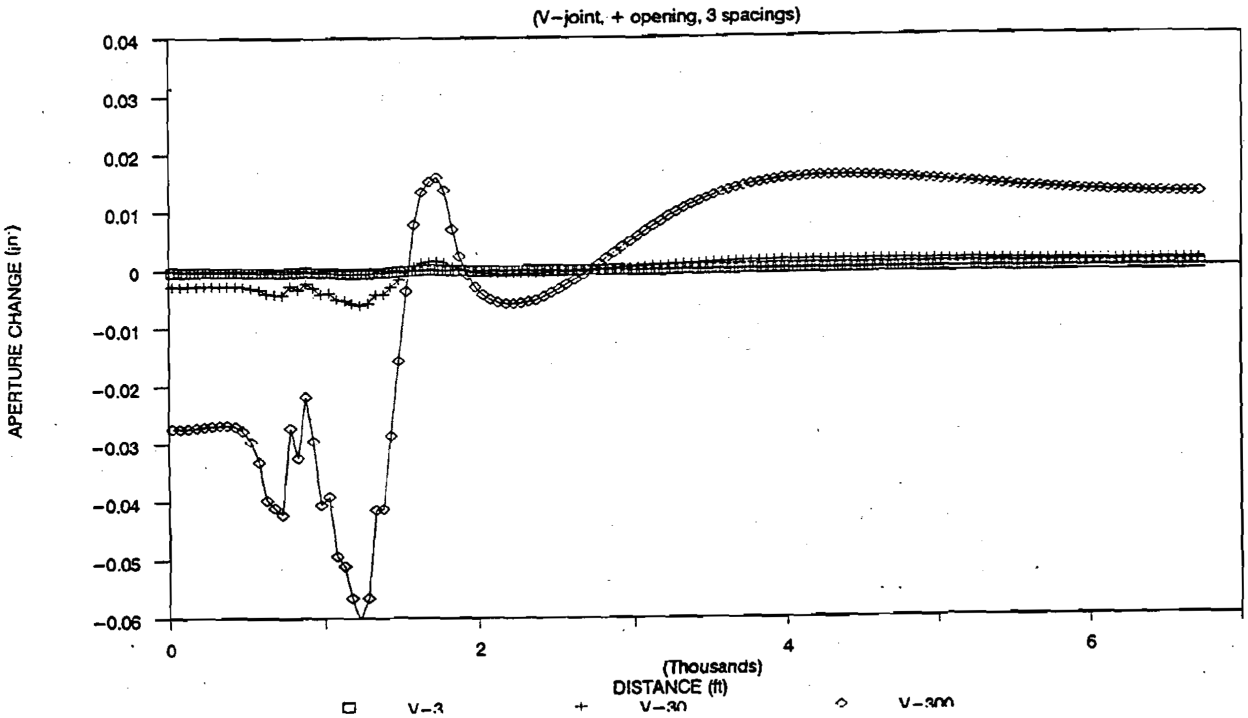

Figure 9-14. Aperture Change in Vertical Joints for Fracture Spacings of 3, 30, and 300 inches and Subsidence Factor of 67.5%

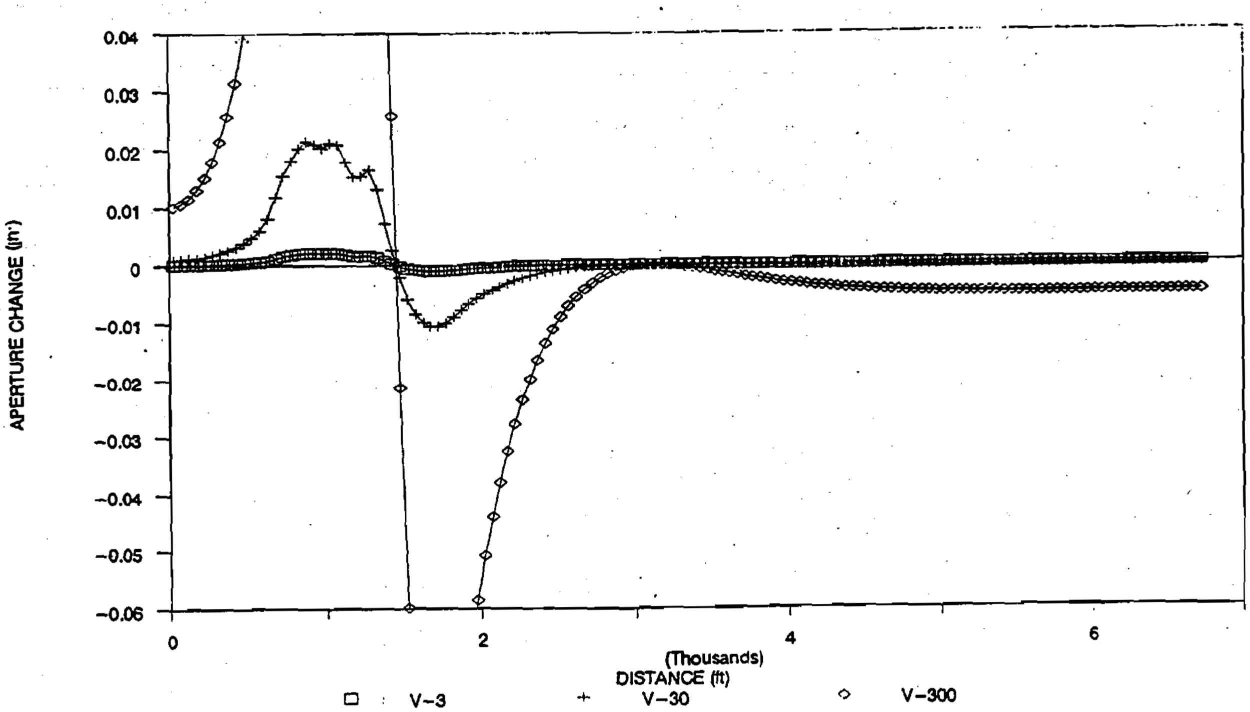

Figure 9-15. Aperture Change in Horizontal Joints for Fracture Spacings of 3, 30, and 300 inches and a Subsidence Factor of 67.5%

Comparison with Case 1, at a 30 inch joint spacing, shows greater horizontal joint opening in this case (somewhat more than 0.02 inches compared with somewhat less than 0.02 inches in Case 1).

Figure 9-16 shows the relative increase in hydraulic conductivity of vertical fractures, spaced 3 inches, that is induced by horizontal tensile strain outside the mined panel. The gap in the plot occurs as the horizontal strain outside the panel changes from tension to compression and then back to tension with distance from the panel edge. The magnitudes of the relative change in hydraulic conductivity of the joints are similar to the previous case. Figures 9-16b and 9-16c present similar results at joint spacings of 30 and 300 inches. As before, the relative increase is greater for smaller, more widely spaced joints or fractures. Relative fracture conductivity changes for horizontal joints are included in Figures 9-17a, b, and c.

Conclusion

Simulation of full extraction mining of 10 ft of potash at a depth of about 1,500 ft near the WIPP shows large vertical tensile strains over the mined panel and slowly decreasing horizontal tensile strains beyond the panel edge. Although generally in the elastic range, the strains, when integrated between assumed fractures, lead to displacements that are significant relative to existing fracture apertures.

9.4.5 Consideration of Other Mining Impacts

In addition to subsidence-induced increased hydraulic conductivity of the Culebra, several other potentially detrimental scenarios were postulated in Section 9.4.2 above. These are discussed in the context of the information presented here.

9.4.5.1 Solution Mining

As described earlier, solution mining of langbeinite is not technically feasible because the evaporite minerals which surround the ore are more soluble than the ore itself. Attempts to solution mine sylvite have not met with success because of the characteristics of the ore body. Thus, it appears unlikely that this technique will be applied to potash ores in the region around the WIPP.

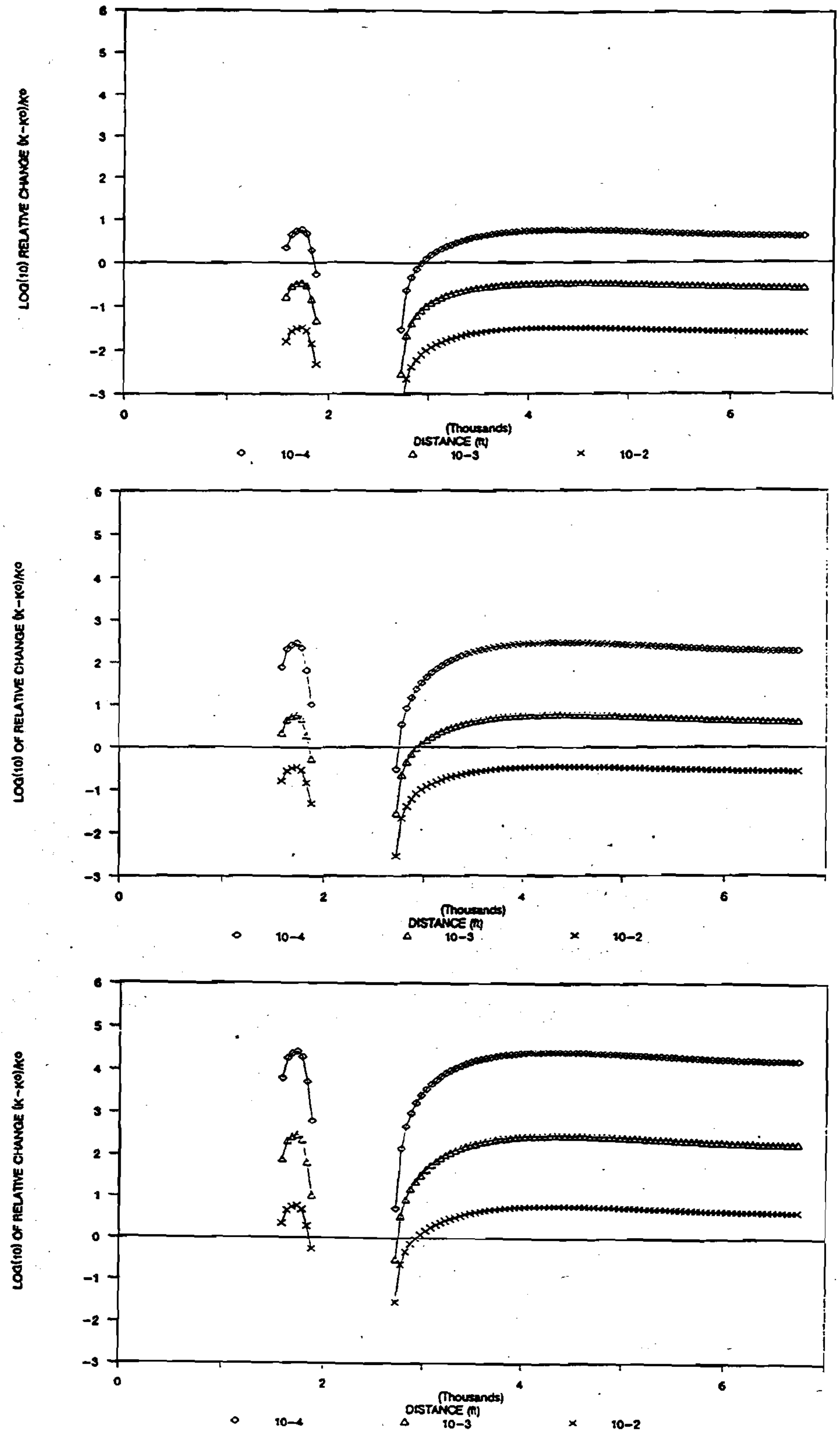

Figure 9-16. Relative Change in Fracture Hydraulic Conductivity for Vertical Joints with various Fracture Spacings, Subsidence Factor of 67.5%, and Fracture Apertures of 10^{-4}, 10^{-3}, and 10^{-2} in. a) 3 inch b) 30 inch c) 300 inch

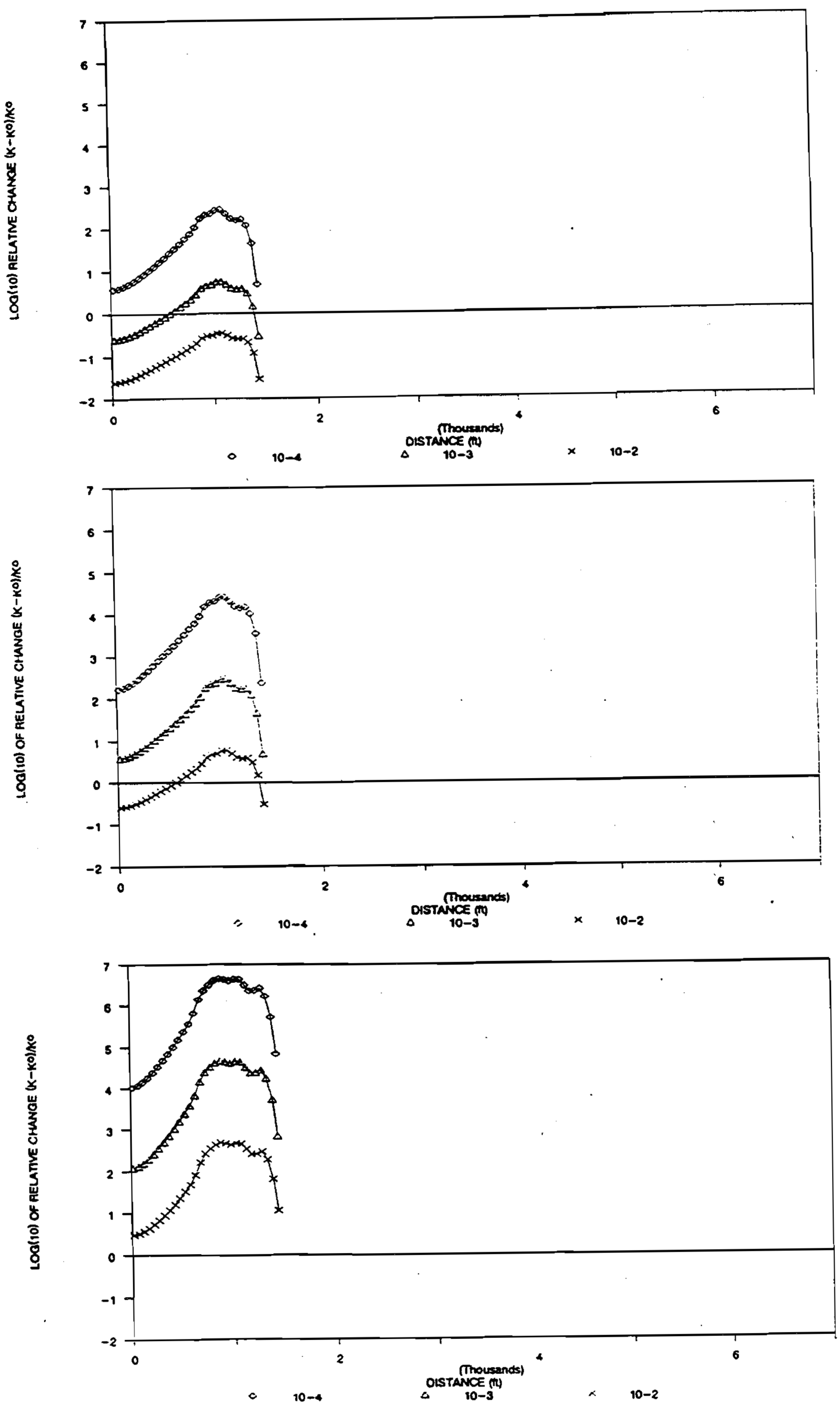

Figure 9-17. Relative Change in Fracture Hydraulic Conductivity for Horizontal Joints with various Fracture Spacings, Subsidence Factor of 67.5%, and Fracture Apertures of 10^{-4}, 10^{-3}, and 10^{-2} in. a) 3 inch b) 30 inch c) 300 inch

9.4.5.2 Change in Flow Direction of Water-Bearing Members if a Vertical Hydraulic Connection Is Created By Subsidence

As discussed in the Section 9.4.2, if a hydraulic connection did occur, the result could be a shifting of flow in the Culebra toward the southwest. According to information presented by Reeves et al. (REV91), the current travel path is toward the southeast and entails a distance about 3,600 m from the center of the waste area to the southern boundary of the withdrawn area. If subsidence produced a hydraulic connection between the water-bearing members of the Rustler Formation and flow shifted toward the southwest, then the travel distance could be shortened to 2,415 m which is the shortest distance from the southernmost panel in the waste area to the southern boundary of the land withdrawal area. This would represent a 33% decrease in travel distance to the accessible environment. However, this shift would also move the contaminant travel paths into zones of lower hydraulic conductivities which would result in longer travel times to the accessible environment (REV91).

9.4.5.3 Formation of Subsidence-Related Surface Depressions Where Water Could Accumulate and Alter Local recharge Characteristics

As noted in Section 9.4.3.2, the maximum observed surface subsidence over existing potash mines in the area is 1.5 m. Using what are believed to be conservative factors (from Sections 9.4.3.1 and 9.4.3.2) in equation 1, including an extraction ratio 90%, a mine height of 2.6 m (8.5 ft), and a subsidence factor of 0.67, the calculated surface subsidence would be 1.6 m. Subsidence of this order is less than the quoted surface relief in the area of 3 meters. Thus, topographical depressions where significant surface water could accumulate and alter local recharge are not likely.

9.4.5.4 Increased Hydraulic Gradient If Significant Flow From Water-Bearing Strata into Mine Workings Occurs

Flow of water from the Culebra and Magenta Members of the Rustler Formation into open shafts has been observed for all four shafts at the WIPP site (CAU90). Leakage into shafts for various area potash mines has also been reported (CAU90). Quoted leakage values for the open WIPP shafts are:

- construction and salt handling shaft - 0.019 to 0.11 l/s (599.0-3469.0 m^3/yr)
- waste handling shaft - 0.019 to 0.038 l/s (599.0-1198.0 m^3/yr)
- exhaust shaft - 0.026 to 0.030 l/s (820.0-946.0 m^3/yr)
- air-intake shaft - 0.030 to 0.056 l/s (946.0-1766.0 m^3/yr)

Flows of this magnitude would not persist if the shafts can be adequately sealed after mining operations have ceased or once the formation is dewatered. The Bureau of Land Management does not currently have in place specific regulations for sealing abandoned mine shafts in the KPLA. Rather, abandonment procedures are initiated by the mining companies and the sealing plans are developed on a case by case basis with the BLM (GRI96, CRA96). For example, a current operation involves local removal of the shaft liner and replacement with a concrete plug which extends from the top of the Salado Formation to the bottom of the Culebra Member of the Rustler Formation. The plug is 16 to 30 feet in length. The water bearing formations above the plug will be sealed by grouting to prevent the buildup of water on the top of the plug. Procedures for future sealing operations may be different. There is no available evidence as to the longevity of these types of seals. It is reasonable to assume, however, that even degraded seals would somewhat impede flow into the shafts.

Since it is not clear that currently contemplated shaft seals will prevent leakage for long periods, it is necessary to consider the impacts of leakage on hydraulic gradients and travel times to the site boundary. To investigate the potential impacts that mining operations may have on groundwater gradients and subsequent contaminant migration rates, a two-dimensional modeling analysis was performed. The analysis assumes that the system is confined and under steady-state conditions. The model also assumes that all groundwater flow is horizontal and occurs within the matrix (i.e, unfractured flow). The Culebra is represented as a homogeneous and isotropic porous medium at a constant thickness of 7.7 m, and an effective porosity of 13.9 percent. A series of simulations were performed in which the hydraulic conductivities (K) were varied from 7 to 500 m/yr to reflect their potential impact on altering contaminant migration rates (Table 9-6).

Since the rate at which radionuclides are transported by groundwater is directly proportional to the hydraulic gradient, any perturbances to the gradient will have a commensurate effect on migration rates. Furthermore, depending upon location, the presence of mining shafts in the vicinity of WIPP could have either a beneficial or detrimental effect on the performance assessment. Shafts located upgradient from a hypothetical human intrusion (i.e., borehole) would tend to lower or even possibly reverse the hydraulic gradients, thus, reducing the contaminant velocities and subsequent radionuclide releases at the WIPP land withdrawal boundary. Alternatively, shafts located downgradient from an intrusion would result in increased gradients towards the shaft which would tend to accelerate groundwater velocities.

Table 9-6. Summary of Results for Mine Shaft Leakage Scenario

Hydraulic Conductivity (m/y)	Time to Travel 2 km without Shaft (yr)	Groundwater Velocity without Shaft (m/y)	Time to Travel 2 km with Shaft (yr)	Groundwater Velocity with Shaft (m/y)	Flow rate into Shaft (m^3/y)
7	12400.0	0.16	9800.0	0.2	161.0
20	4350.0	0.459	3430.0	0.583	460.0
50	1750.0	1.14	1370.0	1.45	1150.0
500	175.0	11.4	137.0	14.45	11500.0

The shortest distance from the southernmost panel of the WIPP repository to the WIPP land withdrawal boundary is due south, approximately 2400 m. The ambient groundwater gradient also has a strong southerly component. Therefore, for this modeling exercise, the hypothetical mine shaft is located 2000 m downgradient from the waste disposal area. This distance was selected to maximize the effects that would occur if the groundwater gradients were affected by mining; in that the mine shaft is not so far away as to have little effect on flow, yet it is not so close as to create a zone of influence in which contaminants flowing past the mine shaft would actually travel slower due to the diminishing gradient effects that will occur downgradient of the mine shaft.

To maximize the effect that the mine could have on the hydraulic gradients, the drawdown at the mine was set almost at the base of the Culebra at 7.7 m, leaving a seepage face of 0.1 m at the shaft. The flow rate due to this drawdown was then computed by the model (Table 9-6). For example, where K = 7 m/yr, the calculated flow rate is 161 m^3/yr. Because the drawdown was maximized, this value represents a reasonable upperbound for the volume of water that would flow into the open shaft at a Culebra transmissivity (hydraulic conductivity multiplied by unit thickness) of 53.9 m^2/yr.

The hydraulic gradient was also computed at selected points upgradient of the hypothesized mine shaft and compared to the ambient gradient of 0.0032 under current non-mining conditions. Since the functional relationship between drawdown and transmissivity can be linearly extrapolated to any value of hydraulic conductivity, the overall effect on gradients that is imposed by varying hydraulic conductivities is virtually identical. To illustrate this relationship, the ratio of the gradient under mining conditions to the original gradient of 0.0032 was computed and is shown on Figure 9-18.

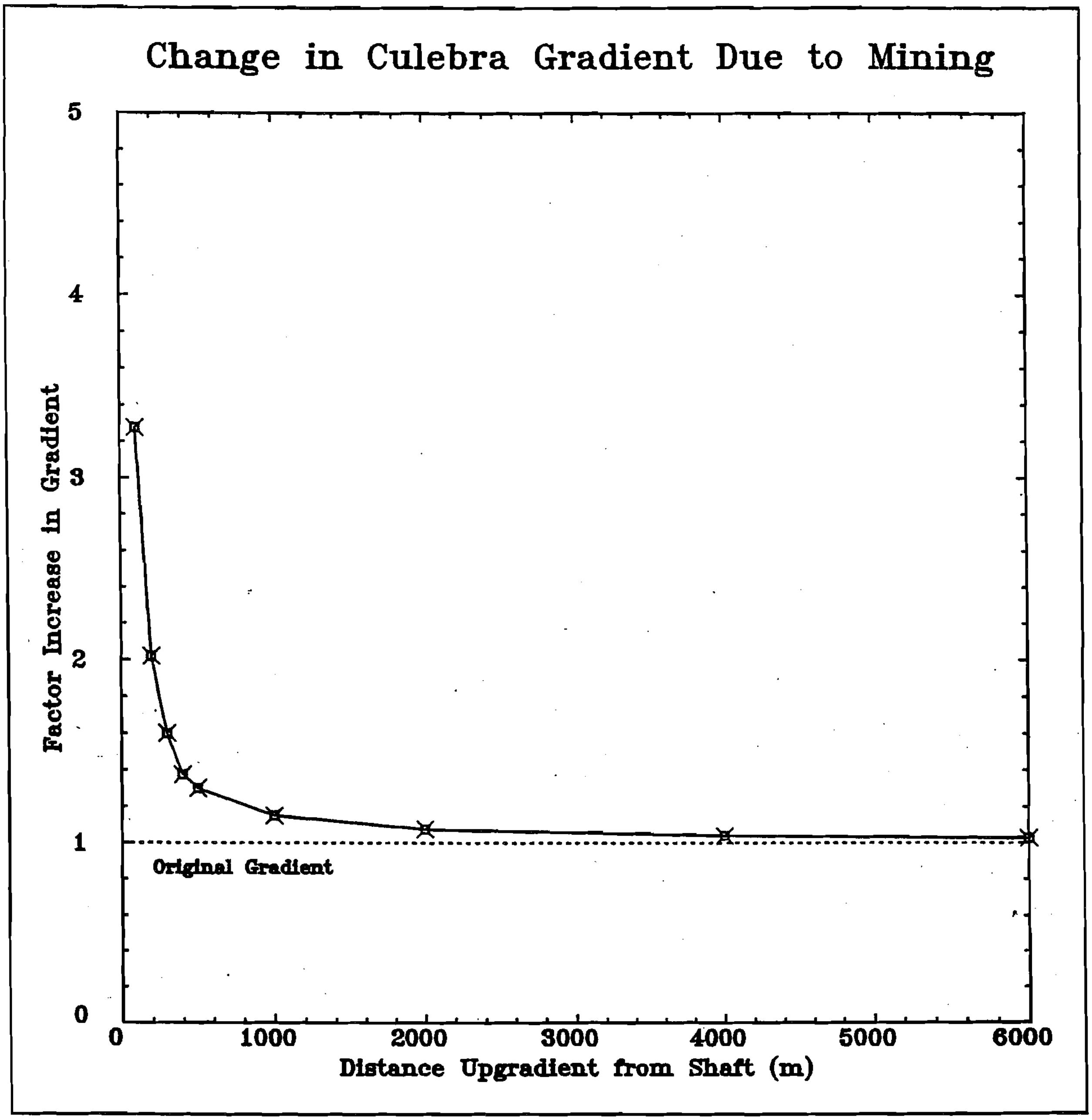

Figure 9-18. The ratio of the hydraulic gradient imposed by mining to the ambient gradient.

To investigate the effect that this change in gradient would have on migration rates, a particle-tracking analysis was performed. This type of analysis moves a particle at the same velocity as the groundwater and the rate is not affected by dispersion, diffusion, or retardation. The results from this travel time analysis are presented in Table 9-6.

In each case, the contaminant would travel approximately 27% faster over the 2000 m distance when the hydraulic gradient is affected by a mine shaft placed in a location chosen to represent mining's maximum expected effect on the hydraulic gradients. The increase for each of the simulations 27% above velocities calculated at ambient gradients and is shown in column 5 of Table 9-6. This increase is small when compared to changes in velocity due to potential increases in the hydraulic conductivity. As required by the rule, hydraulic conductivities will be increased by up to a 1000 fold above their current measured values. To place this travel time change caused by the mine shaft in perspective, groundwater velocities for each of the simulations have been recalculated using hydraulic conductivities that range from 2 to 1000 times their original values and are shown in Table 9-7. In each example, the lowest values for the recalculated velocities fall well above the velocity values that are increased by 27% due to the change in gradient. This velocity comparison indicates that increases in hydraulic conductivity over the range specified by EPA have far greater potential effects on groundwater velocities than increases in the velocities caused by altered hydraulic gradients due to mine shaft leakage. In light of the EPA requirement that DOE perform analyses that are more stringent in evaluating mining effects than those associated with an increase in gradient, it is reasonable to assume that the consequences a 27% decrease in travel time will have on the overall performance assessment will be captured by those additional analyses.

Table 9-7. Groundwater Velocities at Hydraulic Conductives the Range from 2-1000 times those values presented in Table 9-6.

Hydraulic Conductivity (m/y)	Groundwater Velocity
14.0-7000	0.32-161.0
40.0-20,000	0.92-460.0
100.0-50,000	2.30-1151.0
1000.0-500,000	23.0-11510.0

9.4.5.5 Damage to Borehole or Shaft Seals by Subsidence

From the information supporting Figure 9-4, it can be shown that the closest approach of the sylvite reserves (a grade x thickness product of 40) to waste shaft is slightly over 2,500 feet. The top of this sylvite ore zone (the 10th) lies about 1,900 feet below the surface (GRI95). Based on a 45° angle of draw, the impacted area from mining the BLM lease grade reserves would be about 600 feet from the waste shaft at the surface and at proportionately greater distances below the surface where maintenance of the shaft seal is more important (e.g., through the Rustler Formation). Alternatively, if one assumed the most pessimistic angle of draw (58°) reported for the area in ITC94, the maximum extent of the impacted area would be 3,040 feet and the disturbed zone would intersect the waste shaft at about 340 feet below the surface. The juncture is still some 200 feet above the top of the Rustler Formation and thus shaft seals should not be affected at any critical location in transmissive members of this formation.

If all the BLM lease grade reserves within the repository were mined out, a number of boreholes would be undercut by the mining operations and the sealed area of the borehole subject to subsidence-induced strains. Some of these impacted boreholes are shown in Figure 9-4. However, the borehole seals between the repository and the mine workings should not be affected by the mining operations[14].

Thus, it is not expected that mining would breach shaft seals at any critical point along the sealed length and would not affect borehole seals between the repository horizon and the mine workings (about 430 feet). Consequently, pathways would not be opened to the repository by a mining related seal failure mechanism which would facilitate release of radionuclides.

9.4.5.6 Increased Hydraulic Conductivity of the Salado Formation Due to Excavation-Induced Stresses

As discussed in Section 9.4.3.1, the maximum increase in the hydraulic conductivity of the Salado Formation due to stress redistribution around underground openings is expected to be about an order of magnitude and this altered conductivity decreases rapidly as one moves away from the mined opening. At a distance equal to six times the width of the opening, the

[14] Inside the withdrawn area, only four boreholes associated with the WIPP Project (WIPP 12, 13, DOE 1, and ERDA 9) and two earlier oil and gas holes reached or exceeded the depth of the repository.

altered conductivity is only twice that of undisturbed salt. Even with changes of this magnitude, the salt would remain highly impermeable. In addition, creep should cause the salt to revert to near the undisturbed state.

9.4.6 Summary

Extensive potash mining operations are being conducted in the vicinity of the WIPP site with current mine workings less than 1.5 miles from the site boundary (DOE95). Existing potash leases abut the site boundary around much of its perimeter (SIL94) and its is expected that current mining operations will be extended to the land withdrawal boundary.

Reserves and resources of both sylvite and langbeinite exist within the land withdrawal boundary. Based on current BLM lease grade standards (four feet of 4% K_2O for langbeinite and four feet of 10% K_2O for sylvite), the langbeinite reserves are within 3,490 feet of the waste repository footprint and sylvite reserves are within 1,330 feet of the footprint. These reserves cannot be exploited currently because the WIPP LWA prohibits mining within the withdrawn area.

At some time in the future, after active institutional controls are no longer practicable and, if passive institutional controls have failed to warn about the buried hazards, it is a conceptual possibility that mining of the ore remaining within the withdrawn area could occur. Such a hypothetical mining operation would probably require development of a new infrastructure since existing reserves outside the withdrawn area would likely have been depleted prior to the failure of institutional controls.

The most likely detrimental impact of such future mining would be increased hydraulic conductivity of the Culebra Member of the Rustler Formation resulting from subsidence-induced fracturing of the relatively brittle dolomite. This fracturing (or widening of existing fractures) could reduce the lateral transit time for radionuclides to the accessible environment. The increased hydraulic conductivity is of no consequence unless a hydraulic connection exists between the Culebra and the repository 1,440 feet below. Based on current WIPP scenarios, the hydraulic connection could be created by an inadvertently drilled borehole which intersected the repository. Thus performance assessment will need to address the probability and consequence of such a combination of events. Based on studies reviewed here, it does not appear that other mining-related scenarios will have significant detrimental effects on the natural and man-made barriers protecting the repository.

Simulation of full extraction mining of 10 ft of potash at a depth of about 1,500 ft near the WIPP shows vertical tensile strains over the mined panel and slowly decreasing horizontal tensile strains beyond the panel edge. Although generally in the elastic range, the strains, when integrated between assumed fractures, lead to displacements that are significant relative to reasonable fracture apertures. This, in turn, can increase the fracture hydraulic conductivity of the Culebra.

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10. Active Institutional Controls

10.1 INTRODUCTION

10.1.1 Regulatory Requirements Relevant to Institutional Controls at WIPP

In recognizing the many uncertainties inherent in the analyses for the containment criteria, as established in Subpart B of 40 CFR part 191, EPA developed assurance requirements to guarantee that the implementing agencies act cautiously and take steps to reduce such uncertainties. The following six assurance requirements are stipulated in §191.14:

- Active Institutional Controls
- Monitoring
- Passive Institutional Controls
- Barriers
- Resource Disincentives
- Waste Removal

Active institutional controls are defined in §191.12(f) as:

> "Active institutional controls means: (1) Controlling access to a disposal site by any means other than passive institutional controls; (2) performing maintenance operations or remedial actions at a site, (3) controlling or cleaning up releases from a site, or (4) monitoring parameters related to disposal system performance."

Active institutional controls operate sequentially in conjunction with passive institutional controls to protect and mark the WIPP site. Passive institutional controls are defined in §191.12(e) as:

> "Passive institutional controls means: (1) Permanent markers placed at a disposal site, (2) public records and archives, (3) government ownership and regulations regarding land or resource use, and (4) other methods of preserving knowledge about the location, design, and contents of a disposal system."

Active institutional controls are applied after "disposal," (i.e., after all shafts to the repository are backfilled and sealed (§191.02(1)), when the waste has been permanently isolated with no intent of recovery. According to §191.14(a), "active institutional controls over disposal sites should be maintained for as long a period of time as is practicable after disposal; however, performance assessments that assess isolation of the wastes from the accessible environment shall not consider any contributions from active institutional controls for more than 100 years after disposal." In Appendix C of 40 CFR part 191, guidance is provided for implementation of institutional controls that states "the implementing agency will assume that none of the active institutional controls prevent or reduce radionuclide releases for more than 100 years after disposal. However, the Federal Government is committed to retain ownership of all disposal sites for spent nuclear fuel and high-level and transuranic wastes and will establish appropriate markers and records, consistent with §191.14(c)."

Based on the active institutional controls requirement of 40 CFR part 191, EPA included the following compliance criterion under §194.41(a) of the 40 CFR part 194 regulations:

> "Any compliance application shall include detailed descriptions of proposed active institutional controls, the controls' location, and the period of time the controls are proposed to remain active. Assumptions pertaining to active institutional controls and their effectiveness in terms of preventing or reducing radionuclide releases shall be supported by such descriptions."

Examples of <u>active</u> institutional controls employed for the purpose of restricting site access include (EPA88):

- a [maintained] security fence and other barriers,
- security guards
- routine patrols
- electronic surveillance

Examples of <u>passive</u> institutional controls include signs, markers, deed restrictions, land-use controls, records, and legal documents. Passive institutional controls should warn those who attempt to enter the disposal site vicinity of the hazards associated with activities that would disturb the subsurface. Furthermore, passive institutional controls require comprehensive actions that will increase the likelihood that knowledge and information about the disposal site and its contents are passed on to future generations.

10.1.2 WIPP Site Characteristics

10.1.2.1 Site Description

The WIPP site is located in Eddy County, in southeastern New Mexico. The site is 26 miles east of Carlsbad on a relatively flat, sparsely inhabited plateau with little surface water and limited land uses. The land is primarily used for grazing. Other land uses within five miles of the WIPP boundary include potash mining and oil and gas exploration and development (SAN92).

The WIPP is a controlled site of 10,240 acres, which has been withdrawn from all forms of entry, appropriation, and disposal including, without limitation, mineral leasing laws, geothermal leasing laws, material sale laws, and mining laws as described in the WIPP LWA. Areas designated as subdivisions within the WIPP site boundary include Zones I and II. Zone I is an area of 35 acres surrounded by a chain link fence. Zone I encloses all the major surface facilities. Zone II overlies the maximum extent of underground development and encompasses an area of about 277 acres. The WIPP site boundary provides a minimum of a one-mile wide buffer area of intact salt beyond Zone II (DOE93).

10.1.2.2 WIPP Facilities

The WIPP site contains surface and underground facilities interconnected by four shafts. The surface structures accommodate the personnel, equipment, and support services required for the receipt, preparation, and transfer of transuranic radioactive waste from the surface to the underground. The underground facility is constructed in a bedded salt formation 2,150 feet (655 m) below the surface. Existing underground facilities include the TRU waste disposal area, the experimental area, and the underground maintenance and support area (SAN92).

10.1.2.3 Waste Characteristics

DOE will use the WIPP to receive and dispose of TRU waste. TRU waste are those wastes containing radioactive elements with an atomic number greater than 92, a half-life greater than 20 years, and a concentration greater than 100 nanocuries per gram, excluding high-level waste and/other specific waste types. Some of these wastes are co-contaminated with hazardous constituents, making them mixed wastes. The wastes will be shipped in specially designed transportation containers and will be packaged in 55-gallon drums and/or standard waste boxes.

10.1.2.4 Operations

Following receipt and inspection, the waste containers, will be downloaded into the subsurface repository. Ultimately this repository will consist of eight "panels," each of which will contain seven separate disposal "rooms" and interconnecting drifts. After an entire panel is filled, it may be closed to isolate it from the rest of the repository.

DOE expects that waste emplacement will begin in 1998 and continue for a 25-year period until the regulated capacity of the repository of 6,200,000 ft^3 of TRU waste has been reached. This capacity restriction must also include TRU waste derived from any decontamination activities during the disposal phase and decommissioning.

10.1.2.5 Closure/Post-Closure Activities

Current DOE plans indicate that prior to closing the waste disposal area, surface facilities will be decontaminated. Contaminated material that cannot be sufficiently cleaned to be released as uncontrolled material will be emplaced within the waste disposal area.

The final activities within the repository will be the closing of the waste disposal area and the sealing of the shafts. Upon completion of this activity, the remaining surface structures will be dismantled. All surface structures will be removed, except for the concrete Hot Cell structure and a sufficient quantity of salt tailings to support construction of the permanent marker berm. Disturbed land will be regraded and planted to return the site to as near its original condition as is practicable. At completion of the closure phase, DOE will implement the WIPP <u>active</u> institutional controls program.

10.2 ACTIVE INSTITUTIONAL CONTROLS PROPOSED FOR THE WIPP SITE

As part of the active institutional controls program, DOE has developed a set of design criteria that describe how the active institutional controls will be implemented. These criteria are summarized below:

- A fence line shall be established to control access to the repository's footprint area (the waste disposal area projected to the surface). A standard wire fence shall be erected along the perimeter of the repository surface footprint. The fence shall have gates placed approximately midway along each of the four sides.

- An unpaved roadway along the perimeter of the barbed wire fence shall be constructed to provide ready vehicle access to any point around the fenced perimeter, to facilitate inspection and maintenance of the fence line, and to permit visual observation of the repository footprint to the extent permitted by the lay of the land. This roadway shall connect to the paved south access road.

- To ensure visual notification, the fence line shall be posted with signs having, as a minimum, a legend reading "**Danger-Unauthorized Personnel Keep Out**" and a warning against entering the area without specific permission of DOE, or other local authority such as the Eddy County Sheriff's Office.[1]

- Contractual arrangements shall be developed to ensure that periodic inspections and necessary corrective maintenance are conducted on the fence line, its associated warning signs, and the roadway.

- Through direct DOE staffing support and/or contractual arrangements, procedures shall be established to provide routine periodic patrols and surveillance of the protected area by personnel trained in security, surveillance, and investigation.

- Processes will be developed for monitoring and controlling the long-term testing requirements of the permanent marker system.

- Processes will be developed for implementing the periodic monitoring requirements of the disposal system's monitoring program.

- Recommendations will be developed for modifications to the active institutional controls appropriate for access control and surveillance upon installation of the permanent marker system.

- Guidelines will be developed for recommending mitigation actions to be taken to address any abnormal conditions identified during periodic surveillance and inspections.

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[1] DOE is suggesting use of the Eddy County Sheriff's Department to conduct periodic surveillance of WIPP active institutional controls. This surveillance would be conducted pursuant to a contract between the DOE and the Sheriff's Department.

- Reports of activities associated with the post-disposal active access controls shall be prepared in accordance with regulatory requirements for submittal to the appropriate regulatory and legislative authorities.

Details on meeting these criteria were submitted as, "WIPP Active Access Controls After Disposal Design Concept Description." Summarized below are additional noteworthy items delineated in the report.

- Access control. Access to an area approximately 2,780 feet by 2,360 feet will be controlled by a 4 strand (3 barbed and 1 unbarbed in accordance with the Bureau of Land Management specifications) wire fence. A single gate will be placed approximately mid-way along each side of the fence for access. The western gate shall be 20 feet wide; and the remaining three gates shall each be 16 feet wide. Around the perimeter of the fence, an unpaved roadway 16 feet wide will be cut to allow for patrolling of the perimeter. Patrolling of the perimeter is based upon the need to ensure that no mining or well drilling activity is inadvertently initiated which could threaten the integrity of the repository.

- Surveillance monitoring. Surveillance monitoring will consist of drive-by patrolling around the fenced perimeter, two to three times per week. During the course of the patrol, particular note shall be taken of fence integrity, gate integrity, and locked conditions of each gate. Surveillance should also include visual observation of the entire enclosure area for any signs of human activity.

- Maintenance and remedial actions. Anticipated maintenance and remedial action issues during the active control period are minimal and should encompass issues such as fence/road maintenance, evidence of vandalism, potential erection of drilling equipment, grass fires, unauthorized entry in prohibited areas.

- Control and cleanup of releases. DOE intends to complete the decontamination process and disposal of derived radioactive waste prior to final closure of the waste disposal area and sealing of the shafts.

- Long-term monitoring. Details describing the establishment of a network of elevation benchmarks and the development of a data baseline from which to evaluate disposal system performance is described in the Long Term Monitoring Design Concept Description (DOE94). (NOTE: Disposal system monitoring is addressed in §191.14 as a separate assurance requirement; therefore this topic is discussed in detail in Chapter 11).

10.3 INSTITUTIONAL CONTROLS AT OTHER FACILITIES

For comparison, a review was conducted of active institutional controls proposed or implemented at other facilities and their corresponding regulations. (It should be noted that, although the focus of this chapter is active institutional controls, in practice and in the regulations there may not always be a clear delineation between active and passive controls.) DOE and Department of Defense (DOD) facilities that contain special nuclear material, NRC-licensed nuclear reactor facilities, low-level waste disposal facilities, uranium mill tailings disposal sites, and Superfund sites were examined. This review focused on those institutional controls specifically designed for protection against human intrusion because they have the most relevance to the WIPP.

10.3.1 Facilities Containing Special Nuclear Material

A number of DOE and DOD facilities must protect special nuclear material. The access controls at these facilities represent the extreme end of the controls continuum that could be considered for application at the WIPP. Typically, these controls include continuous monitoring by armed guards, double rows of chain link fence topped with barbed wire, motion detectors, infrared detectors, and visual surveillance using remote TV cameras. These controls are designed to prevent intentional intrusion into critical areas where the special nuclear material is stored, and to ensure the material is not stolen or sabotaged. These controls also prevent inadvertent intrusion. Many of the specific control elements in place at these facilities resemble the proposed controls for WIPP. For example, the fact that the TRU waste will be over 2,000 feet below the surface should be at least as effective a control as the fencing arrangement at DOE special nuclear facilities such as Pantex.

10.3.2 Retired Nuclear Reactor Facilities

When a nuclear reactor has reached the end of its useful life, it must be decommissioned in accordance with the requirements established in 10 CFR part 50. NRC regulations define "decommissioning" as the process of reducing residual radioactivity to a level that permits release of a facility for unrestricted use and termination of an NRC license. In effect, this definition means that, after the radioactivity exceeding NRC limits for unrestricted use has been removed, no further institutional or administrative controls are required.

Licensees may request and have been granted exemptions to the unrestricted use requirement. One interim decommissioning alternative that has been used by several retired facilities is termed safe storage (SAFSTOR). Safe storage is defined as those activities required to place and maintain a nuclear facility in such condition that future risk from the facility to public safety is within acceptable bounds and that the facility can be safely stored for as long as desired.

During the SAFSTOR period, irradiated fuel assemblies and in-core fission chambers are stored in the spent fuel pool. The onsite storage of spent fuel requires the continued operation of numerous plant systems, such as (1) service systems, (i.e., ventilation, spent fuel pool service, fire protection, and electrical), (2) waste disposal systems, and (3) monitoring systems, (i.e., stack gas radiation monitoring systems, process water monitoring, offsite environmental monitoring stations, etc.).

Active institutional controls at reactor facilities in a safe storage condition are extensive and are, therefore, not limited to protection against unauthorized entry. A permanent plant staff for the operation of necessary plant systems, preventative/corrective maintenance of structures, systems, components, and equipment, and onsite/offsite environmental monitoring must be maintained during the SAFSTOR period. During SAFSTOR, a licensee is required to maintain a full-time, onsite security force to prevent unauthorized access or deliberate intrusion into the facility. Additionally, a system of multiple locked physical barriers and warning signs/signals must be maintained to control access into areas where exposure to radiation is possible (NRC94).

10.3.3 Low-Level Radioactive Waste Disposal Facilities

The Nuclear Regulatory Commission established regulations under 10 CFR part 61 to cover all phases of land disposal of low-level radioactive waste (LLW). A LLW disposal facility licensed under 10 CFR part 61 consists of the land, buildings, and equipment required for the near-surface disposal of LLW. These regulations also require the use of a waste classification system, where high-activity Class C wastes are to be placed deep in the ground (at depths below 5 meters) or behind barriers to limit human intrusion.

Six commercially-operated LLW disposal facilities, located at Beatty, Nevada; Maxey Flats, Kentucky; West Valley, New York; Richland, Washington; Barnwell, South Carolina; and

Sheffield, Illinois, have been licensed and operated in the United States. These facility were licensed prior to the promulgation of 10 CFR part 61 and use shallow land burial designs. The Richland and Barnwell facilities continue to operate as disposal facilities for LLW, whereas the other four sites have closed.

Under the Low-Level Radioactive Waste Policy Act of 1980 and the Low-Level Radioactive Waste Policy Amendments Act of 1985, states are responsible for the disposal of commercial LLW generated within their respective boundaries. Since this legislative directive, several states and regional compacts are in various stages of planning and licensing new LLW disposal facilities. All new facilities will be licensed under 10 CFR part 61 or compatible Agreement State regulations. In addition, Envirocare of Utah, Inc., has applied to NRC for a license to construct and operate a facility to receive, store, and dispose of uranium and thorium byproduct material.

Institutional control requirements for LLW land disposal facilities, as cited in §61.59, specifically address control of access, environmental monitoring, surveillance, minor custodial care, and administration of funds to cover the costs for these controls. The primary institutional control to protection against inadvertent intrusion is physical security (e.g., barriers, fences) to limit site access. Other active controls include periodic inspection of the site, maintenance of disposal unit covers, revegetation of the disposal area, and maintenance of the security fence. For example, the site stabilization and closure plan for the LLW facility operated by U.S. Ecology Inc. in Richland, Washington, has proposed the following active institutional controls as part of their Site Stabilization and Closure Plan (USE95):

- At closure, security around the facility will be maintained by the existing 8 foot high galvanized chain-link fence, which is topped with three strands of barbed wire.[2]

- Two times each year, during the 5 to 54 year post-closure and maintenance period, a crew of two men and foreman will spend three days each visit performing miscellaneous maintenance.

- Annually, during the 55 to 100 year post-closure period, a crew of two men and a foreman will spend three days performing necessary maintenance. Also during this period, the fence surrounding the facility will be replaced.

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[2] This fence is much more robust than that proposed for the WIPP site; however the waste at Richland is shallow lying and hence more prone to disturbance by surface activities.

Although 10 CFR part 61 specifies that institutional controls cannot be relied upon for more than 100 years, some of the new LLW disposal facilities are proposing the use of active controls for longer than 100 years. For example, a minimum of 100 years of active controls is proposed for new facilities in California and Nebraska (KAR95); and the license application for a new facility in Illinois contained a 300-year active institutional control period (NRC93).

10.3.4 Uranium Mill Tailings Disposal

Uranium mill tailings are a byproduct waste that results from the processing of ore to extract uranium. Historically, uranium mill tailings have been stored in large surface impoundments. The principal health concern is exposure to radon-222, a radioactive decay product of uranium.

Long-term stabilization and disposal regulations were developed under the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA) by EPA and NRC and set forth in 40 CFR part 192. In addition, the NRC developed specific licensing and design criteria, which are addressed in 10 CFR part 40, to implement EPA's environmental standards.

In accordance with existing regulations, uranium mill tailings must be stabilized for 1,000 years, to the extent reasonably achievable, and, in any case, for at least 200 years without active maintenance. Therefore, controls for stabilization and safe isolation of the tailings primarily rely on site characteristics and engineering designs.

Site closure activities, which are intended to reclaim and stabilize the site to such a degree that no active, ongoing maintenance is required, typically consist of the following:

- dewatering the tailings ponds,
- implementation of a ground water remediation program,
- filling the impoundment area with a sufficient quantity and type of material to reclaim and stabilize the site (reduce radon to acceptable levels) in an environmentally sound manner,
- dismantling, disposing, or salvaging mill site buildings and material,
- decontamination of mill site soils,
- establishment of an appropriate environmental monitoring program for closure and post-closure needs.

Institutional controls to protect against inadvertent intrusion are neither explicitly identified or designated in the regulations for surface remediation of tailings disposal sites, nor do they provide definitions of, or specific criteria that distinguish between, active and passive institutional controls. However, provisions in EPA standards and NRC regulations that contribute directly and indirectly to intruder prevention and protection include (1) transfer of ownership and control of the site, to a government agency (usually DOE) for long-term custody, records control, and deed and land-use restrictions; and (2) periodic site inspection and surveillance, monitoring, and, if necessary, maintenance during the post-closure period.

10.3.5 Superfund Sites

EPA is responsible for remediation of hazardous releases into the environment under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. This program, commonly referred to as the Superfund Program, involves the remediation of more than 1,400 contaminated sites. CERCLA requires that Superfund sites comply with the organizational structure, procedures, and criteria specified in the National Contingency Plan (NCP), 40 part CFR 30(

By the end of 1993, Superfund remedial actions at 21 radioactively contaminated sites had been determined. Institutional controls were included as part of the selected remedies for 12 of these sites. However, the institutional controls at eight sites were only selected for an interim period until the final remedy was implemented, which required development of offsite waste disposal capacity.

Institutional controls selected to support temporary remedies include access control, fencing, waste storage, surveillance, and monitoring. For three sites with permanent remedies, institutional controls included access controls (typically fences), deed restrictions, leachate collection and treatment, groundwater monitoring, drilling and pumping restriction, cover maintenance, and procedural controls. For example, at the Maxey Flats low-level waste disposal facility in Kentucky, EPA's final remedial action includes institutional controls to restrict use of the site and to ensure monitoring and maintenance of the site in perpetuity, since the radioactive and hazardous waste, once stabilized, will remain onsite.

In terms of institutional controls, the NCP is sufficiently general to allow the use of a wide range of institutional controls, if necessary, to protect human health and the environment.

Detailed selection of institutional controls occurs as a part of the remedial design, after the selection of the remedy in the Superfund Record of Decision. EPA or the state agency negotiates the type and necessary duration of the institutional controls with responsible parties and affected interests. Since the majority of selected remedies to date ultimately require the removal of radioactively contaminated materials, the use of institutional controls are typically passive, such as deed restrictions and ordinances to limit access or resource use.

10.3.6 Applicability to WIPP

Institutional controls defined by Federal regulations at various other facilities are primarily affected by post-closure conditions and characteristics and accessibility of the hazardous materials. As discussed above, active institutional controls for restricting site access can range from a combination of full-time security guards, visual and electronic surveillance, and multiple locked barriers at facilities in SAFSTOR to facilities, such as uranium mill tailings disposal sites, where the closure goal is intended to reduce the necessity for and reliance on active institutional controls.

Due to profound differences in siting, waste characteristics and form, accessibility of emplaced hazardous materials, and post-closure conditions between WIPP and the above-cited facilities, the active institutional controls employed at these sites are not directly applicable. However, the range of active institutional controls at these sites can serve as a basis for establishing bounding criteria for the controls required by 40 CFR part 194. It should be noted that no nuclear facility subject to active institutional controls has been in existence for more than about half the 100-year post-closure period allowed for active institutional control credit in 40 CFR part 194, thus limiting the experience available to determine the adequacy of these safeguards. One can cite other governmental institutions where active institutional controls have been in place for more than 100 years (e.g., Sing Sing Prison), but the applicability of such experience to a geologic repository is questionable.

10.4 ADEQUACY OF PROPOSED ACTIVE INSTITUTIONAL CONTROLS FOR WIPP

As previously defined, active institutional controls refer to the deliberate actions taken to restrict access to and use of the site.

The primary considerations in waste disposal siting strategies and design features are their effectiveness in isolating the waste and protecting against inadvertent intrusion into the disposal area. Siting features include selecting a location where the benefits of the site outweigh the detriments. Detriments could be concerns that population growth could affect the site or that future exploration for natural resources (e.g. hydrocarbons, minerals, water) could effect repository performance. Design features consist of using natural and engineered barriers to isolate the waste and minimize/mitigate the effects of human intrusion.

Massive geologic formations between the waste and the earth's surface are undoubtedly the primary design feature that limits inadvertent intrusion to buried waste. Perimeter fences, barriers, warning signs, and controlled use of access roads provide a second level of control measures to protect against inadvertent intrusions. A third level involves surveillance. Surveillance may be continuous or periodic, conducted through visual inspection by security personnel, and supplemented by electronic devices.

The adequacy of institutional control measures must, therefore, be assessed in terms of the effectiveness by which control measures limit intrusions. The effectiveness of institutional controls can be assessed for a number of intrusion scenarios; however, the active institutional controls being considered for the WIPP consider drilling as the only intrusion scenario that could credibly breach the repository. The section that follows describes alternate intrusion scenarios, and examines them with respect to: 1) probability of occurrence, 2) consequences, and 3) effect of additional active institutional controls on the probability of their occurrence.

10.4.1 Inadvertent Intrusion Scenarios

An intruder may encounter a closed waste disposal site and, due to a temporary or permanent breakdown in institutional controls, engage in a variety of activities. Such unintentional intrusions may be transient, short-term, or even permanent (NRC84). Potential intrusion scenarios, their likelihood of occurrence, and potential radiological consequences are discussed below.

10.4.1.1 Recreational

This scenario encompasses numerous plausible activities involving trespassing of hikers, campers, off-road vehicle operators, etc.

- <u>Probability of Occurrence</u> - A perimeter fence and warning signs and periodic security inspections that verify their integrity minimize the possibility of inadvertent intrusion. Under unusual conditions in which fence and warning signs are removed but security inspections are maintained, such intrusions would be limited to less than a four-day time period.

- <u>Potential Consequence</u> - The pre-closure decontamination and removal of surface structures and restoration of land to pre-operational conditions would ensure that exposure from contact with existing surface materials, including soil, is below regulatory limits. Thus, for recreational intrusions that do not significantly modify the site and are of short duration, potential radiological consequences are insignificant.

10.4.1.2 Agricultural

In this scenario, the inadvertent intruder is assumed to plant crops on the disposal site for human or farm-animal consumption.

- <u>Probability of Occurrence</u> - The aforementioned institutional controls at WIPP, which include construction and maintenance of a perimeter fence, warning signs, and periodic security inspections, preclude the likelihood of the intruder-agriculture-scenario. Even the transient loss of these institutional controls for a period of days to weeks is insufficient to support a growing period of weeks to months required for agricultural crops.

  A significant factor in this scenario is that site characteristics, defined by soil quality and rainfall, would not support agricultural activities. Thus, the probability of occurrence for this scenario is insignificant during the period for which active controls will be in place.

- <u>Potential Consequence</u> - Although crops cannot be affected by waste disposed at a depth of more than 2,000 feet below the surface, garden crops and animal forage become contaminated from radioactivity contained in soil as a result of root uptake and foliar deposition of resuspended soil particles.

  The level of residual soil contamination at the WIPP following closure can be assumed to comply with current standards that limit soil contamination within the root zone to 5 pCi/g and to 15 pCi/g below the root zone. These values are likely to represent bounding values for the agricultural intruder scenario and would cause only minimal impact with regard to human exposure.

10.4.1.3 Home Construction

This scenario assumes that an intruder inadvertently proceeds with construction of a home on the disposal site. Construction includes excavation for concrete footers, basement, utilities, etc. These typical activities should not be expected to involve depths in excess of 15 feet. One noteworthy exception, however, is drilling for well water, which is discussed separately below.

- <u>Probability of Occurrence</u> - Full implementation of proposed institutional controls renders this scenario highly improbable. Only with an extended breakdown in active institutional controls is it conceivable that construction could inadvertently progress through the initial phase of home construction that includes excavation of a basement, septic system, and grading of the construction site.

- <u>Potential Consequences</u> - Disturbance of site surface layers that are assumed not to exceed 15 pCi/g would expose construction workers to low-level airborne environments and external radiation during this brief period of construction. Intruder exposure from these pathways is very low.

10.4.1.4 Groundwater Scenario

There are several potential groundwater scenarios depending upon the intended use of the site. A well may be drilled on behalf of the agricultural intruder scenario, the home-construction intruder scenario, or for cattle grazing on the open range.

- <u>Probability of Occurrence</u> - Drilling for water can be expected to occur only if there is a prolonged breakdown of institutional controls. The concern for well drilling and mining at the WIPP can be addressed by considering that, using current drilling technology, it typically requires at least 2-3 days for a driller to setup a deep drilling rig and commence actual drilling operations. To attain the 655 meter depth that would approach the repository horizon takes at least another week to 10 days. Patrolling the fenced area 2-3 times weekly would identify potential drilling activity well before any breach of the repository could occur.

Active wells exist in the Dewey Lake Red Beds 3.2 to 3.4 miles south of the repository (about 1.2 miles south of the southern boundary of the Land Withdrawal Area) (DOE93a).

Beyond these temporal limitations, the improbability of drilling for water is more likely to be due to common knowledge among local well drillers that there are no known potable aquifers in the immediate vicinity of WIPP.

- Potential Consequences - Deep well drilling could bring water from the Culebra Member of the Rustler Formation to the surface. The water may be contaminated and contain radiologically significant quantities of waste only if the water well drilling activity has been preceded by an intrusion into the repository.

According to DOE, "water quality of the Culebra in the vicinity of the WIPP is naturally poor and the waters are not usable for human consumption or for agricultural purposes," (DOE93a).

10.4.1.5 Drilling for Hydrocarbons

Exploratory drilling for oil and gas is a common activity around the WIPP site. As domestic and world oil and gas supplies dwindle over the next 100 years, the incentive for exploratory drilling may escalate.

- Probability of Occurrence - As discussed with respect to the water drilling scenario above, when proposed institutional controls are maintained, the likelihood of inadvertent commercial drilling for hydrocarbons must be considered highly improbable. Only with prolonged or sustained breaks in institutional controls (i.e., greater than 3-4 weeks) could this scenario progress sufficiently far to pose a radiological threat. Assuming that "rank wildcat" exploration is carried out at a rate of about 3×10^{-4} drill holes per square kilometer per year (TRA91),[3] for the 277-acre fenced area at WIPP, this would imply a probability of 6×10^{-2} that a single bore hole would be drilled inadvertently into the repository over a 100-year period. This probability is based on a sustained breakdown of institutional controls for the entire 100-year period.

- Potential Consequence - Potential radiological consequences resulting from exploratory drilling for hydrocarbons are greater than those previously identified in the water drilling scenario because the deeper hydrocarbon boreholes are more likely to intercept the buried waste.

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[3] SAN92 states that, based on guidance in Appendix B of the Standard, "a maximum of 30 boreholes/km^2 were allowed in 10,000 years."

10.4.2 Intentional Intrusion Scenarios

In this chapter intentional intrusions scenarios refer to activities associated with individuals who willfully and knowingly violate institutional control efforts. Intentional intrusion scenarios can be further categorized as benign and hostile.

10.4.2.1 Benign Intentional Intrusion Scenarios

There are numerous scenarios that can be labeled as benign intentional intrusion. The activities associated with benign intrusions generally do not go beyond willful trespass and, therefore, do not pose a radiological threat. Intruders in this category are likely to include tourists, curiosity seekers, souvenir collectors, people intent on mischief/vandalism, etc.

- Probability of Occurrence. Population expansions and encroachment by future communities at the WIPP site will undoubtedly raise the probability and frequencies of these intrusions so as to make them commonplace. A sincere desire to impede this type of willful intrusion would require that the proposed 4-strand wire fence be replaced by a more effective fence (e.g., operating nuclear power plants employ an eight-foot typhoon fence topped with several coils of razor wire for primary perimeter protection).

- Potential Consequence - In general, benign willful intrusions are likely to have no radiological significance. Of potential consequence might be a scenario in which a souvenir hunter by means of a metal detector finds an accessible contaminated metal object that had failed detection during pre-closure cleanup efforts.

10.4.2.2 Hostile Intentional Intrusion Scenarios

This classification of intrusion is defined by activities aimed at accessing disposed waste for purposes of sabotage and/or terrorism. Although the waste is protected by more than 2,000 feet of overlying geological formation consisting of soil, sand, rock, and salt, only drilling equipment (as used in drilling water, gas, or oil wells) is needed to penetrate the repository horizon. Acts of sabotage or terrorism may involve the introduction of chemical and physical agents, inclusive of explosives, that would impact containment integrity of stored waste and possibly result in the immediate release of radioactivity to the surface, as well as long-term releases to geologic formations surrounding the breached waste.

- Probability of Occurrence - The inadvertent intrusion scenarios involving drilling for water and hydrocarbons, state that drilling activities are likely to require a period of up to two weeks before the well depth reaches that of the buried TRU waste.

  An act of sabotage or terrorism is technically feasible, but may be logistically impossible.

  Since historical acts of sabotage and terrorism have been few and sporadic and may be motivated by political, social, and other factors, a quantitative estimate of probability is inappropriate.

- Potential Consequence - The radiological consequences of an act of sabotage or terrorism is dependent on the methods employed for accessing the repository and damaging contained waste. However, any successful act may pose a potentially severe immediate and long-term radiological threat.

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11. Monitoring

11.1 THE NEED FOR MONITORING

11.1.1 EPA Disposal Standards

Predictive models are used in the design of the WIPP. Computer simulations of the repository environment are used to provide information to engineers and scientists during the design of the facility. The computer simulations use analytical, empirical, and statistical predictive models to simulate various interconnected aspects of the disposal system. These computational simulations and predictive models reflect the state of knowledge of the characteristics of the disposal system at the site, and include, for example, chemical, physical, radiological and biological components.

Analytical techniques are highly useful in predictive modeling due to the conceptual nature of their formulation. However, such models are based on the current state of knowledge of highly complex systems and are susceptible to imperfect understanding of individual or systemic components. A result of this imperfect state of knowledge is the introduction of uncertainty into the model results. Thus, it is desirable to augment predictive models with empirical data to lower inherent modeling uncertainties.

Since the predictions associated with long-term compliance have inherent uncertainty, the final disposal standards issued by EPA in 1985 included a provision requiring monitoring of disposal systems to assure their compliance. EPA surveyed the capabilities and expectations of long-term monitoring approaches. As explained in the preamble to the 1985 disposal regulations (50 FR 38081, September 19, 1985):

> Evaluating this information led the Agency to several conclusions:
>
> (1) Perhaps most importantly, the techniques used for monitoring after disposal must not jeopardize the long-term isolation capabilities of the disposal system. Furthermore, plans to conduct monitoring after disposal should never become an excuse to relax the care with which systems to isolate these wastes must be selected, designed, constructed, and operated.
>
> (2) Monitoring for radionuclide releases to the accessible environment is not likely to be productive. Even a poorly performing geologic

repository is very unlikely to allow measurable releases to the accessible environment for several hundreds of years or more, particularly in view of the engineered controls needed to comply with 10 CFR part 60 [for facilities subject to regulation by NRC]. A monitoring system based only on detecting radionuclide releases -- a system which would almost certainly not be detecting anything for several times the history of the United States -- is not likely to be maintained for long enough to be of much use.

(3) Within the above constraints, however, there are likely to be monitoring approaches which may, in a relatively short time, significantly improve confidence that a repository is performing as intended. Two examples are of particular interest. One involves the concept of monitoring groundwater sources at a variety of distances for benign tracers intentionally released to the groundwater in the repository; this approach can evaluate the delay involved in groundwater movement from the repository to the environment and can serve to validate expectations of the performance expected from the system's natural barriers. Another concept involves monitoring the small uplift of the land surface over the repository in order to validate predictions of the system's thermal behavior. Both of these approaches can be carried out without enhancing pathways for the wastes to escape from the repository.

Based on these conclusions and the public comments on this question, EPA decided to include an assurance requirement in 40 CFR part 191 for long-term monitoring after disposal: "Disposal systems shall be monitored after disposal to detect substantial and detrimental deviations from expected performance. This monitoring shall be done with techniques that do not jeopardize the isolation of the wastes and shall be conducted until there are no significant concerns to be addressed by further monitoring." (§191.14(b)).

To support post-closure monitoring and to provide a baseline for comparison with future measurements, the monitoring of parameters which are important to the long-term integrity of the disposal system must also be performed prior to closure. This type of monitoring can provide important information about the disposal system and can contribute to a better understanding of how the disposal system is likely to perform after closure. Furthermore, such information can be used to verify assumptions (about the disposal system) which form the basis for PA.

The word "monitoring" is not defined in 40 CFR part 191. However, monitoring is considered as a form of active institutional control. According to §191.12(f), "active institutional control means:.....(4) monitoring parameters related to disposal system performance." §191.14(a) requires active institutional controls to be "maintained for a long a period of time as is practicable after disposal," but contributions of active institutional controls in PA are limited to a maximum of 100 years. In the preamble to 40 CFR part 191, EPA noted that many commenters believed "a few hundred years" as originally proposed was too long a period for active institutional controls to be effective and consequently limited reliance on active institutional controls to 100 years (50 FR 38080). By inference, reliance on monitoring for more than 100 years was not contemplated in the final rule.

11.1.2 RCRA Regulations

40 CFR part 264 contains the standards for operating hazardous waste treatment, storage and disposal facilities. Subpart F specifies the requirements for monitoring. It describes the monitoring program which must be conducted, the hazardous constituents to be monitored for, and the applicable groundwater protection standards. The thrust of Subpart F is to detect any hazardous components of the waste released to groundwater.

Subpart F also contains a waiver to its requirements for monitoring. §264.90(b)(2)(vii) states that the Administrator can waive the requirements of Subpart F if it is shown to a reasonable degree of certainty that the facility will not allow hazardous constituents to migrate beyond the outer containment layer prior to the end of the post-closure care period. Since this waiver is essentially describing the PA for the site, a waiver to the monitoring described in Subpart F could be granted. However, if ground-water monitoring wells are employed during the disposal phase, then the wells must be operated during a thirty-year post-closure phase, as well (EPA86).

40 CFR part 268 contains the regulations and requirements for land disposal of hazardous wastes. §268.6 describes petitions to allow land disposal of prohibited waste. The No-Migration Variance Petition (NMVP) requires a monitoring plan to detect migration at the earliest practicable time when disposing of prohibited waste in ground. This plan must include the following information:

- the media monitored,
- the type of monitoring conducted,

- the location of the monitoring stations,
- the specific hazardous constituents to be measured,
- the implementation schedule,
- the equipment used,
- the sampling and analysis techniques, and
- the data recording and reporting procedures.

Since the monitoring requirements specified in 40 CFR part 268 are general in nature, sufficient flexibility should be available to develop a monitoring program which complies with this regulation and the long-term monitoring requirements of 40 CFR part 194.

11.2 PRE-CLOSURE MONITORING

In order for the WIPP to comply with the requirements of 40 CFR part 194, predictive modeling techniques must be used. EPA has specified that analyses need to be performed to identify the parameters subject to pre-closure monitoring (§194.42(d)). The required analysis will define which additional parameters will be subject to pre-closure monitoring. The information obtained from these monitoring activities will contribute to a better understanding of how the disposal system is likely to perform after closure.

As discussed above, the objective of the monitoring assurance requirement in 40 CFR part 191 is to detect "substantial and detrimental deviations from expected performance" after disposal. In order to have a basis for future measurements, an adequate pre-closure baseline must be established though measurements taken prior to repository closure. This pre-closure monitoring is not for the same purpose as much of the pre-operational monitoring undertaken at the WIPP site by DOE and the New Mexico EEG.

11.2.1 Pre-Disposal Monitoring to Support Operations and Closure

EEG was authorized to conduct independent site monitoring under the July 1981 Agreement for Consultation and Cooperation between the State of New Mexico and DOE ("the Agreement"). EEG developed a preoperational environmental monitoring plan for the WIPP site in 1984 (SPI84).

According to the Appendix A of the Supplemental Stipulated Agreement to "the Agreement" dated December 28, 1982 (SPI84), EEG will conduct:

- preoperational monitoring
- monitoring during the operational phase
- monitoring during and at least two years after the decommissioning and decontamination phase
- limited post-operational phase monitoring (i.e., after termination of decommissioning and decontamination) for not less than five years

For a number of years, DOE has also conducted a program to define the environmental baseline for the WIPP site (DOE93, DOE94). The Operational Environmental Monitoring Program (OEMP), which is intended to continue during operation and through decommissioning.

A major element of the nonradiological monitoring is meteorology which involves measurement of wind speed, wind direction, temperature, dew point, and precipitation. Seismic activity is measured routinely at four stations around the WIPP site.

11.2.2 Pre-Closure Monitoring to Support Assurance Requirements

The EPA compliance criteria (§194.42(c)) requires preclosure monitoring of significant parameters as identified by an analysis by DOE. The analysis will identify parameters that affect the disposal system's ability to contain waste or the ability to verify predictions abouts its future performance.

The following is a discussion of several parameters which could potentially be identified as significant for monitoring. Brine-related parameters, room closure, subsidence, and geophysical monitoring are discussed because they are examples of parameters that can be monitored at a mined facility and may already be monitored by DOE to support operational activities or meet other regulatory requirements. Consideration of the many parameters that can be monitored in association with a mined facility supported the Agency's decision to require an analysis of parameters that can be monitored to determine those with significance to the containment of waste within the disposal system.

11.2.2.1 Brine quantity, flux composition, and spatial disposition

EPA has reviewed DOE and DOE contractor reports on in situ tests and repository monitoring to characterize brine flow into the repository. This work has been broken down into three specific programs:

- Large-scale brine inflow test (Room Q)
- Brine sampling and evaluation program (BSEP)
- Small-scale brine inflow experiments

Large-Scale Brine Inflow Test

The Room Q test which operated from July 1989 until May 1994 was designed to obtain information on brine inflow into the WIPP from an excavation which approached the scale of a repository disposal room. Room Q was a horizontal cylindrical excavation 108 meters long and three meters in diameter sealed with two bulkheads. The rate of brine seepage into the closed room was measured by various collection methods. During the 1,800-day test approximately 210 liters of brine were collected.

Brine Sampling and Evaluation Program

The BSEP program, which has been conducted since 1985, collects general repository wide information on brine inflow. The three program elements include:

- brine flow to boreholes
- brine flow to underground openings
- laboratory measurements of brine chemistry and brine content of rock samples

A total of 119 boreholes have been monitored for various periods of time since 1984. Of these, 51 never produced brine or stopped producing brine during the monitoring period. As of September 1994, 105 of the holes had been dropped from the monitoring program due to contamination from construction activities or because the holes were lost to mine related events (HOW94). Thirteen boreholes have continuously produced brine with typical yields being on the order of tens of milliliters per day.

Brine seeps on the walls of the excavated surfaces are also monitored. Mapping studies have shown that clay seams rather than the halite and anhydrite are the preferential brine sources.

Small-Scale Brine-Inflow Experiments

This experimental work, which was conducted from September 1987 through June 1993, involved monitoring brine inflow into 17 boreholes ranging in diameter from 5 to 90 centimeters (HOW94). Some brine inflow was observed in all but two of the holes.

Room Closure

One of the defining characteristics of the WIPP repository is closure of the disposal rooms due to creep of the salt. Room closure includes any displacement change induced by mining. Roof sag and floor rise are examples. Displacement is the simplest and most reliably measured geotechnical variable associated with repository excavation and operation. Generally displacements are largest near the most recently excavated room and diminish roughly linearly with distance from a room. A large number of displacement measurements have been made at WIPP for the purpose of code validation and calibration. These measurements have been made at the surface of excavated rooms and in boreholes, also excavated in salt. Creep of salt induces a time-dependency in the displacement field about the repository. Other rock types, for example, anhydrite, are not considered to creep significantly. Displacement change in these rock types ordinarily occurs concurrently with excavation. However, salt creep constrains the motion of adjacent strata that otherwise do not creep. Displacement measurement by itself is not sufficient for model validation. Stress measurements are needed in addition to displacement measurements. Other mechanical measurements and observations are also possible within the scope of pre-closure monitoring of repository rooms.

Displacement Measurements

Instrumentation for displacement measurement commonly consists of: (1) reference points directly attached to excavation walls, roof and floor, and (2) reference points anchored in boreholes (borehole extensometers). The latter provide for displacement measurement within the rock mass enclosing an excavation. Extensometer lengths of 100 ft (30 m) are common. Instrument readings may be direct and mechanical, for example, by dial guage. Reproducibility of readings is generally a few thousandths of an inch (a few hundredths of a millimeter). The same is true of measurements at excavation walls which are often done by precision tape measurements between walls and between roof and floor.

Displacement measurements are not only the most reliable measurements made in the realm of geotechnical monitoring, they are also the most readily used in model validation and calibration studies. Almost all computer codes for rock mechanics analysis solve for displacements as the primary unknowns. For this reason, direct comparison between displacement instrument readings and corresponding computer code output is easily done.

The quick (instantaneous) displacement response of a rock mass to excavation is largely controlled by Young's modulus, while the delayed (time-dependent) component is controlled by rock mass (salt) viscosity. After an advance of the mining face, a period of transient creep ensues that is followed by steady state creep, provided the interval between advances is sufficient. Plotting displacement as a function of time, as measured and as modeled, readily demonstrates the agreement (or lack) between the two. Separation of data into instantaneous and time-dependent components is possible. Better agreement between model and measurement may then be obtained by changing Young's modulus and viscosity and rerunning the model. This circular exercise may eventually calibrate a model that otherwise simulates geology, excavation geometry, possible bed separation, and transient creep, but does not really validate constitutive equations at the heart of a model. Displacement data only feed one side—the strain side—of the constitutive equations. Independent measurements that feed the stress side of the constitutive equations are needed for model validation. Of course, only a properly calibrated and validated model has the potential for demonstrating "predictability." Pre-closure room monitoring should therefore provide for additional measurements, independent of displacements, that would serve model validation as well as calibration.

Stress Measurements

Stress changes are the second most common type of geotechnical data collected in monitoring programs. Stress-change data are independent of direct displacement measurements, although all instruments move to some degree according to design. Pillars between rooms are usually the regions of greatest interest for the obvious reason that they must support the overburden and thereby insure large-scale stability of the mine. Local stability and safety relative to roof falls, for example, is provided by local support, perhaps by roof bolts or by the intrinsic strength of the roof strata alone. Borehole stress gages of various types are used to monitor stress changes in pillars. An elastic response is generally assumed for stress measurement data reduction. Extension of such procedures to the viscoelastic domain would be necessary for current salt creep models used for WIPP analyses. Salt creep data may already be available from prior *in situ* stress measurements. When linked to borehole extensometer measurements, stress monitoring may provide data for technically sound model validation studies.

Other Mechanical Room Measurements

Other measurements and observations that may be relevant to purely mechanical aspects of pre-closure repository performance include roof bolt load measurement, and borehole televiewing for fracture development and bed separation. Off-the-shelf instrumentation is commercially available for making these observations.

Although not strictly a "room" measurement, observations of displacement and stress change adjacent to repository shafts are desirable, especially near aquifers above the repository horizon. Shaft tilt determined from inclinometer measurements would be of particular interest. Tilt refers to deviation of the shaft line from the vertical that may be induced by repository mining and is related to the larger issue of subsidence. Inclinometer instrumentation is relatively expensive.

Subsidence Monitoring

Subsidence can be divided into two broad categories: surface and subsurface ground motion. Although surface subsidence is usually implied in discussions of mine subsidence and only the vertical component of surface displacement is considered ("settlement"), the general concept encompasses both categories of ground motion. The rock mechanical features of repository performance are almost synonymous with ground motion, so subsidence is of considerable importance to rock mechanics analyses that contribute to the demonstration of computer model predictability for performance assessment. Enlargement of a mine monitoring plan to include not only surface displacement measurements, but also measurements within the rock mass between repository room level and the surface, is desirable. Surface measurements and subsurface observations would serve the twin purposes: (1) providing physical measurements for model validation, and (2) forewarning of any threatening departure from predicted performance. Empirical and rational subsidence approaches, each with advantages and disadvantages are available for subsidence analysis.

Empirical Surface Subsidence Estimation

There are several well-known empirical and semi-empirical approaches to estimating surface subsidence (settlement). The best known technique is the procedure described in the Subsidence Handbook developed by the National Coal Board in the United Kingdom. This procedure is two-dimensional and for mines using the longwall method that result in almost 100 percent extraction, unlike the room and pillar WIPP plan with about 22% extraction (SAN92). Stratigraphy and rock properties are ignored. The best known semi-empirical approach is the influence function technique which is guided by elasticity theory and then fit to existing surface measurements. Both techniques could be successfully adapted to WIPP site conditions after calibration against subsidence troughs associated with underground mines in similar geologic environments. The outcome would be a simple estimate of a WIPP surface subsidence, an estimate easily done by hand calculation. Analyses of this type have been conducted by IT Corporation for the WIPP site to support backfill studies (ITC94).

Perhaps the simplest surface subsidence estimation is to neglect volume change of the rock mass influenced by mining and then impose an angle of draw which defines the extent of subsidence at the surface. The ratio of average depth of surface subsidence to mining height is then $R/[1+2(H/W)\tan\delta]$ where R is the area extraction ratio (0.20 for WIPP), H is mine depth (about 2,000 ft or 610 m), W is mine width, and δ is the angle of draw. This rough estimate indicates surface subsidence of about 1 ft (1/3 m), a realistic estimate in view of previous surface subsidence estimates at the WIPP site. A more formal volume conservation approach is possible through a diffusion of voids model. The advantage of empirical approaches is clearly the ease of calculation.

A serious defect associated with empirical methods is that no account can be made of subsequent measurements that are not in agreement with the empirical estimate. For example, a qualification of plus or minus 10 percent—meaning measured subsidence is expected to be within $\pm 10\%$ of the empirical estimate—may not be helpful if the deviation is caused by sinkhole formation. In fact, this claim is made in the Subsidence Handbook of the National Coal Board only for coal mines in the United Kingdom where geological conditions are similar. Coal mine subsidence in sedimentary basins throughout the world is not the same and claims to accuracy based on statistical summaries of subsidence surveys in other parts of the world are not available.

Empirical methods tacitly imply subsidence occurs in the form of a smooth trough or depression over the mined region. The ground surface is assumed to deform continuously, regardless of tensile strains induced by curvature of the subsidence trough. In fact, large vertical cracks often form at the surface and subsidence may occur with fault-like motion on these induced cracks and on preexisting cracks as well. The formation of step-like features over mined regions is frequently the case and loose, unconsolidated surface burden may mask the development of cracks in shallow brittle rock strata below. Subsidence may also occur in the form of chimneys, sink holes, or pipes that propagate by caving from mine level to surface where a "glory hole" may develop. Subsurface caving may cease and the overlying strata deform by flexing to form a smooth trough or possibly a stepped trough at the surface. The presence of major joint systems and faults will also influence subsidence below and at the ground surface. Experience of nearby mines often provides valuable guidance as to the type of subsidence expected. With such experience, empirical methods may be useful, but are generally at a disadvantage when predictability from first principles is desired. For example, no empirical method is known that will indicate in advance whether trough or chimney formation is the likely subsidence mode.

Rational Subsidence Estimation

The rational approach to subsidence estimation is through a technically sound computer model—i.e., one based on fundamental principles. A full account can then be made of the effects of mining geometry (past and planned), repository stratigraphy (including aquifers), geologic structure, rock mass properties, and pre-repository stress field. In this regard, the same computer model used for room and pillar rock mechanics analysis should also be used for subsidence analyses, if indeed, model calibration and validation are required beyond that afforded by a small, two-dimensional "strip" model of a generic half-room and half-pillar. In this regard, there is always a danger of oversimplification of site details that are included in a computer model. Unless the major features of mine geometry and geology are included, the computer model will produce results of questionable utility.

Comprehensive computer modelling of mine subsidence is indeed a significant technical challenge because of the large size of the model region and the amount of detail needed, especially about rooms and pillars. Nonlinearity in the form of ductile flow of salt and possibly caving after creep rupture complicates the constitutive description as do strata interfaces, clay seams, and the presence of other rock types, some of which are water-bearing. However, some large-scale three-dimensional finite element modeling has been done, so there is a possibility for incorporating stratigraphy into an improved model for subsidence analysis. The outcome would be a rational forecast of surface and subsurface displacement, strain and stress field changes as time passes and operations continue during the pre-closure period. Direct and timely comparisons between measured and simulated station histories could then be made, and significant deviations could be easily identified for further investigation. Such a forecast could also be used to plan a network of surface subsidence stations.

Subsidence Instrumentation

Surface subsidence is often monitored by repeated level surveys over a grid of survey stations extending beyond the limits of expected surface movement above the mined area. A rule of thumb for spacing of surface survey points is to limit spacing to 1/20th of the mining depth. This rule suggests a maximum spacing of about 100 ft (31 m) at the WIPP site. The rule is based on differences between stations required to resolve horizontal surface strains. Frequency of surface surveys should be appropriate to the mining rate and the amount mined between surveys. The minimum amount of incremental extraction underground should be determined for this purpose. Because of salt creep, this amount will be time-dependent. Surveys more frequent than the rate of extraction multiplied by the minimum required for detection may be of questionable benefit in relation to cost. In this regard, the expense of high precision leveling between stations may not be warranted in view of computer code scatter and variability in the amount of subsidence forecast by empirical methods. Level surveys to millimeter accuracy would not be informative when predicted subsidence varies by tens of centimeters.

A common practice for subsidence surveys in the mining industry is to use aerial photography and carry out surveys annually. During the early years of repository operation, quarterly surveys may be desirable. Subsidence determination from aerial photographs in the form of present and past contour plots may be substituted for leveling.

Subsidence instrumentation could be installed in boreholes below ground surface as well as at the surface above the repository. The first would require reconsideration of boreholes as threats to repository integrity. Some boreholes are planned for hydrologic monitoring. This suggests that boreholes of limited depth that do not penetrate the repository horizon or the zone of influence of the repository rooms may be acceptable with proper seals.

Several types of instrumentation could be installed in boreholes for monitoring subsurface subsidence. Two borehole techniques used successfully in the past are cross-hole seismic monitoring and time domain reflectometry. The principal objective of both is to detect caving above the mining horizon. Cross-hole seismic wave velocity decreases dramatically as the caved zone propagates upwards between instrumentation holes. An array of geophones in boreholes and at the surface would allow for general monitoring of "rock talk," that is, micro-seismic events associated with rock mass motion induced by repository mining and operation. The location, amplitude, frequency, and other characteristics of the mining-induced seismicity could be helpful in identifying the onset of anomalous rock mass behavior. Investigation of the phenomena during the pre-closure phase would be helpful in determining applicability during the post-closure phase when direct access to the repository is not possible. The second borehole method involves installation of an electrical conductor that subsequently breaks with advance of the cave zone. Signal time to the break is measured and the cave height determined by time domain reflectometry. Establishment of successful borehole monitoring procedures during the pre-closure phase would be particularly advantageous during the post-closure phase.

Geophysical Monitoring

Several geophysical phenomena can be utilized to characterize subsurface features which are dependent on the physical composition of the subsurface materials and include, but are not limited to: conductivity, magnetic susceptibility, dielectric permittivity, radioactivity, density, rigidity and morphology. These physical parameters control geophysical observations which can be exploited to monitor target objects and phenomena. Several geophysical sensors are available to directly or indirectly measure subsurface geophysical phenomena and are described below.

Passive geophysical techniques are used to measure fields caused by the presence of anomalous bodies, not those caused by external sources. These observations include the Earth's magnetic field, gravitational fields, and temperature, for example. Active geophysical techniques are based on the measurement of the response of the media to external sources of excitation. Examples include ground penetrating radar, induced conductivity, acoustic and seismic methods, and nuclear activation techniques. Active geophysical methods are distinguished by having a source and receiver, whereas passive methods only have receivers.

In order to evaluate the performance of the facility, a monitoring system will need to be highly sensitive to changes in subsurface conditions. The sensitivity and subsequent effectiveness of monitoring techniques can be significantly enhanced through the use of differential measurement techniques. With differential methods, redundant, identical measurements are carried out over regular time intervals. The complex features contained in many types of geophysical data are thus reduced through numerical comparison of previous measurements. The collection and analysis of monitoring data with identical instrumentation and configuration will serve to enhance the observation of temporal changes in repository conditions.

Various geophysical phenomena can be exploited in order to evaluate the state of the WIPP repository after closure. Existing sensors are available to make highly accurate and relevant measurements which can be used to evaluate the performance of the facility. Further, the geophysical sensor industry is very active in developing new and more sensitive instruments which will likely be applicable to post-closure monitoring. For the purpose of current planning, however, only existing sensor technologies need be considered.

11.3 POST DISPOSAL MONITORING

11.3.1 Jeopardizing Waste Isolation

11.3.1.1 Introduction

Data collected post-closure could be used to compare the predicted repository conditions to the actual repository conditions. Subsequently, deviations in conditions from those of the predictive modes could be used to validate or dispute the validity of the predictive constructs, and to further quantify expected future performance.

To explicitly address the potential detrimental effects of environmental monitoring, the EPA stated in §191.14(b) that any post-closure monitoring be conducted with technologies that do not jeopardize the isolation of the waste. There are several ramifications of this requirement which affect the conceptual and operational aspects of post-disposal monitoring.

11.3.1.2 Ramifications of Non-Threatening Monitoring

The explicit requirement to perform all monitoring activities without jeopardizing the integrity of the repository has physical, conceptual, and logistical ramifications. First, this requirement may limit or exclude the use of direct monitoring techniques within the repository or within boreholes placed in the strata above the repository. It is likely that this requirement will limit most or all sensor deployments to the surface, and impose strong reliance upon remote monitoring technologies.

Second, the spatial separation between the monitoring sensors and the repository, in excess of 2000 feet, increases the need for highly sensitive instrumentation. High sensitivity is required due to the decrease in amplitude of most geophysical observations with increased sensor-to-source distance. The need for enhanced sensitivity may require monitoring plans to incorporate advanced or innovative techniques, such as differential measurement strategies.

Third, the requirement of safe and remote monitoring at WIPP may make the evaluation of important repository performance parameters difficult, ambiguous or impossible to perform. In such cases, observable parameters may be identified which correlate with performance-sensitive un-observable parameters. As such, an evaluation of critical performance parameters should be performed which includes the ability of available monitoring technologies to make accurate parameters estimates. In cases where significant performance parameters cannot be determined through monitoring, correlated parameters should be identified, if possible.

Direct measurements of important parameters within the repository after closure can be performed only if there are no detrimental effects to the repository caused by the monitoring activity. Presently, technologies are being developed which may allow for monitoring directly within the excavated rooms without a physical connection between the repository and the surface.

Post-closure monitoring must be comprised of existing and available sensing and data collection technologies. While a new technical development may provide additional options in the future, present requirements must be met with present technologies.

The restrictions and goals of post-closure monitoring lead to the likely use of surface or near surface monitoring techniques. Given the parameters and correlated parameters of interest discussed above, the employed surface techniques will predominantly exploit geophysical measurement and monitoring technologies as described in Section 11.3.2.

11.3.1.3 Bore Hole Techniques

The placement of sensors within bore holes located above the repository represents a potential monitoring advantage compared to surface deployed monitoring equipment. This potential improvement in monitoring performance comes from the geometrical aspects of borehole techniques. First, borehole sensors, by their very nature, can be located closer to the repository. Depending on the maximum safe depth of the borehole, significant improvements in target proximity can be achieved. This is particularly important in repository monitoring, where measurement of small variations in background conditions are desired. Physical phenomena such as temperature, electromagnetic field strength, gravitational field strength, and elastic waveform amplitudes decay rapidly with distance. Thus, monitoring capabilities may be significantly improved through the deployment of down hole sensors.

Second, the effectiveness of many geophysical techniques is diminished due to the contamination of geophysical data by noise. The detection of features in geophysical data which can lead to the estimate of targeted performance evaluation parameters is based on both the strength of the observational feature as well as the degree of noise in the data. The important factor in environmental monitoring is thus captured in the signal to noise ratio (SNR). Subtle important features in monitoring data may be used for parameter estimation if noise levels are sufficiently low to achieve a high SNR. Bore hole sensors, by their isolation and distance from the surface, can achieve extremely low noise conditions.

Third, the geometry of geophysical monitoring arrays, through the deployment of bole hole sensors, can have a positive impact on the post-closure monitoring program. The relatively planar feature represented by the ground surface above the repository limits geometrical observational considerations. Bore holes, conversely, can be optimally positioned to maximize observation resolution. As mentioned previously, cross-hole seismic measurements made in bore holes straddling the repository may be highly effectual in monitoring deformational changes in repository structures.

11.3.2 <u>Geophysical Methods</u>

In this section a series of possible monitoring techniques are discussed which are separated into three categories depending on the repository attribute targeted by the monitoring activity. These categories include; direct measurements, geoelectrical properties, and geophysical properties. The associated technologies which can be used in these areas are listed below:

- Direct Measurements
  - Surface Subsidence
  - Direct Repository Monitoring
  - Groundwater Monitoring
- Geoelectrical properties
  - Electromagnetic
  - Resistivity
- Geophysical properties
  - Seismic
  - Gravity
  - Magnetic

11.3.2.1 Surface Subsidence.

Pre-disposal subsidence monitoring was discussed in Section 11.2.2.3. This is a simple technology by which subsurface repository characteristics are estimated through the collection and analysis of data describing the changes in the surface topography above the repository. Relative motions of surface can be upward or downward, and are referred to as uplift and subsidence, respectively. Typically, a reference point within the study area is assumed to be constant, and all motions are calculated relative to this pseudo-stationary point. Such surveys are relativistic, and do not attempt to describe the regional uplift or subsidence trends overall. The technology utilizes relative vertical height measurements between benchmarks located on the ground surface. Various conventional methods are used to make these measurements throughout a network of stations over regular time intervals. Through the simple processing of these data, a deformational history of the surface can be determined. With existing technologies vertical motion of the order 0.01 inch can resolved.

Since subsidence can be caused by a variety of factors including mining, water extraction, dissolution and hydrocarbon production, the determination of the cause of subsidence observations can be highly non-unique. Further, the spatial and temporal resolution of the parameters affecting the surface observation may be lower than is required to make useful conclusions regarding the repository performance.

While subsidence monitoring is attractive due to operational and financial considerations (subsidence monitoring is simple and inexpensive), the measurement of the deformation history of the ground surface over 2000 feet from the repository, may not have the required sensitivity to assess desired performance characteristic parameters.

11.3.2.2 Direct Repository Monitoring

The most effective way to monitor post-closure repository performance is to make direct measurement of the repository. Unfortunately, no viable technologies are presently available to connect the sub-surface repository sensors systems to the surface without direct physical connection. The risk of jeopardizing repository integrity by creating a borehole to the repository or by establishing a cable connection from the surface are unacceptable. Thus, direct repository monitoring must be accomplished without direct connection.

Currently, both industrial and governmental groups are developing technologies which may facilitate remote communication between the ground surface and the repository. Both very low frequency (VLF) and ultra low frequency (ULF) electromagnetic propagation methods are being developed. If this technology matures significantly, then it may provide a means to deliver direct repository measurements for performance evaluation.

11.3.2.3 Groundwater Monitoring

Groundwater monitoring is a form of direct measurement of environmental conditions which may be useful for the evaluation of the WIPP repository performance. Groundwater monitoring consists of the selection of borehole locations, drilling of the boreholes, groundwater well installation and sampling.

Prior to installation of the monitoring wells, depth and diameter of the well should be established to meet the specific monitoring needs of each location. Specification of adequate well depth and diameter depends on the purpose of the monitoring system and the geologic system it is monitoring. Wells of different depth and diameter can be employed in the same groundwater monitoring system. Varying the depth interval covered by the well screens in several wells, or in one multi-level well, can help to determine the vertical distribution of hydraulic heads and the levels at which contaminants are present. The quality of the groundwater may vary with depth due to several factors, such as the density of the contaminant-water solution, lenses or layers of varying permeability, and geologic features that may form barriers diverting fluid flow. A fully penetrating well cannot be used to quantify or vertically locate a contamination plume, since groundwater samples collected in wells that are screened over the full thickness of an aquifer will be representative of average conditions across the entire screened interval. However, fully penetrating wells can be used to establish the existence of contamination in an aquifer.

The decision concerning the depth of placement and length of the well screen is based on: aquifer depth, thickness, and uniformity; head distribution and estimated flow in the aquifer; permeability of the aquifer; specific yield of existing wells; anticipated depth, thickness, and characteristics (e.g., density relative to water) of potential contaminants; expected fluctuation in groundwater level; the expected presence of volatile organic compounds; and the type of borehole geophysical logs expected to be deployed.

Sampling strategy decisions, including the amount of flushing a well should receive prior to sample collection and the selection of sampling devices, depend on the intent of the monitoring program and the in situ hydrogeologic conditions. Programs to determine overall quality of water resources may require long pumping periods to obtain a sample that is representative of a large volume of that aquifer. The pumped volume may be specified prior to sampling so that the sample can be a composite of a known volume of the aquifer. Alternately the well can be pumped until the parameters such as temperature, electrical conductance, and pH have stabilized. Sampling instrument selection is dependent of several factors including cost, power requirements, sample isolation requirements, decontamination requirements, sample volumes, etc. Bailers, suction pumps, gas-lift samplers, and submersible pumps may be applicable.

Several factors will contribute to the potential usefulness of groundwater monitoring techniques in providing data for the evaluation of repository performance. These include, but are not limited to: the number, type, and depth of wells located above and around the repository; the chemical and radiological analyses performed on extracted samples; and the time interval between subsequent sampling events.

One groundwater monitoring technique which has been employed at other locations involves the use of synthetic tracers. The State of New York Department of Ecology (NYDEC) is interested in using synthetic tracers to "spike" individual landfill cells to facilitate the detection and identification of future leaks. To support this objective, the NYDEC sponsored a detailed tracer study, designed to evaluate the relative characteristics of numerous tracers in the laboratory and field. Work included laboratory tests, several natural gradient tests and recirculation/injection tests. Numerical simulations were performed to analyze the collected data. Similar technology has also been used to detect and identify leaks from large petroleum tank farms.

Since the travel time for non-sorbing tracers is shorter than for radionuclides subject to chemical retardation, such tracers could conceptually provide a leading indicator for radionuclide release from the repository. This approach is consistent with the concepts outlined by EPA in 1985 and discussed in Section 11.1.1 above. Depending upon the results of ground-water flow calculations, various tracers might be placed in the repository at closure and down stream monitoring for tracer migration in the marker beds near the repository horizon be conducted at the site boundary. This might be particularly useful in assessing any detrimental effects caused by waterflooding of vicinity oil fields to enhance recovery.

11.3.2.4 Electromagnetic Conductivity

Electromagnetic (EM) waves can be used to determine electrical properties of subsurface materials within the earth. Techniques based on propagating electromagnetic energy into the earth and measuring responses to that input have been used extensively in geophysical exploration and characterization applications for several years.

When an alternating current is applied to a looped transmitter antenna, it acts as an alternating magnetic dipole source. The resulting alternating magnetic field, the primary field, induces current flow in subsurface conductors. Good conductors, like buried metal objects or saline ground water, produce strong induction currents that decay more slowly than induced currents in poor conducting materials. The induced current in the buried conductor thus produces a secondary field observed at the surface.

Since variation in magnetic permeability in the ground is small, for a fixed frequency and fixed transmitter-to-receiver coil distance, the fields produced by the induced electric currents will be proportional to the conductivity of the subsurface. The most common field measurement for these systems is the ratio of the primary to secondary magnetic field. Different relative orientations of transmitter to receiver coils respond differently depending on the spatial geometry of the conductive bodies. In particular, the quadrature component of the secondary field is considered most appropriate for measuring broad anomalous conductive layers like contaminant spills. In-phase component measurements, on the other hand, are more sensitive to the effects of local highly conductive objects like buried metal objects.

Depth of penetration and resolution of the EM induction depends on several parameters, including average ground conductivity, source power, source frequency, and antenna spacing. Systems used in a depth-sounding configurations, with expanding source to receiver spacing, can estimate the depth to anomalous conducting bodies. In a profiling mode, the source-to-receiver spacing is fixed and the area is surveyed on grid lines. This type of survey can produce 2-D surface anomaly maps.

EM systems can be used to make estimates of the conductivity of the subsurface. In turn, these estimates can inferentially be related to subsurface geophysical and geochemical properties such as porosity, permeability, and concentrations dissolved electrolytes, for example. The EM response of the subsurface is highly sensitive to water content and thus may be useful in the mapping of aquifers and brine bodies. Highly conductive metal objects, such as pipes, metallic debris and structures are readily detected and mapped.

EM techniques have operational limitations inherent to active geophysical techniques, including the accurate positioning of source and receivers. EM techniques have the further weakness of having restricted resolution due to the averaging of the media conductivity between source and receiver. The operational concerns at WIPP must be investigated to determine the specific usefulness of EM techniques in assisting with repository performance evaluations.

11.3.2.5 Resistivity

Like electromagnetic conductivity methods, resistivity techniques represent well established methods for determining the electrical properties of the subsurface. Resistivity is the inverse of conductivity, and is thus affected by the same factors described for the electromagnetic conductivity technique above.

The resistivity technique utilizes a series of electrodes on the surface. Two electrodes are energized to establish a electric current in the earth between them and two other electrodes are used to measure the potential developed by the first pair. By varying the number, type, and position of the electrodes, as well as varying the input currents, subsurface resistivity parameters can be estimated.

Resistivity methods can be used to determine the thickness of electrically distinct strata as well as the location of aquifers or brine layers.

11.3.2.6 Seismic Techniques

Seismic techniques exploit well understood elastic wave propagation phenomena and can be used for a variety of applications ranging from the determination of the depth, thickness and composition of geologic structures, to the identification of subsurface fracture zones or voids. The subsurface is mapped by modeling measured seismic observations in terms of the travel times and shapes of the recorded waveforms. The paths, velocities and amplitudes of the waves are controlled by the distribution of the elastic moduli of the media, including the bulk modulus (volumetric response), shear modulus (torque response), and Young's modulus (stretch response).

Oil and gas industry seismic techniques are generally based on the recording and interpretation of reflected and/or the refracted waves generated by controlled sources. Various forward and inverse waveform modeling procedures have been established to process data for interpretation of the sub-surface geologic structure. Data are collected on geophones located either on the surface or in boreholes in one, two, or three-dimensional configurations. The wave propagation energy source is generally a dropped weight or controlled explosive. A wide variety of source and receiver configurations can be utilized to exploit various wave propagation effects.

Seismic methods based on the observation of reflected waves and refracted waves (bent due to Snell's Law) are regularly used to map hydrocarbon reserves, to locate aquifer boundaries, and make estimates of subsurface velocity and density parameters. These highly developed methods may be applicable to the evaluation of the performance of the WIPP site after closure.

Additionally, seismic surveillance techniques may assist in determining the post-closure repository performance. These methods are based on the continuous monitoring of ground motions on the surface or in boreholes located above and around the repository. Best known for detecting and locating earthquakes, seismic networks can also be used to locate and characterize microseismic perturbations within the repository.

11.3.2.7 Gravitation

The gravitational method involves systematic measurements of small deviations in the earth's gravitational field. Observations of the gravitational forces, described by Newton's Law, are sensitive to mass and density variations in the lithosphere. Gravity surveys can be used to detect and map structural changes in the subsurface, such as faulted or bending strata. Gravimeter data is collected on a grid and interpreted to provide a broad picture of the density distribution of the media.

At WIPP, it is unlikely that gravity variations will provide sufficient spatial or temporal resolution of parameters which describe the repository performance. However, this technique may be useful in constructing a comprehensive and accurate understanding of the substructure when combined with the data from other sensors.

11.3.2.8 Magnetization

Like the gravity method described above, the magnetic method takes advantage of naturally occurring force fields. An additional similarity is that, with the magnetic method, small deviations in the force field, relative to the primary field, are required. Anomalies in the magnetic field of the earth provide an effective geophysical observation to be exploited for the detection and characterization of underground buried ferrous objects. This phenomenon is based on the fact that some ferromagnetic minerals (magnetite, ilmenite, pyrrhotite) have magnetic susceptibilities more than 10,000 times that of non-ferromagnetic materials. Materials composed of ferromagnetic minerals have elevated bulk magnetic susceptibilities which can alter the magnetic field. Variations in the magnetic field can be measured and modeled to determine the relative distribution of ferromagnetic materials below the surface.

Clearly, magnetic techniques are only useful in detecting and characterizing ferromagnetic objects, typically those made of iron or steel. At WIPP, the magnetic method, by itself, will not provide a robust or comprehensive technique for assessment of the repository post-closure performance. However, a magnetic field survey may provide important information about the distribution of subsurface materials which may simplify, through modeling, the interpretation of effects observed in other data types.

11.4 CONCLUSION

As technological advances continue, the options for monitoring will expand. However, fundamental aspects regarding the measurement of the environment at WIPP will remain indefinitely. These aspects are related to the basic physics of the repository and include, for example, the location of the repository structures, the employed construction techniques and materials, the backfill composition, and the type, location, and quantity of naturally occurring brine. An evaluation of critical repository performance parameters suitable for monitoring must be performed to define the monitoring requirements and this evaluation is included in the compliance criteria of 40 CFR part 194.

Monitoring at WIPP may include measurements of the repository itself as well as measurements of the surrounding environment. Sensors may be deployed to perform a variety of geophysical, meteorological, and radiological measurements, and may include, for example, seismometers, magnetometers, ground penetrating radar, pulsed induction sensors, conductivity sensors, resistivity sensors, acoustic devices, bench mark leveling devices, global positioning system equipment, groundwater sampling devices, radiation sensors, and meteorological instruments.

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12. Passive Institutional Controls

12.1 INTRODUCTION

In developing the 40 CFR part 191 rule, EPA recognized that the quantification of risk over long periods of time was subject to considerable uncertainty and consequently introduced assurance requirements into the rule to qualitatively address this uncertainty. One of these assurance requirements deals with passive institutional controls. Passive institutional controls are designed to reduce the probability of inadvertent human intrusion into a repository by conveying information about location, design, and hazards of the WIPP. Preliminary PA runs conducted by SNL have shown that human intrusion presents the most serious problem in demonstrating compliance with the disposal standards (SAN92). Human Intrusion can disturb the natural and engineered barriers used in the repository to contain the waste.

In this chapter the necessity of incorporating passive institutional controls in the WIPP compliance criteria is discussed in terms of their ability to reduce the likelihood of human intrusion.

12.1.1 Regulatory Background

This sub-section defines passive institutional controls from a regulatory point of view. The regulations of principal interest are 40 CFR parts 191 and 194. NRC rules involving site markers and records are included to furnish perspective on a similar regulatory approach.

EPA Regulations

Passive institutional controls (PICs) are defined in §191.12(e) as follows (50 FR 38085):

(1) permanent markers placed at the disposal site,

(2) public records and archives,

(3) government ownership and regulations regarding land or resource use, and

(4) other methods of preserving knowledge about the location and contents of a disposal system.

PICs are one of the assurance requirements specified in §191.14. The assurance requirements are designed to provide additional confidence that the containment requirements (§191.13) are realized. Substantial uncertainty is inherent in the long-term, 10,000-year prediction of disposal system performance necessitated by the Containment Requirements. The Assurance Requirements balance the quantitative uncertainties involved in calculating the magnitude of radioactive releases to the accessible environment. As noted in the preamble to the 40 CFR part 191 Standards, "Each of the assurance requirements was chosen to reduce the potential harm from some aspect of our uncertainty about the future" (50 FR 38072).

The specific regulatory requirement stipulating the use of passive institutional controls is included as §191.14(c), which states:

> "Disposal sites shall be designated by the most permanent markers, records, and other passive institutional controls practicable to indicate the dangers of the wastes and their location."

The role of passive institutional controls is to reduce the probability of inadvertent human intrusion into the repository during the regulatory time frame. Therefore, the possibility that institutional knowledge of the repository will be lost must be considered.

The compliance criteria related to passive institutional controls are included in §194.43 of 40 CFR part 194. This section requires the compliance certification application to include "detailed descriptions of the measures that will be employed to preserve knowledge about the location, design, and contents of the disposal system" and estimates of "the period of time passive institutional controls are expected to endure and be understood."

Conceptually, some credit could be allowed in PA for the use of PICs. In theory, providing such credit might create an incentive for enhanced PICs. EPA proposed allowing credit for PICs and solicited public comment on such in the 40 CFR part 194 (60 FR 5766) proposal. In finalizing 40 CFR part 194, EPA consulted the WIPP Review Committee of the National Advisory Council on Environmental Policy and Technology (NACEPT) on three issues, including PICs. The Committee agreed that PICs would be likely to decrease the possibility of inadvertent intrusion into the WIPP but expressed concern about the ability of a rigorous method by which to determine the appropriate reduction due to PICs in the future. Some members of the Committee stated that, if credit were to be approved, the size of the credit should not reflect that PICs would be effective for more than a small fraction of the 10,000-year regulatory time frame.

NRC Regulations

Though WIPP is not subject to NRC licensing regulations, NRC regulations covering disposal of high-level wastes in geologic repositories similarly require the use of site markers and records (10 CFR part 60). License applications must contain a SAR which includes:

> (8) A description of the controls that the applicant will apply to restrict access and to regulate land use at the site and adjacent areas including a conceptual design of monuments which would be used to identify the controlled area after permanent closure (§60.21c).

When the repository is ready for permanent closure, a license amendment must be obtained which provides:

> (2) A detailed description of the measures to be employed - such as land use controls, construction of monuments, and preservation of records - to regulate or prevent activities that could impair the long term isolation of emplaced waste within the geologic repository and to assure that relevant information will be preserved for future generations. As a minimum, such measures shall include:
>
> > (1) Identification of the controlled area and geologic repository operations area by monuments that have been designed, fabricated, and emplaced to be as permanent as practicable;....... (§60.51a).

12.1.2 <u>General Background</u>

A 1984 study conducted by the Human Interference Task Force for the Office of Nuclear Waste Isolation (ONWI)(HUM84) concluded that long-term communication is the primary method for reducing the likelihood of human intrusion at nuclear waste repositories (GIL85). Vehicles for such communication can involve both markers and records. The two are closely intertwined. A limited record can be inscribed on a marker, a marker can designate the location of an on-site vault containing records, or a marker can specify off-site archives where records are located.

The ONWI Task Force asserted that, for messages on markers to be communicated, they must be detectable, durable, comprehensive, conveyed at several levels of sophistication and imparted by several techniques. The logic diagram developed by the Task Force to provide a framework for modeling future communication, taken from ONWI 84, is presented in Figure 12-1.

Assuming the markers survive and the messages inscribed on them remain legible, several scenarios can be postulated. If society either continues to advance technically or remains static, the message may be understood.[1] However, it is likely that the inscribed message will be understood at the site only if the message is periodically updated. Sebeok relates a widely accepted generalization in the field of semeiotics (communication through signs); namely, all natural language and human communication systems change over time (SEB84). An example can be drawn from the evolution of the English language. General comprehension of Middle English (ca. 1,100 - 1,500 A.D.) is limited and general comprehension of Old English (ca. 400 - 1,100 A.D.) is virtually non-existent. It has been estimated that only about 12% of basic English words and an even lower percentage of complex vocabulary items will exist in 12,000 A.D. (GIV82). The Nordic Committee for Nuclear Safety Research (NKS) provides an interesting example of this English language change over the past 600 years. The quotation is interesting because it illustrates the changes in the English language and typifies the difficulty that society may have in just a few centuries understanding English of today. The following is a quotation from "Sir Gawain and the Green Knight" written in about 1375 A.D. (JEN93):

> The stele of a stif staff the sturne hit bi gripte
> That was wounden with iron to the wandes ende,
> And al bigraven with grene in gravios werkes.[2]

[1] In the context used here, society refers to present day U.S. society.

[2] The grim man gripped it by its great strong handle, which was wound with iron all the way to the end, And graven in green with graceful designs.

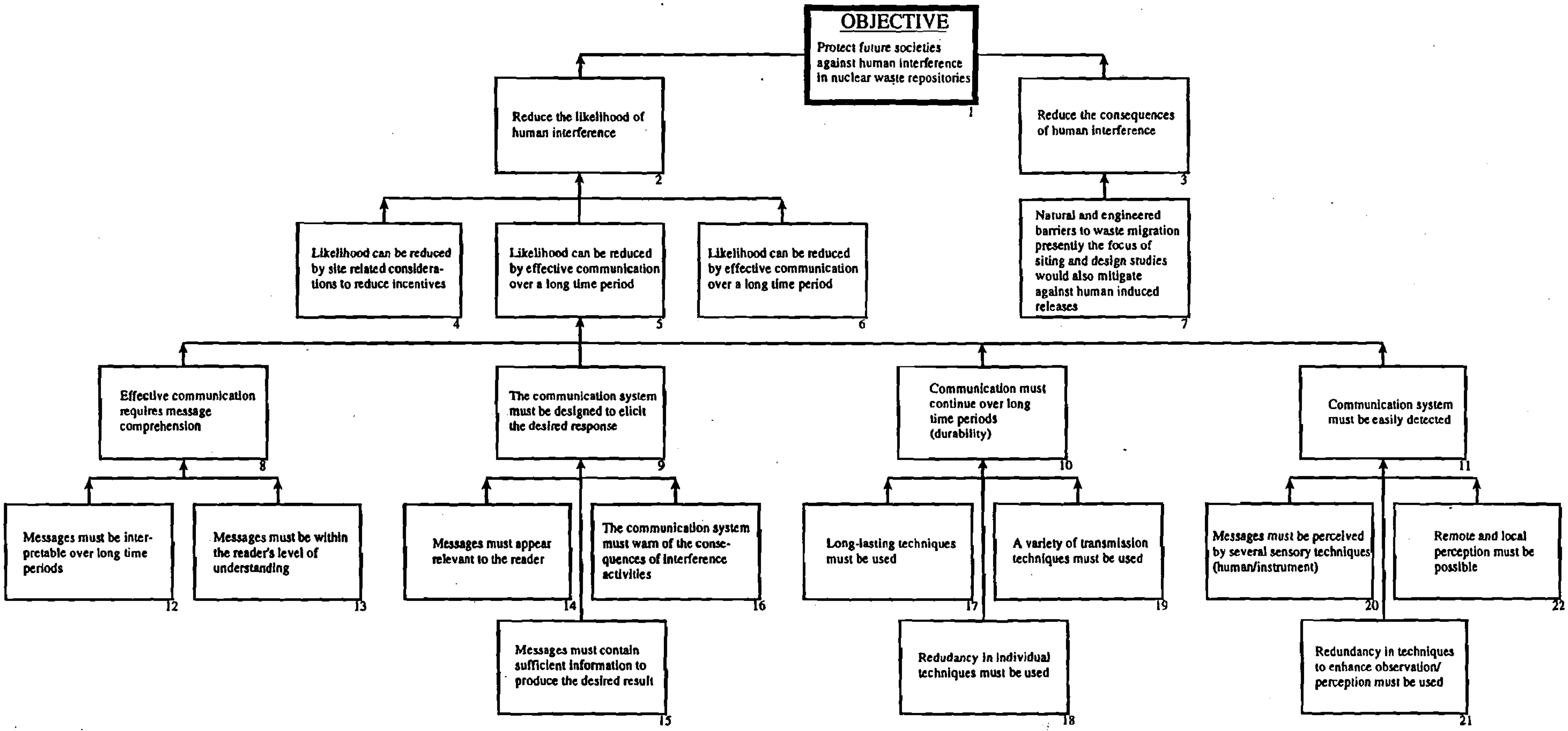

Figure 12-1 Human Interference Logic Flow

The message may not be understood by societies of the future. Such future societies possibly would not have the technology or the motivation to intrude into a deep geologic repository. However, a future society might take actions which could represent indirect interference with a geologic repository. One example would be the development of large scale irrigation or reservoir projects which could disrupt ground water flow patterns (HUM84). Large scale irrigation has been employed for millennia. Durant noted that extensive irrigation was used by the ancient Sumerians beginning about 4,000 B.C. This was the cornerstone upon which the Sumerian culture was built (DUR54, p. 124). If society regresses and then advances to a state of civilization akin to today's society, the new society might not understand any message which survives on the site markers. Language continuity may be lost. Future linguists might be able to decipher the marker inscriptions, but timing and knowledge of such decoding at the repository site might not be contemporaneous with the intent to explore for resources. The roles of markers and messages and the extent to which they may be expected to persist will be discussed more fully in subsequent sections.

The following sections discuss the four categories of passive institutional controls identified in the 40 CFR part 191 standards: (1) permanent markers, (2) public records and archives, (3) government ownership and regulations, and (4) other methods of preserving knowledge about the disposal system. It should be noted that records can be located either on-site or off-site. Since on-site records are closely tied to markers, they will be discussed with markers in Section 12.2, while off-site records will be considered in Section 12.3.

12.2 PERMANENT MARKERS

Permanent markers are the foundation of any passive institutional control strategy. This section includes examinations of archeological monuments to provide an historical perspective on the persistence and understood purpose of various monuments. Examples of monuments and megaliths which have endured and whose purpose is clearly understood are described. Ancient structures which have not persisted and/or been understood are described here to the extent possible. Programs conducted by various government agencies related to the marking of radioactive waste repositories are also discussed. The merits of a no-marker strategy are briefly recounted, although such a strategy would not be acceptable from a regulatory viewpoint. As mentioned previously, the discussion of permanent markers also includes the messages embodied in or contained on the markers.

This section focuses on permanent surface markers. Underground markers are considered in Section 12.5.

12.2.1 Archeological Analogues

12.2.1.1 Introduction

EPA has long recognized that the study of ancient markers or monuments may provide insight into the effectiveness of passive markers. At the very least, WIPP planners can learn about materials and forms of construction which are expected to last for very long periods of time. Beyond this, it is conceivable that the study of ancient monuments can provide information on how best to record messages and build markers in order to convey clearly a message to future civilization.

In 1982, DOE's Human Interference Task Force (HITF) engaged The Analytic Science Corporation (TASC) to develop recommendations of marker design based on a study of selected archeological sites. The resulting technical report by Maureen F. Kaplan (KAP82) considered the pyramids of Egypt, Stonehenge in England, the Nazca Lines in Peru, Serpent Mound in the United States, the Acropolis of Athens, Greece, and the Great Wall of China.

Kaplan classified potential messages regarding the WIPP into four levels:

- Level I: Attention getter, i.e., "something is here."
- Level II: Attention getter and warning, i.e., "something is here and it is dangerous."
- Level III: Basic information, i.e., what, who, when, why, what actions to avoid, and where to find information.
- Level IV: Full record of information, i.e., plans, drawings, environmental impact statements, etc.

Kaplan pointed out that "the medium of the message may determine the level of information the marker can convey." An earthwork, for example, can convey little beyond a Level I or perhaps a Level II message. On the other hand, the media usually employed to convey Level

IV messages (paper, plastic, metal, electronic media) are not nearly as likely to survive the millennia as is an earthwork.

Kaplan emphasized the importance of identifying the audience to whom a message is addressed and the undesirable actions to be warned against. She went on to discuss such actions. She concluded that "the primary emphasis in the marker system design should be on detection by sight," and noted that "the distance at which the message is detectable may be determined, in part, by whether it is desirable to actively call attention to the site or to warn people once they have decided to investigate the area." She discussed various possible marker designs and message contents, stressing that because "Level III and Level IV information may only be carried by the written word," it is important to incorporate written text into on-site monuments and to store records elsewhere as well.

Kaplan's study served as the primary basis for the analysis of monuments that appears below. Among her important observations were:

- Monuments that require no maintenance survive best;
- Monuments made of stone or earth survive best;
- Metals are not suitable marker materials; since they tend to be recycled;
- Markers should be shaped and sized to minimize their potential for reuse;
- The majority of ancient monuments were meant to be detected by sight, at ground level;
- If the component parts of a marker are small, and the public is not excluded from the vicinity of the marker, the chance that the marker's message (to say nothing of the marker itself) will survive are relatively slim.

A logic diagram formed from these observations led to the conclusion that the WIPP marking system should be comprised of durable, megalithic, monolithic stones with engraved symbols. Kaplan proposed that if the markers were to be visible from the air, an earthwork should be incorporated into the design. A basic design was proposed that consisted of outer rings of monoliths conveying Level I and II information. The outer rings surround a tumulus over a vault in which Level IV information would be stored. Immediately surrounding the vault are megaliths conveying Level III information. Kaplan concluded with a discussion of media in which Level IV information can be encapsulated and of potential designs for the monoliths.

Other HITF reports relevant to this study include *Communication Measures to Bridge Ten Millennia* (SEB84), *Communications Across 300 Generations: Deterring Human Interference with Waste Deposit Sites* (TAN84), *Reducing the Likelihood of Future Human Activities That Could Affect Geological High-Level Waste Repositories* (HUM84), and *Expert Judgement on Markers to Deter Inadvertent Human Intrusion into the Waste Isolation Pilot Project* (TRA93). The last report will be addressed in the conclusion of this section.

When developing the 40 CFR part 194 proposal, EPA examined a range of ancient monuments wider than that previously investigated by DOE. Published discussions of twenty-five ancient monuments and classes of monuments were examined in an attempt to answer the following seven questions:

- What message(s) were the monument's creators attempting to convey?
- Were they trying to convey this message to future civilizations or to their own people?
- What has been involved in interpreting the message by modern scholars?
- How sure are we that we have the message right?
- If the message had been "Don't dig here because it is dangerous," is it likely that we would have gotten the message before digging there?
- What physical and environmental characteristics have permitted the monument to withstand the ravages of time and vandalism?
- What physical and environmental characteristics have permitted the monument to convey its meaning clearly through the millennia?

In many, if not most cases, the published literature does not contain explicit answers to all of these questions. Answers often had to be inferred from the evidence.

In addition to previous monument studies connected with the WIPP (e.g., KAP82), results from other studies were used. No new archeological research was conducted which would most likely would have been redundant.

Below, four examples from the 25 archeological analogues listed below are discussed with reference to the seven questions. Summary observations are made at the end of this sub-section. The 25 archeological examples studied are: pyramids of Egypt, Egyptian funerary and temple monuments, monuments of Mesopotamia, Great Wall of China, pyramids and related monuments of Mesopotamia, Adena and Hopewell mounds, Mississippian mounds, Wisconsin effigy mounds, John East mound, Stonehenge, West Kennet long barrow, Knowth passage tomb, Avebury stones, Maltese temples, Easter Island statues, Nan Madol, Nazca lines, Intaglios of the California, Arizona, and Nevada deserts, Chacoan roads, Lascaux caves and similar paleolithic painted caves, Australian rock art, African rock art, Adamgarh painted caves, general rock art in the Western United States, and North Fork and Jeffers petroglyphs.

12.2.1.2 Monuments of Mesopotamia

Duration: Up to ca. 6,000 years so far.

Description: The ancient Sumerians, Babylonians, Assyrians, and other civilizations of Mesopotamia (roughly, modern Iraq) constructed major urban centers with extensive fortifications and religious and secular buildings. Emblematic of the Sumerians, and to some extent, their successors was the ziggurat, virtually a constructed mountain made of brick, topped with a religious structure. Some ziggurats rivaled the Egyptian pyramids in scale. Most Mesopotamian buildings were made of mud brick, so their upper parts have tended to collapse, forming mounds or "tells." Foundations and lower rooms are often preserved within these tells, as are the remains of older buildings that were covered by later construction. Fired clay tablets containing written material in cuneiform script are commonly found in Mesopotamian tells, as are elaborately carved statuary and bas-relief panels portraying rulers, wars, rituals, and aspects of daily life (WOO63; MAL65).

- What message(s) were the monument's creators attempting to convey?

Cuneiform writing, both on tablets and on monuments, transmitted historical data, religious observations, proclamations of law, and political propaganda. Tablets also contain more humble writings such as inventories, financial accounts, textbooks, and student's essays. Huge structures such as palaces and ziggurats were presumably intended to impress the viewer and, in the case of the ziggurat, to convey a sense of religious awe.

- Were they trying to convey this message to future civilizations, or to their own people?.

Some Mesopotamian monuments were rather explicitly addressed to the future. For example, around 500 B.C. the Persian emperor Darius had the following inscribed in cuneiform script in three languages (Old Persian, Elamite, and Akkadian) on the Rock of Bihistun along the caravan road between Babylon and Ecbatana:

Saith Darius the King:
Thou who shalt hereafter
Behold this inscription
Or these sculptures,
Do thou not destroy them
(But) thence onward
Protect them as long
As thou shalt be in good strength.

Having at the time some three thousand years of rising and falling civilizations to look back upon, and having extensive contact with cultures other than his own (e.g. the Greeks), Darius may certainly have contemplated the idea of communicating with other civilizations in the future. However, Mesopotamian monuments appear to have been designed to communicate information, ideas, directions, and impressions to both the people of the communities in which they existed and to surrounding contemporary groups.

- What has been involved in interpreting the message by modern scholars?

Archeological research, including major excavations, has been conducted extensively in Mesopotamia for over a century. One major breakthrough occurred in the late 1830s, when Henry C. Rawlinson was successful in translating the cuneiform script on the Rock of Bihistun. An excavation uncovering the library of Nineveh in the 1850s produced some

25,000 tablets that provided a rich source of messages from the ancient Assyrians. Increasing scholarly fluency in reading cuneiform script has been the key to interpreting such messages.

- How sure are we that we have the message right?

Scholars can be quite certain that they understand straightforward written messages correctly. Religious parables and the propaganda of warriors and rulers, however, are less firmly understood.

- If the message had been "Don't dig here because it is dangerous," is it likely that we would have gotten the message before digging there?

Because of increased fluency in reading cuneiform script, this message would certainly be understood. However, many excavations took place in Mesopotamia before scholars became familiar with cuneiform. Moreover, since most cuneiform records are buried, it is impossible to read their messages <u>without</u> digging.

- What physical and environmental characteristics have permitted the monument to withstand the ravages of time and vandalism?

Since the mud-brick structures of the Mesopotamian cities have collapsed, they have not entirely withstood environmental degradation. They have also been the victims of extensive vandalism. However, as upper walls have settled down over lower rooms and stabilized, the lower rooms have been protected. Monuments carved on hard stone have survived well, as have tens of thousands of fired clay tablets of cuneiform script.

- What physical and environmental characteristics have permitted the monument to convey its meaning clearly through the millennia?

The fact that cuneiform texts were both inscribed on stone monuments and imprinted on fired-clay tablets has been the key to understanding the messages of the ancient Mesopotamian.

12.2.1.3 Intaglios of the California, Arizona, and Nevada Deserts

Duration: Up to 10,000 years (DAV80).

Description: The intaglios consist of gigantic geometric, anthropomorphic, and zoomorphic figures scratched into a "desert pavement." This hard surface is created by soil deflation in arid areas or by aligning rocks which become cemented in as part of the pavement. While they are most commonly found in the California desert west of the Colorado River, others have been discovered east of the river in Arizona, in Nevada, and elsewhere.

- What message(s) were the monument's creators attempting to convey?

There is no widespread agreement about what messages the intaglios were intended to convey. They have been interpreted as reflecting shamanistic symbols, messages about water, astronomical observation points, maps, gaming facilities, and "random, perverse behavior" (DAV80, HUD79, RAV85).

- Were they trying to convey this message to future civilizations, or to their own people?

There is no evidence that the builders of the intaglios were trying to communicate with future civilizations.

- What has been involved in interpreting the message by modern scholars?

Contemporary scholars have used vertical and oblique aerial imaging, intensive surface survey and mapping, and test excavation to interpret the intaglios.

- How sure are we that we have the message right?

There is no general agreement among scholars about the message of the intaglios.

- If the message had been "Don't dig here because it is dangerous," is it likely that we would have gotten the message before digging there?

Because of the hardness of the desert pavement, the intaglios are not particularly conducive to digging. On the other hand, there is nothing in their character that discourages digging.

- What physical and environmental characteristics have permitted the monument to withstand the ravages of time and vandalism?

The extreme aridity of the desert and the stability of the desert pavement have tended to preserve the intaglios. Their remoteness has also been crucial in their preservation.

- What physical and environmental characteristics have permitted the monument to convey its meaning clearly through the millennia?

The intaglios convey a message with only Level I complexity.

12.2.1.4 Australian Rock Art

Duration: ca. 25,000 years so far (possibly 35,000 years).

Description: Australian rock art includes paintings, engravings, and peckings. Subjects and styles vary with time and location and contain both simple and complex representations. Most are polychromatic. Many pictures overlap or are superimposed on one another. Some of the art includes symbols that appear to convey information on direction, movement, the act of speaking, and events in the time known today as "the dreamtime." Australian rock art is found in rock shelters and overhangs. Aboriginal Australians continue to create rock art.

- What message(s) were the monument's creators attempting to convey?

The messages encoded in Australian rock art have been the subject of intense debate. Chalapka asserts that the art portrays a wide variety of human experiences which reflect the artist's physical, social, and cultural environment. For example, many motifs relate to hunting, plant gathering, and swamp life. Dominant plant and animal figures may represent the local subsistence base. Paintings reflect economic and socio-cultural activities, as well as "mythic" events and spirits (CHA84, GRA93). Some intent to record contemporary events, and possibly to influence them, is suggested by such sites as the Emu Dreaming and Pig galleries on the Cape York Peninsula. At this site, "a half dozen white men with rifles are depicted. In the Pig Gallery, birds are shown standing atop the bodies of two of the men, beaks thrust into their armpits" (GRA93).

- Were they trying to convey this message to future civilizations, or to their own people?

The intended recipients of the messages are also the subject of considerable debate. There is, however, nothing to suggest an intention to communicate with future civilizations.

- What has been involved in interpreting the message by modern scholars?

Since aboriginal Australian culture remains alive today, ethnography, oral history, studies of folklore, and consultation with Aboriginal experts have been primary bases for what is known about Australian rock art. Archeological research and comparative analysis of artistic elements have also made important contributions.

- How sure are we that we have the message right?

The messages of Australian rock art are not thoroughly understood.

- If the message had been "Don't dig here because it is dangerous," is it likely that we would have gotten the message before digging there?

Although much Australian rock art is very abstract, much of it is also highly representational. Often both the external and internal characteristics of animals are portrayed. It is conceivable that a representational pictograph warning against digging would be understood. It is also conceivable that a pictograph representing a human's internal structure becoming afflicted would be understood as well.

- What physical and environmental characteristics have permitted the monument to withstand the ravages of time and vandalism?

Although the painted pictures are especially fragile, they have been protected from the weather and preserved by their location in rock overhangs. Some paintings may have also been maintained over the years, because they have continued to figure in the ceremonial life of Aboriginal communities.

Chalapka identifies five variables that affect the survival of the Australian rock art:

1. Degree of protection. The less moisture present, the greater the isolation from humans and animals, and the greater the distance from the exterior of the shelter, the more likely the paintings will survive.

2. Type and matrix of host rock. The harder and more stable the rock, and the greater its ability to absorb pigment, the more likely the art will survive.

3. The properties of the pigment. The pigment's ability to be absorbed is a variable of survival. Hematite-based pigments survive best.

4. The method of application. If the pigment is applied directly to the rock, rather than onto a clay base, the painting will survive longer.

5. Climate at the time of execution. If the climate is dry, the pigment is more likely to be absorbed and has a better chance of having a protective mineral coating form over it.

- What physical and environmental characteristics have permitted the monument to convey its meaning clearly through the millennia?

To the extent that Australian rock art has conveyed its meanings, it has done so because of the physical survival factors listed above. Also, Aboriginal Australians are still living today and are able to interpret the paintings.

12.2.1.5 Rock Art in the Western United States (General)

Duration: ca. 10,000 years so far.

Description: Many Native American groups of the western United States produced both pictographs (painted rock art) and petroglyphs (pecked, ground, scratched, or incised rock art). Such art, particularly pictographs, has been produced in recent times and is probably being produced today. However, the rock art tradition dates back at least several millennia, and rock art sites up to 10,000 years old have been reported (HED83). Styles and motifs vary widely from tribe to tribe, region to region, and through time, but geometric, anthropomorphic, zoomorphic, and abstract styles are common.

- What message(s) were the monument's creators attempting to convey?

Much of the rock art in California, particularly pictographs in the Chumash area along the south coast, is thought to represent astronomical phenomena (e.g. HED83, HUD78). Some sites are ethnographically associated with specific rituals, such as the initiation of girls into womanhood (e.g. TRU88). Some petroglyphs are identified as trail markers and other mnemonic devices, vision quest location markers, and hunting ritual depictions (e.g. MUR87). Several scholars see representations of sexual parts and acts in rock art as part of fertility rituals. Others identify elements of rock art as vehicles to telling and remembering of origin stories and other traditions. Rock art may also serve as markings for social group boundaries (HED83). Petroglyphs in the form of Hopi clan symbols in the Southwest are thought to have marked the route to sacred sites, and as reflecting the journeys of the Hopi ancestors recorded in tribal tradition (JUD50). In short, western North American rock art probably was intended to convey a wide array of messages, most of which are not completely understood today.

- Were they trying to convey this message to future civilizations, or to their own people?

Rock art was probably intended to communicate messages with the artist's fellow religious practitioners, or hunters, other members of the artist's family, clan, or tribe, and (in the case of boundary markers and some trail markers) with other groups. Some rock art may have been intended for communication with the supernatural. There is no evidence to suggest an attempt to communicate with future civilizations.

- What has been involved in interpreting the message by modern scholars?

Interpretation of rock art in the American west has involved ethnographic consultation, excavation of rock art sites, photography, rubbings and tracings, and a wide range of comparative analyses.

- How sure are we that we have the message right?

There is little agreement about what messages are embedded in western American rock art. In a few cases, the testimony of ethnographic consultants has generated a fair amount of certainty about the meaning of particular rock art sites (e.g. TRU88).

- If the message had been "Don't dig here because it is dangerous," is it likely that we would have gotten the message before digging there?

In cases where rock art is representational, it is possible that such a message could be transmitted. However, the highly abstract, presumably symbolic, forms that dominate much western American rock art would not be likely to convey such a message readily.

- What physical and environmental characteristics have permitted the monument to withstand the ravages of time and vandalism?

Pictographs survive best when well protected from exposure to the elements. Petroglyphs often survive on exposed surfaces, but do erode and weather. Petroglyphs deeply pecked or polished into very hard rock, like granite, survive best. Pecked and polished petroglyphs survive more readily than scratched or engraved forms. Burial under sand or silt can preserve petroglyphs in almost pristine condition (TUR94). Since human vandalism is a major cause of petroglyph destruction, remoteness from human settlements promotes survival.

- What physical and environmental characteristics have permitted the monument to convey its meaning clearly through the millennia?

On the whole, the meaning of western North American rock art has not been clearly conveyed.

12.2.1.6 Summary Observations on Archeological Analogues

The review of archeological analogues to the WIPP marker system suggests that there are few specific analogues which address all the questions posed in this section. There is little evidence to suggest that the monuments, structures, and other markers discussed above were explicitly intended to convey much -- if any -- information into the distant future. Even highly permanent and seemingly message-rich structures like the various pyramids and the megalithic structures of England and Europe have contemporary functions such as housing the dead, supporting temples, making astronomical observations, and impressing the population with the power of the government or the awesomeness of religious rites. To the extent messages were encoded in the structures, they seem for the most part to have been, or at least are today understood as, fairly simple Level I or II messages, on the order of "the pharaoh who built this structure was very powerful."

Some of the monuments were certainly intended to mark historical events for future reference. The stelae of the Maya and other Mesoamerican civilizations are an example, as are the painted tombs of the Egyptian pharaohs, Australian rock art, and such Mesopotamian monuments as the Rock of Bihistun. With the exception, perhaps, of markers like the Rock of Bihistun, there is little reason to think that these monuments were meant to convey information to future civilizations that their creators thought would be substantially different from their own. There is little reason to believe that anyone who created a monument in the past designed it with an eye to communication across thousands of years of cultural and linguistic change.

Some monuments do communicate warnings against disturbance, but these have been notably ineffective. Tombs explicitly marked as protected by supernatural sanctions have routinely been looted by treasure seekers and excavated by archaeologists. In almost all cases of archeological analogues, the value of what was contained or hidden was vastly understated, and the threat or hazard was overstated or imaginary. Of course, no one in the past warned against deep drilling, so the possible effectiveness of such a warning cannot be directly assessed.

The review of archeological analogues has produced some information relevant to the WIPP, however, which may be summarized as follows:

1. The "monuments" that have managed to convey fairly detailed information over millennia (e.g., paleolithic rock art, Australian rock art, Egyptian tomb paintings and carvings, Mesopotamian cuneiform inscriptions, and Mesoamerican stelae) have done so because they have been inside something very protective, like a cave, rock shelter, or excavated tomb, or because they have been buried.

2. In some cases of European paleolithic and Australian rock art, images have survived for possibly up to 35,000 years. These images are often portrayed in the very fragile medium of paint.

3. Certain graphic images communicate clearly through the millennia. Anthropomorphic and zoomorphic figures painted on cave walls during the paleolithic period in Europe and Africa and by Australian aborigines and prehistoric Native Americans are easily recognizable as such today. Geometric figures that presumably had symbolic meaning

when they were produced, such as intaglios, the Nazca lines, and prehistoric rock art, convey their meaning much less reliably, if at all.

4. Detailed (ca. Level IV) information on ancient monuments has for the most part survived to the present because it was inscribed or otherwise written on the monuments themselves (e.g., Mayan stelae, Egyptian tombs, Mesopotamian monuments), embodied in a literature that has survived or been recovered (Great Wall of China, pyramids of Egypt, Mesopotamian monuments), or embodied in the oral history and cultural practices of a population that remained resident in the vicinity (Mesoamerican pyramids and other structures).

5. The other major source of information on ancient monuments has been archeological research. This has almost always involved excavation. Excavations conducted in and around such monuments have never reached depths that would compromise waste containment if conducted at the WIPP site. Future excavations could be taken to such depths if archaeologists believe that there is something important to be learned and do not realize the danger of deep excavation.

6. Most ancient monuments have attracted people to dig into or around them in search of treasure or recyclable material, or for purposes of scientific research. An exception is the Chacoan road system, which has not enticed or suggested that it would be profitable to dig. This is because the roads do not convey the impression that anything would be gained by digging in their vicinity.

12.2.1.7 The WIPP Markers Panel Report

In late 1993, DOE published the opinions of two expert panels assembled by SNL to offer advice about the WIPP marker system (SAN93). The recommendations of the panels can be summarized as follows:

<u>Team A</u>

1. Warnings should be conveyed through a gestalt sense of place, through written languages and scientific symbols, and through the use of the human face with expressions.

2. The WIPP and a buffer area should be surrounded by earthen berms, jagged and threatening in shape, to create a threatening sense of place.

3. Within the "keep" created by the berms there should be multiple "message kiosks" containing Level II messages in some seven languages -- the languages of the United

Nations plus a local indigenous Native American language. The messages should be inscribed on a granite wall protected by a partially encircling "mother wall."

4. Also, a world map should be constructed within the "keep" showing other disposal sites, together with the original WIPP buildings, which should be left to decay. The map should be visible from the tops of the berms.

5. Level IV information should be contained in concrete rooms buried at the four corners of the berm system, designed to permit access but preclude the removal of the information. The information should be inscribed on redundant layers of stone tablets in multiple languages, each tablet being too large to be removed intact through the entryway, which would be blocked by a sliding stone plug.

6. Construction should employ materials that are too large, too difficult, and too worthless to tempt recycling or relocation to museums.

7. Message design should include the use of inscribed pictographs[3] of human faces expressing shock and disgust.

Team B

1. The marking system should employ both surface and buried markers.

2. The messages must be truthful.

3. The outer extent of the marker system should be visible from the center.

4. The area marked should be surrounded by berms, which should not include a buffer area. The berms should be spiked with materials having anomalous properties (e.g. magnetic, radar reflective, dielectric).

5. The warning messages should be conveyed in number of ways so that if one message is not completely understood, the message in another form can be used to fill in the gaps. Messages should be conveyed in multiple languages, scientific symbols, and pictographs. They should be inscribed on stone monoliths and buried in "time capsules."

[3] The word "pictograph" is often used to mean painted rock art, as opposed to incised, pecked, or inscribed "petroglyphs." Following common WIPP practice, the term is used in a more general sense here, to mean pictures on stone -- in this case, inscribed.

6. The original WIPP buildings should be left in place for future archeological study, which will preserve knowledge of what was done there.

7. Detailed information should be stored off-site.

8. The marker system should include a map showing other disposal sites around the world, and perhaps an international radiation warning symbol.

9. In the center of the marked area there should be a granite structure containing detailed information about the WIPP and its dangers, in both textual and pictograph form, inscribed on large stone slabs.

10. Testing marker designs for durability and cross-cultural understanding should be undertaken between now and the time of implementation.

EPA reviewed the report of the Markers Panel and its recommendations as an aid in what types and to what extent PICs should be required at the WIPP.

12.2.2 NRC Studies

No NRC work on markers has been uncovered in the development of this background information document.

12.2.3 NASA Studies

Four NASA deep space probes which have left the solar system contained symbolic messages for other possible civilizations in the universe. These included the Pioneer 10 and 11 and the Voyager 1 and 2 spacecraft. A gold-anodized plaque on Pioneer uses various symbols to depict the position of our sun relative to various pulsars, the relative size and physiognomy of male and female compared to the spacecraft, and the track of the spacecraft from Earth past Jupiter (NGS75).

Each Voyager spacecraft included a copper disc (protected by an aluminum cover) with greetings from Earth people in 60 languages. The record also contained samples of music from different cultures and ages ranging from the 1958 recording of "Johnny B. Goode" by Chuck Berry to Beethoven's Fifth Symphony and various Earth sounds (NGS90, NASA 77). The record also contained digitized pictures describing the blue planet. Instructions and equipment were included in the spacecraft for retrieving the contained information.

12.2.4 NEA/OECD Studies

In 1990, a Working Group on Future Human Actions at Radioactive Waste Disposal Sites was established by the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD). This group's purpose was to review and summarize work of OECD member countries regarding treatment of future human actions on post closure safety assessments of geologic repositories (NEA93). In discussing site marker systems, the Working Group noted that some markers have already survived for 5,000 years and, consequently, the task of devising markers which will persist and be understood "appears daunting but feasible." The Working Group described surface marker studies conducted by DOE in the United States and Agence National pour la Gestion des Dechets Radioatifs (ANDRA) in France. (DOE work will be documented in Section 2.5 below.) The French approach is based on concern that on-site messages may be misunderstood. Site markers may arouse curiosity and thereby encourage intrusion. The elements of this approach as presented by the Working Group are:

- Markers should not be located directly above the repository, but rather 10 to 20 km away. This distance should limit direct intrusion due to curiosity and allow the markers to be located in the same political and geographical region as the repository itself.

- Markers should be sufficiently large enough to be recognized by any people living in the vicinity of the site.

- Markers should contain redundant messages indicating the exact position of the disposal site. This information should be in a form recoverable by a civilization knowing the basic elements about radioactivity; otherwise, the situation would be equivalent to that for a marker built directly above the repository. Thus, the messages and particularly the location of the disposal site should be encoded, for example, using the symbols and quantities used in nuclear physics.

The Working Group concluded as follows:

> "In summary, the Working Group considers that marker systems can form a useful part of a system of warnings to future generations about the location and contents of the repository. While well-designed markers may be durable and interpretable for long periods of time, the Working Group notes that it will be difficult to take credit for marker longevity for periods much beyond one thousand to several thousand years from repository closure and decommissioning."

The NEA Working Group also met with the WIPP Markers Panel to hear presentations on the expert judgments rendered by the Panel and to audit the probability elicitation session of one of the Markers Panel teams (TRA93).

12.2.5 DOE Studies

DOE has done a significant amount of work on markers for geologic waste repositories. This work falls broadly into two categories:

- Studies in the early 1980s under the aegis of the Office of Nuclear Waste Isolation (ONWI) directed toward repositories for high-level waste (KAP82, HUM84)

- Studies beginning in the late 1980s and continuing today on markers for the WIPP site (HOR91)

Some of the concepts developed in the ONWI work were subsequently considered by DOE for application at a low-level waste disposal site being studied at Hanford, Washington (ADA86). Further information from these two DOE programs is presented in the following sections.

12.2.5.1 ONWI Program

A Human Interference Task Force operating under the direction of ONWI conducted extensive studies on reducing the likelihood of human-initiated processes and events affecting geologic waste repositories. The multi-disciplinary Task Force included members with expertise in law, sociology, political science, nonverbal communication, nuclear physics, environmental science, archeology, climatology, linguistics (and semeiotics), behavioral psychology, materials science, nuclear waste management and engineering (HUM84, SEB84, TAN84).

Assuming a remote, flat, non-glacial site, the Task Force proposed that granite markers about seven meters high and spaced at intervals no greater than 1000 meters should be used to define the perimeter of the site. The monolithic triangular pyramids would be inscribed with appropriate messages and warnings in several languages, supplemented with symbols and pictograms. The site would also be centrally marked with three large triangular monuments defining the location of three granite storage vaults where site records would be stored.

The Task Force suggested that these markers could be supplemented with earthworks and anomalies capable of being detected by remote sensors. Recommended earthworks included an arrow-shaped central plaza about 100 meters across and several meters high, on which are located the central markers and storage vaults described above and a segmented berm located several hundred meters from the central plaza, as shown in Figure 12-2. To enhance the durability of these earthworks, the Task Force suggested that they be covered with 0.15 to 0.30 meters of an aggregate asphalt mixture. This proposal was based on the fact that natural asphalts have been used since antiquity. This protective layer would also hinder growth of vegetation on the earthworks. Because various materials would be used in constructing the central plaza, it should create an anomaly which would remain recognizable by several remote sensing techniques.

The Task Force reached no conclusions as to the effectiveness of markers and other measures to reduce the likelihood of human intrusion. The Task Force noted that any such conclusions must be based on site-specific analysis. These analyses should use probabilistic assessment techniques to estimate the effectiveness of a highly redundant system even though some elements may fail. The Task Force observed that the expected longevity of earthworks, monuments and vaults was a subject requiring further investigation.

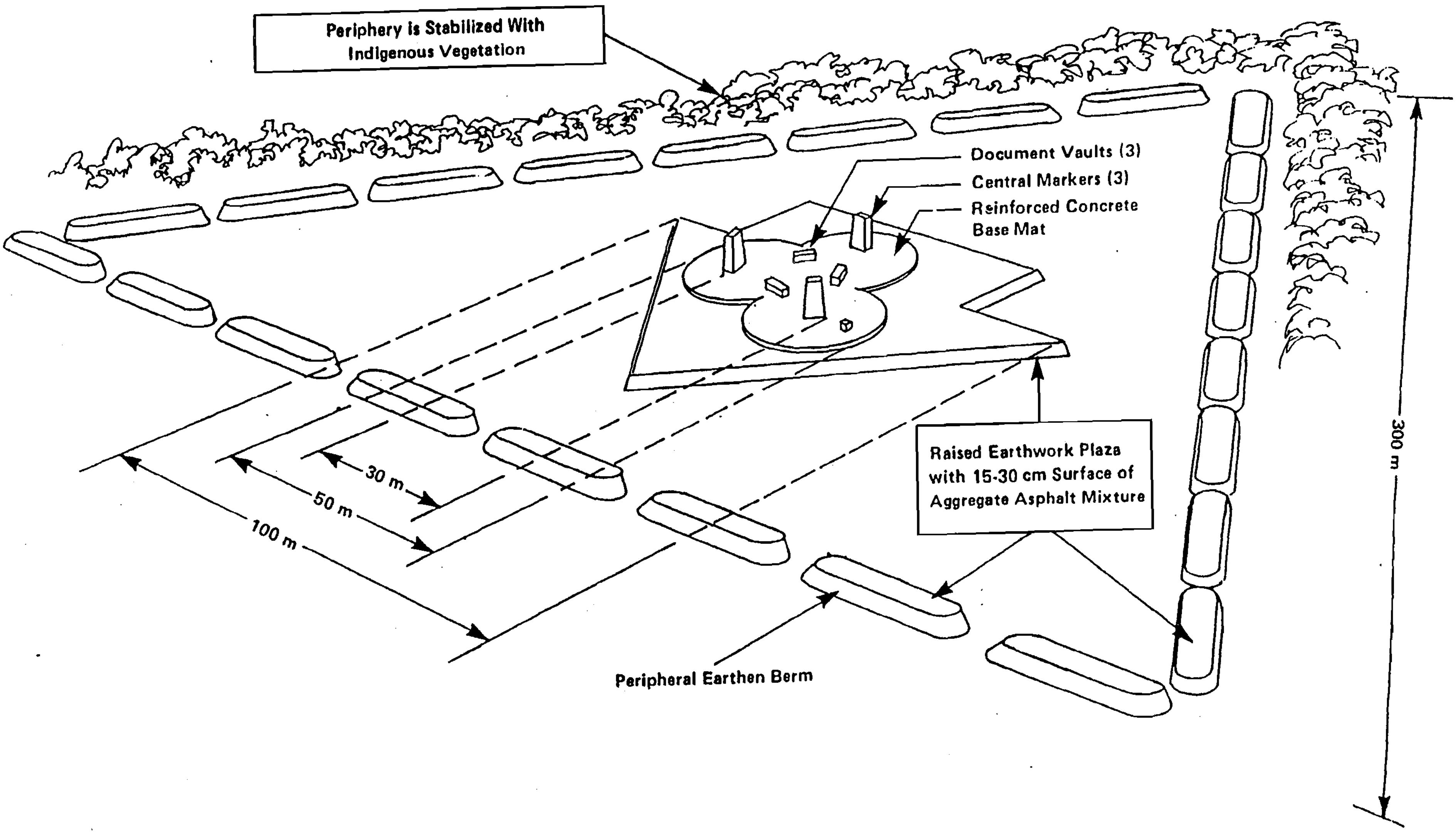

Figure 12-2. ONWI Conceptual Design of Site Markers for Geologic Repository

12.2.5.2 WIPP Program

In a 1979 study conducted by the WIPP Technical Support Contractor (WTAC) for DOE, crude probabilistic estimates were made of the time over which monuments and records would persist beyond the period of effectiveness for active institutional controls (BRA79). The probabilistic estimates were based on considerations such as the observations that records of land ownership and transferral in the U.S. can be traced back to the 1700s, and grave stones in U.S. cemeteries are still legible after about 300 years. From this type of anecdotal evidence, it was estimated that there was a 50% probability that markers would persist for 200 years beyond active institutional controls. There was also a 50% probability that accessible records would be available for 110 years after markers were lost. The study assigned a 95% probability to the postulate that active institutional controls would last for 100 years. It was also assumed to be likely that economically recoverable hydrocarbon resources would be depleted by the time that active and passive institutional controls were lost. However, it was presumed that a 50% probability of drilling at the WIPP still existed for a 50 year period beyond loss of institutional controls. Based on these assumptions, the time of isolation was calculated to be at least 450 years with 50% probability. Probabilities of various isolation periods are summarized in Table 12-1.

Table 12-1. Isolation Times Prior to Drilling in the WIPP Site Area

Probability[a]	Time of Isolation (years)
0.50	450
0.90	300
0.95	250
0.98	200
0.99	150

[a] Probability that Time of Isolation beyond active institutional controls is at least this duration.

The credit for active and passive institutional controls estimated in the WTAC study is relatively short compared to the 10,000 year containment period required by 40 CFR part 191. More recently, in support of its WIPP-related PA activities, DOE and SNL organized four teams of experts (the Futures Panel) to provide judgments on the probability of future human-initiated processes and events. The Southwest Team of experts cited an instance in their summary report where marking of a radioactive location near WIPP has been vitiated (HOR91, p. D-15). Under the aegis of the Plowshare Program (see 12.2.5.3 for more detail), an underground nuclear detonation was conducted in 1961 at the Gnome Test Site, about six miles from the WIPP. The test was performed in a bedded salt formation at a depth of about 1,250 feet, as compared to the WIPP repository depth of 2,150 feet. The Gnome Site was marked with a single monument which, according to the Southwest Team, already shows signs of weathering and has shifted from its original location.

WIPP Markers Panel.[4] Using a formal process similar to that involved in setting up the Futures Panel, SNL organized an expert judgment panel called the Markers Panel 1991. The panel served the following two purposes:

- Qualitative - to develop design guidelines for markers and messages needed to communicate with future societies concerning the location and dangers associated with buried TRU wastes at WIPP.

- Quantitative - to estimate the probability that markers would survive for the required time period and convey the intended message.

The Markers Panel was divided into two multi-disciplinary teams with expertise in such areas as anthropology, materials science, architecture, linguistics, environmental engineering, astronomy, semeiotics, archeology, and communications. Each team developed a total marker system design which addressed architectural design, material properties, linguistics, message levels, message media, and other marking components (e.g., international symbols and standards). Based on the conceptual marker systems, each team was asked to estimate probabilistically:

- the durability of the marker system for various periods up to 10,000 years

- the ability of future societies to understand the message embodied in the marker system

The teams were asked to assume three different levels of technology in future society; higher than current levels, at current levels, and lower than current levels. In assessing these

[4] See also Section 6.2.1.7.

probabilities, Team A divided the regulatory future into time periods of 200; 500; 1,000; 5,000; and 10,000 years after closure of the WIPP repository while Team B considered periods of 500, 2,000 and 10,000 years after closure. Each member of Team A developed individual probability estimates while Team B developed a consensus estimate. Results of these expert elicitations, reproduced from Reference SAND 93, are included as Tables 12-2 and 12-3.

Team A's estimates that the marker system would persist for 500 years ranged from 0.85 to 0.99. The lowest probability estimates are for a society where a high level of technology is dominant. Some Team A members felt that such a society might be able to remove the entire WIPP repository markers. Presumably, they would understand the consequences of such action. Team B estimated the probability of marker persistence after 500 years to be 0.9, independent of the state of technology.

While both teams estimated that there was a high level of probability that the marker system would persist for a considerable period, it should be noted that the Panel was directed to exclude cost as a factor in the conceptual marker system designs (TRA93, p. F-21). The extent to which the elicited probabilities would be reduced if a cost perspective was included is unknown, but interviews with some of the members of the Markers Panel suggest that this should not have a significant effect. The materials proposed for the marker systems are of intrinsically low cost. What is not clear is whether the design and construction are also of relatively low cost. They may not be.[5] One member of Team A observed that a successful marker system at WIPP "will have to be one of the greatest public works ventures in history." This statement was predicated upon more elaborate earthworks than the Team A consensus recommendation. If DOE is to take credit for a marker system capable of persisting for several millennia, DOE must be prepared to make a concomitant obligation for the construction of such a system. A scenario developed by one of the Futures Panel teams posed the possibility that a future bureaucracy functioning in the year 2020 might become embroiled in a major debate on closure costs and choose to authorize only a modest marker system (BEN91). The scenario, as outlined from the perspective of someone recounting the debate 25 years hence, is as follows:

---

[5] The NKS Working Group KAN-1.3 indicated that the structures proposed by the WIPP Markers Panel might cost tens of millions of dollars (NKS93).

> "The markers recommended by a panel of experts convened by the now defunct Department of Energy in 1990 are widely viewed as extravagant in view of the fact that the WIPP repository has not been used to capacity and is such a controversial topic. It now seems unlikely that the site could ever be forgotten, its potential hazard is thought to be less than originally foreseen, and it seems politically dangerous to advocate large sums of money for it in view of the pressing current social problems which followed the costly conventional weapons buildup of the 1990s. After protracted debate lasting several years, Congress finally appropriates money for the markers, although design compromises must be made because it is not enough to pay for the extensive marker system envisioned in 1990."

In reviewing such a scenario, EPA recognized a more probable future argument in which an elaborate system of PICs had been described in a long ago compliance application because they were, "the right thing to do." The Department of the future was tasked with justifying the expenditures of limited funds so that they could provide the most protection for the public and the environment. Without a documented and quantifiable benefit to justify implementing such a system, more pressing needs with quantifiable benefits could take priority.

In eliciting expert judgment as to the probability that the message contained on/in the markers would be correctly interpreted by future intruders, various levels of technology and various time periods were considered in a manner similar to that used to assess the probability of marker persistence. In addition, five conceivable motivations for intrusion were appraised including drilling for water, mineral exploration, drilling to create injection wells for waste disposal, archeological investigation, and other scientific investigation. Generally, the panelists grouped the first three intrusion modes together and treated the last two as a second group. Probabilities estimated by the two panels for intrusion driven by mineral exploration are summarized in Table 12-4 (TRA93).

Table 12-2. Probabilities of Marker System Persisting - Team A

Expert	Dominant Technology	Years After Closure				
		200	500	1,000	5,000	10,000
Ast	High Medium Low	.99 .99 .99	.98 .98 .98	.95 .95 .95	.75 .75 .75	.50 .60 .60
Brill	High Medium Low	.99 .99 .99	.98 .98 .98	.95 .95 .95	.70 .70 .85	.50 .50 .80
Goodenough	High Medium Low	.99 .99 .99	.98 .98 .98	.90 .95 .98	.85 .90 .95	.70 .75 .80
Kaplan	High Medium Low	.95-.99 .95-.99 .95-.99	.95-.99 .95-.99 .95-.99	.90-.95 .90-.95 .90-.95	.80 .80 .90	.70 .70 .85
Newmeyer	High Medium Low	.90 .95 .95	.85 .90 .90	.70 .85 .85	.65 .80 .85	.60 .60 .65
Sullivan	High Medium Low	.90 .95 .95	.85 .90 .90	.80 .85 .85	.70 .80 .80	.50 .70 .70

Source: Table 5-1 TRA93

Table 12-3. Consensus Probabilities of Marker System Persisting - Team B

Dominant Technology	Years After Closure		
	500	2,000	10,000
High Medium Low	.90 .90 .90	.85 .80 .70	.85 .60 .40

Source: Table 5-2 TRA93

Table 12-4. Probability of Correct Interpretation of Marker Message Intrusion by Mineral Exploration

Expert	200 Years Technology =			500 Years Technology =			1,000 Years Technology =			5,000 Years Technology =			10,000 Years Technology =		
	H[a]	M	L	H	M	L	H	M	L	H	M	L	H	M	L
Ast	.99	.99	.98	.98	.95	.70	.95	.90	.50	.90	.20	.10	.90	.20	.05
Brill	.99	.99	.95	.95	.95	.90	.95	.95	.70	.95	.95	.60	.95	.95	.50
Goodenough	.99	.99	.99	.95	.95	.70	.90	.90	.50	.65	.60	.15	.50	.40	.02
Kaplan	.99	.98	.95	.98	.90	.70	.97	.85	.65	.95	.80	.50	.90	.75	.02
Newmeyer	.99	.99	.90	.90	.85	.80	.80	.70	.50	.70	.60	.40	.50	.30	.20
Sullivan	.95	.95	.80	.90	.90	.60	.85	.85	.40	.70	.70	.10	.40	.40	.01
Team B	500 Years			2,000 Years			10,000 Years								
	.90	.90	.80	.90	.85	.70	.99	.80	.30						

[a] The levels of technology being more advanced than today (H), similar to today's level (M), and less advanced than today (L).

Source: Table 5-4, TRA93

Turning again to Team A's 500 year estimates, it can be seen that the probability of correct interpretation of the marker message ranged from 60 to 90% for a technologically less advanced society to 90 to 98% for a technologically more advanced society. On the same basis, the Team B probability estimates ranged from 70% to 90%. Higher probabilities were assigned to understanding the marker message by potential intruders seeking archeological or other scientific knowledge.

If one averages the individual Team A estimates and then averages Team A and Team B estimates, the probability of correct interpretation of the marker message by a future society conducting mineral exploration with the same level of technology as today is 0.91 at 500 years after closure. Performing the same type of averaging for marker system persistence, the probability that the system will persist at the current level of technology after 500 years is 0.93. The probability that the markers will persist and that their message will be correctly interpreted is therefore 0.84.

The Markers Panel recommended to DOE that additional study is warranted in three areas:

- Durability of marker materials under the WIPP site conditions including the mechanism for attaching or inscribing messages and the interaction of wind, sand, and water with marker materials and configurations

- Interpretation of graphic or pictorial messages that are independent of culture

- Interpretation of written messages that are independent of culture

EPA did not review the Markers Panel Team's results in order to apply numerical values to credit for PICs or even develop a credit methodology. Instead, EPA noted the great variability and uncertainty in the efforts of the two teams.

12.2.5.3 Project PLOWSHARE and Related Tests

The Atomic Energy Commission (AEC) established the PLOWSHARE program in June 1957, under the technical direction of the Lawrence Radiation Laboratory (LRL), now Lawrence Livermore National Laboratory (LLNL). The program consisted of 27 nuclear detonations conducted at the Nevada Test Site (NTS) and other sites in Colorado (2) and New Mexico (2) from 1961 to 1973. The nuclear tests were all underground, either shaft or cratering shots, and had yields of no more than 200 kilotons. The PLOWSHARE nuclear detonations were designed to explore nonmilitary applications of nuclear explosives. The primary potential use envisioned was in large-scale engineering projects such as canal, harbor, and dam construction, the stimulation of oil and gas wells, and mining.

The 1963 atmospheric nuclear test ban treaty caused cancellations of many of the plans, such as those for dredging canals and excavating harbors. Other factors contributing to the failure of PLOWSHARE to fulfill its goal were changes in national priorities, Government and industry's disinterest in the program, public concern over the health and safety aspects of using nuclear power for civil applications, and shortages in funding. Several other underground nuclear tests (Vela Uniform Events and weapons tests) were also conducted away from the NTS. A total of 11 underground nuclear tests were conducted at locations other than the NTS since the beginning of testing through December 1973.

Comments on a few of these tests relevant to human intrusion and PICs are discussed below.

Project Gnome:

> Project Gnome, a shaft detonation, was fired on December 10, 1961, at a site 40 kilometers southeast of Carlsbad, New Mexico. The site was in the Salado formation of the Delaware Basin. This geologic formation consisted primarily of halite (rock salt), with minor traces of anhydrite, polyhalite, silt, and claystone. The top of the salt formation was approximately 710 feet below the site surface. The device was buried 1,184 feet underground in bedded rock salt at the end of a 1,116-foot hooked tunnel meant to be self-sealing. A shaft 1,216 feet in depth and ten feet in diameter ended in a station room connected to the tunnel. The detonation, which had a yield of 3.1 kilotons, resulted in an underground dome-shaped chamber 60 to 80 feet high and 160 to 170 feet in diameter.
>
> All Gnome site decontamination and decommissioning activities were completed and terminated on September 23, 1979. A concrete and bronze monument was erected at the Gnome surface ground zero location as an historical marker. The following wording was inscribed on two bronze plates:

Historical plate:

United States
Atomic Energy Commission
Dr. Glenn T. Seaborg, Chairman

Project Gnome

December 10, 1961

The first nuclear detonation in the Plowshare Program to develop peaceful uses for nuclear explosives was conducted below this spot at a depth of 1,216 feet in a stratum of rock salt. The explosive, equivalent to 3,100 tons of TNT, was detonated at the end of a horizontal passage leading from a vertical shaft located 1,116 feet southwest of this point. Among the many objectives was the production and recovery of useful radioactive isotopes, the study of heat recovery, the conduct of neutron physics experiments, and the provision of seismic source for geophysical studies.

Restrictive plate:

No excavation and/or drilling is permitted to penetrate Section 34, Township 23 South, Range 30 East, New Mexico Principal Meridian, at any depth between the surface and 1,500 feet. (DOE81)

If Section 34 is leased, a "special stipulation" is to be put into the lease by the U.S. Geological Survey (USGS). This stipulation would require the drilling operator to abide by the lease stipulation to protect the area between the surface and 1,500 feet below the surface; no exceptions are to be allowed. The BLM is to ensure that no drilling or excavation will occur.

Project Rulison:

Project Rulison was an experiment co-sponsored by AEC and Austral Oil Co. to determine the technical and economic feasibility of using nuclear explosives to stimulate the flow and recovery of natural gas from the Mesa Verde formation in the Rulison Field, Garfield County, Colorado. The test, conducted near Rifle, CO on September 10, 1969, consisted of a 43 kiloton nuclear explosive emplaced at an 8,426 foot depth. Production testing began in 1970 and was completed in April 1971. Cleanup was initiated in 1972 and wells were plugged in 1976. Some surface contamination resulted from decontamination of drilling equipment and fallout from gas flaring (burning). Soil was removed during the cleanup operations.

Project DRIBBLE:

Project DRIBBLE was comprised of four explosive tests, two nuclear and two gas. It was conducted in the Tatum Salt Dome area of Lamar County, Mississippi, near the communities of Baxterville and Purvis, under the Vela Uniform Program. The purpose of Project DRIBBLE was to study the effects of decoupling on seismic signals produced by explosives tests. The first test, SALMON, was a nuclear device with a yield of about 5.3 kilotons, detonated on October 22, 1964, at a depth of 2,710 feet. This test created the cavity used for the subsequent tests, including STERLING, a nuclear test conducted on December 3, 1966, with a yield of about 380 tons, and the two gas explosions, DIODE TUBE, conducted on February 2, 1969, and HUMID WATER, conducted on April 19, 1970.

The nuclear tests resulted in the release of radioactive elements into the salt rock. Although most of these radioactive elements remain in the salt dome, some contamination in the form of radioactive drill cuttings, drilling muds, and water was brought to the surface during the drilling of boreholes into the shot cavity. Today, the Tatum Dome Test Site has largely returned to its original state. Except for the monument the U.S. Department of Energy erected over the location of the actual subsurface detonations (called Surface Ground Zero), there is little indication of any of the past activities at the site. The areas where soils were excavated have been backfilled and seeded and now have a well established cover of vegetation. Wildlife is abundant at the test site and the area is used for timber production and hunting.

Although the residual levels of radioactivity remaining at most of the test sites are not extensive enough or high enough to pose an imminent or substantial risk to the environment or public health, DOE, in conjunction with EPA and the involved states, has continued to investigate and monitor the sites. These continued investigations are driven, in part, by the environmental laws of the states and federal governments and, in part, by the concerns that have been raised by the public with respect to the safety of the sites. For example, U.S. Senator Lott identified four major issues related to the Tatum Dome Test Site in an October

1989 letter to the U.S. Department of Energy. One of those issues was: "The control of access to Surface Ground Zero"(DOE93b).

In addressing Senator Lott's issues, DOE has committed to conducting additional investigations and studies at the Tatum Dome Test Site. As such, DOE will conduct a Remedial Investigation at the site to determine if the use of the nonradioactive hazardous substances at the site has resulted in contamination of the soil, groundwater, or surface water. A feasibility study will also be performed to determine what measures can be taken to reduce risks associated with the site. One of the measures that will be evaluated is the need for fencing of the site to maintain institutional control over access to the facility.

The routine annual site visits by the Environmental Monitoring Systems Laboratory include groundwater, air, and biological sampling. Results are reported annually in EPA's Off-site Environmental Monitoring Report.

As to how much radioactivity was released and how much is left, the Nevada Environmental Restoration Project (ERP) is presently sponsoring a determination of this for all underground tests at the NTS. This work is being performed by the LLNL and the LANL. To date, similar work for NTS off-site tests has not been funded. For the NTS on-site tests, ERP personnel are calculating inventories of fuel, fission products, and activation products initially and at the end of 1992. The work and calculations for the NTS on-site PLOWSHARE are probably complete by now, however, the results are classified, but DOE/NV expects to declassify summaries (DOE94a).

All NTS off-site PLOWSHARE sites have been decommissioned. This has included plugging wells into the cavities and cleanup of surface structures and waste sites. Remedial investigations/feasibility studies are being conducted. Monuments were erected at Gnome and the Tatum Dome sites warning against excavating at the sites. Similar warnings were attached to the property deeds. Status of site markings at the other NTS off-site locations is not well documented and is currently being investigated (DOE94b).

12.2.6 No Marker Strategy

§191.14 requires sites to be "designated by the most permanent markers, records, and other passive institutional controls practicable to indicate the dangers of the wastes and their location." In spite of this regulatory admonition to mark the WIPP site, some have argued that a no-markers strategy is preferable and some have argued that markers should be located away from the site of the repository.

The presence of markers on which the meaning of the inscriptions has been lost might create a desire by future archaeologists to understand the function of the site. This desire could result in intrusion. The markers could constitute an, "attractive nuisance", encouraging intrusion. Kaplan suggests that a marker with a so-called Level I message which serves solely as an attention-getter might have this result (KAP82). She also suggests that such a situation could be avoided if a Level II message is conveyed which is both an attention-getter and a warning ("something is here and it is dangerous"). Kaplan points out that an earthwork marking a site may convey only a Level I message. But, if the earthwork were in the form of a recognizable hazardous/radioactive waste symbol, the marker could reduce the likelihood of human intrusion rather than serve as an invitation to future intrusion. However, Givens remarks that prohibitions, curses, and other dire warnings have been "sorry failures" in deterring tomb robbers (GIV82).

The no-marker strategy was rejected by the WIPP Marker's Panel and the NKS Working Group KAN-1.3, but the working group report did not elaborate on the basis for their decision (JEN93). It should also be noted that the recent NAS report on the Yucca Mountain high-level waste repository briefly states a conclusion about the desirability of marking a repository site (NAT95, p. 108), namely:

> ... passive markers could attract the curious and actually increase the risk of intrusion. Nonetheless, we conclude that the benefits of passive markers outweigh their disadvantages, at least in the near term.

As discussed below, two of the four teams on the WIPP Futures Panel recommended that consideration be given to not marking the site, or at least not employing surface markers, out of concern that markers would draw attention to the site and possibly encourage curiosity seekers (below-grade markers could still be detected by and warn off technically advanced societies). However, both teams on the Markers Panel rejected that advice and concluded that the site must be marked in some manner, including surface and sub-surface markers, to reduce the risk of inadvertent intrusion.

The French national waste management authority, ANDRA, has expressed similar concerns to those of the two Futures Panel teams. ANDRA has suggested that markers might be misunderstood by persons in a future society that lacked a knowledge of radioactivity, engender curiosity in such persons, and, if the society was sufficiently advanced to have deep drilling capabilities, lead to human intrusion into the repository. ANDRA proposes an alternative marking strategy in which markers would be placed off-site and information about the location of the repository encoded so that it could only be recovered by a civilization understanding basic elements of radioactivity. This strategy will be discussed in greater detail subsequently.

The WIPP Markers Panel did not consider the use of off-site markers nor (apparently) review the ANDRA proposal.

12.2.6.1 Futures Panel

The 1991 Futures Panel for the WIPP site (HOR91) consisted of four separate review teams (Boston, Southwest, Washington A and Washington B). On the issue of markers, two teams—Boston and Southwest—recommended that consideration be given to <u>not</u> marking the WIPP site. The Boston Team recommended as follows (HOR91, pp. C-68 to 69):

> The marker panel should consider the possibility of not marking the site. There is at least some reason to believe that markings of any kind will be attractive to a future society and draw special attention to the region of WIPP. Most of the potential intrusions we studied would, if truly inadvertent, be extremely unlucky to penetrate the repository by chance. For example, without knowledge of the specific location of the transuranics at WIPP, a future wild cat driller would have an extremely small chance of hitting the wastes stored at WIPP. We ask that the marker panel at least consider whether the small risk of a coincidental penetration is more or less favorable than attracting attention to the site with permanent markers. (Another panel on hearing this recommendation suggested subsurface markers - no markers on the surface - but clear markers underground near the site.)

This recommendation was based in part on various intrusion scenarios the team postulated. For example, the team postulated one scenario in which institutional memory of WIPP is lost but local folklore holds that something valuable was dumped in the area years ago. "Treasure hunters" locate the markers and interpret them as warning people to stay away from the treasure, confirming their conviction that they choose the correct site to dig for the treasure.

> The markers had an effect opposite to that intended by the WIPP designers: the treasure hunters understood the warnings as confirming their selection of the site as containing something valuable and they started to excavate. As they encountered

additional warning markers on different levels, they became increasingly convinced that they had picked the correct location. (p. C-45)

The Southwest Team Report within HOR91 made similar recommendations (p. D-44):

- **No-marker strategy?** Consider a "no surface marker" strategy, or a "soft" marker which erodes in a few centuries, to meet short-term marking needs. Hidden markers could still be placed underground. This avoids attracting curiosity seekers, yet the hidden markers below can warn off high technological societies. The risk lies in the Seesaw Scenario, since wildcatters in a reviving era receive no warning at all.

- **To Mark or Not to Mark:** The crucial decision confronting the Marker Panel is whether to use surface markers at all. A "soft" surface marker which erodes in a few centuries will cover the short-term possibilities, and then avoid curiosity seekers in the far future. High technologies will still be able to sense the buried markers.

  Much of the Egyptian legacy came from King Tut's tomb, the only major unviolated burial site. It was covered by the tailings of a later tomb. Unmarked, it escaped the grave robbers.

  But not marking the WIPP imposes ignorance on our descendants, who may wish to avoid the site but could no longer locate it well. Also, low-tech wildcatters in re-emergent technological societies would have no warning.

12.2.6.2 Markers Panel

The 1993 "Markers Panel" report for the WIPP site (TRA93) was based on two expert panel reports: Team A (AST92) and Team B (BAK92).

Section 1.3 of AST92 addressed the question -- "Should the site be marked?" -- and concluded:

> We... feel that it is essential that the WIPP site be marked in some manner, and cannot agree with the conclusions of two of the Futures panel teams and other authors [ROC77][6] which suggested not marking it. We take it as uncontroversial that all people have an inherent right to understand as far as possible the forces that might profoundly affect their well-being...

Similarly, the preface to BAK92 states that the panel reached a unanimous opinion that:

> The site should be marked, on the assumption that leaving it unmarked would pose greater risks to the future. Current mining activities in the area, alone, would make the choice of not marking extremely risky for present-day (i.e., living) humans, and cumulatively more dangerous for those living between now and 12,000 A.D. At present the WIPP is in an area of active oil production, gas production and potash mining...Surface and buried markers should be used in tandem to enhance message redundancy...Only the land directly above the waste panels themselves -- about a ½ square-kilometer area -- should be marked. (A) this would put the marker system on a cognitive scale better geared to human perception than one spread thinly over 16 square miles. (B) Additionally, it would reduce confusion that could arise from boring beneath a marker system beyond the panels and uncovering nothing unusual....

AST92 stated as one of its criteria for the marking system that:

> The site must be marked. Aside from a legal requirement, the site will be indelibly imprinted by the human activity associated with waste disposal. We must complete the process by explaining what has been done and why. (p. F-11)

[6] ROC77 states: "Intelligent life is notoriously incautious in indulging its curiosity. Construction of a large concrete mausoleum, for example, would almost guarantee that concerted efforts would be made to breach it by intelligent, but uninformed, life. On social grounds, such a method is held to be quite reversible. Additional irreversibility cannot be provided by warning messages, symbols, or labels. We cannot assume that even a society that has the technology to undo rather irreversible storage will know enough about radioactivity to proceed cautiously, or that it will be able to decipher a message it cannot read... Indeed, the presence of such an indecipherable message would only arouse additional interest. 'Interesting' geological formations such as salt domes are equally likely to draw attention. The society that drills into them may know nothing of radiological hazards, but still be sufficiently advanced technologically and scientifically to be curious about the formation itself and its possible contents... A condition for site location that aids irreversibility is that it be as uninteresting as possible, and so draw no attention for other reasons." (p. 27)

In other words, the site's presence will be detectable whether or not it is marked. The report states that:

> so much buried metal and radioactive material will leave a 'signature' that scientists of the future will have no difficulty in detecting. What we need to do, of course, is to 'complete' the marking by letting them know why it is there. Also, it is projected that after settling of the excavated and filled salt deposits, ground levels will be depressed by at least a half foot. Even today's geologists and archaeologists can detect such a depression; those of the future will presumably be able to do so even more readily. (p. F-24)

12.2.6.3 ANDRA Off-Site Marker Concept

Discussions in an OECD Nuclear Energy Agency working group on human intrusion inspired work in France on a different design for marker systems (NEA95). The design was motivated by concern that on-site messages may not be correctly understood, and that the markers may arouse curiosity and actually increase the risk of human intrusion.

A paper by the French national waste management authority, ANDRA, describes a concept for off-site markers based on the reasoning outlined below (RAI93). (The paper notes that a report published in 1987 by a special working group in France recommended a study of the potential benefits as well as disadvantages of marking nuclear waste repositories (GOG87). The ANDRA paper notes that some of the participants in this working group defended the concept of marking the surface of a repository site, but others remained unconvinced, which was the basis for the study.)

In RAI93, ANDRA considered three options:

1. Markers built directly above the disposal site
2. Leaving the site unmarked and allowing its existence to be forgotten
3. Markers built off-site

The ANDRA researchers explained the justification for off-site markers as follows:

> ...if messages are misunderstood or not understood at all, the marker may stir up curiosity as a probe of an ancient civilization or valuables. It could therefore increase

the probability of human intrusion in the sense that it is only useful to prevent inadvertent intrusion and not intrusion due to curiosity. Other possibilities have thus to be thought out.

> We propose a different marking system that presents the advantages of a marker but do (sic) not increase the risk of intrusion: the marker is not located directly above the disposal but several kilometers away. It is monumental enough to resist to erosion and to be known by any people living around, but it is far enough from the site to prevent any intrusion due to misunderstanding of the messages and therefore to curiosity.
>
> We think that 10-20 kilometers away from the site would be a good distance since the marker and the site have to be in the same geographical and political region. (p. 217)

The ANDRA authors propose to describe both the contents and the location of the repository in messages written on the marker. However, they would encode the message about the location so that the information would only be recoverable by a civilization knowing basic elements about radioactivity (such as by encoding with symbols and values commonly used in nuclear physics). In this manner, a civilization unable to understand the message regarding the dangers of the repository would not be lured to dig there.

The core of ANDRA's analysis is an evaluation of the probability of human intrusion resulting from inadvertence <u>or</u> misunderstanding of markers, as a function of technological level, for each of the three marker concepts. The analysis is summarized as follows:

- At a <u>low technological level,</u> there is a low potential for human intrusion regardless of the marker concept because humans would not have the capability to drill deep into the repository.

- At an <u>intermediate technological level,</u> humans would have the capability to drill deeply but would not have an understanding of radioactivity.[7] Because of the capability to drill, the risk of inadvertent human intrusion is higher than at the low technological level even if the site is not marked. If the site is marked, there is an additional risk that the message will be misunderstood and will actually encourage

[7] The authors suggest that this technological level corresponds to the period from the Roman era, when 400 m-deep mines were dug, to the end of the 19th century, when radioactivity was discovered.

human intrusion. (This analysis assumes that the net effect of on-site markers for this technological level is negative: the probability that the markers will be misunderstood and will encourage intrusion is much greater than the probability that the markers will be understood and will prevent inadvertent intrusion.)

- At a high technological level (equal to or greater than our own), the encoded messages would be understood. Either an on-site or off-site marker will prevent inadvertent intrusion. The risk that an on-site marker will be misunderstood and encourage intrusion is also eliminated, making the effectiveness of on-site and off-site markers equal. Both marker concepts are preferable to no marker because they prevent inadvertent intrusion.

In effect, ANDRA separates the analysis of the potential for human intrusion into different cases depending on technological level, and finds very different results for intermediate and high technological levels. The ANDRA researchers agree that markers prevent inadvertent intrusion if civilization is sufficiently advanced to understand them, but feel that such prevention can be equally achieved through off-site markers that would not invite a less advanced civilization to explore the site out of curiosity.

EPA did not reconsider the "no markers" option because markers are an established and codified requirement. The same arguments that were used to support the "no markers" argument could be applied to the "no credit" argument. However, the Agency found that the primary responsibility was to require that the site be marked with markers that had the highest probability of surviving, being understood, and therefore protecting the public and the environment.

12.3 PUBLIC RECORDS AND ARCHIVES

This section discusses the use of public records and archives as passive institutional controls. Such controls are designed to increase the probability that institutional knowledge of the WIPP repository will not be lost by future societies. This section deals specifically with records and archives located away from the repository site. With regard to the types of records to be considered for archival purposes, the NKS Working Group has suggested the following (JEN93):

- Geographical location of the repository
- Chemical and physical properties of the waste
- Design of the repository including physical shape and barriers
- Background information and data used in the final safety (risk) assessment
- Various background materials including the final safety assessment, laws and regulations, general information from and about society, and operational records of the repository

12.3.1 Regulations

12.3.1.1 WIPP Land Withdrawal Act (LWA)

Under the terms of the WIPP LWA, 16 square miles of land around the WIPP site are withdrawn from all forms of entry, appropriation, or disposal under the public land laws. According to Sec. 3(c), of the LWA, Land Description, the boundaries of the land withdrawn for the WIPP site are described on a map, issued by BLM which is entitled "WIPP Withdrawal Site Map," dated October 9, 1990, and on file with the New Mexico State Office of the BLM. Under the LWA, the Secretary of the Interior is required to publish a description of the withdrawal area in the *Federal Register* and to file copies of the legal description of the withdrawal area and the site map with the U.S. Congress, the Governor of the State of New Mexico, the Secretary of Energy, and the Archivist of the United States.

On November 24, 1993, BLM published a description of the WIPP in the *Federal Register* as required by the LWA (57 FR 55277). The notice is included as Appendix 12A. BLM also submitted the required documentation to various governmental organizations on November 16, 1992. A sample transmittal letter is included as Appendix 12B. (While this information was supplied to the Archivist of the United States and presumably has been filed, the existence and location within the Archives have not been uncovered in spite of numerous inquiries.)

12.3.1.2 40 CFR part 194

§194.43 specifies that the compliance certification application include a detailed description of plans for the "placement of records in the archives and land record systems of local, State, and Federal governments, and international archives, that would likely be consulted by individuals in search of unexploited resources." The records must identify:

- The location of the controlled area and the disposal system
- The design of the disposal system
- The nature and hazard of the waste
- Geologic, geochemical, hydrologic, and other site data pertinent to the containment of waste in the disposal system
- The results of tests, experiments, and other analyses pertinent to the containment of waste in the disposal system

12.3.2 Historical Perspective on Use and Survivability of Records

Although records describing the WIPP site have been filed with various government agencies, the key question to be asked is "Will these records persist and for how long?" An essential element in the efficacy of records as a component in a passive institutional controls strategy is survivability of the records. Written or pictographic records have endured for almost 6,000 years. Sumerian inscriptions have been documented on stone dating from about 3600 B.C. and on clay tablets from about 3200 B.C. Egyptian hieroglyphics on various monuments date from about the same time. The famous Code of Hammurabi was inscribed on diorite in about 2100 B.C. (DUR54). Written Chinese, which dates to the Shang dynasty (1766-1123 B.C.), has remained substantially unchanged over the millennia.

Various investigators have suggested that records be located in numerous locations and include several vehicles such as maps, land-use records, geological surveys, and archival facilities (TAN84, GIL85, GIV82). This redundancy in record keeping will increase the probability that records will survive at some location. Even so, Tannenbaum has observed that storage materials may not last for the required 10,000 years; therefore, records must be periodically reproduced and perhaps translated into contemporary language (TAN84). Such reproduction will require the existence of a "responsible institutionalized authority" to periodically undertake this reproduction and revision. Since the availability of long-term record-keeping materials and the existence of a responsible authority to maintain records for the entire regulatory period are questionable, the future availability of repository records in useful form for the entire regulatory period is also questionable.

Gillis mentions a downside to record-keeping redundancy (GIL85). Dispersal of the information to ensure its survivability may reduce detectability by persons at the site for whom it is most relevant.

A second key question regarding records is whether they will be understood if they do survive. These are the same key questions which must be answered with regard to markers. The example of the Rosetta Stone, a three language monument used in unlocking Egyptian hieroglyphics, is often cited as an example of how maintenance of records in several languages will promote future understanding (KAP86). However, as Givens has pointed out, translation may be accomplished "at the expense of years of sometimes painful decipherments" (GIV82). He also notes that some ancient scripts remain undeciphered even today, citing Mayan, Indus Valley, Minoan Linear A, Germanic and Turkish runes, and certain African scripts. With regard to the use of icons to covey messages, Givens observes that even the most simple and obvious iconic signals left by antiquity may not be completely understood by a future society.

Seboek also takes issue with use of the Rosetta stone as a "success story" vis-a-vis language redundancy as an aid to communication with future societies (SEB84). He observes that, although the stone's importance was instantly identified as a possible key to deciphering hieroglyphics upon its discovery in 1799, its "mere existence .... did not make solution automatic." The puzzle was not solved until 1822. Kaplan takes a more optimistic view of the deciphering of the Rosetta stone, noting that one month after the stone was made available to scholars, the Greek text had been translated and presented at a scientific meeting (KAP82). This certainly argues for a multiple language approach.

The NEA Working Group cited historical examples, drawn from French experience, of lost records (NEA93). In the civil war of 1870, a fire in the Tuileries Palace destroyed archives relating to Paris. In World War II, many records were destroyed during bombing raids. These examples reinforce the need for worldwide, redundant record storage. Despite past problems, the Working Group felt that it was reasonable to assume maintenance of records for 500 years.

The Nordic Working Group KAN-1.3 commissioned studies on German archives in the 20th century and the Vatican archives since their inception (JEN93). Both studies provided examples of major losses of archival information as well as successful attempts to protect and shelter the information. In the German study, the interesting observation was made that many losses occurred after World War II. The German people, driven by extreme poverty, found paper in the poorly guarded archives to be useful for such basic needs such as fuel or wrapping groceries. The NKS Working Group deduced from these studies that loss of archival information is often engendered by forces different from or external to the institutions which created the archive. Accordingly, they concluded that "an international and internationally respected archive would represent a robust strategy." The Working Group suggested that IAEA might be a candidate archive manager.

12.3.3 Survivability of Land Ownership Records

12.3.3.1 Introduction

EPA disposal regulations include a requirement that "[d]isposal sites shall be designated by the most permanent . . . passive institutional controls practicable to indicate the dangers of the wastes and their location."[8] The definition of PICs includes "public records," which incorporate state and federal land records. The issue presented in this section is whether existing state and federal land records will effectively delineate the WIPP so as to provide the most "permanent . . . passive institutional controls practicable."

If the benchmark of "practicable permanence" is the time period over which cumulative releases are to be limited, there are innumerable complexities and uncertainties. Use of historical analogues is largely inadequate to determine whether land records of the WIPP withdrawal would survive for even a significant portion of the 10,000 year period following disposal. Writing is believed to have been developed in Mesopotamia as cuneiform only 5,000 to 6,000 years ago. Slightly later, hieroglyphics were developed in Egypt. Chinese script is the oldest writing still in use. The fact is, however, that writing itself has only been in existence for about 5,000 years. Based upon historical precedent, it would be sheer speculation to conclude that any written record would last for 10,000 years.

[8] 40 CFR § 191.14(c).

12.3.3.2 Historical Land Records

Land ownership records were maintained by different civilizations for a variety of reasons. In most instances, preserving an accurate list of current land owners was not a high priority. In many civilizations, alienation of land (i.e., disposal) was not widespread. In some societies, (e.g., 6th century B.C. Athens) alienation of land from the owning family was largely prohibited. The legendary Doomsday Book, compiled in 1086 A.D. at the behest of William the Conqueror, is the greatest land record of medieval Europe. (It is currently displayed at the Public Record Office in London.) This book was not intended to be an ongoing record of land transfers. It was used as a means of settling feudal controversies that had arisen from the Norman conquest so that the King could obtain needed assurances from all his feudal tenants of substance.

From at least the 2nd century B.C., the Romans had a Cartesian system of land records that was very precise. To the extent that the records have survived, they demonstrate a concern with obtaining an accurate "snapshot" of land ownership from time to time, rather than a record of land transfers. This is consistent with the purpose for which the records were maintained, namely obtaining the correct amount of tribute from each landholder in the provinces.

Some historical land records showing a "snapshot" of land ownership have survived, largely by historical accident. There is no indication that the keeper of the records considered them to be of lasting significance. Thus, there is no way of judging, for example, how durable Roman provincial land records would have been had there been any premium placed upon their lasting existence.

Ironically, the ancient people with the greatest sense of history, the Jews, had no enduring need for land records because of political domination by others and a nomadic existence. This irony was heightened two millennia later in England. In medieval England, an effective system of recordation and registration of security interests in lands was developed by the Exchequer of the Jews. The registration of sealed contracts before officials at the Jewish Exchequer in certain towns in England was an effective recording system and provided necessary notice to all concerned. It thus fulfilled the chief objectives of livery of seizing[9]

[9] Ancient ritual involving the giving of notice of land ownership.

and was an extremely successful incursion into the feudal system. The system was too successful to suit those who had a considerable interest in the maintenance of the feudal system and ended with the expulsion of the Jews from England in 1290.

12.3.3.3 State Land Records in the United States

In this country, real estate recording is usually done at the county level under state law. The systems generally resemble the type first used in the Massachusetts Bay Colony in the 1600s. Documents which may affect title to real estate are presented for recording. Recording gives legal priority over possible conflicting interests. Otherwise, title may be lost to a subsequent transferee who has recorded his deed or other document affecting title.

As a rule, recording is not a prerequisite to legal validity between the parties to a land transaction. Deeds and other instruments may create interests in property even if they are not recorded. Furthermore, recording a void instrument will not normally make it effective. Unless there is a land registration system in effect, which is unusual in this country, acceptance of an instrument for recordation is not an official determination that the instrument is legally effective.

Recording systems tend to use either a grantor-grantee or tract index, the former being older and more prevalent. In a grantor-grantee index, instruments are indexed alphabetically according to the grantor's and grantee's surnames. The grantee index is used to search from the present back to the beginning of the recording system to establish the chain of owners. The grantor index is used to find adverse recorded conveyances made by or through each owner during the time that the owner was the apparent or actual owner of the property in question. This type of index is inexpensive to maintain but difficult to use.

A tract index organizes instruments according to the property they affect. Instruments affecting each segment of land are indexed for that parcel. A tract index is easy to use, but more expensive to maintain than a grantor-grantee index.

Recording system in this country do not necessarily show who is the actual owner of a particular piece of property. Unrecorded interests may be valid and recorded interests may be void. It would be unusual for these records to show a withdrawal of public land.

A system of title registration, as opposed to recordation, is used in a few parts of the United States and throughout the United Kingdom and Scandinavia. Perhaps the most popular system of land registration is the so-called Torrens system, which is modeled after a title registration method used for ships. Under this system of land registration, the government actually determines that a valid conveyance has been made. In other words, each time a document is registered, there is an administrative determination analogous to the judicial determination made in a quiet title action[10]. Registration of a conveyancing document is a prerequisite to its validity in most of those jurisdictions having a registration system. Therefore, a registration system is much more likely than a recordation system to show who is the actual owner of a particular piece of property. However, governmental action, such as a reservation or withdrawal of public lands, would not necessarily be reflected in a registration system.

12.3.3.4 Public Land Records

Public land records are maintained by the BLM. These records generally consist of a master title plat, a use plat, mineral lease plats, an historical index, a serial register, and case files. The master title plat is a copy of the official survey or a composite of several surveys. It contains references to all patents, reservations, withdrawals, rights-of-way, and similar actions. The references on the master title plat have generally consisted of weighted lines and abbreviations. The use plats show what uses are being made of public lands. Exceptions are grazing leases. Oil and gas leases appear on a separate use plat. Other mineral leases appear on separate plats.

The historical index is a chronological narrative of reservations, withdrawals, and other actions that have affected the use or title to public lands. Much of the same information will appear on the master title plat and the use plat.

The serial register is an index to all filings made with respect to a particular application, such as an offer to lease. In the serial register, an offer to lease, for example, would be the date of

[10] Quiet title actions are lawsuits that are brought to settle land ownership disputes. The court decides who owns the land and , after all appeals have been exhausted, that decision is controlling. The point being made here is that under a system of land registration, every time a document is registered, the administrative body that registers the document has to decide whether the document is valid and whether there has been a conveyance, i.e. who owns the land. This is similar to what a court does in a quiet title action, and very dissimilar to what most county "recording" offices do when they simply accept for filing, a document that is given them, and make no determination concerning its validity or who actually owns the property.

issuance of the lease, approval of any assignments, and any applications for extension. There is a serial register sheet for each filing.

The case file contains the original instruments that have been filed for an oil or gas lease, the land office copy of the lease or application, and related correspondence. Case files are listed under the serial number for the particular offer, application, or lease.

In addition to the records listed above, there are other public land records that are available, but these are of solely historic significance because they do not necessarily contain current information. These are the tract books and the plat books. The plat book contains plats arranged by township and range numbers. The tract book contains entries affecting lands by land description.

Because the WIPP is located on public lands, the durability and reliability of the public land record system is relevant to determine the extent to which there would be permanent, passive, institutional controls. The United States Supreme Court attempted[11] to define away much of the problem of ownership of public lands by excluding from the definition of "public lands," lands that were subject to the claim of a third party, whether or not that claim was valid.[12] If lands to which any questions exist regarding title are excluded from the definition of "public lands," administration of the public lands becomes easier.

12.3.3.5 Past Problems With Public Land Records

It is possible to describe particular circumstances in which the public land records system has not proven to be a reliable indication of land use, title,[13] or description. These have been

[11] The Court has not been consistent in its definition of "public lands." To the extent, however, that they attempted to define away the problem, as stated in the text, they probably succeeded in alleviating some of the burdens associated with administering the public lands, i.e., the federal land management agency's problems, but did little to solve the problems of the claimants who may otherwise have had a valid claim to public lands.

[12] *Newhall v. Sanger*, 92 U.S. 761, 763 (1875); *Bardon v. Northern Pacific R.R.*, 145 U.S. 535, 545 (1892).

[13] Traditionally the public lands were equated with the public domain obtained by the United States from the 1780s until 1867. This definition has been expanded over the years and now includes interests in land and "acquired lands." 43 U.S.C. § 1702(e). But see, *Columbia Basin Land Protection Association v. Scheslinger*, 643 F.2d. 585, 601 (9th Cir. 1981). Acquired lands were lands that had been in non-federal ownership and, subsequently, were granted or sold to the United States by an individual or a state.

recurrent problems that can be examined to see whether or not the public land records are a passive institutional control that is permanent and practicable for purposes of describing the WIPP withdrawal.

The previously mentioned approach taken by the Supreme Court over a century ago to alleviate the problem of third party claims is indicative of one problem that has beset the public land record system and the administration of the public lands for many years. In the Treaty of Guadalupe Hidalgo in 1848, the United States obtained lands that had previously been owned by Spain. The United States was confronted with claims of title based upon Spanish grants. Some of these were recognized by the United States; others were not. However, this is not a problem that should have any bearing on the public land records accurately and enduringly depicting the WIPP withdrawal.

Another issue with the public land records system that was ultimately recognized by Congress when it enacted the Federal Land Policy and Management Act ("FLPMA")[14] in 1976, was inaccurate surveys.[15] Some of the original surveys of the public lands erroneously omitted entire tracts of land. Omission of these lands from the surveys was due to simple error, laziness, or, in some cases, outright fraud on the part of the surveyors. Generally, it has been held that title to these omitted lands is in the United States and that they are subject to administration under applicable public land laws. Although this could be a problem in administering the WIPP withdrawal and identifying the lands withdrawn based upon existing public land records, this is extremely unlikely.

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[14] 43 U.S.C. §§ 1701-1782.

[15] Section 211 of FLPMA authorizes the Secretary to convey omitted lands and unsurveyed islands to states or their political subdivisions without regard to the acreage limitations contained in the Recreation and Public Purposes Act. In some circumstances such lands could also be conveyed to an individual occupying and developing such lands for a period of five years prior to January 1, 1975. 43 U.S.C. § 1721.

Until 1976, when FLPMA was enacted, there were no reliable records of unpatented mining claims. The holder of the mining claim did not have to file any notice of the location[16] with the federal government. A valid, unpatented mining claim is a property right and BLM was faced with a serious problem in administering the public lands without any reliable indication of where these claims were. Since enactment of FLPMA, notice of all mining claims, past and future, must be filed with BLM. If the required notice is not filed, the claim is deemed abandoned. Consequently, this is no longer a problem.

A situation that BLM has occasionally encountered arises from administering interests, e.g., oil and gas rights, in land that has not been surveyed under the System of Rectangular Surveys. In Texas, for example, surveys are by metes and bounds and do not always close, which may cause the description to be inadequate. This, however, is not a problem in New Mexico and should not affect the WIPP withdrawal.

Managing 200 years of paperwork relating to the public lands[17] is complicated. This is especially true in light of the roughly 3,000 public land laws that have been enacted, repealed, or amended at various times in our history. Furthermore, BLM public land records are maintained at various offices in the western states and in an eastern state office. This amount of paperwork could affect the viability of BLM public land records as suitable passive institutional control, i.e., the most permanent passive institutional control practicable. Fortunately, as discussed below, the BLM public land records are being converted to disks and a software has been developed that will make such records readily accessible.

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[16] There is no reason to delve into the refinements of the Mining Law of 1872. At the risk of oversimplification, a mining claim is "located" when the miner stakes out his claim and complies with the Mining Law of 1872. No action is required by BLM or the Department of the Interior in order for this claim to be valid. The miner is entitled a patent of the lands containing his claim for which he must make a nominal payment, but he is not required to obtain a patent. If a miner does "proceed to patent" and the Department of the Interior finds that there has not been a valid discovery, not only will the miner not receive the patent, but also the claim will be invalidated.

[17] One of the first problems confronted by the Continental Congress was how to dispose of the western lands that the original states had ceded to the new federal government. The Continental Congress responded by enacting the Land Ordinance of 1785, which established the rectangular system of survey and subsequently, in 1787, the Northwest Ordinance, which provided for new states to be admitted into the union on an equal footing with the existing states when certain conditions were met.

With regard to land withdrawal, it should be noted that since 1976 the Secretary of the Interior has had authority under FLPMA to withdraw federal lands[18] from "settlement, sale, location, or entry" under the general land laws. Prior to 1976, the Secretary had withdrawal authority delegated to him by the President.

Although there are two cases[19] that suggest otherwise, the well-understood rule is that a withdrawal has no effect upon discretionary disposals, such as oil and gas leases, but simply upon non-discretionary disposals, e.g., settlements, sales, locations, and entries. This is consistent with how withdrawals were defined for the 200 years preceding FLPMA.

The rationale behind this definition is that lands do not need to be "withdrawn" from the operation of the mineral leasing laws, for example. The Secretary of the Interior can simply refuse to issue a lease. On the other hand, when someone can acquire rights in the land without the Secretary or any other official doing anything, such as "locating a mining claim" under the Mining Law of 1872, a withdrawal may be necessary to prevent the lands from passing out of federal ownership or control. Mineral leasing would not be an immediate concern to a knowledgeable BLM employee simply examining New Mexico land records with a view towards a possible withdrawal of those lands from settlement, sale, location, and entry.

Furthermore, Congress itself withdrew the lands comprising the WIPP.[20] There are procedures established in FLPMA that may have uncovered any oil and gas leases and any other "natural resource uses and values of the site and adjacent public and non-public

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[18] The term "federal lands" is broader than "public lands" and includes land administered by agencies other than BLM.

[19] *Mountain States Legal Foundation v. Andrus*, 499 F. Supp. 383 (D. Wyo. 1980). The court in *Nat'l Wildlife Federation v. Watt*, 571 F. Supp. 1145 (D.D.C. 1983) assumed that the withdrawal provisions in FLPMA could be used to prohibit mineral leasing. Neither opinion is particularly cogent in this regard. The terms used in FLPMA -- "settlement, sale, location, and entry" -- contemplate the transfer of title, not the issuance of a mineral lease. *Udall v. Tallman*, 380 U.S. 1 (1965). For a Court of Appeals decision, albeit pre-FLPMA, that recognizes the distinction between a refusal to issue a lease and a withdrawal, see *Duesing v. Udall*, 350 F.2d 748 (D.C.Cir. 1965), *cert. denied*, 383 U.S. 912 (1966).

[20] Section 2(22) of the WIPP Land Withdrawal Act defines "withdrawal" to mean an area of land, rather than in its usual sense, which is removing that land from settlement, sale, location, and entry.

lands"[21] had those procedures been followed. This does not suggest that Congress may not, or should not, exercise its virtually limitless power over public lands and withdraw such lands when the need arises. However, when Congress does so, procedures that Congress itself has established in FLPMA may be ignored, and existing uses of the lands to be withdrawn are not fully assessed or understood.

12.3.3.6 Automation of Public Land Records

BLM is in the midst of an effort to have its public land records placed in a computerized, "user friendly" data base. The focus of these efforts is the Automated Land and Minerals Records System (ALMRS), which combines records of ownership, authorizations, and use affecting the public lands. This information will come from BLM's 400,000 land and mineral case files. Also included will be data on legal land parcels defined in the Public Land Survey System (PLSS). These data will form the Geographic Coordinate Data Base (GCDB), which will incorporate the PLSS and will tie map information to points on the ground by latitude and longitude.

GCDB will allow ALMRS data to be overlaid on discrete parcels and will provide immediate access to data on land ownership, use, and authorizations. This data base will probably be operational by the mid-1990s. In addition, by the year 2000, resource data will be integrated with the ALMRS data to depict the resource values and management concerns relevant to each parcel of public land.

12.3.4 Contemporary Examples of Lost Government Records

The following sections describe several contemporary examples where records have been "lost" or at least were unknown or unavailable to those in need of them on a timely basis (e.g., from archives that would likely be consulted by individuals in search of unexploited resources).

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[21] 43 U.S.C. § 1741(c)(2). Although the Congressional veto provision in 204(c)(1) of FLPMA, 43 U.S.C. § 1741(c)(1), is probably unconstitutional, *Immigration & Naturalization Serv. v. Chada*, 462 U.S. 919 (1983), there is no reason why Congress cannot direct the Secretary to provide it with certain information concerning a proposed withdrawal as it did in section 204(c)(2).

12.3.4.1 Oil and Gas Leases Near WIPP

The New Mexico Environmental Evaluation Group (EEG) conducted a detailed analysis of oil and gas leases in the vicinity of the WIPP. EEG described a situation in which the U.S. Department of Energy failed to document the presence of a producing oil and gas well under the southwest corner of the WIPP Land Withdrawal Area (EEG92). A brief history of this loss in institutional knowledge, derived from the EEG report, is described below.

May 1952 - Conoco obtains an oil and gas lease NMPM Lease # NM 02953 covering all of Section 31, T22S, R31E. (This lease lies wholly within what is now the WIPP land withdrawal boundary described in 12.3.1.1 above.)

February 1959 - Conoco lease is divided. The southern half assigned to Richardson and Bass as Lease NM 02953-C.

November 7, 1976 - Bass files for a permit to drill a well on Lease 02953-C.

December 10, 1976 - Energy Research and Development Administration (ERDA), now DOE, files notice in the *Federal Register* of intent to withdraw 17,000 acres of public land including Section 31 T22S, R31E for waste disposal site.

January 20, 1977 - U.S. Geological Survey (USGS) approves Bass application to drill on Section 31.

February 9, 1977 and **December 7, 1977** - ERDA files suit condemning both oil and gas leases on Section 31 from surface to a depth of 6,000 feet.

February 12, 1979 - The court condemns leases on Section 31 to 6,000 feet and awards damages to Conoco, Bass and others.

1980 - DOE issues the Final Environmental Impact Statement which does not show existence of leases on Section 31.

December 11, 1981 - Bass files an application to drill hole on Section 6, T23S, R31E deviating into Section 31.

December 16, 1981 - The USGS district office transmits the drilling request and notes "drillsite not considered politically sensitive area."

September 13, 1982 - Well deviating under Section 31 is completed and tested.

August 4, 1987 - DOE signs a second modification to the Consultation and Cooperation Agreement with State of New Mexico committing to a prohibition of "slant drilling from under the site from within the site or from outside the site," even though DOE did not have the right to make such a commitment.

May 1990 - DOE reaffirms commitment to prohibit slant drilling under the WIPP in Final Safety Analysis Report.

October 26, 1990 - DOE signs Memorandum of Understanding with Bureau of Land Management (BLM) under which "BLM will prohibit directional drilling underneath the WIPP site boundary, except as may be required for the development of two leases located under Section 31; drilling may be allowed below 6,000 feet of the surface."

As matters currently stand, the rule does not preclude lease holders from drilling additional holes under Section 31 within the WIPP site, as long as the holes penetrate the site at more than 6,000 feet below the surface.

Some observations which may be distilled from the above chronology include the following:

- In spite of the fact that detailed records as to the existence of the oil and gas leases within the WIPP site existed, DOE did not acknowledge such existence over a ten-year period.
- Divided, poorly defined, and/or conflicting responsibilities among various governmental agencies and various levels of organization within the agencies contributed to selective instances of loss of institutional knowledge.

The existence of records, per se, does not guarantee that institutional knowledge will be retained at the locations and be available to those who "need to know." The significant events surrounding this oil and gas lease chronology cover a period of less than 20 years. If this example were typical, it would be inappropriate to assume that records alone can provide adequate information so that adverse actions do not occur over a period of many years.

The example suggests that considerable attention must be directed to the issue of <u>how</u> records are to be retained. The mere existence of records may not be adequate.

It could be asserted that the example described here is a record-keeping anomaly and thus is not a relevant criticism of systematized long-term record-keeping, the goal of which is to ensure that basic knowledge of the WIPP repository is retained. The argument that "If a good record-keeping system was in place, this would not happen," has some merit. It is certainly necessary to establish a system which defines the kinds of records that should be retained, the retention locations, the materials used for record keeping, and their potential availability to those who need them on a timely basis.

Similar concerns about record keeping were echoed by one of the Futures Panels assembled by SNL. The Washington A Team enumerated the following potential issues with records (HOR91, pp E-7 to E-10):

- Records are inadequate
- Records exist but are not accessible to intruders
- Records are accessible but not understood
- Records are accessible and understood but ignored
- Records are accessible and understood but information is lacking regarding effects of nearby activities such as large scale mining or water withdrawal

In a total record-keeping system, steps can be taken to deal with all of these issues, except the case where records are accessible and understood, but ignored. The burden of that type of conscious action lies on future society, not current society. Nevertheless, the duration of the effectiveness of the best record-keeping system is unknown.

12.3.4.2 Lost AEC Records

Another recent example of the failure of records to maintain knowledge of waste burial operations pertains to low level nuclear waste buried on U.S. Air Force controlled land under the authority and purview of the AEC.[22] This example in no way establishes or suggests that the sites in question pose an immediate or long term risk to human health or the environment. Neither is there any implication of negligence on the part of individuals or the federal government. It is merely intended to illustrate the institutional and social processes that can contribute to the success or failure of passive controls.

[22] The information presented here is taken from a document entitled *Burial of Radioactive Waste in the USAF* (USA72 and revisions).

Most of the sites in question were created in the 1950s, under the auspices of the AEC and in accordance with accepted industry waste disposal standards. The waste materials consisted of radioactive electron tubes, solid and liquid waste from weapons maintenance, radium oxide paint, and medical research wastes. Some burials were made in accordance with specific AEC (now Nuclear Regulatory Commission) licenses.

"Guidance on constructing and maintaining typical sites was given technical order procedures which included identifying site location on appropriate maps and posting and fencing to prevent unauthorized entry. The Air Force switched to disposal at licensed commercial sites in the 1958-1959 time frame and the technical order requirements for burial, and site maintenance requirements was rescinded. Unfortunately, no alternate instructions were provided on maintaining existing sites and a gradual loss of site records ensued. In 1971, the Air Force initiated an effort to find and consolidate existing site records and reestablish site maintenance."

A review of the facts regarding these sites is as follows:

1. Materials were buried under authorized procedures (Air Force and AEC).

2. The materials were buried on active duty military reservations that themselves could be considered to be under active control. However, the disposal sites were under passive control.

3. The loss of knowledge occurred because of a lapse in institutional reporting and maintenance procedures.

4. The lapse was not longer than 12 years (1958-1971).

5. The 12-year lapse resulted in the loss of many radioactive waste burial sites. Many are still unaccounted for in 1994.

The following three scenarios could account for the reported losses:

1. The facilities at the time of burial did not comply with the technical directive, therefore no location records exist.

2. Interviews with base personnel resulted in an assertion of a burial site but there is no location information. These sites are then reported as lost. The sites may or may not exist.

3. The facilities did comply, but when active maintenance was lost the site fence and placards were destroyed and the historical records, if any, were not sufficient to establish a location.

12.3.4.3 Spring Valley Munitions Dump

The Spring Valley site in Washington DC is a highly visible example of the burial of potentially hazardous substances (i.e., World War I era chemical munitions) and the subsequent loss of knowledge of these activities until accidental discovery during construction related excavation many years later (BAK94).

The site history begins in 1916-1917 when the U.S. Bureau of Mines established Camp Leach to study chemical warfare agents. American University donated land for this effort during the war emergency. In 1917-1918, the U.S. Bureau of Mines activity was consolidated under military command with the establishment of the American University Experimental Station, under the Chemical Warfare Service. By 1918, there were 1800 staffers at the station.

The burial of chemical munitions at the site was not documented by the Experimental Station. Burial activities were considered routine and not exceptional in terms of present or future hazards. The standing order for burial was that the material must be buried three feet under the surface and not in contact with groundwater.

In 1921, the Secretary of American University, Albert Osborne wrote an article describing the burial of chemical munitions at the site. He did not provide a location for the burial site. After this article, knowledge of the site and any dumping conducted there was apparently lost. Records did exist at American University and at the National Archives in Suitland, Maryland but there was no general awareness of the records.

In 1986, a backhoe operator dug up a cache of chemical munitions. He notified the authorities and the knowledge of the site was reestablished in the subsequent investigation. The investigation revealed the prior discovery of a "bomb" in the 1950's on the site of the Experimental Station.

Personal memories of the site also existed, but were not part of the institutional memory. One citizen, Eric Olsen, was in possession of and had knowledge of photographs showing burial activities at the Station, taken by his grandfather (BAK94).

The following key points can be derived from the Spring Valley incident:

- There was no real effort or intent of the authorities at the time of burial to retain some sort of institutional memory of the activities.
- One case of early warning of the activities made by A. Osborne, was apparently dismissed as a matter of little interest.
- While records of the activities existed in certain archives, there was no person or institution who retained a knowledge of them.
- The activities were institutionally rediscovered through excavation activities.
- It is not known if other chemical munitions were discovered at the site during the years of residential development, but not reported.

12.3.5 <u>Format for Records</u>

In order to ensure that messages on site markers are understood, it has been suggested that the message be recorded in several languages. For example, the WIPP Markers Panel recommended that the marker message be recorded in the six official languages of the United Nations (English, Chinese, Arabic, French, Spanish, and Russian) as well as Navaho and/or Apache (KAP86, GIV82, ADA86, TRA93). For perspective, it is helpful to recognize that Chinese is the most widely used language spoken on Earth today (Durant). Numbers of people speaking various languages are as follows (TRA94):

- Chinese (Mandarin) - 907 million
- English - 456 million
- Hindi - 383 million
- Spanish - 362 million
- French - 123 million

While comments on the use of multiple languages have primarily involved markers, the same logic can be applied to records. Records should be written in multiple languages as well. As previously suggested in this chapter, consideration of recording information in the major languages used by religious scholars (i.e., Hebrew, Latin and Arabic) also warrants consideration. The ONWI Human Interference Task Force envisioned that detailed information (e.g., 500 to 1,500 pages) in English and a more condensed version (e.g., 200 pages) in multiple languages would be archived (HUM84). There may be a question of institutional will about the extent to which detailed records will be translated into various languages for archival purposes.

Again, drawing a parallel with marker considerations, records must be stored on durable materials. The ONWI Task Force reported that some types of acid-free paper may survive a millennium under reasonable conditions (HUM84). Paper made from cotton or linen fibers has lasted for 1,000 years. Papyrus had survived for considerably longer in Egypt. The Task Force recommended that conventional paper would be a suitable storage medium for records which are periodically updated or maintained, but it proposed that more permanent records be prepared using special papers and stored in a protected environment. The importance of incorporating disposal site information on large numbers of maps widely distributed in the United States and throughout the world was stressed.

The NEA Working Group noted that the principal media currently used for conserving information include paper, microfilm, and magnetic and optical disks (NEA93). They quoted a lifetime of 1,000 years for paper, 200-400 years for microfilm (with one regeneration cycle), and less than 10 years for magnetic and optical media. On this basis, NEA felt that paper and microfilm were the preferred media for long term storage. The same position was adopted by the Nordic Committee for Nuclear Safety Research - NKS (JEN93).

12.4 GOVERNMENT OWNERSHIP AND REGULATIONS

12.4.1 General Comments

While government ownership and regulations regarding land and resource use are embraced in the definition of passive institutional controls, substantive questions have been raised as to the persistence of such governmental controls over the millennia. Historical continuity of governments has ranged from days to centuries.

In studying inadvertent human intrusion, SNL convened four expert panels to estimate modes and likelihoods of future intrusion (HOR91). The teams felt that the likelihood of continued

U.S. political control over the WIPP was small or non-existent. Changes in government control can lead to loss of information about a repository. Although physical destruction of information can be predicted for some scenarios (e.g. war, insurrection, and changes in record-keeping practices), one possible result of change in governmental control would be a change in policies regarding the importance of protecting the WIPP site and its records. Even with continuity of government, there is no guarantee that such continuity can be equated to continuity of government policies or continuity of government control over the WIPP site. Governmental policies vary significantly from one administration to the next. A future government might decide it was no longer necessary to maintain ownership of the site or update records for changes in language or technology. However, if some future government makes a conscious decision to take action detrimental to the repository, it is appropriate that the burden of that decision lie with that future society.

History provides numerous examples of instances where government has changed dramatically over the centuries, but institutional knowledge has not been lost. This is particularly true where symbolic or written language is associated with an artifact. The Egyptian pyramids are a classic example. Built nearly 5,000 years ago by an ancient society that is not reflected in the Egyptian society of today, located in an area subjugated by many conquerors since, documented in a symbolic language vastly different than today's languages, and desecrated by thousands of years of vandalism, the funerary monuments still convey a message understood by modern society about their design, construction, and function. The NEA Working Group cited French experience with institutional controls. Louis XVI created the Office of Quarries in Paris to prevent disturbances to buildings constructed over quarry sites (NEA93). The Office is still in existence and maintains control over portions of the Paris infrastructure, in spite of historical trauma including passing from an absolute monarchy to a series of republican governments with interspersed revolution, civil war, invasion, and riot. Institutions frequently outlive the governments which inaugurate them.

12.4.2 WIPP Land Withdrawal Act

Under Sec. 3(a) of the LWA, a sixteen square mile area was "withdrawn from all forms of entry, appropriation and disposal under the public land laws, including without limitation the mineral leasing laws, the geothermal leasing laws, the material sales laws (except as provided in section 4(b)(4) of this Act[23]), and the mining laws." Jurisdiction over the withdrawn lands is assigned to the Secretary of Energy. The LWA does not give to the U.S. Government a right to any water which it did not already possess at the time the LWA was passed. If the U.S. Government wishes to obtain water rights for purposes associated with the LWA, it must do so in accordance with the laws of the State of New Mexico.

Sec. 4(b)(5) of the LWA prohibits, in perpetuity, surface and subsurface mining or oil and gas production, including slant drilling from outside the withdrawal area on the withdrawn lands. There is one exception to the drilling prohibition. Rights under two existing oil and gas leases are not affected, although, if dictated by regulatory requirements, the Secretary of Energy can acquire these leases. As discussed in Section 3.4.1, slant drilling from outside the withdrawal area into these two leases, which lie in the southwest corner of the WIPP site, is currently permitted at depths below 6,000 feet (EEG92).

Sec. 13(b) of the LWA requires that DOE prepare, within five years of the date of enactment (i.e. October 1997), a plan for the management and use of the withdrawn area after decommissioning. This has yet to be done. However, DOE has prepared a plan for the management and use of the withdrawn area <u>prior</u> to decommissioning as required by Sec. 4(b)(1) of the LWA (DOE93a).

EPA examined actions planned by DOE in the current Land Management Plan as possible precursors to future actions associated with the post-decommissioning plan. DOE has specified that drilling and mining activity within one mile of the WIPP land withdrawal boundary be monitored by DOE in coordination and cooperation with the BLM and/or the State of New Mexico. These agencies have agreed to forward to DOE for review and comment all Applications for Permit to Drill in this boundary zone, together with mining and reclamation plans. According to the Land Management Plan, "this review will afford DOE the opportunity to verify that the proposed oil and gas or mining activities surrounding the withdrawal area will not encroach upon the withdrawn lands." It is possible that if DOE judges a hole is to be drilled too close to the WIPP site boundary, they could request that the permit granted to the operator include a condition that DOE be provided with downhole vertical deviation surveys contemporaneous with the drilling activity. If the surveys detect subsurface deviation which could encroach upon the WIPP site, the driller could be required

[23] Section 4(b)(4) permits the disposal of salt tailings which were produced during mining of the repository but are not needed for backfill.

to take corrective measures or cease drilling. Enforcement of such a provision will probably require continuous monitoring of the drill bit location.

12.5 OTHER METHODS OF PRESERVING DISPOSAL SYSTEM KNOWLEDGE

12.5.1 Subsurface Markers

To provide redundancy in the event that surface markers are destroyed by vandalism, erosion, other aging processes, or natural disaster, it has been suggested that subsurface markers be employed to augment surface markers (ADA86, BEN91). If the surface markers are destroyed or removed, buried markers may still provide a warning to intrusion.

12.5.1.1 Passive Markers

Fired clay subsurface markers were proposed to DOE by DOE contractors specifically for shallow burial grounds at Hanford based on archeological evidence of the longevity of such materials (ADA86). In the Hanford study, it was recommended that three layers of subsurface markers be emplaced at depths of 2, 4 and 16 feet to deter activities such as farming or building construction on the site. While such subsurface markers might deter surface excavation, they might not be discovered in the process of exploratory drilling into an underlying geologic repository. It is highly unlikely that a drilling crew would detect the presence of the markers. The buried markers would create no impediment to the drilling process and would probably be destroyed when contacted by the drill bit or missed entirely. Emplacement of such markers would involve extensive surface excavation.

12.5.1.2 Buried Sensors

Another approach to subsurface markers is to employ buried sensors of various types (BEN91). These could include buried objects or materials which would create an acoustic, magnetic, or radioactive anomaly. To create an acoustic anomaly, large granite shapes whose acoustic signal would define the center of the repository could be buried. Magnetic markers might include buried iron ore or special high field permanent magnets. Radioactive markers could be located outside the boundaries to signal the presence of the repository to intruders entering from various directions. All of these were suggestions made by the Southwest Team of the Futures Panel.

Team B of the WIPP Markers Panel suggested that earthworks at the WIPP site could be spiked with relatively inexpensive, high dielectric constant materials such as metal sulfides or magnetite which provide a strong radar signal to anyone exploring the site by remote sensing (TRA93). The ONWI Task Force felt that the site markers themselves would be readily visible to remote sensors carried by satellite (HUM84).

12.5.2 Protective Barriers

It has been suggested in a report by Ptyalin that the final defensive measure in a defense-in-depth strategy for reducing the likelihood of human intrusion could be a protective barrier system (TOL93). In theory, the protective barrier could reduce the likelihood of drilling in the event that markers and records were lost. The Ptyalin study uncovered no published research on concepts or actual designs of a protective barrier system. Ptyalin outlined the key features which a protective barrier system would need to provide. They are as follows:

- "be capable of disabling a drill bit, be impervious to a drill bit or, at a minimum, be capable of deflecting the drill bit safely away from the disposal system;
- be potentially capable of withstanding multiple encounters with a drill bit without the loss of function;
- be composed on materials of little economic value and will not degrade over the 10,000 year, post closure period; and
- not attract unwanted attention to the site or encourage exploration activities."

Possible locations for the conceptual protective barriers included at the surface of the repository site, just beneath the surface, just above the emplaced waste, and within the waste panels. Combinations of these options are also possible. Location of barriers at or just below the surface would require significant amounts of materials to cover the 0.5 square kilometer footprint of the repository. Ptyalin noted that operators have encountered problems in drilling into old landfills containing layers of rubber tires (at least 10 meters thick), layers of steel fencing, and baling wire. Encounters with these materials resulted in loss of circulation of the drilling mud, inability to cut through the materials, and difficulty in removing the drill string from the borehole. These problems occurred when using small truck-mounted rigs. There is no information to suggest that similar problems would be encountered when using a large stationary rig capable of drilling to depths of 3,000 to 5,000 meters. The long term stability of such artificial layers is also open to question.

No suitable materials for protective barriers located just above the wastes have been identified. To reduce effectively, the likelihood of drilling intrusion, the material would need to be resistant to attack by the drill bit, have corrosion resistance in the repository environment, and be emplaced with a sufficient areal density to effectively blanket the waste. Advanced materials such as tungsten carbide composites might meet these specifications. However, such an approach would be extremely costly. The buried material could be of sufficient economic value to represent a recoverable resource to some future generation. The impact of further disruption of the natural geologic barriers to accommodate emplacement of a protective barrier would need to be addressed.

The same conceptual material problems exist in considering encasing the waste drums with some sort of armor. While there are materials which might hinder the encroachment of a drill bit, such materials are costly and they may be an attractive resource to future generations. Also, their longevity in the repository environment has not been demonstrated.

EPA's review of the many options for PICs considered by DOE and DOE expert panels supports the approach taken in the rule by clearly demonstrating that while there may be no definite proof of the effectiveness or survivability of a particular PIC system, there are many approaches with positive characteristics and many proposals that seem to hold promise for improving the WIPP disposal system and thus protecting the public health and the environment.

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Appendix 12A:
Federal Register Notice Identifying WIPP Land Withdrawal Area

[NM-920-4210-06; NMNM 55234]

Legal Description for the Waste Isolation Pilot Plant (WIPP) Withdrawal; NM

AGENCY: Bureau of Land Management (BLM), Interior.

ACTION: Notice of Legal Description for the WIPP Withdrawal.

SUMMARY: On October 30, 1992, Public Law (PL) 102-579, the Waste Isolation Pilot Plant Land Withdrawal Act was signed into law. Section 3 of Public Law 102-579 requires that within 30 days after the date of the enactment of the Act, the Secretary of Interior shall publish in the Federal Register a notice containing a legal description of the Withdrawal. This Notice contains that legal description.

FOR FURTHER INFORMATION CONTACT: Clarence F. Hougland, BLM, New Mexico State Office, 505-438-7593.

SUPPLEMENTARY INFORMATION: Pursuant to Section 3 of PL 102-579 the legal description for the WIPP Withdrawal is as follows:

New Mexico Principal Meridian

T. 22 S., R. 31 E.,
Secs. 15 to 17 inclusive;
Sec. 18, lots 1 to 4, inclusive, E½, and E½W½;
Sec. 19, lots 1 to 4, inclusive, E½, and E½W½;
Secs. 20 to 22 inclusive;
Secs. 27 to 29 inclusive;
Sec. 30, lots 1 to 4, inclusive, E½, and E½W½;
Sec. 31, lots 1 to 4, inclusive, E½, and E½W½;
Secs. 32 to 34 inclusive.

The area described contains 10,244.60 acres, more or less, in Eddy County, New Mexico.

Dated: November 13, 1992.

Monte G. Jordan,

Associate State Director.

[FR Doc. 92-28458 Filed 11-23-92; 8:45 am]

BILLING CODE 4310-FB-M

Appendix 12B:
Letter to U.S. Archivist Transmitting WIPP Land Withdrawal Information

United States Department of the Interior

BUREAU OF LAND MANAGEMENT

NEW MEXICO STATE OFFICE
1474 RODEO RD.
P.O. BOX 27115
SANTA FE, NEW MEXICO 87502-7115

TAKE PRIDE IN AMERICA

IN REPLY REFER TO:

NMNM 55234
2310 (923)

NOV 16 1992

Dr. Don Wilson
Archivist of the United States
National Archives
Rm. 111
Washington, D.C. 20408

Dear Dr. Wilson:

In accordance with Section 3 of Public Law 102-579, the Waste Isolation Pilot Plant Withdrawal Act, enclosed are the map and the legal description for the Waste Isolation Pilot Plant Withdrawal.

Section 3 requires that copies of the map and the legal description for the Withdrawal be filed with the Congress, the Secretary of Energy, the Governor of the State, and the Archivist of the United States.

Please contact Clarence Hougland at (505) 438-7593, if you have questions or need further assistance.

Sincerely,

Larry L. Woodard
State Director

2 Enclosures:
1 - Withdrawal Map
2 - Legal Description (1 p)

13. Engineered Barriers

13.1 REGULATORY BACKGROUND

13.1.1 Environmental Protection Agency Regulations

The Assurance Requirements contained in Subpart B of 40 CFR part 191 require, under §191.14(d), that

> Disposal systems shall use different types of barriers to isolate wastes from the accessible environment. Both engineered and natural barriers shall be included.

The disposal standards (§191.12) define a "barrier" as

> any material or structure that prevents or substantially delays movement of water or radionuclides toward the accessible environment. For example, a barrier may be a geologic structure, a canister, a waste form with physical and chemical characteristics that significantly decrease the mobility of radionuclides, or a material placed over and around the waste, provided that the material or structure substantially delays movement of water or radionuclides.

Use of barriers was also specified in the WIPP LWA. Section 9 of the Act -- Environmental Protection Agency Disposal Regulations -- specifies in §9(g) -- Engineered and Natural Barriers, Etc, -- that DOE shall use both engineered and natural barriers and waste form modifications to isolate the waste after disposal to the extent necessary to comply with Subpart B of 40 CFR part 191. The Act defines "engineered barriers" to mean backfill, room seals, panel seals, and any other manmade barrier components of the disposal system.

As is the case for all Assurance Requirements, the intent of the requirement for engineered barriers is to enhance the WIPP's long-term compliance with the Containment Requirements (§191.13). While Engineered Barriers are required pursuant to the Assurance Requirements of §194.14(d), Engineered Barriers are not necessarily required to meet the Containment Requirements of §191.13. However, unlike most other Assurance Requirements, which provide some qualitative measure of increased confidence in the ability of the disposal system to do its job for the 10,000 year regulatory period, natural and engineered barriers are an inherent part of the disposal system. Thus, quantitative performance of the disposal system is evaluated by examining the disposal system as a whole. The effects of Engineered

Barriers employed at the WIPP must be considered as performance assessments; excluding such barriers would result in inaccurate modeling of the disposal system as defined in §191.12(a).

In 40 CFR part 194, EPA reiterates that engineered barriers are required as originally specified in §191.14(d). To ensure that a defensible position on the assurance aspects of engineered barriers is developed, EPA requires that DOE evaluate the benefits and detriments of various engineered barrier alternatives, such as cementation, shredding, supercompaction, incineration, vitrification, improved waste canisters, grout and bentonite backfill, melting of metals, alternative configurations of waste placement in the disposal system, and alternative disposal system dimensions. The potential benefit of the engineered barrier alternatives would be the prevention or substantial delay of movement of water or radionuclides toward the accessible environment. Potential detriments might include increased worker exposure involved in barrier implementation, increased total system costs, and significant program delays. The DOE application for certification of compliance must include justification for the selection or rejection of each type of engineered barrier evaluated.

Waste inventory scheduled for disposal at the WIPP is in a state of flux. Some waste is in packages which presumably meet the waste acceptance criteria (WAC) for the repository; some of the existing waste must be repackaged to meet the WAC; some of the existing waste must be treated to meet the WAC; and a significant portion of the waste has not been generated (BIR95). Consequently, DOE is required in its benefit/detriment study of engineered barrier alternatives to separately consider wastes in various packaging states.

13.1.2 Nuclear Regulatory Commission Regulations

The NRC has promulgated regulations for "Disposal of High-Level Radioactive Wastes in Geologic Repositories" as 10 CFR part 60. The NRC definition of "barrier", i.e.. "any material or structure that prevents or substantially delays movement of water or radionuclides", is very similar to the EPA definition. In addition, the NRC rule also defines "engineered barrier system" as the waste packages and the underground facility. "Underground facility" is a defined term meaning underground structure, including openings and backfill materials, but excluding shafts, boreholes, and their seals. The NRC specifically excludes shaft seals as an element of the engineered barrier system, while EPA regulations and the WIPP LWA do not specifically mention shaft seals. Shaft seals could, by inference, be included as "any other manmade barrier components of the disposal system" in the engineered barriers definition in the WIPP LWA.

The NRC license application for such a repository requires a Safety Analysis Report (SAR), which includes an analysis of the effectiveness of natural and engineered barriers against the release of radioactive material to the environment (§60.21(c)(1)(ii)(D)). This analysis must incorporate a comparison of the effectiveness of alternatives to the major design features affecting waste isolation, with emphasis on those features which provide longer radionuclide containment and isolation. The NRC rule further requires that the waste packages provide "substantially complete" containment of the high-level waste for a period of 300 to 1,000 years. The release rate from the engineered barrier system after this containment period for any radionuclide is limited to one part per 100,000 per year, based on the amount of the nuclide present 1,000 years after the repository is closed (§60.113(a)(1)(ii)(B)). The NRC regulations are designed to address the containment of high-level wastes, which pose somewhat different containment issues than transuranic wastes.

13.2 CONSIDERATION OF ENGINEERED ALTERNATIVES

13.2.1 Engineered Alternatives Task Force

In 1989, DOE formed an Engineered Alternatives Task Force (EATF) whose objectives were to identify plausible engineering modifications to the existing WIPP design, and to evaluate the feasibility and effectiveness of these modifications in facilitating compliance of the WIPP with EPA disposal standards contained in 40 CFR part 191 (DOE91a). Potential repository problems addressed by the EATF included gas generation by the waste and consequences of future, inadvertent human intrusion. DOE was concerned that these problems might interfere with the WIPP's compliance with the containment requirements of 40 CFR part 191. The EATF activities were not designed to address the assurance aspects of engineered barriers.

The first step in the EATF methodology was to identify and screen potential engineered alternatives. To accomplish this, an Engineered Alternatives Multidisciplinary Panel (EAMP) was formed by assembling a group of experts with relevant backgrounds. The EAMP met in late 1989 and early 1990 to conduct identification and screening activities. A total of 64 alternatives were identified for initial consideration as summarized in Table 13-1 taken from the EATF Final Report (DOE91a).

The EAMP's list of potentially useful alternatives was distilled down to 14 alternative scenarios which considered various combinations of waste treatments, backfill options, waste container changes, waste emplacement options, and facility design changes. Recognizing that all waste is not amenable to the same treatment option, EAMP categorized wastes as sludges, solid organics, and solid inorganics for the study. Each alternative was compared with a baseline which assumed no waste form modifications, no container modifications, no load management of the wastes, no facility design changes, and use of a salt backfill. The alternatives are summarized in Table 13-2.

Because the processes which can affect the WIPP are often coupled and non-linear, it is difficult to assess the impact of various engineered alternatives by inspection and logic. Consequently, DOE developed the Design Analysis Model to assist in the quantitative assessment of alternatives. The Design Analysis Model, which is deterministic rather than probabilistic, modeled the following processes:

- creep closure of the surrounding rock
- gas generation, consumption, and dispersion
- brine inflow, consumption, and dispersion
- panel seal leakage
- consolidation of the shaft seals and advection of gas and brine through the shaft seals
- diffusion and advection of gases into the host rock and adjacent anhydrite beds
- gas compressibility
- waste compaction
- development of a disturbed rock zone around the storage rooms, and
- radionuclide releases caused by three types of inadvertent human intrusion scenarios into the repository.

The peak gas pressure reached in the repository was the figure of merit used to assess the effect of various engineered alternatives on gas generation potential. Gas pressures calculated with the Design Analysis Model exceeded lithostatic pressure (i.e., the pressure of the surrounding host rock) in the base case and for Alternatives 1, 2, 3, 10, 11, 12, and 14. Lithostatic pressures were not exceeded for the other seven alternatives. For each of those

Table 13-1
Potentially Useful Engineered Alternatives Considered By the Engineered Alternatives Multidisciplinary Panel (EAMP) (From DOE91a)

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

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

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

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

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

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

Waste Container Alternatives
Change Waste Container Shape
Change Waste Container Material

Table 13-2
Engineered Alternatives Evaluated by the EATF Relative to the Baseline Case (From DOE91a)

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.

alternatives where lithostatic pressure was not exceeded, rigorous thermal processing techniques (incineration, metal melting, and/or vitrification) were assumed to be used to modify the waste form.

To assess the impact of the engineered alternatives on human intrusion, the figure of merit used was the "Measure of Relative Effectiveness" (MRE) which compares the cumulative releases of selected radionuclides for each alternative to the releases from the baseline design. Lower values of the MRE are indicative of improved performance as compared to the baseline. For an E1 scenario, where a borehole penetrates the repository and a brine pocket in the underlying Castile Formation, Alternatives 7, 8, 9, and 13 in Table 13-2 were effective in reducing the consequences of inadvertent human intrusion. As noted above, these same alternatives were effective in reducing gas pressures as well, but involved rigorous thermal processing.

For the E2 scenario, where a borehole penetrates the repository but not an underlying brine reservoir, Alternatives 3, 5, 6, 7, 12, 13, and 14 were effective in reducing the consequences of human intrusion. Of these attractive alternatives, Alternative 3 is the probably the simplest since it only requires cementing or shredding and cementing of the waste and a cement grout backfill.

For the E1E2 scenario, where two boreholes penetrate the same panel in the repository and one also penetrates an underlying Castile brine reservoir, all of the alternatives except No. 11 were efficacious. Alternative No. 11 was unattractive for all conditions examined.

If some type of waste form modification involving thermal processing is to be considered for TRU wastes, there are major cost and schedule implications. Metal melting and incineration have been practiced on low-level waste, and incineration to a limited extent, on TRU waste. Vitrification has not been fully developed and reduced to practice for routine waste processing. Substantial periods of time (probably at least a decade) are required to design thermal treatment facilities for TRU wastes, obtain budgetary approvals, obtain the required environmental permits, construct the facilities, and conduct extensive startup tests before waste processing can begin.

If such rigorous alternatives are not necessary to demonstrate regulatory compliance, then there may be other, easier to implement, alternatives which may satisfy the assurance requirements of 40 CFR part 191. For example, with alternative backfills it may be possible to control the brine pH, thereby minimizing radionuclide solubility or narrowing the range of expected solubilities. Backfill may also serve as a vehicle for carbon dioxide removal from the disposal rooms, thus reducing gas pressure buildup in the repository.

13.2.2 Engineered Barriers Study for §194.44

The 40 CFR part 194 compliance criteria specify that an evaluation of engineered barrier alternatives be included in the application for certification of compliance. The rule also specifies a minimum number of alternatives which must be considered. These are basically the same alternatives as DOE examined under the aegis of the EATF study in 1991. However, it should be noted that the EATF study combined the various individual alternatives into the 14 summary alternatives listed in Table 13-2. Consequently, it was not possible to distill from that study the effects of individual alternatives. For example, any changes associated with alternative container materials are probably masked by changes in other alternatives which were simultaneously considered.

Whereas the EATF study focused on reduction of gas generation and consequences of inadvertent human intrusion, §194.44 requires a broader look at engineered barrier alternatives, including:

- ability of the barrier to prevent or substantially delay movement of water or waste
- altered worker exposure
- ability to remove waste from the repository
- transportation risks
- uncertainty in performance assessments
- public input
- impact on other waste disposal programs
- system costs, and
- mitigation of human intrusion consequences.

It should also be noted that the EATF study did not include remote-handled (RH) TRU wastes. Only contact-handled (CH) TRU was considered. While RH TRU wastes account for only about 4% of the total repository design volume, it is currently estimated that RH TRU accounts for about 37% of the total radioactivity in the repository (BIR95). Additionally, RH TRU underlies about 11% of the surface area of the repository that might be intercepted by inadvertent human intrusion. Clearly, RH TRU needs to be considered in an engineered barriers evaluation.

13.2.3 Waste Inventory

Selection of an appropriate waste form modification is dependent on the nature of the waste to be treated/modified. Use of the same treatment technology for modification of all wastes is probably not possible. For example, organic waste streams may be amenable to incineration, but this technology would be inappropriate for heterogeneous and metal wastes. DOE sites which generate or store transuranic (TRU) waste have identified about 360 different TRU waste streams. Based on their physical/chemical matrix, these waste streams are assigned waste matrix codes (WMCs), and WMCs with similar physical and chemical properties are grouped into the 11 waste matrix code groups (WMCGs) listed below:

- Solidified Inorganics
- Salt Waste
- Solidified Organics
- Soils
- Uncategorized Metal
- Lead/Cadmium Metal Waste
- Inorganic Non-Metal Waste
- Combustibles
- Graphite
- Heterogeneous
- Filters

Quantities of waste in each waste matrix code group have been estimated in the WIPP Baseline Inventory Report (BIR95). These inventory quantities are based on retrievably stored TRU waste currently located at each site, and projections of future volumes of waste which have not yet been generated. If the volumetric sum of the stored waste plus projected waste volumes is less than the repository capacity, the projected volumes are scaled upward to obtain the anticipated volume (i.e., the additional volume which would fill the repository to capacity). Estimates of the WIPP inventory for both contact-handled and remote-handled TRU waste by waste matrix code group are included in Table 13-3. The anticipated volumes are scaled based on the assumption that the CH TRU capacity of the WIPP is 6.2 million

Table 13-3
Transuranic Waste Disposal Inventory for WIPP
(Volumes in Cubic Meters) (From BIR95)

Waste Matrix Code Group	Stored Volumes	Projected Volumes	Anticipated Volumes	WIPP Disposal Volumes
Contact Handled Waste				
Combustible	7.1E+03	2.7E+04	3.4E+04	6.2E+04
Filter	4.3E+02	1.1E+03	1.5E+03	2.6E+03
Graphite	6.7E+02	4.3E+01	7.1E+02	7.6E+02
Heterogeneous	3.0E+04	4.6E+03	3.5E+04	3.9E+04
Inorganic Non-metal	1.2E+03	3.2E+02	1.5E+03	1.8E+03
Lead/Cadmium Metal Waste	5.6E+01	1.3E+02	1.8E+02	3.1E+02
Salt Waste	3.3E+01	6.0E+01	9.2E+01	1.5E+02
Soils	3.7E+02	4.5E+02	8.3E+02	1.3E+03
Solidified Inorganics	1.7E+04	8.0E+03	2.5E+04	3.4E+04
Solidified Organics	1.5E+03	3.0E+02	1.8E+03	2.1E+03
Uncategorized Metal	1.2E+04	8.6E+03	2.1E+04	3.0E+04
Unknown	1.7E+03	0.0E+00	1.7E+03	1.7E+03
Total CH Volumes	**7.3E+04**	**5.1E+04**	**1.2E+05**	**1.8E+05**
Remote Handled Waste				
Combustible	1.5E+01	3.2E+00	1.8E+01	2.0E+01
Filter	8.9E-01	2.1E+00	3.0E+00	4.3E+00
Heterogeneous	4.4E+02	3.3E+03	3.8E+03	5.9E+03
Lead/Cadmium Metal Waste	0.0E+00	6.0E+00	6.0E+00	9.8E+00
Salt Waste	0.0E+00	2.8E+00	2.8E+00	4.6E+00
Solidified Inorganics	6.1E+02	1.7E+02	7.9E+02	9.0E+02
Uncategorized Metal	8.8E+01	8.6E+01	1.7E+02	2.3E+02
Unknown	1.1E+01	2.4E+01	3.5E+01	3.5E+01
Total RH Volumes	**1.2E+03**	**3.6E+03**	**4.8E+03**	**7.1E+03**
Total TRU Waste Volumes	**7.4E+04**	**5.4E+04**	**1.3E+05**	**1.8E+05**

cubic feet (176,000 m^3) and the RH TRU capacity is 250,000 cubic feet (7,080 m^3).[1] §194.44 requires that the benefit and detriment of engineered barriers be examined separately for:

- existing waste already packaged
- existing waste requiring repackaging
- existing waste not yet packaged, and
- to-be-generated waste.

Table 13-3 shows that about two-thirds of the anticipated volumes of both the CH TRU and RH TRU waste is yet to-be-generated. With regard to existing wastes, it should be noted that for wastes to be acceptable for shipment to the WIPP, they must be packaged either in 55-gallon drums or standard waste boxes (SWBs) that meet DOT Type A packaging requirements (DOE91b). In addition, some wastes in 55-gallon drums or SWBs may not meet the current WIPP WAC. For example, a number of waste matrix codes involve liquid waste streams which must be solidified to ensure that the wastes contain no more than 1% free liquid. While these wastes are listed as solidified organics or inorganics in the BIR, they must be treated and repackaged to comply with the WIPP WAC (DOE91b).[2] As specified in §194.44(d), these types of existing wastes must be examined separately from existing wastes which are currently certifiable for shipment to WIPP.

A significant fraction of the waste planned for disposal at the WIPP is mixed waste containing both hazardous and radioactive components. DOE has estimated that about 60,000 m^3 of mixed TRU waste is currently in inventory or will be generated over the next five years (DOE94). Of this volume, about 20,000 m^3 is expected to meet the WIPP WAC without further treatment, while the balance will require additional treatment before shipment to the WIPP.

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[1]This exceeds the WIPP LWA limit of 6.2 million ft^3 on the total of RH and CH TRU for disposal at the WIPP.

[2]The most recent version of the WIPP WAC is 1991. It is not clear at this time what changes DOE will make to the existing, and possibly dated, waste acceptance criteria to ensure compliance.

13.3 REFERENCES

BIR95 "Waste Isolation Pilot Plant Transuranic Waste Baseline Inventory Report," CAO-94-1005, Revision 1, prepared by WIPP Technical Assistance Contractor for U.S. Department of Energy, February 1995.

DOE91a U.S. Department of Energy, "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, Revision 0, July 1991

DOE91b U.S. Department of Energy, "Waste Acceptance Criteria for the Waste Isolation Pilot Plant," DOE/WIPP-069, Revision 4, 1991.

DOE94 U.S. Department of Energy, "National Summary Report of Draft Site Treatment Plans," vol. 1, final draft, November 1994.

14. Individual and Groundwater Protection Requirements

14.1 INTRODUCTION

Both the individual and groundwater protection requirements of the disposal regulations -- 40 CFR part 191 subparts B and C -- apply to doses received from the wastes in the disposal system assuming that it is not disrupted by the occurrence of human intrusion or unlikely natural events. Specifically, the individual protection requirements at §191.15 limit the annual committed effective dose of radiation to any member of the public to no more than 15 millirem. The ground-water protection requirements §191.24 of subpart C, which limit releases to ground water to no more than the limits set by the MCL for radionuclides established in 40 CFR part 141. Both are concerned with human exposure to radionuclides from disposal systems and both limit such exposure for 10,000 years. Based on the similar forms of the two numerical requirements, EPA decided to adopt an approach that combines compliance criteria for these requirements into one section addressing the following issues:

- the definition of a protected individual,
- consideration of exposure pathways,
- consideration of underground sources of drinking water,
- the scope of compliance assessments, and
- the basis for a determination of compliance with these requirements (results of compliance assessments).

14.2 GROUNDWATER PROTECTION

The groundwater protection requirements of 40 CFR part 191 apply to USDWs in the accessible environment. Those USDWs that lie within the controlled area are not considered to be protected groundwater and the requirements of subpart C of 40 CFR part 191 do not apply. In 40 CFR part 194, the Agency implemented the requirements of subpart C of 40 CFR part 191 with the expectation that USDWs which lie closer to the disposal system will have a greater chance of being affected by releases of waste. In view of this, the analysis of the doses received from USDWs located large distances from the disposal system would not be likely to reveal information about the disposal system's performance not already disclosed by the analysis of those USDWs proximal to the disposal system. As a result, the groundwater protection requirements as implemented for the WIPP in §194.52 apply to those USDWs in the accessible environment that are expected to be affected by the disposal system over the regulatory time frame. The determination of which USDWs are expected to be affected shall be based upon the underground interconnections among bodies of surface water, ground water, and underground sources of drinking water.

Additionally, since the MCLs are applied equally to all USDWs, the "maximally exposed" aquifer will be determinative of compliance with the groundwater protection requirements. In other words, if the maximally exposed USDW is in compliance, then those lesser exposed USDWs, perhaps lying further from the disposal system, will likely be in compliance as well.

The Agency established the definition of the underground source of drinking water (USDW) in the promulgation of 40 CFR part 191 in 1993. The definition of USDW is taken directly from the Agency's underground injection control regulations found in 40 CFR parts 144 through 146. The complete description of the definition of USDW and the rationale which underpins it may be found in the Federal Register noticed which promulgated 40 CFR part 191, found at 58 Fed. Reg. 66398-66416.

In addition to considering interconnected USDWs, 40 CFR part 194 requires that the calculations of doses received from USDWs should assume that drinking water is withdrawn directly from the contaminated USDW and consumed at a rate of two liters per day. This requirement re-states the requirements of §141.16 of 40 CFR part 141. This latter regulation, which established the MCLs applicable to community water systems, stipulated that "dose equivalents shall be calculated on the basis of a 2 liter per day drinking water intake." This consistency between the two regulatory regimes reflects the Agency's desire to apply the underlying substantive requirements of the Safe Drinking Water Act to its program that regulates the disposal of spent nuclear fuel, high-level and transuranic radioactive wastes such as the WIPP.

In furtherance of this goal, the groundwater protection requirements of subpart C directly incorporate the maximum contaminant levels (MCLs) established under the Safe Drinking Water Act at 40 CFR part 141. Disposal systems shall therefore be designed to provide a reasonable expectation that 10,000 years of undisturbed performance after disposal shall not cause the levels of radioactivity in any USDW in the accessible environment to exceed the limits specified in 40 CFR part 141 as they exist on January, 19, 1994. Current SDWA MCLs for radionuclides were promulgated on July 9, 1976 (41 FR 28402) and became effective on June 24, 1977.

14.3 INDIVIDUAL PROTECTION

The requirements of §194.51 apply to the maximally exposed individual located in the accessible environment. The Agency designated the maximally exposed individual as the protected individual consistent with the stated objective of the disposal regulations. As noted in the promulgation of the disposal regulations in 1993:

> The EPA has chosen a 15-millirem CED [committed effective dose] per year limit because it finds the lifetime risk represented by this level of exposure to present an acceptable risk for the purposes of this rulemaking since it involves only a small number of potential sites and would result in only a small number of people potentially exposed to the maximum allowed individual risk.

Thus, to ensure that only a small number of persons will be potentially exposed to waste at the WIPP, the Agency required that, in compliance assessments of undisturbed performance, the protected individual must be the maximally exposed individual. Additionally, §191.15 of the disposal regulations specifies that "the disposal system shall not cause the committed effective dose, received through all potential pathways to the disposal system, to any member of the accessible environment to exceed 15 millirems." In the final rule for the WIPP, §194.52, therefore requires that the dose to individuals be calculated via all potential exposure pathways. In developing criteria for individual protection, the Agency reviewed the technical bases for release, transport, exposure, and dose and risk analyses supporting the promulgation of the disposal regulations. These analyses strongly suggested that the release and transport of radionuclides from a disposal system would most likely occur via ground water, and that the maximum radiation dose delivered to any individual beyond the site boundary would be the sum of the doses delivered through the water-dependent exposure pathways, e.g., consumption of contaminated drinking water, ingestion of products (i.e., meat and milk) from animals fed contaminated water, ingestion of crops irrigated with contaminated water, and direct radiation exposure due to radionuclides deposited on ground surfaces due to irrigation, among others. EPA also recognized that different dose and risks estimates were possible depending on the land use exposure scenario selected.

14.3.1 Consideration of Exposure Pathways (§194.52)

Given a plausible release scenario involving migration of contaminants from a disposal system via ground water to the accessible environment, several water-dependent exposure pathways are theoretically possible, including:

- ingestion of contaminated drinking water;
- ingestion of contaminated home-grown produce (fruits and vegetables) irrigated with contaminated well water;
- ingestion of meat (beef) from livestock fed contaminated well water or contaminated crops irrigated with contaminated well water;
- ingestion of contaminated milk from livestock fed contaminated well water or contaminated crops irrigated with contaminated well water;
- ingestion of contaminated soil irrigated with contaminated well water;
- dermal contact with contaminated soil irrigated with contaminated well water;
- inhalation of airborne suspended or resuspended contaminated soil irrigated with contaminated well water; and
- direct radiation exposure to photon-emitting radionuclides in soil irrigated with contaminated well water.

The maximum radiation dose delivered to the protected individual depends on several factors, including (but not limited to):

- all radionuclides and their range of concentrations in ground water;
- surface media that may become contaminated as a result of the potential ground water uses (e.g., drinking water, irrigation, dust suppression, etc.);
- exposure scenarios and pathways based on potential land uses (e.g., residential, commercial, industrial, agricultural, etc.); and
- exposure factor assumptions (e.g., intake rates, exposure times, etc.) and dose-to-risk conversion factors.

In order to implement an all-pathways analysis of the radiation dose that a member of the public receives it is necessary to decide: (1) where the person is to be located; (2) the human intake, radiation risks, and dose calculations to be used; and (3) the environmental pathways to be considered, the appropriate scenarios, and pathway parameter values to be used.

14.3.2 Location of Protected Individual

§191.15 limits the annual dose from the waste in the disposal system to any member of the public in the accessible environment. The definition of the accessible environment includes the ground surface on the WIPP Site. However, the preamble to the Final 40 CFR part 191 Rule says that "Groundwater withdrawn for consumption directly from within the controlled area need not be included in the analyses because geologic media within the controlled area. are an integral part of the disposal system's capability to provide long-term isolation" (58 FR 66403).

14.3.3 Calculation of Radiation Dose

Appendix B of 40 CFR part 191 describes how the Annual Committed Effective Dose is calculated once individual organ doses in rads are obtained. Consistent with the future states assumptions, the radiation weighting factors and the tissue weighting factors are assumed to remain unchanged in the future. The dose calculations also require concentrations of individual radionuclides present in the air, water, and foods taken into the body and the applicable rates of air, water, and food intakes. Then, dose conversion factors are necessary to relate the intake of a radionuclide to the Committed Effective Dose.

14.3.4 EPA's Standardized Exposure Scenarios and Default Exposure Parameter Values for Human Health Risk Assignment

One example of the treatment of exposure scenarios is that used by EPA's Superfund program and Office of Radiation and Indoor Air (ORIA) to assess human health risks to individuals due to exposure to hazardous chemical substances and radionuclides from cleanup sites. These exposure scenarios provide an example of an approach that uses all-pathways of exposure to a maximally exposed individual. The specific application of the final rule, 40 CFR part 194, will depend on the specific considerations of the WIPP site and the surrounding region. These EPA guidelines assume reasonable maximum exposure (RME) conditions under different post-cleanup cases including the following four land-use classifications: 1) residential, 2) commercial/industrial, 3) agricultural, and 4) recreational. This section defines, for each scenario, the principal exposure pathways, key exposure parameters, and standardized default parameter values. Several EPA documents may be consulted for additional information (see references: EPA89a, EPA89b, EPA91a, EPA92, and EPA94). For additional illustration, Table 14-1 compares EPA, DOE, and NRC intake rates and exposure assumptions that could be used as default values in the scenarios.

EPA's Superfund program currently defines exposure scenarios within the context of the four land-use classifications listed above (EPA89a and EPA91a). EPA defines RME as "the maximum exposure that [any individual] is reasonably expected to [receive] at a site" (EPA89a) or as the "high-end individual exposure" (EPA91a). In both cases, EPA describes the RME concept as an approach which uses standardized exposure pathways and default exposure factor values to calculate maximum reasonable estimates of contaminant intake and risk for individuals in an exposed population.

The RME approach provides estimates of individual intake and risk that are protective and reasonable, but not the worst possible case. EPA developed the RME concept and standardized exposure scenarios and assumptions to: (1) reduce unwarranted variability in assumptions used in baseline risk assessments to characterize potentially exposed populations, and (2) achieve consistency in evaluating site risks and setting cleanup goals at CERCLA sites.

The Agency recognizes that exposure conditions at specific sites can and often do differ from the generic case described above. For this reason, in the Superfund program EPA has encouraged the use of site-specific scenarios and exposure factors to estimate intakes and risks at Superfund sites, provided these assumptions can be justified and documented (EPA89a).

Table 14-1. Comparison of EPA, DOE, and NRC Intake Rates and Exposure Assumptions

Factor Category	Parameter (Units)		Agency Default Values			Distribution of Values Reported in the List References					Comments
			EPA	DOE	NRC	Mean±SD	90th%	95th%	RME	Range	
Intake Rates	Drinking Water Ingestion Rate (l/d)	Residential	2	1.4	2	1.4±0.4	1.9		2	0.3-3	For worker exposures, EPA assumes half the residential daily intake consumed during an 8-hour work day.
		Commercial/ Industrial	1	NS*	NS						
	Inhalation Rate (m^3/d)	Residential	20	23	29	14±4			30		DOE uses ICRP reference man data: 16 hours resting. NRC also uses ICRP data but assumes 24 hours of light activity.
		Commercial/ Industrial	20	NS	NS						
	Soil Ingestion Rate (mg/d)	Child Resident	200	NS	NS	105±82				0-800	EPA assumes exposure durations of 6 years for children and 24 years adults. The weighted intake rate is 120mg/day for 30 years.
		Adult Resident	100	100	50	71±77				0-800	
		Commercial/ Industrial	50	NS	NS					0.5-480	
	Leafy Vegetables (g/d)	Total	NS	38	30	40±15	75	95	175	3-200	EPA does not distinguish "leafy vegetables" from all vegetables.
		Contaminated Fraction	NS	0.5	0.25	0.25			0.4		
		Actual Intake (total x fract.)	NS	19	7.5	10			70		
	Non-Leafy Vegetables (g/d)	Total	200	236	140	200±83	314	422	770	26-510	DOE values assume that non-leafy vegetables are 54% of total intake of fruits, vegetables, and grains.
		Contaminated Fraction	0.4	0.4	0.25	0.25			0.4		
		Actual Intake (total x fract.)	80	118	35	50			308		
	Fruits (g/d)	Total	140	96	126	140±58	268	327	313	30-487	DOE values assume that fruits are 22% of total intake of fruits, vegetables, and grains.
		Contaminated Fraction	0.3	0.5	0.25	0.2			0.3		
		Actual Intake (total x fract.)	42	48	32	28			94		

Table 14-1. Comparison of EPA, DOE, and NRC Intake Rates and Exposure Assumptions (Continued)

Factor Category	Parameter (Units)		Agency Default Values			Distribution of Values Reported in the List References					Comments
			EPA	DOE	NRC	Mean±SD	90th%	95th%	RME	Range	
Intake Rates	Grains (g/d)	Total	NS	105	189	125					EPA does not use grains in risk calculations (0% of homegrown grains are consumed). DOE values are calculated assuming grains are 24% of total intake of fruits, vegetables and grains.
		Contaminated Fraction	0	0.5	0.25						
		Contaminated Intake	NS	53	47						
	Milk (ld)	Total	0.4	0.25	0.27	0.4±0.01			0.85	0.25-1.0	DOE assumes 100% of the milk is contaminated for areas greater than 20,000m², and applies a correction factor for smaller areas. NRC lists 0.31/day as an average daily intake.
		Contaminated Fraction	0.4	1	NS	0.4	0.75				
		Contaminated Intake	0.16	0.25	NS	0.16			0.3		
	Beef and Poultry (g/d)	Total	170	173	214	100±2			300	67-124	DOE assumes 100% of the meat is contaminated for areas greater than 20,000m², and applies a correction factor for smaller areas. EPA numbers are for beef only: data was available for poultry and eggs. NRC lists 260 g/day as an average daily intake.
		Contaminated Fraction	0.44	1	NS	0.44					
		Actual Intake (total x fract.)	75	173	NS	44			75		
	Fish (g/d)	Total	54	15	27	12±12		42	58	0-140	Mean and 95th% values listed are for all consumers. A median 90th% for fishermen are 30 g/day and 140g/day. NRC assumes 19 g/day as an average daily intake.
		Contaminated Fraction	1	0.5	NS						
		Actual Intake (total x fract.)	54	7.5	NS				54		
	Other Seafood (g/d)	Total	NS	2.5	NS	2.1±2.0			14		EPA and NRC do not specify separate values for "other seafood." NRC assumes 2.7g/day as an average daily intake.
		Contaminated Fraction	NS	0.5	NS						
		Actual Intake (total x fract.)	NS	1.2	NS						

Table 14-1. Comparison of EPA, DOE, and NRC Intake Rates and Exposure Assumptions (Continued)

Factor Category	Parameter (Units)		Agency Default Values			Distribution of Values Reported in the List References					Comments
			EPA	DOE	NRC	Mean±SD	90th%	95th%	RME	Range	
Exposure Assumptions	Exposure Time (h/d)	Indoors-Residential	NS	12.5	13	14.2±2.5	24			2-24	
		Indoors-Commercial/ Industrial	NS	NS	NS	7.5±6.9	11.2			0-16	Calculated from EPA89 assuming 8 hours as an average work day.
		Outdoors-Residential	NS	6.3	4.7	0.72±0.89	2.4			0-24	
		Outdoors-Commercial/ Industrial	NS	NS	NS	0.5±0.6	1.8			0-7.7	Calculated from EPA89 assuming 8 hours as an average work day.
	Exposure Frequency (d/y)	Residential	350	350	365					0-365	EPA assumes 2 weeks vacation per year away from home.
		Commercial/ Industrial	250	NS	NS					0-365	EPA assumes 5 d/wk, 50wk/yr.
	Exposure Duration (y)	Residential	30	30	NS	9±9	30			0->33	
		Commercial/ Industrial	25	NS	NS		25				
Other Factors	Gamma Shielding Factor		0.8	0.7	0.33					0-1	
	Soil Concentration in Air ($\mu g/m^3$)		0.2	200	100	113±95			200	9-1800	
	Ratio of Indoor Dust to Outdoor Dust		NS	0.4	0.5					0-1	
	Dilution Factor for Drinking Water		1-100	C*	C					1-100	EPA assumes dilution factors of 1, 10, and 100.
	Livestock Soil Intake Rate (kg/d)		NS	0.5	0.6	0.6±0.7				0.2-2.9	
	Fodder Intake Rate for Beef (kg/d)		NS	68	44						DOE based on IAEA92, NRC based IAEA82.
	Fodder Intake Rate for Milk (kg/d)		NS	55	67						DOE based on NCRP91, NRC based on IAEA82.

Table 14-1. Comparison of EPA, DOE, and NRC Intake Rates and Exposure Assumptions (Continued)

Factor Category	Parameter (Units)		Agency Default Values			Distribution of Values Reported in the List References					Comments
			EPA	DOE	NRC	Mean $\pm$ SD	90th%	95th%	RME	Range	
Other Factors	Volatilization Factor for Rn-222 (pCi/m^3 per pCi/g)	Indoors	NS	C*	NS	1250 ± 3110	3400	5000	4000	400	Data from EPA's National Residential Radon Survey assuming 1pCi/g Ra-226.
		Outdoors	120	C	NS	120 ± 110				30,000 20-500	
	Volatilization Factor for Rn-220 (pCi/m^3 per pCi/g)	Indoors	NS	C	NS						Assumes 1pCi/g Ra-224 in soil.
		Outdoors	5	C	NS	100 ± 96				25-500	

* NS = Not Specified by Agency; NC = Not considered in soil model calculations; C = Calculated by RESRAD.

EPA References:

EPA89 Exposure Factors Handbook, Office of Health and Environmental Assessment, EPA 600/8-89 043, 1989.

EPA91 Risk Assessment Guidance for Superfund, Volume 1: Human Health Evaluation Manual, Supplemental Guidance, "Standard Default Exposure Factors", OSWER Directive 9285.6-03, 1991.

DOE References:

DOE92 Data Collection Handbook for Establishing Residual Radioactive Material Guidelines with RESRAD, 1992.

NRC References:

NRC92 Residual Radioactive Contamination from Decommissioning, NEUREG/CR-5512, PNL-7994, 1992.

NRC77 Calculation of Annual Doses to Man from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR 50, Appendix 2, Reg Guide 1.109, 1977.

Other References:

IAEA82 Generic Models and Parameters for Assessing the Environmental Transfer of Radionuclides from Routine Releases; Exposure of Critical Groups, Safety Series No. 57, 1982.

IAEA92 Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments, 9th Draft, 1992.

NCRP91 Screening Models for Releases of Radionuclides to Air, Surface Water, and Ground Water, draft document, 1991.

Residential Exposure Scenario. The Superfund guidelines employ residential exposure scenarios whenever there are homes on or near a contaminated site, or whenever future residential development is a reasonable expectation based on consideration of local zoning laws, land-use trends, and site suitability. Five exposure pathways are evaluated routinely under these scenarios to assess risks from radionuclides in soil (EPA91a): 1) direct external radiation from photon-emitting radionuclides in the soil, 2) inhalation of resuspended contaminated dust, 3) inhalation of radon and radon decay products (only when radium is present in soil), 4) ingestion of contaminated drinking water, and 5) ingestion of contaminated soil. Two additional pathways–consumption of contaminated home-grown produce and fish are also considered at some residential sites, but only when site-specific circumstances warrant inclusion.

Commercial/Industrial Exposure Scenario. The Superfund guidelines utilize occupational exposure scenarios whenever the land use is, or is expected to be, commercial or industrial. These scenarios typically assess adult worker exposures that assume exposure occurs at the workplace during an 8-hour work day, five days per week, 50 weeks per year, for 25 years. Exposure pathways considered under these scenarios are identical to those evaluated for residential exposures, with the omission of pathways for consumption of home-grown produce and fish. Values for exposure factors and intake rates assumed for commercial/industrial exposures are generally less than those assumed for residential exposures.

Agricultural Exposure Scenario. The Superfund guidelines utilize agricultural exposure scenarios whenever individuals live or work in contaminated areas zoned for farming activities, such as growing crops or raising livestock. Under these scenarios, EPA assumes farm family members are exposed through the same five principal pathways evaluated for individuals under the residential setting, plus the mandatory inclusion of the plant pathway (i.e., consumption of home-grown produce). EPA also considers additional pathways for the ingestion of contaminated beef and dairy products, but only when such pathways are valid for the site conditions and lifestyles of the onsite populations.

Additional soil exposure pathways considered under the agricultural exposure scenario include: 1) ingestion of home-grown produce (fruits and vegetables) contaminated with radionuclides taken up from soil, 2) ingestion of meat (beef) containing radionuclides taken up by cows grazing on contaminated plants (fodder), and 3) ingestion of milk containing radionuclides taken up by cows grazing on contaminated plants (fodder).

Recreational Exposure Scenario. Under the recreational exposure scenario, the Superfund guidelines include pathways for consumption of locally caught fish – both for subsistence and recreation – and for dermal exposures that might occur during swimming and wading. Fish pathways are evaluated only when there is access to a contaminated water body large enough to produce a consistent supply of edible-sized fish over the anticipated exposure period. Pathways for assessing exposures during swimming and wading are currently being re-evaluated by EPA, along with other potential recreational exposure pathways, such as hunting and dirt-biking.

14.3.5 Exposure Scenarios Considered by DOE and the NRC

In general, the Department of Energy and the Nuclear Regulatory Commission consider similar land-use scenarios in the remediation of actual sites (DOE93 and NRC92). However, in some cases, DOE or NRC may evaluate additional exposure scenarios and pathways that are not based on any specific land-use consideration – such as the intruder exposure scenario – or may apply different default values for exposure factors and intake rates than those currently recommended by EPA. Table 14-1 compares EPA, DOE, and NRC default exposure factor values. It should be noted that all three agencies strongly recommend the use of site-specific data for modeling doses and risks, but only when the data are available and meet appropriate data quality objectives and data usability requirements.

14.4 SCOPE OF COMPLIANCE ASSESSMENTS (§194.54)

In accordance with §191.15(a) and §191.24(b), calculations of compliance with the individual and ground-water protection requirements must consider the undisturbed performance of the disposal system. "Undisturbed performance" is defined at §191.12(p) as "the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human-intrusion or the occurrence of unlikely natural events."

To clarify the Agency's intent for this requirement, §194.54 specifies that any application for certification of compliance shall include information which:

(1) identifies the potential processes, events, or sequences of processes and events that may occur over the regulatory time frame;

(2) identifies the processes, events, or sequences of processes and events that may be included in compliance assessment results provided in any compliance application; and

(3) documents why any processes, events or sequences of processes and events identified under paragraph (a)(1) of this section were not included in compliance assessment results provided in any compliance application.

Unlike the containment requirements, the individual and groundwater protection requirements do not apply to cumulative releases nor do they contain probabilistic requirements, such as the requirement that certain releases be less than 1 in 1,000 likely to be exceeded (191.13). Instead, the individual and groundwater requirements apply to the doses received during one individual's lifetime, versus 10,000 years for the containment requirements. Further, the expected value of the dose received -- the mean value -- <u>must</u> be less than the applicable dose limit, for example, 15 mrem in the case of the individual protection requirements. There is no regulatory significance to the <u>probability</u> with which the dose limit will be exceeded, and hence these requirements cannot be treated analogously to the probabilistic containment requirements. Therefore, providing a numerical cut-off for probability, such as the 1 in 10,000 threshold test applicable to performance assessments, would not be applicable. However, some screening of processes and events was contemplated in 40 CFR part 191, which in the definition of "undisturbed performance" in 40 CFR part 191 state that compliance assessments may exclude from consideration any unlikely natural processes and events.

Several differences emerge upon examination of the performance assessments needed for the containment requirements and the compliance assessments needed for the individual and groundwater protection requirements. For example, the individual protection requirements apply only to the accumulation of dose over an individual's lifetime versus 10,000 years in the containment requirements. Second, as just explicated, the individual and groundwater protection requirements are not probabilistic, unlike the containment requirements. Third, whereas the focus of the individual and groundwater protection requirements is on the contribution of natural processes and events to doses to individuals, the containment requirements focus on the contribution such processes and events make toward releases of radionuclides to the accessible environment. In view of these considerations, the Agency recognized that the significantly different form of the containment requirements versus the individual and groundwater protection requirements necessitated a different treatment of the screening of processes and events.

In compliance assessments, therefore, the Agency requires that a qualitative judgment be made regarding the likelihood with which groundwater and individual exposure pathways will be affected, over the time scale of an individual's lifetime (not 10,000 years as in the containment requirements) by the occurrence of different natural events. Although the universe of processes and events considered in the performance assessments (for the containment requirements) will closely resemble that of compliance assessments, the different regulatory requirements attending each analysis, as noted above, might allow for subtle differences regarding whether the individual events should be included in the analysis. As with performance assessments, the final rule at §194.54(a) requires compliance applications to document why any processes and events or sequences of processes and events that may occur over the regulatory time frame were not included in compliance applications.

14.5 RESULTS OF COMPLIANCE ASSESSMENTS (§194.55)

As discussed above, the part 191 disposal standards require that compliance assessments include consideration of the uncertainties associated with the undisturbed performance of the disposal system. To accomplish this assessment, it is necessary to identify all disposal system parameters that can affect the performance of the WIPP, as well as to identify the uncertainty associated with each parameter. This approach is identical to the one used to certify and demonstrate compliance with the containment requirements of 40 CFR part 191.

As part of this approach, EPA requires a three-step process, whereby:

1. all uncertain disposal system parameters are identified;
2. probability distribution functions are developed for these parameters (a probability distribution function assigns a probability of occurrence to each value for a given parameter); and

3. following steps 1 and 2, statistical sampling techniques are used to draw random samples from across the full range of probability distributions for parameter values used in compliance assessments.

The Agency believes that this process will help ensure that all possible values of a parameter have been considered in compiling compliance assessment results.

Two types of statistical sampling techniques are used frequently, namely the Monte Carlo and Latin Hypercube techniques. The Monte Carlo technique uses a random sampling scheme, which, as the name implies, involves the selection of values for a particular parameter at random within the predefined probability function for the parameter. The major disadvantage of this technique is that a large number of iterations is necessary to ensure that the selected values are sampled adequately. In comparison, the Latin Hypercube technique uses a special case of stratified sampling that involves the systematic partitioning of the range of values for a particular parameter into some number of strata. The principal advantage of this technique is that it requires less sampling iterations to ensure that the entire range of values is represented, because it draws samples from each stratum.

Also under §194.55, EPA requires that the range of estimated radiation doses to individuals (as generated through use of the computational techniques referred to above), and the range of estimated radionuclide concentrations in ground water must be large enough such that the maximum estimate generated exceeds the 99th percentile of the population of estimates with at least a 95% probability. The "population of estimates" refers to the set of all possible estimates that can be generated from all disposal system parameter values used in compliance assessments. A single estimate, in effect, samples this population.

The Agency is including this provision for the purpose of ensuring that there is a 95% probability that 99% of all possible values have been exceeded by the maximum estimate generated. This is similar to the requirement for the number of CCDFs (complementary cumulative distribution functions) which must be generated for purposes of compliance with the containment requirements.

In order to assure that all pertinent information is provided to the Agency, EPA is also requiring that compliance applications display the full range of estimated radiation doses and the full range of estimated radionuclide concentrations. The Agency believes that this requirement will help ensure that a full range of values is considered in compliance assessments.

Finally, the Agency requires that any compliance certification application provide information which demonstrates that there is at least a 95% level of statistical confidence that the mean and the median of the full range of estimated radiation doses and of the full range of estimated radionuclide concentrations meet the requirements set forth in sections 15 and subpart C of 40 CFR part 191. The mean estimate provides a measure of compliance that expresses the average impacts of the disposal system on individuals and ground water. The median estimate provides a measure of compliance that expresses the central tendency of a population of estimates. Specifically, the median represents the point that a calculated estimate would be equally likely to fall above or below. Insofar as both statistics contain useful information, the Agency's approach assures that both meet the limits of the individual and ground-water protection requirements.

It is important to note that a reasonable expectation of compliance with the individual and ground-water protection requirements will not be based solely on a final statistical estimate of doses to individuals or radionuclide concentrations in ground water. Whether a reasonable expectation of compliance will be achieved or not will be evaluated on the basis of the full record before the Agency and a thorough consideration of the methods and assumptions that produced compliance assessment results. For instance, in certifying and determining compliance, the Agency will consider such factors as the reasonableness of the processes and events considered, the appropriateness of any expert judgment elicitation used to provide inputs to the assessments, the adequacy of peer review, the quality of the models, and the quality of data inputs to those models.

14.6 REFERENCES

DOE93 Department of Energy, "Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.0," Final Draft, 1993.

EPA89a Environmental Protection Agency, "Risk Assessment Guidance for Superfund, Volume 1, Human Health Evaluation Manual, Part A," EPA/540/1-89-002, 1989.

EPA89b Environmental Protection Agency, "Exposure Factors Handbook," EPA/600/8-89/043, 1989.

EPA91a Environmental Protection Agency, "Risk Assessment Guidance for Superfund, Volume 1, Human Health Evaluation Manual. Part B, Development of Risk Based Preliminary Remediation Goals," PB92-963333, 1991.

EPA92 Environmental Protection Agency, "Guidance on Risk Assessment for Risk Managers and Risk Assessors," Memo from F. Henry Habicht II to Assistant and Regional Administrators, February 26, 1992.

EPA94 Environmental Protection Agency, "Draft Guidance for Soil Screening Level Framework, Quick Reference Fact Sheet, Review Draft," 1994.