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Events and Processes for Constructing Scenarios for the Release of Transuranic Waste From the Waste Isolation Pilot Plant, Southeastern New Mexico

Regina L. Hunter

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
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EVENTS AND PROCESSES FOR CONSTRUCTING SCENARIOS FOR THE RELEASE OF TRANSURANIC WASTE FROM THE WASTE ISOLATION PILOT PLANT, SOUTHEASTERN NEW MEXICO

Regina L. Hunter
Project Management and Systems Integration Division
Sandia National Laboratories
Albuquerque, New Mexico

ABSTRACT

The Waste Isolation Pilot Plant (WIPP), located in southeastern New Mexico, is a research and development facility to demonstrate safe disposal of defense-generated transuranic waste. The US Department of Energy will designate the WIPP as a disposal facility only if it meets the US Environmental Protection Agency's standard for the disposal of such waste, which includes a requirement for a performance assessment. Performance assessment comprises scenario development and screening and probability assignment; consequence analysis; sensitivity and uncertainty analysis; and comparison with a standard. This report examines events and processes that might give rise to scenarios for the long-term release of waste from the WIPP and begins to screen and assign probabilities to them. The events and processes retained here will be used to develop scenarios during the WIPP performance assessment; the consequences of scenarios that survive screening will be calculated and compared with the standard.

The events and processes retained for scenario development are the normal flow of ground water, climatic change, drilling of exploratory boreholes, solution mining, seal performance, the effects of drilling into a brine pocket beneath the repository, leaching of the solid waste, nuclear criticality, waste/rock interaction, and waste effects. Numerous other events and processes considered by earlier workers are dismissed from further analysis during the WIPP performance assessment on the basis of physical unreasonableness, low probability, negligible consequence, or regulatory guidelines.

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1. INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is a research and development facility to demonstrate safe disposal of defense-generated transuranic (TRU) waste that the US Department of Energy (DOE) may designate as requiring deep geologic disposal (Figure 1). The WIPP also provides a separate underground facility in which in situ experiments may be conducted. All wastes placed into the WIPP for intended disposal will be retrievable for the periods required to demonstrate the safety of the disposal concept; these periods are not expected to exceed five years for TRU waste. Wastes used in the experimental program will be removed at the conclusion of the experiments, if necessary for compliance with applicable environmental standards or the WIPP waste acceptance criteria. If the safety of the disposal concept is demonstrated and all applicable regulations are satisfied, the WIPP will become a disposal facility for TRU waste.

The WIPP is located in southeastern New Mexico, about 30 miles from Carlsbad (Figure 2). The underground workings are being emplaced at a depth of 2150 ft in bedded salts of the Salado Formation (Fm.) (Figure 3). The DOE has conducted investigations to refine existing knowledge of geologic and hydrologic processes at and near the WIPP site and to address issues on which the State of New Mexico has asked for further information.

The WIPP Project will assess compliance with the requirements of the US Environmental Protection Agency's (EPA) *Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes--40 CFR Part 191* (the Standard, EPA 1985). Although Subpart B of the Standard was remanded to the EPA by the United States Court of Appeals for the First Circuit, the WIPP Project will continue to respond to the Standard as first promulgated until a new Standard is in place (DOE and State of New Mexico, 1981).

Performance assessment consists of a series of analyses that will predict the performance of the site and compare the predicted performance with the Standard. Performance assessment includes four major components: (1) scenario development and screening and probability assignment; (2) consequence analysis; (3) sensitivity and uncertainty analysis; and (4) comparison with a standard (Hunter et al. 1986). These processes are iterative. Analyses of consequences of initial scenarios may suggest areas of further research, which may in turn suggest new scenarios. This iterative process has been taking place within the WIPP Project for over a decade, and numerous events and processes have been considered in prior work. This report, a portion of the WIPP performance assessment, reevaluates these events and processes and determines which may be dismissed from and which will be retained for the WIPP performance assessment. The events and processes retained here will be used to develop scenarios, which in turn will be further screened. The consequences of those scenarios that remain after screening will be analyzed.

Several previous reports have described scenarios for the release of waste from a repository at the WIPP site (Table 1). Claiborne and Gera's (1974) WIPP scenarios were among the earliest descriptions of possible releases from a radioactive-waste repository. Bingham and Barr (1979) developed the most comprehensive set of scenarios for the WIPP performance assessment. The DOE

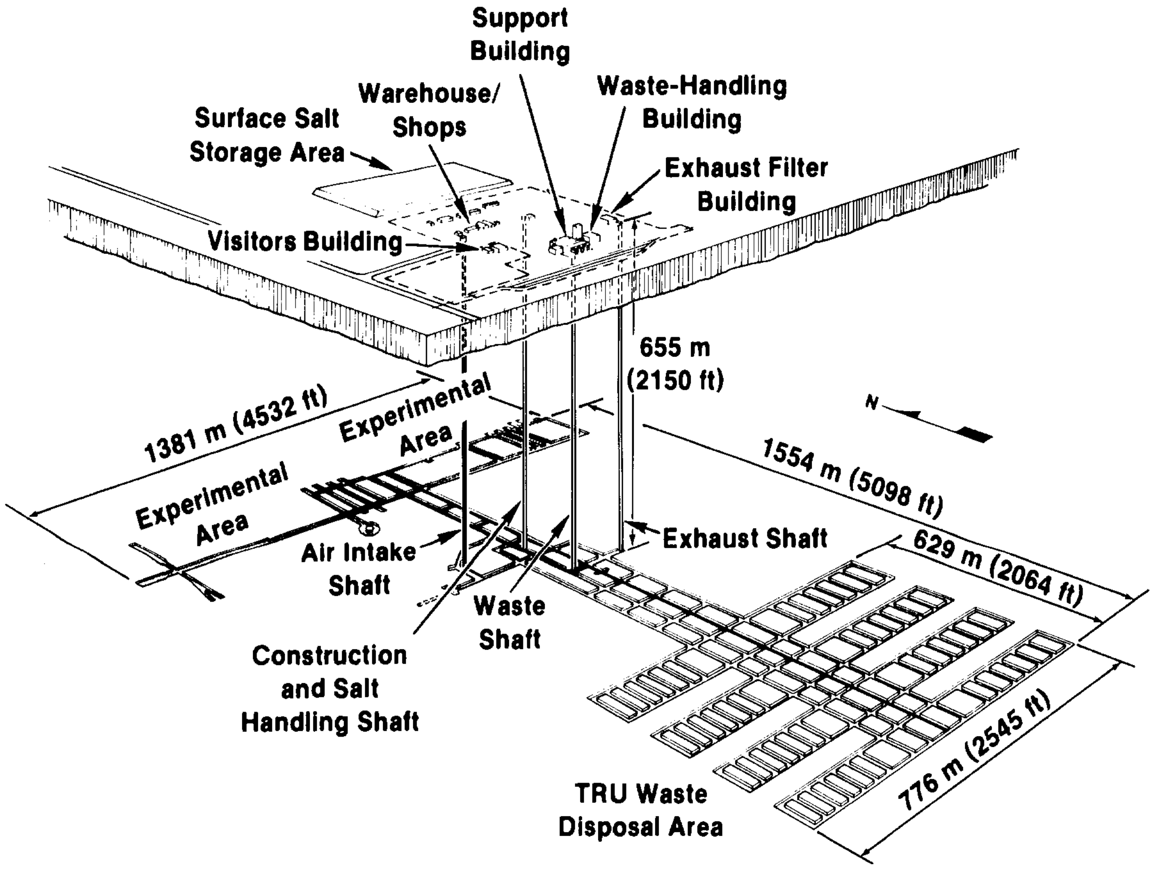

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Figure 1. Perspective drawing of the WIPP (after Waste Management Technology Department 1987).

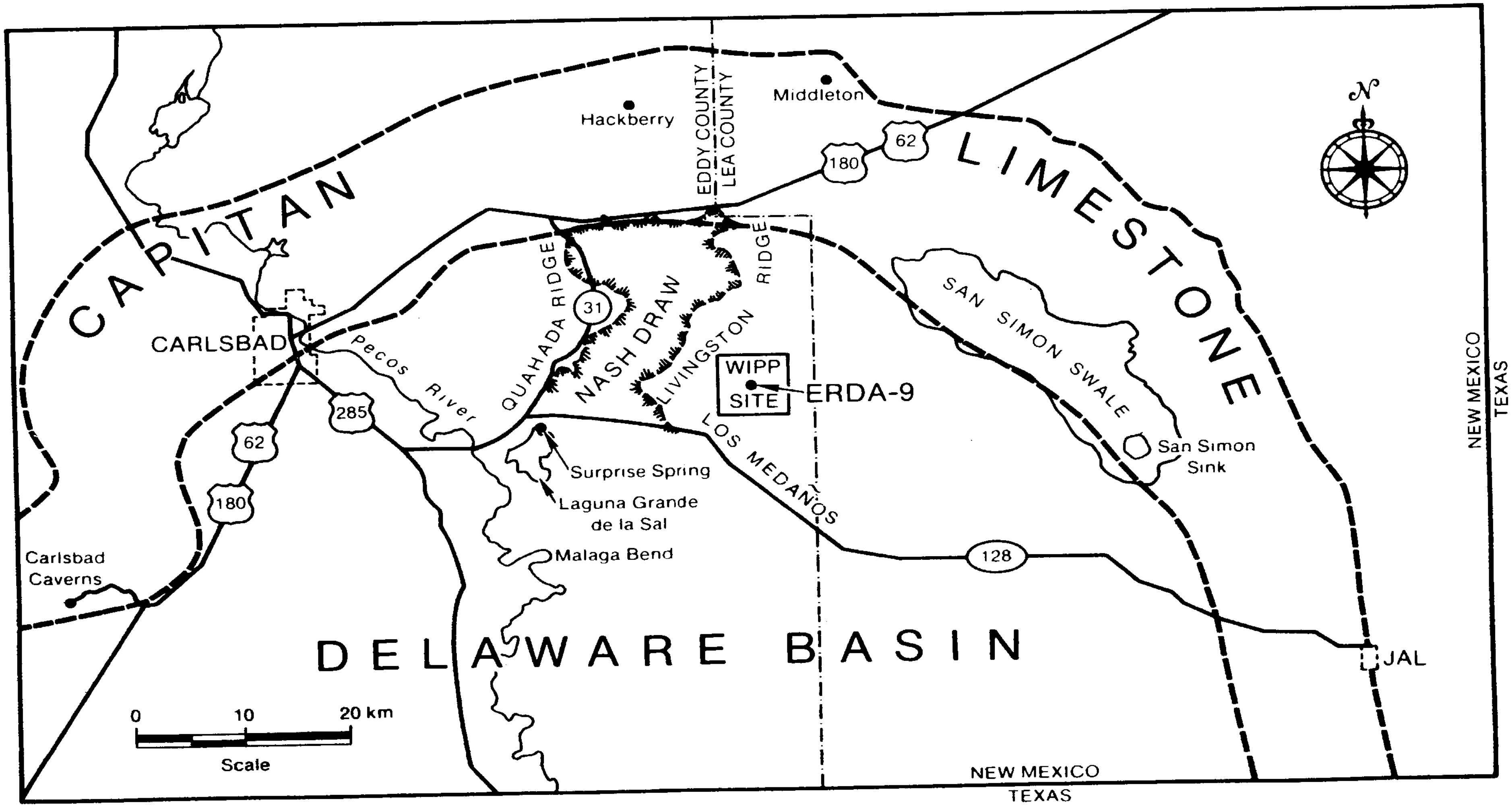

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Figure 2. Location map showing the WIPP site and selected features referred to in the text (after Lappin 1988, Figure 1.1).

System	Series	Group	Formation	Member
Recent	Recent		Surficial Deposits	
Quaternary	Pleistocene		Mescalero Caliche	
			Gatuña	
Triassic		Dockum	Undivided	
Permian	Ochoan		Dewey Lake Red Beds	
			Rustler	Forty-niner
				Magenta Dolomite
				Tamarisk
				Culebra Dolomite
				unnamed
			Salado	
			Castile	
	Guadalupian	Delaware Mountain	Bell Canyon	
			Cherry Canyon	
			Brushy Canyon	

TRI-6330-16-0

Figure 3. WIPP stratigraphy (Lappin 1988, Table 1.1).

Table 1. Events and processes considered by earlier workers

	WIPP Project					Other Bedded Salt Investigations		
	Claiborne & Gera 1974	Bingham & Barr 1979	DOE 1980a, Vol. 1, Section 9.7	EEG Staff	Other	Arthur D. Little, Inc. 1980	Cranwell et al. 1982	Other
Ground-Water Flow	x	x	x	1, 2, 5, 6		x	x	3, 4
Climate Change, Glaciation		x				x	x	4
Drilling into Repository	x	x	x	2	7	x	x	4
Effects of Brine Pocket			x	1, 2, 8, 9, 6, 10	7			
Effects of Mining for Resources		x	x	1, 2, 6, 11				
Seal Performance		x						4
Nuclear Criticality		x	x					
Waste/Rock Interaction		x	x					
Waste Effects (e.g., gas generation, radiolysis		x	x	1				
Dissolution		x	x	2, 6		x	x	3, 4
Migration of Brine Aquifer		x	x					
Breccia Pipe Formation				6, 12		x		
Migration of Brine Inclusions			x			x		

Table 1. Events and processes considered by earlier workers (concluded)

	WIPP Project					Other Bedded Salt Investigations		
	Claiborne & Gera 1974	Bingham & Barr 1979	DOE 1980a, Vol. 1, Section 9.7	EEG Staff	Other	Arthur D. Little, Inc. 1980	Cranwell et al. 1982	Other
Induced Diapirism		x	x			x		3, 4
Diffusion		x	x					
Exhumation, Sedimentation	x	x				x	x	3, 4
Faulting	x	x				x	x	3, 4
Igneous Intrusion	x	x				x	x	4
Meteorite Impact	x	x				x	x	3, 4
Sabotage, Warfare	x	x					x	
Subsidence, Repository-Induced		x	x					
Thermal Effects		x	x					

1. Neill et al. 1979
2. EEG 1980
3. Proske 1977
4. Logan and Berbano 1978
5. Wofsy 1980
6. EEG 1982
7. Woolfolk 1982
8. Bard 1982
9. Channell 1982
10. Spiegler 1982b
11. Little 1982
12. Spiegler 1982a

(1980a) and the State of New Mexico Environmental Evaluation Group (EEG, e.g., 1980) have also developed and analyzed WIPP release scenarios. Other investigators have considered releases from real and hypothetical bedded-salt repositories other than WIPP (Table 1); the work of Cranwell et al. (1982) is probably the most comprehensive in this group. New evidence and new regulatory developments have combined to make some of the events and processs considered by earlier workers unimportant; these are described in Chapter 2.

Chapter 2 presents all the events and processes that have been dismissed from the scenario development on the basis of physical unreasonableness, extremely low probability, negligible consequence, or regulatory guidelines. No scenarios including these events and processes will be included in consequence modeling, because current information about them conservatively indicates that they are not of regulatory interest. They are presented here to show the broad range of events and processes that were considered and to describe in detail the reasons for their dismissal at this time. Chapter 3 describes the events and processes that may be of interest to the performance assessment. They are retained for analysis either because their probabilities are above the EPA's cutoff or because they appear capable of giving rise to scenarios whose consequences do not seem at first glance to be negligible.

2. EVENTS AND PROCESSES SCREENED OUT

The events and processes that might affect geologic repositories and the scenarios that could be developed from these events and processes, especially in the absence of regulatory guidelines, far outnumber the scenarios that can practicably be modeled during consequence analysis. Before the promulgation of the Standard by the EPA, performance-assessment workers did not know what bounds would be placed on the analyses required to demonstrate the safety of a nuclear-waste repository. Some workers (e.g., Proske 1977, Bingham and Barr 1979, Foley et al. 1982) considered very long time periods, e.g., 10^6 years, to be appropriate windows for projection of repository performance. The effects of very-low-probability events, such as meteorite impact, were also examined (e.g., Claiborne and Gera 1974). When the Standard was promulgated, it set 10,000 years as the period of performance to be predicted. The EPA (1985, Appendix B) also suggested that performance assessments need not consider events or processes with probabilities of occurrence less than 1 in 10^4 in 10^4 years. Events and processes that would lead to negligible consequences may also be omitted from the detailed consequence analysis. As a result, detailed analysis of many of the events and processes treated by earlier workers would be inappropriate in the WIPP performance assessment. Table 1 (p 5) lists events and processes considered in prior work on WIPP scenario development and several reports for other real and hypothetical bedded-salt sites. Only a few of these were thought by earlier workers to be significant at the WIPP even before the Standard was in place.

Four screening criteria have been developed that are in line with the EPA Standard (e.g., Cranwell et al. 1982, Hunter et al. 1986): physical reasonableness, probability, potential consequences, and regulatory guidelines. The events and processes described in this chapter are screened from further analysis during the WIPP performance assessment on the basis of one or more of these criteria.

For the most part, the events and processes discussed in this chapter have very low probabilities, so low in fact that some workers may question the appropriateness of calculating probabilities at all. For example, if a process such as tectonic faulting has not been active in the northern Delaware Basin for at least 200 million years, many geologists would assume that the probability of faulting in the next 10,000 years is very close to zero, not the 10^{-7} calculated below. If comparison with the cutoff in Appendix B of the Standard is desired, however, some discrete probability must be calculated, and that has been done here. In general, the probabilities calculated are conservatively high in three ways:

- Processes are assumed to be active at the WIPP site at the present time, even if the geologic evidence suggests that this is untrue.
- The rate of occurrence is maximized by assigning all examples of an event or process the age of the youngest example.
- The size of the disturbance is maximized by assigning all examples of an event or process the size of the largest example.

The calculated probabilities are so conservative and so low that no great investment of time in making them very precise has been deemed appropriate, so a straightforward frequentist approach has been taken. (For a thorough discussion of approaches to probability assignment and their application to waste management, see the work of Hunter et al. (1989).)

Dissolutional Processes

Dissolution

The processes discussed in this section generally all have been called dissolution except when they have been assigned more specific, descriptive names by individual workers. The near-field process called "dissolution" here (following the usage of Bingham and Barr 1979, among others) is similar to leaching in that waste might be dissolved, but differs in that rock too is dissolved by fresh water or unsaturated brine introduced into the repository by some other event or process. This dissolution is limited to repositories in salt. It not only does not depend on the natural occurrence of ground water in the repository horizon, but is in fact unrelated to the naturally occurring ground water, because it requires that the introduced water be unsaturated.

The introduction of unsaturated water into the repository almost requires deliberate human intrusion, however: a fracture or uncased borehole would transmit only saturated brine to the repository; a cased borehole would pass unsaturated water through the repository without significant loss of water to the rooms. Therefore fresh water cannot enter the room, and dissolution of the repository horizon by fresh water (except by solution mining) is dismissed.

Several far-field dissolution mechanisms have been considered by previous workers associated with the WIPP Project (see Lambert 1983a for an excellent summary and discussion); these mechanisms give rise to three phenomena that have been of interest to performance assessment. The first of these phenomena, migration of the brine aquifer, acts some distance away from the repository to remove salt. This process may create a new land surface nearer the repository, thus reducing the extent of the natural rock salt barrier. The brine aquifer is associated with Nash Draw, but not completely confined to it. The second phenomenon, vertical dissolution, acts at the surface near the site and removes so much salt that the repository is exhumed; this process differs from the "erosion" of Bingham and Barr (1979) in that most of the material is removed beneath the land surface in solution in ground water, not by mechanisms for the movement of particles, such as wind or glaciation. The third far-field dissolution phenomenon, breccia-pipe formation, forms a deep-seated rubble chimney through the salt to the surface.

Bachman (1984) examined the regional geology of the evaporites in the northern Delaware Basin. He concluded that dissolution in the western part of the Delaware Basin occurred under hydrologic conditions "radically different" from current conditions and that the probability of further dissolution near the repository is remote.

Migration of Brine Aquifer

The first of the three far-field processes, when acting at the surface for a long enough period of time to affect the repository, was called "brine aquifer arrives above repository" by Bingham and Barr (1979). It was called "horizontal shallow dissolution" by the DOE in the WIPP FEIS (cf. rates given by Bingham and Barr 1979, p 86, para. 4, and DOE 1980a, p 7-98, last para.) Based on the work of Bachman and Johnson (1973) and Bachman (1980), Bingham and Barr and the DOE concluded that the brine aquifer will not arrive above the repository for more than 100,000 years. The DOE gave rates of horizontal migration of dissolution of 6 to 8 miles per million years. More recent work by Lambert (1983b) supports this estimate, even though he postulated a more efficient mechanism, stratabound dissolution. Any difference in consequences of the dissolution front being 0.08 miles closer to the repository in 10,000 years will be well within the uncertainty of the consequence analysis; migration of the brine aquifer is therefore dismissed from the scenario development on the basis of negligible consequence. It has been suggested that when acting below the repository, say at the base of the Salado Fm. or of the Castile Fm., salt removal might give rise to breccia pipes or to a less effective subsidence of the repository and its host rock. Breccia pipes are discussed in detail and dismissed below.

Vertical Dissolution

The second of the three far-field processes has been called vertical dissolution (Bingham and Barr 1979, DOE 1980a). Before vertical dissolution can begin to remove the salt directly above the repository at the WIPP site, the dissolution front created by the above processes must migrate eastward from its present position and arrive at the site. Bingham and Barr (1979) and the DOE (1980a) concluded that a repository at WIPP would not be exposed by the dissolution of salt for 2 to 3 million years. This process is dismissed from the scenario development, because it would not give rise to releases within 10,000 years.

Breccia-Pipe Formation

Breccia pipes are vertical chimneys filled with collapse breccia. Collapse seems to be initiated by deep-seated dissolution resulting from the concurrence of soluble rock and relatively fresh water under relatively high hydrostatic head at depth. Breccia pipes generally contain large blocks of undissolved soluble rock. In the Delaware Basin, known breccia pipes are closely associated with the Capitan reef. They are expressed at the surface as low hills containing younger, down-faulted rock in the center and older, intact but outwardly dipping rock in an outer ring. Extensive field study and drilling of numerous low hills in the Delaware Basin, with and without obvious breccia, have shown that only four are confirmed or probable breccia pipes (Snyder and Gard 1982, p 55): Hills A and C are confirmed and Hills B and Wills-Weaver are probable breccia pipes. San Simon Sink may be a breccia pipe in the process of forming (Lambert 1983a). On the basis of the existing literature, breccia pipes are screened from the WIPP performance assessment on three grounds. First, the occurrence of a future breccia pipe at the site is not physically reasonable, because it does not overlie a source of fresh water such as the Capitan reef. Second, granting for the sake of argument that one might occur, the probability of intersecting the repository is about the same as the EPA's suggested cutoff. Third, preliminary analysis of consequences has shown them to be negligible, or even zero, during the 10,000-year regulatory period.

Physical Reasonableness. Based on field studies of the known and suspected breccia pipes and the regional geology, Bachman (1980) suggested that the formation of breccia pipes at Hills A and C depended on high hydraulic heads in the Capitan aquifer system during Gatuña time. Easterly movement of fluids was restricted by a submarine canyon complex, resulting in upward migration of unsaturated fluids along fractures. These fluids dissolved the soluble rock above, leading to collapse. Snyder and Gard (1982) suggested that the cavity may have formed in the Capitan Ls. In either case, breccia pipes are closely associated with the Capitan reef. Neill et al. (1983) concluded on the basis of an extensive literature review that Bachman's explanation of the origin of the breccia pipes is reasonable. Although R. Y. Anderson (e.g., EEG 1979, p 13; 1980, p 13; and 1982, p 18; Neill et al. 1983, p 7) and P. Davies (EEG 1982, p 22) have suggested that other mechanisms exist that might give rise to breccia pipes inside the basin, Borns and Shaffer (1985) showed that the evidence Anderson and Davies used to support the hypothesis of dissolution can be used more compellingly to support the hypotheses of depositional responses to existing topographic irregularities or of salt flowage. The absence of confirmed breccia pipes away from the reef, even though such features have been sought, suggests that the mechanisms proposed by Anderson and Davies are, at most, inactive.

Spiegler (1982a) compared rates of creep and salt removal and concluded that under present hydrologic and geologic conditions, no large cavern can form at the Bell Canyon-Castile interface at the WIPP site. By ignoring creep and considering only salt removal, he calculated a time of collapse into a cavern of appropriate size to be 27,000 years. (Spiegler's work was done before the publication of the final EPA Standard.)

The available literature suggests that no breccia pipes have occurred at sites geologically similar to the WIPP site, that no confirmed mechanism exists for their formation at the WIPP site, and that if a mechanism is postulated, the time of formation is longer than the regulatory period of 10,000 years. Thus any scenarios incorporating such an event would be physically unreasonable.

Probability. As stated above, no mechanism is known to exist for the formation of breccia pipes at the WIPP site. One could argue, however, that some unknown mechanism does exist, and that it is merely coincidence that none have formed outside the reef. By assuming that a mechanism does exist and that they will continue to occur randomly in space and time in the general vicinity of the WIPP site, one can calculate a probability of occurrence during the next 10^4 years using the following technique (described in detail by Cranwell et al. 1982, Appendix C).

There are four confirmed or suspected breccia pipes associated with the Capitan reef near the WIPP site. Based on the presence of well exposed, relatively undisturbed Gatuña gravel and Mescalero caliche at Hills A and C, Bachman (1980) concluded that the pipes formed prior to 500,000 years ago. Hill B also contains Gatuña and Mescalero rocks.

Bachman (1980) stated that the known breccia pipes are no more than 800 ft in diameter at the surface; Neill et al. (1983) suggested a typical diameter of less than 1000 ft. The pipes are subcircular in cross section. The dimensions of the repository are roughly 4800 ft x 2600 ft. The smallest circle that encompasses all four known and suspected breccia pipes and the WIPP site is about 116,000 ft (22 miles) in diameter, an area of 10^{10} ft^2.

The probability of a breccia pipe occurring inside the larger circle and intercepting the repository is

$$P = 1 - e^{-rpt}$$

where

$r = 4$ events/5×10^5 years $= 8 \times 10^{-6}$ events/yr, the rate of occurrence of breccia pipes inside the larger circle,

$p = 6800$ ft $\times$ 4600 ft/10^{10} ft^2, the ratio of the target (this is roughly equivalent to area of a breccia pipe being "rolled around the edge" of the repository) to the area of the larger circle,

$t = 10^4$ years, the time period considered.

Substituting the values given above, we obtain

$$P = 1 - e^{-(8 \times 10^{-6})\ (3 \times 10^{-3})\ (10^{4})}$$

$$\sim 2 \times 10^{-4}$$

as a conservatively high estimate of the probability of interception of the repository by a breccia pipe in 10^4 years. If San Simon Sink is added, the area encompassing the five breccia pipes enlarges to about 35 mi in diameter, and $P \sim 10^{-4}$. These probabilities are about the same as the EPA cutoff of 1 in 10^4 in 10^4 years.

Consequences. Spiegler (1982a) performed a preliminary analysis of the consequences of the occurrence of a breccia pipe at the WIPP repository. His results were presented as a concentration and therefore are not directly comparable to the EPA Standard, but he pointed out that the concentration of Pu-239 in brine reaching the surface would be less than that specified in 10 CFR Part 20. Spiegler's most important result for comparison with the Standard is that no releases would occur by this mechanism for 27,000 years. Appendix B of the Standard suggests that events and processes whose consequent releases contribute negligibly to the complementary cumulative distribution function (CCDF) for 10,000 years can be omitted from the performance assessment.

Migration of Intracrystalline Brine Inclusions

The potential for releases resulting from migration of intracrystalline brine inclusions through salt in response to thermal gradients has been considered by the DOE (1980a, p 9-156) and Arthur D. Little, Inc. (1980, p 194). The inclusions do not migrate in response to geothermal gradients, but they have been shown to migrate in response to thermal gradients imposed by simulated high-level-waste canisters (Shefelbine 1982). The hottest waste to be disposed in the WIPP will be contained in remotely handled (RH) canisters emplaced in holes drilled into the walls of the rooms. Experiments simulating the disposal of RH TRU waste (Tyler et al. 1988, pp 254-255) have shown that little or no brine migrates into the holes in response to the thermal gradients imposed. Brine entering the repository in response to other gradients differs chemically from the brine inclusions (Lappin 1988, Section 3.3.2), also suggesting that the brine inclusions are not migrating. Therefore, no treatment of the migration of intracrystalline brine inclusions is warranted.

Induced Diapirism

Several investigators have considered whether the heat generated by radioactive waste in a salt repository could cause a loss of containment by the creation of buoyant forces. Buoyancy of the salt and its contained waste, if significant, might cause the formation of a diapir-like structure that could eventually release waste at the surface directly above the repository. Not even heat loadings that might be associated with high-level-waste emplacement, however, have been calculated to cause significant vertical movements. The DOE (1980a, Vol. 1, Section 9.7.2.1) calculated a maximum displacement of about a centimeter for a conservatively high WIPP heat loading. Citing earlier calculations carried out at Sandia Laboratories, both Bingham and Barr (1979) and Arthur D. Little, Inc. (1980) concluded that diapirism will not be induced. Logan and Berbano (1978) and Proske (1977) considered diapirism to be important only over periods of 10^6 years. Induced diapirism is physically unreasonable and therefore will not be retained for consequence analysis in the WIPP performance assessment.

Diffusion out of the Repository

Diffusion in response to a concentration gradient could move waste through any water introduced into the repository. Bingham and Barr (1979) assigned diffusion a probability of 1 in any case involving the presence of water and suggested that the consequences of a scenario including diffusion be modeled. The DOE (1980a, Vol. 1, Section 9.7.1.3) modeled a diffusion scenario that assumed a stagnant pool connecting the Rustler Fm. with either 1% or 50% of the total repository area, with a waste form that dissolved at the same rate as the salt. Dissolution of the repository's waste took about 66 million years for the 50%-connection case and about 3.3 billion years for the 1%-connection case.

DOE's modeling was carried out before promulgation of the EPA Standard; results were not presented as cumulative releases. If the releases are assumed to occur at a constant rate, then in 10,000 years about 0.0003% (i.e., $10{,}000/3.3 \times 10^9$) of the waste (roughly 30 Ci) could be released to the Rustler Fm. (not the accessible environment) in the 1%-connection case. One percent of the area of the mined portion of the waste panels is a square 114 feet on a side; this is substantially larger than all shafts and boreholes combined. No mechanism is known that would allow a stagnant pool of such great size to develop, not to mention stay in existence for 10,000 years. Furthermore, WIPP waste is for the most part much less soluble than salt. Diffusion of significant amounts of waste to the accessible environment is physically unreasonable and is dismissed from further analysis.

Exhumation or Sedimentation

Claiborne and Gera (1974) concluded that exhumation of waste in a WIPP repository could be neglected, because it would take several hundred thousand to several million years. Logan and Berbano (1978) and Bingham and Barr (1979) assigned a probability of 0 to exposure of the waste by erosion within 1 million years. Arthur D. Little, Inc., (1980) concluded that neither erosion by wind or water nor sedimentation is cause for concern within 10,000 years. Cranwell et al. (1982) dismissed releases resulting from both erosion and sedimentation on the grounds of physical unreasonableness. Proske (1977) considered erosion only over a period of 1 million years.

Exhumation and sedimentation are dismissed from further consideration, because any consequences would be negligible within 10,000 years.

Faulting

The Delaware Basin, although uplifted and tilted, has not been subject to significant local tectonic deformation since Permian time, and no tectonic faults have been discovered in the WIPP area. Reexamination of two suggested faults on the western margin of the Delaware Basin, the Barrera and Carlsbad faults, led Hayes and Bachman (1979) to conclude that they do not exist. Previous performance-assessment workers (Bingham and Barr 1979, Claiborne and Gera 1974) treated the occurrence of a new fault as a possible breaching event at the WIPP site prior to Hayes and Bachman's work, however. There are no known earthquake epicenters within about 25 miles of the WIPP site (DOE 1980b, Section 2.9.4), and no faults have been found in the Salado Fm. in the vicinity of the site (DOE 1980b, Section 2.7.3.3.2).

The absence of faulting during the past 200 million years suggests that scenarios including faulting during the next 10,000 years would be physically unreasonable. In addition, the probability of faulting, even assuming the existence of the Barrera and Carlsbad faults and the occurrence of two similar faults during the next 200 million years, is much less than the EPA suggested cutoff. Claiborne and Gera (1974) calculated a probability that two such faults will occur and that either will intercept the repository to be 4×10^{-11} per year. Bingham and Barr (1979), using Claiborne and Gera's method but a different repository size, calculated the probability to be 5×10^{-11} per year or 5×10^{-7} at 10,000 years. Thus on the bases of physical unreasonableness and low probability, faulting is screened from the WIPP performance assessment.

Glaciation

Glacial loading of a repository site could cause moderate mechanical disruptions of the repository (Wahi and Hunter 1986), but no such effects are expected at the WIPP site (Bingham and Barr 1979). Because detailed geologic studies have revealed no evidence suggesting that the site has ever been glaciated, glaciation of the repository site will not be considered during consequence analysis. The Guadalupe Mountains were not glaciated during Pleistocene time, and alpine glaciation there, if it were to occur during a future ice age, would be too far away to affect the site and probably too far in the future to be of regulatory concern. Climatic changes accompanying continental or alpine glaciation to the north are likely during the next 10,000 years, and climatic changes of this sort will be considered in the WIPP performance assessment.

Igneous Intrusion

A mid-Tertiary lamprophyre dike about 80 miles long passes within 9 miles of the WIPP site (Jones 1973; DOE 1980a, p. 7-27). The dike is about 30 million years old and a few inches to several feet in width. The method of Logan et al. (1982, Appendix B) gives the relation

$$P = \frac{P(A)}{A} (2rl + \pi r^2)$$

where

P = probability of intersection of the repository by a similar dike,

$P(A)$ = $10^4/(3 \times 10^7) = 3.3 \times 10^{-4}$, the probability of occurrence of a similar dike in the Delaware Basin in 10^4 years,

A = 3×10^{11} ft^2, the area of the Delaware Basin,

r = 2000 ft, the radius of a circle with area equivalent to the repository, and

l = 4×10^5, the length of the dike.

For the WIPP repository,

$$P = \frac{3.3 \times 10^{-4}}{(3 \times 10^{11})} (2\ (2000 \text{ ft})\ (4 \times 10^5 \text{ ft}) + 3.14\ (2000 \text{ ft})^2)$$

$$= 2 \times 10^{-6}\ .$$

This probability, 2×10^{-6} in 10^4 years, is much less than the EPA cutoff, and disruption of the repository by igneous events is dismissed.

Meteorite Impact

Claiborne and Gera (1974) estimated the probability of impact of a meteorite capable of producing a crater 1 km in diameter to be roughly 10^{-13}/km^2 per year, or about 10^{-9}/km^2 per year over 10,000 years, and the probability of an impact that could cause the direct release of waste from a WIPP repository to be 2×10^{-14}/km^2 per year. Using the work of Claiborne and Gera and other assumptions about repository area, etc., Logan and Berbano (1978), Bingham and Barr (1979), and Cranwell et al. (1982) estimated the probability of releases caused by meteorite impact to be roughly 10^{-9} over 10,000 years. For meteorites causing craters 1 to 2 km in diameter, Arthur D. Little, Inc., (1980) calculated a repository failure rate of 3×10^{-11} events per year, which is 3×10^{-7} over 10,000 years. Proske (1977) considered meteorite impact only for the 10^6-year period.

All estimates of the probability of releases initiated by meteorite impact are several orders of magnitude lower than the EPA's suggested probability cutoff of 10^{-4} over 10,000 years; meteorites are dismissed from further investigation on the basis of low probability.

Sabotage or Warfare

Claiborne and Gera (1974) and Bingham and Barr (1979) concluded that neither sabotage nor warfare present a credible threat to a sealed repository. Even if they presented a threat, the EPA (1985) has implied that considering such human intrusions is unproductive, because no reasonable design or siting precautions could alleviate them. Therefore the analysis of release of waste from the WIPP repository by sabotage or warfare seems unnecessary according to the Standard.

Subsidence

Salt is a plastic rock that immediately begins creeping into any large cavity at depth. Subsidence features occur at the surface in southeastern New Mexico both in areas of subsurface dissolution and above potash mines. Creep into the WIPP repository and subsidence at the surface is therefore a normal and expected part of the repository's projected performance, and releases arising from subsidence have been considered by Bingham and Barr (1979) and the DOE (1980a). Subsidence could also be related to conventional or solution mining for potash or to oil or gas extraction (e.g., Ege 1979). Subsidence associated with the repository and with conventional potash mining and oil and gas extraction is discussed here.

However caused, subsidence could conceivably initiate releases from the repository in three ways: by increasing the hydraulic conductivity of the country rock, by creating fractures through the country rock, or by disturbing the surface drainage. Each of these is discussed and dismissed below.

Increased Hydraulic Conductivity

Stormont (1988) has concluded, based on the work of Holcomb and Shields (1987) and IT Corp. (1987), that reconsolidated crushed salt having a fractional density of .95 has a permeability about equal to that of intact rock salt. As stated above, the total excavated area of waste panels is projected to be roughly 1.3×10^6 ft^2, encompassed in an area of 5.3×10^6 ft^2; room height will be about 13 ft. The total excavated volume in the waste panels will be about 1.7×10^7 ft^3. The repository depth is 2150 ft; the volume of salt overlying the panels (including ribs) is about 1.1×10^{10} ft^3 (i.e., 5.3×10^6 $ft^2 \times 2{,}150$ ft). Therefore the initial void volume in the waste panels represents only about 0.2% of the volume of the overlying salt, and the permeability of the salt can not be uniformly increased beyond that of intact salt by subsidence. Subsidence outside the controlled area as a result of mining or oil or gas extraction would affect the repository even less.

Three conservative assumptions in this calculation tend to maximize the projected increase in permeability. First, all of the initial void volume of the rooms, rather than the initial void volume minus the volume of waste and backfill, has been assumed to be taken up by the salt. Second, all of the void volume has been assumed to translate directly upward, rather than outward at the angle of draw (DOE 1980a, p 9-150). Third, the void volume has been assumed to be completely taken up in the Salado Fm. rather than to reach the surface, although in fact subsidence is often quickly and accurately expressed at the surface above potash mines in the vicinity of the WIPP. Increased permeability in the Salado Fm. as a result of subsidence is dismissed on the basis of negligible consequence.

Fractures

The possibility that void volume will translate to the overlying rock as fractures rather than uniformly increased porosity has also been considered. Bingham and Barr (1979) thought such a situation to be unlikely. At this time, consensus is growing within the WIPP Project that the Salado Fm. will respond to the excavation of the repository by coherent far-field creep, not by fracturing. Observations in nearby potash mines with two levels of extraction show that subsidence into the lower mined area results in flexure, not fracture, of the upper horizons of the potash zones. Effects on the Culebra Member are unknown, however. Increased permeability in the Salado Fm. as a result of fractures from the repository to the Rustler Fm. is dismissed as physically unreasonable. (If later investigations show that the Salado Fm. may fracture in the far field after excavation of the repository, fractures will be reconsidered.)

Disruption of Surface Drainage

Disruption of the surface drainage might change the erosional regime enough to initiate releases from a repository. The DOE (1980a) calculated that surface subsidence for the WIPP repository would be less than 2 ft and pointed out that there is no integrated surface drainage to be disrupted. Increased releases as a result of subsidence and disruption of surface drainage is physically unreasonable.

Thermal Effects

The waste scheduled for emplacement in the WIPP repository will generate very little heat. The DOE (1980a) calculated that the maximum temperature rise in the repository would be less than 2°C at 80 years after emplacement and that the temperature will fall steadily after that. Bingham and Barr (1979) considered the possibility that a convective cell might form in fluids heated by the waste, but assigned convective-cell formation a probability of 0 at 1000 years and later.

Heat generated by nuclear waste may cause expansion of the host rock and, as a result, uplift of the surface above the repository. DOE (1980a) calculated a maximum surface uplift of less than one centimeter as a result of emplacing TRU waste at the WIPP repository. Consequences of this amount of uplift would be negligible; in any case, a calculated one-centimeter surface uplift will be invisible in light of the expected subsidence of the overburden into the repository.

The waste to be emplaced in WIPP is not expected to induce significant thermal effects (Tyler et al. 1988, p 52). Thermal effects are dismissed from the WIPP performance assessment on the basis of negligible consequence.

3. EVENTS AND PROCESSES RETAINED FOR SCENARIO DEVELOPMENT

This chapter discusses the events and processes retained for the development of scenarios that will be used in assessing compliance with Section 191.13, containment requirements, of the Standard. These few initiating events and processes could not be dismissed in Chapter 2 on the basis of physical unreasonableness, low probability, negligible consequence, or regulatory guidelines. The inclusion of an initiating event in this chapter does not necessarily mean that any scenario arising from it will contribute to the CCDF generated by the performance assessment, because the criteria used to eliminate the events and processes in Chapter 2 are stringent; for example, only events and processes with probabilities less than 1 in 10,000 of occurring in 10,000 years have been screened out on probabilistic grounds.

The effects of human intrusion, repository construction, and waste emplacement are likely to dominate the development of scenarios for the WIPP. For the most part, natural events and processes other than ground-water flow and climatic change are unlikely to contribute to scenarios for release of waste from the WIPP. The WIPP site is located in the Delaware Basin in soluble rocks more than 200 million years old. As indicated in Chapter 2, most natural events that occur in southeastern New Mexico take place so infrequently, affect such small areas, or change the system so slightly that they cannot give rise to scenarios that are of concern to the performance assessment. Thus the initiating events and processes considered here are ground-water flow, climatic change, human intrusion by drilling or solution mining, and seal performance. Other phenomena retained for scenario development include the effects of brine pockets, waste/rock interactions, waste effects, and nuclear criticality.

Natural Processes

Ground-Water Flow

The general geohydrology of the WIPP site and the Los Medaños area was described by Mercer (1983). In the general vicinity of the WIPP, four principal water-bearing zones could potentially transport waste between the repository and the accessible environment: the Rustler-Salado residuum and the Culebra and Magenta Members of the Rustler Fm., all of which are above the repository horizon, and the Bell Canyon Fm., below the repository horizon. Modern flow in the Rustler-Salado residuum is southwest across the WIPP site, toward Nash Draw; the residue on ignition at 105°C from the residuum brines ranges from 79,800 to 480,000 mg/l across the WIPP site. Flow in the Culebra Member is generally southerly; residues range from 3200 to 420,000 mg/l. Flow in the Magenta Member is westward toward Nash Draw; residues range from 5460 to 270,000 mg/l. Brines in the Bell Canyon Fm. move slowly to the northeast; dissolved solids range from 180,000 to 270,000 mg/l. Lappin (1988) summarized the data collected between 1983 and 1988 and the conclusions drawn from them, with particular emphasis on the Culebra Member of the Rustler Fm. Data collected from individual wells has been compiled in a series of hydrologic data reports (Hydro Geo Chem, Inc. 1985; Intera Technologies, Inc., and Hydro Geo Chem, Inc. 1985; Intera Technologies, Inc. 1986; Saulnier et al. 1987; Stensrud et al. 1987; Stensrud et al. 1988).

The geohydrology of the Delaware Basin in Texas and New Mexico was described by Richey et al. (1985). Although their study area was substantially larger than Mercer's, they presented a similar overall picture of moderately productive to unproductive water-bearing units, commonly with high concentrations of dissolved solids, except along the Pecos River, where the Capitan Limestone in the north and the alluvial aquifers in the south tend to produce more water of better quality.

The studies mentioned above described the hydrologic setting as it exists now. Other recent studies (e.g., Lambert and Harvey 1987, Lambert 1990) suggest that the hydrologic setting of the WIPP site has been transient on a scale of 10,000 to 20,000 years. This transience will probably be considered as a part of normal flow during performance-assessment modeling. The pathways of normal ground-water flow are not described here; that is the function of site characterization and consequence analysis. The pathways may change slightly over the next 10,000 years as a result of climatic or topographic change; such changes are here included in normal flow.

Ground-water flow has long been considered the most likely means of transporting waste away from a waste repository. Because several water-bearing units are present at the WIPP site and because most previous workers examining the projected performance of the WIPP considered ground-water flow to be important (Table 1), ground-water flow is retained for scenario development.

Climatic Change

Bingham and Barr (1979) and Logan and Berbano (1978) considered glaciation of the WIPP area (dismissed in Chapter 2), but apparently these workers did not consider the effects of less drastic changes in climate. Hunter (1985) speculated on the climatic changes and their effects that can reasonably be expected at the WIPP during the next 10,000 years, based on the literature describing climates of the Southwest and New Mexico during the past 10,000 to 13,000 years.

The existing literature (summarized by Hunter 1985 and Bachman 1989) is limited and does not always agree on the variability in the climate of southeastern New Mexico during that period. For example, Patton and Dibble (1982) concluded that the climate in west Texas has become steadily more arid during the last 10,000 years, although from 9000 to 7000 years ago and from 3000 to 2000 years ago, the trend was temporarily interrupted. Horowitz et al. (1981) interpreted pollen data at four sites ~150 mi west of the WIPP to mean that more precipitation was available between ~2500 B.C. and ~1700 A.D. than today. Harris and Findley (1964) concluded, on the basis of Late Pleistocene through Holocene vertebrates, that the area west of Isleta, New Mexico, has become steadily warmer and drier. Martin and Mehringer (1965) concluded that fossils and archeology throughout the Southwest indicate a change to warm and dry postglacial climates ~12,000 years ago. Baumhoff and Heizer (1965) suggested that the period of maximum warmth and dryness was 8000 to 4000 years ago. Bretz and Horberg (1949) and Bachman (1976, 1980) examined caliche in the WIPP region and concluded that late Pleistocene to Holocene climates have alternated between relatively arid and relatively humid phases. Bachman (1980, p 91) also thought, however, that the climate has been continuously semiarid for 300,000 to 500,000 years. Van Devender (1980), who examined packrat middens near Carlsbad, found that the climate of the area has been gradually getting drier over the past 11,000 to 12,000 years, although the data allow the possibility that the period 4,000 to 10,000 years before present had greater summer precipitation than today.

The evidence that the climate of southeastern New Mexico has varied during the past 10,000 years seems conclusive, but the trend of the variation is ambiguous, and the impact of the change on ground-water flow is unknown. The available data seem to suggest that both wetter and slightly drier climates would be possible near the WIPP in the next 10,000 years.

There is evidence to suggest that recharge to the aquifers east of Nash Draw, in the immediate vicinity of the WIPP site, ceased at least 12,000 years ago (Lambert 1987). This result is not inconsistent with the limited paleoclimatic data summarized above nor with the WIPP water budget (Hunter 1985). At the WIPP site proper, the head relationships for tested intervals preclude modern recharge to the Rustler Fm. (Lappin 1988, Section 4.1.1.2).

Because the climate is likely to change at the WIPP site during the next 10,000 years, and because the effects of changes in climate on waste containment are currently unknown, climatic change is retained for examination during the performance assessment.

Human Intrusion

The EPA has sharply limited the kinds and severity of human-intrusion scenarios that need be considered in a performance assessment. Appendix B of the Standard explicitly states that intrusion by inadvertent, intermittent exploratory boreholes can be the most severe intrusion scenario assumed by the implementing agencies. Other kinds of human intrusion of lesser severity cannot be ruled out at the WIPP site, however. For example, conventional or solution mining for potash and exploitation of oil and gas resources outside the disposal site might have some effect on the repository and its contained waste. This section and Chapter 2 consider each of these possibilities.

Four portions of Appendix B of the Standard contain suggestions and assumptions that should guide the development of scenarios for human intrusion and assignment of probabilities to them:

> ...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 wastes from the accessible environment shall not consider any contributions from active institutional controls for more than 100 years after disposal.
>
> ...The Agency assumes that, as long as such passive institutional controls [as are described in Section 191.14(c)] endure and are understood, they: (1) can be effective in deterring systematic or persistent exploitation of these disposal sites; and (2) can reduce the likelihood of inadvertent, intermittent human intrusion to a degree to be determined by the implementing agency. However, the Agency believes that passive institutional controls can never be

> assumed to eliminate the chance of inadvertent and intermittent human intrusion into these disposal sites.
>
> ...The Agency believes that the most productive consideration of inadvertent intrusion concerns those realistic possibilities that may be usefully mitigated by repository design, site selection, or use of passive controls... Therefore, inadvertent and intermittent intrusion by exploratory drilling for resources...can be the most severe intrusion scenario assumed by the implementing agencies. Furthermore, the implementing agencies can assume that passive institutional controls or the intruders' own exploratory procedures are adequate for the intruders to soon detect, or be warned of, the incompatibility of the area with their activities.
>
> ...The implementing agencies should consider the effects of each particular disposal system's site, design, and passive institutional controls in judging the likelihood and consequences of such inadvertent exploratory drilling. However, the Agency assumes that the likelihood of such inadvertent and intermittent drilling need not be taken to be greater than 30 boreholes per square kilometer of repository area per 10,000 years for geologic repositories in proximity to sedimentary rock formations...

To comply with Section 191.14 of the Standard, the DOE must designate the disposal site with "the most permanent markers, records, and other passive institutional controls practicable." The EPA has not defined "disposal site," but the WIPP Project has concluded that the WIPP disposal site is conterminous with the controlled area (DOE 1989c). The EPA's assumption that such controls "can be effective in deterring systematic or persistent exploitation of these disposal sites" for as long as they endure and are understood, in combination with the suggestion that exploratory boreholes can be the most severe human-intrusion scenarios, allows five conclusions for the WIPP performance assessment:

1. No human intrusion of the repository will occur during the period of active institutional controls. Credit for active institutional controls can be taken only for 100 years after closure.

2. While passive institutional controls endure, no mineral exploitation will be carried out deliberately inside the controlled area, but reasonable, site-specific exploitation outside the controlled area may occur and should be considered in the performance assessment.

3. Intrusion of the repository leads to its detection. No mechanism for detection need be advanced, although this report describes several possible mechanisms. The EPA's use of the word "incompatibility" allows the conclusion that the intruders will plug and abandon their boreholes to avoid the effects of the repository, because incompatible means "incapable of association ..., unsuitable for use together because of undesirable chemical or physiological effects" (Woolf 1980).

4. While passive institutional controls endure, the number of exploratory boreholes assumed to be drilled inside the controlled area may be reduced below 30 boreholes/km^2 per 10,000 years (but not to zero), if there is reason

to believe that the controls will be effective. At least one borehole must be assumed to have some finite probability of occurring. Because the EPA addresses the probability of drilling by prescribing a rate, the phrase "most severe human intrusion scenario" is taken to refer to a ranking of potential consequences.

5. When passive institutional controls fail, exploratory boreholes will be drilled at a rate no greater than 30 boreholes/km^2 per 10,000 years, but no other scenarios for human intrusion inside the controlled area need be considered.

Three kinds of human intrusion are considered in this report. Exploratory drilling and solution mining are discussed below. The effects of conventional mining for potash or the emplacement of oil or gas fields outside the controlled area are dismissed in Chapter 2.

Boreholes

Whether drilling will take place in the Delaware Basin between 100 and 10,000 years from now and the number of boreholes that might be drilled are and will remain unknown during the WIPP performance assessment. More serious and more benign human intrusion scenarios than drilling can be imagined. In line with Appendix B of the Standard (EPA 1985), however, the WIPP performance assessment will assume that inadvertent and intermittent intrusion by exploratory drilling for resources will be the most severe intrusion and that no more than 30 boreholes per square kilometer of repository area will occur during the 10,000-year lifetime of the WIPP. The Standard requires various institutional controls, including passive markers, and assumes that the implementing agency may reduce the probability of drilling by using such controls; however, no passive markers or other institutional controls have been designed for the WIPP at this time. The probability of drilling 30 boreholes per square kilometer of repository area at the repository during the next 10,000 years is therefore taken to be 1 until such designs are available for analysis.

The current projection of the area of the WIPP repository (Figure 4) is 1.8 x 10^7 ft^2 or 1.7 km^2; therefore no more than 51 boreholes (i.e., 30 boreholes/km^2 x 1.7 km^2) are projected to be drilled through the repository during the next 10,000 years.

Just as the number of future boreholes is impossible to know, the future of drilling and monitoring techniques is unknown. Whatever their technology, however, future drillers should know approximately what to expect when drilling through the Salado Fm. The area of the repository is 1.7 km^2; the area of the Delaware Basin is about 31,000 km^2. The chance that the first borehole drilled by a society that knows nothing about the stratigraphy of the Delaware Basin will intercept the repository is about 5 x 10^{-5} (i.e., 1.7 km^2/31,000 km^2). Therefore the chance that the society has drilled previous boreholes and is familiar with the stratigraphy of the basin is about 1. An occurrence of iron, organic compounds, and actinides inside the Salado Fm. will be recognized as unusual, even if intact man-made items cannot be identified. Appendix B of the Standard encourages the assumption that future intruders "soon detect, or are warned of, the incompatibility of the area with their activities." They need not necessarily realize that the area is a waste

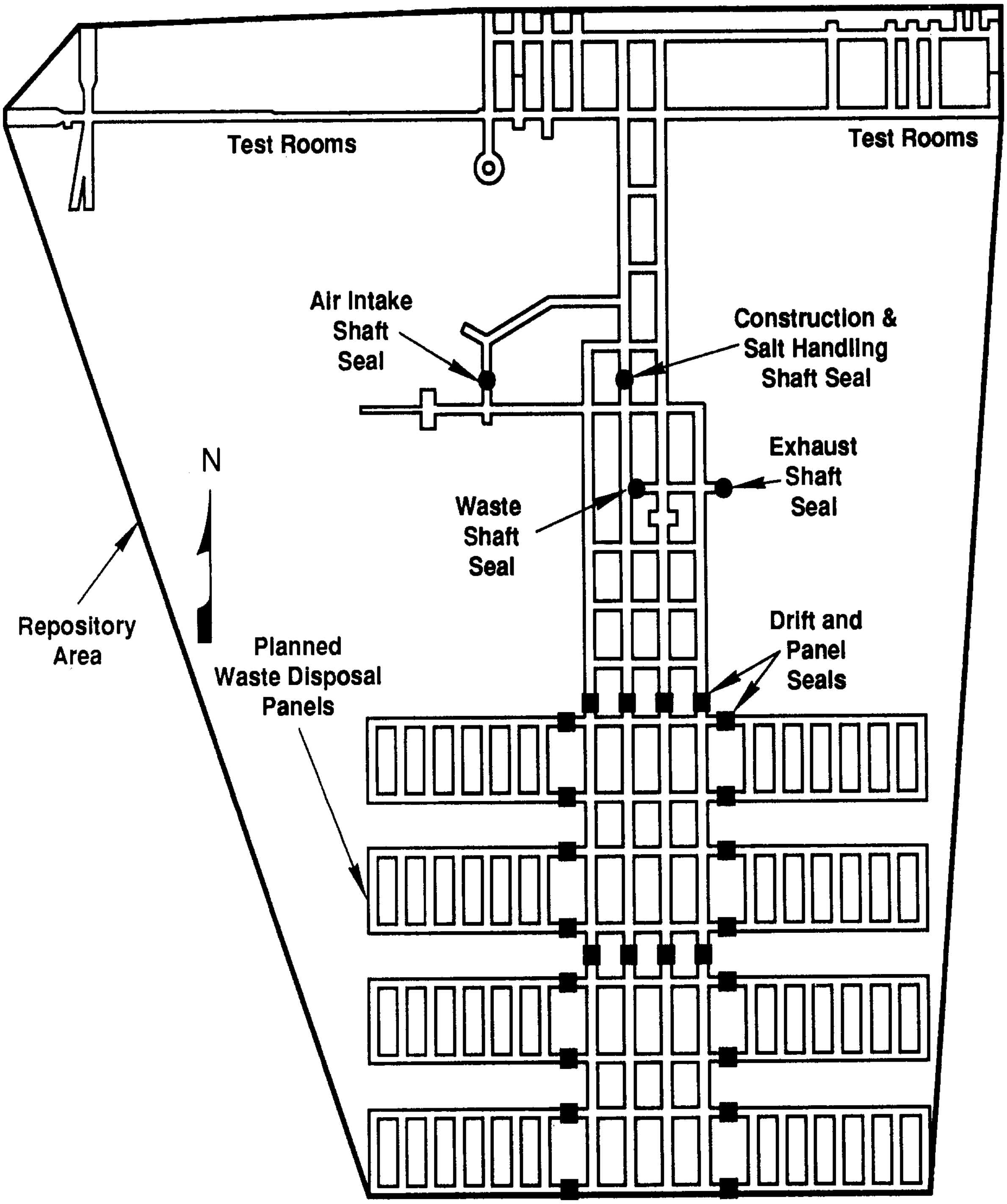

Figure 4. WIPP repository design, showing planned locations of panel seals and repository and waste-panel areas.

repository. Having detected or been warned of something incompatible with their activities, they presumably will take steps to protect themselves and their society.

Many drilling scenarios can be imagined that are compatible with various aspects of current drilling technology and practice, but it is impossible to say with assurance whether the most benign or the most damaging of these scenarios is more likely. Currently available technology makes monitoring radiation levels of cuttings from a borehole possible, so that a horizon with high levels of radioactivity could be discovered within minutes of drilling into it. Frequently, core or cuttings from an exploratory hole are monitored by a geologist or other experienced worker either as they come out of the hole or within a few hours, at which time the repository could almost certainly be detected. The potash and petroleum industries routinely use gamma logging for stratigraphic mapping. Given this existing technology and practice and the wording of the Standard, the WIPP Project might reasonably assume that any interception of a panel by an exploratory borehole would be detected very soon and that releases would be small. There is no geological reason, however, to particularly expect that a borehole in the Delaware Basin will intercept radioactive rock; thus there may not be an automatic radiation monitor, and the geologist examining the cuttings, upon seeing the unusual materials from the repository, may not think to measure radiation. For these reasons, even though not required by the Standard, a more conservative approach is recommended here. It should be assumed that radioactive core or cuttings that reach the surface initially are either not monitored or temporarily ignored, but that if a second unusual occurrence takes place during the drilling of a given borehole, the cuttings or core will be carefully examined. It should also be assumed that only one borehole is necessary for the intruders to detect or be warned of the repository if the second unusual occurrence takes place. Radioactive brine that could reach the surface if not prevented from doing so by drilling fluid gives the drillers a second chance at discovery, because the chemical composition of the brine will be anomalous. Thus it can be concluded that brine at the surface quickly reveals the presence of the repository. This assumption is not intended to be "scientifically proven," because no data with which to prove it are or will become available, rather it is intended to be technically logical and compatible with the guidance offered in Appendix B of the Standard.

All boreholes that pass through the excavated portion of a waste panel, however, will cause releases to the accessible environment in the form of core, cuttings, or similar material entrained in the drilling fluids, although not all exploratory boreholes are expected to pass through waste panels at the WIPP site. (This is a conservative assumption: the drillers might instead lose circulation, pump in lost-circulation materials until the room is sealed, and resume drilling, with no return of waste to the surface.) A typical exploratory borehole is currently 8 to 10 inches in diameter, an area of less than one square foot. The total excavated area of waste panels is projected to be roughly 1.3×10^6 ft^2. The waste will be more-or-less evenly distributed over the entire floor of the waste panels. Thus the fraction of waste that would be released to the accessible environment by cuttings or core from an exploratory borehole could be less than one part in 10^6 of the total inventory. Such a release by itself probably will not violate the Standard. These releases are an integral part of every scenario that entails drilling through a waste panel, however, and they must be included in the final CCDF resulting from the consequence analysis if they significantly change the remaining probability distribution of cumulative release.

Exploratory boreholes may or may not reach the repository horizon. Boreholes that do not reach the repository horizon might be exploratory holes for potash in the upper portions of the Salado Fm. or holes in the Rustler Fm. for either general geological or hydrological exploration. Boreholes that extend below the repository horizon might be exploratory holes for oil or gas below the evaporites or for general geological or hydrological information. Even for arbitrarily assigned probabilities as high as 0.8 for the event that any single borehole ends above the repository, the probability that all 51 holes end above the repository, $(p)^{51}$, is negligible, and the probability that one or more boreholes reach the repository horizon is effectively 1.

Not all boreholes that reach the repository horizon will hit a waste panel. The total area of the repository is about 1.84×10^7 ft^2. All accessways south of panel seals (Figure 4) will also be filled with waste. The total excavated area of the 10 waste panels, excluding the disturbed rock zone, is about 1.30×10^6 ft^2 (Figure 4). In addition, RH waste will occupy about 22,000 ft^2 in the pillars. Thus the probability that a hole drilled at random inside the repository area to the repository level will hit a mined portion of a waste panel is 1.30×10^6 ft^2/1.84×10^7 ft^2, or 0.070, and the probability that a hole will hit an RH canister is 0.001. The probability of a miss is $1-(0.070+0.001) = 0.929$. The probability that all boreholes will miss the panels and RH canisters is $(0.929)^{51}$, or 0.02. The probabilities might differ slightly if the disturbed rock zone were considered part of the repository.

In the consequence analysis, the separate calculation of the consequences of 1, 2, ..., or more boreholes intercepting a panel or RH canister may be necessary, depending on the probability. The probability that of 51 boreholes, 51 - n will hit waste, is given by successive terms in the binomial expansion

$$(p + q)^{51} = \sum_n \binom{51}{n} p^{51-n} q^n .$$

where p is the probability of a hit, and q is the probability of a miss; $p + q = 1$.

For example, for $p = 0.07$,

$$P_n = \binom{51}{n} .07^{51-n} .93^n .$$

The probability of 12 or fewer interceptions, assuming a probability of interception by any given borehole of 0.07, is 0.9999 (Table 2). The probability of 13 interceptions is less than the round-off error in the prior calculations. The expected number of hits, i.e., drillholes that penetrate a waste-filled room, is 3.57 (i.e., 51 boreholes x 0.07) over the 10,000 years, assuming the occurrence of 51 boreholes and a probability of 0.07 that any

Table 2. Probabilities of 1, 2, ..., or 12 boreholes intercepting a waste panel or RH canister, assuming 51 boreholes and a probability of 0.07 of interception by any given borehole

Interceptions, Given 51 Boreholes	Probability	Interceptions, Given 51 Boreholes	Probability
0	0.0247	0	0.0247
1	0.0948	≤ 1	0.1195
2	0.1784	≤ 2	0.2979
3	0.2193	≤ 3	0.5172
4	0.1981	≤ 4	0.7153
5	0.1402	≤ 5	0.8555
6	0.0809	≤ 6	0.9364
7	0.0391	≤ 7	0.9755
8	0.0162	≤ 8	0.9917
9	0.0058	≤ 9	0.9975
10	0.0018	≤ 10	0.9993
11	0.0005	≤ 11	0.9998
12	0.0001	≤ 12	0.9999

given borehole will be a hit (i.e., that all boreholes reach the repository level). The Standard does not suggest how these holes should be distributed in time. Their distribution in time, however, may affect the consequence of any given borehole release, and therefore assumptions about their distribution will affect the predicted risk during consequence analysis.

The probability that at least two boreholes will be drilled directly above the same panel is

$$P = \sum_{k=2}^{k=n} \binom{n}{k} p^k (1-p)^{n-k} \left(1-\frac{b(b-1)\ldots(b-(k-1))}{b^k}\right)$$

where

n = 51 boreholes drilled at the repository,
b = the number of panels, and
p = 0.07, the probability that any given borehole will be drilled through any panel.

For n = 51 and p = 0.07, the following approximation can be used (Burington and May 1970, p. 107),

$$\frac{x^k e^{-x}}{x!} = \frac{n!}{(n-k)!\,k!} \quad 1\text{-}p^{k} \quad p^{n-k} \quad ,$$

where x = np. Taking the central accessways to be two panels, there are 10 panels, and P = 0.40. Although the WIPP design does not call for seals separating rooms within a panel, the probability of two boreholes intercepting the same room may also be of interest. The main storage panels have 7 rooms apiece; for 70 rooms, P = .084. The possibility that two boreholes will be drilled though a panel or room is retained for scenario development.

Brine Pockets

If boreholes that miss waste panels stop above the Castile Fm., then they would not lead to any direct release, although they might provide shortened paths from the repository horizon to the Rustler Fm. or to the Dewey Lake Red Beds for some time. Because no flow occurs in these boreholes, diffusion in response to a concentration gradient in the stagnant brine is the only mechanism to move the waste. This process is dismissed (as discussed in Chapter 2).

Some boreholes might be deeper and penetrate the Castile Fm. The Castile Fm. is known to contain large, high-pressure pockets of saturated brine (e.g., Popielak et al. 1983). The Earth Technology Corporation (1988) has shown using resistivity measurements that brine pockets in the Castile Fm. underlie approximately one half of the WIPP waste-panel area, although this estimate is uncertain. If it is assumed that Castile brines underlie half the waste panels, then an exploratory borehole penetrating the Castile Fm. will either hit or miss the brine pocket with a probability of about .5. Boreholes that miss the brine pockets might provide shortened paths, like the shallower holes, but are dismissed for the same reason. Other holes, however, might hit a brine pocket, with various possible results. Lappin et al. (1989) have discussed some possible effects of drilling into a brine pocket and have modeled doses to humans that might result. The Draft WIPP Supplemental Environmental Impact Statement (DOE 1989b) also calculated potential releases and compared them with the release limits given in 40 CFR 191. The results of both studies suggest that the effects of brine pockets could be important.

Because the probability of drilling through the repository into a Castile brine pocket is high and because the effects probably are important, the effects of drilling into such a brine pocket are retained for scenario development.

Solution Mining

Southeastern New Mexico produces the vast majority of the potash mined in the United States (Chemical & Engineering News 1985); production is carried out exclusively by conventional techniques. Solution mining is used elsewhere to extract potash from ore bodies that are difficult or uneconomic to mine using conventional techniques, for example, in gassy or very deep mines (Husband 1971, Jackson 1973). In the future, solution mining conceivably could be used in southeastern New Mexico to extract ores in the vicinity of the WIPP site. Little (1982) examined the radiological consequences of solution mining for potash at the WIPP site and concluded that the resultant doses would not significantly threaten public health. Total releases, required by the Standard promulgated later, were not calculated, however, and so Little's work can not be used here to dismiss solution mining from further consideration.

Davis and Shock (1970) demonstrated the technical feasibility of solution mining thin-bedded sylvinite in the Carlsbad Potash Basin by removing a block of potash from the Third Ore Zone of the Salado Fm., where the zone is about 4 feet thick and 1150 feet deep. Brausch et al. (1982) mapped sylvite and langbeinite reserves near the WIPP site. They stated that langbeinite is not amenable to solution mining, because it is less soluble than halite and sylvite. In addition, they were not optimistic about the potential for solution mining of sylvite near the WIPP site, because of the low grade of ore, the thinness of the ore beds, problems with pumping and heating the injection water, and scarcity of suitable water supplies. In view of Davis and Shock's successful field experiments, the current lack of suitable water supplies seems to be the dominant factor. Harbaugh (1989) has pointed out the difficulty of assigning probabilities to future mining on the basis of current economic and technical factors.

In developing scenarios beginning with solution mining of potash near the WIPP repository, it should be assumed (in line with the above discussion of the EPA Standard) that passive institutional controls endure and are understood. The work of Kaplan (1982) suggests that well-designed markers supplemented by written records can be expected to last for 5000 years and may well last 10,000 years. The miners will therefore know the location of the repository and the controlled area and what the repository contains, and they will attempt to avoid contact between their mine and the controlled area. A solution mine that does not directly affect the repository might alter the hydraulic characteristics of the surrounding rock. In addition, miners' attempts to avoid contact do not guarantee that contact will be avoided (Gold 1981). For this reason, two general types of scenarios should be developed: those in which mining proceeds as planned and those in which the repository or controlled area is accidently intruded.

Passive institutional controls should alert the miners to monitor for radioactivity (cf. Appendix B of the Standard). If mining intercepts either waste that has been transported away from the repository or the repository itself, the situation should be noted very soon. The mine will be abandoned and boreholes will be plugged.

Wherever a solution mine is developed, the overburden will collapse into the mine after it is abandoned. Although major disruptions of the hydrologic system around conventional potash mines near the WIPP site have not been seen, the effects on the Culebra Member are unknown. Brausch et al. (1982) concluded that stress relief would increase hydraulic conductivity of the rock greatly near the openings and slightly farther away from the openings. In addition, subsidence into the mine would increase hydraulic conductivity of the rock between the mine and the surface. Changes in hydraulic conductivity will change the ground-water flow regime.

Because solution mining has been conducted in successful field experiments and because future economic and technical factors are difficult or impossible to predict accurately, solution mining is retained at this time. It may not be necessary to develop scenarios for solution mining for two reasons, however. First, when passive markers are developed for the WIPP, they may reduce the probability of solution mining substantially. Second, further consideration of potential solution mining may reveal that the consequences of such mining would be unimportant.

Waste and Repository Effects

Shaft- and Panel-Seal Performance

Stormont (1988) has described the preliminary seal design for both shaft and panel seals. The primary seal component will be reconsolidated salt for the shaft seals and quarried salt blocks for the panel seals. Concrete and bentonite sections in the shaft seal will protect the reconsolidating salt from brine inflow from above. Salt will not be used in the section of the shaft seal that passes through the Rustler Fm. The objective of the seal-design program is to attain salt seals that have a porosity of no more than 5%, because measurements have shown that at this porosity, the hydraulic conductivity of the seal is indistinguishable from that of the intact salt.

The DOE and the State of New Mexico (1981) have agreed that shaft and panel seals will be a part of the WIPP repository design. Because seal performance is an integral part of the overall repository performance, it is retained for scenario development.

Near-Field Dissolution: Leaching

Leaching, dissolving the waste by whatever ground water is present in a repository, followed by its transport in solution through relatively unaltered rock, is not limited in its occurrence to salt repositories (e.g., Claiborne and Gera 1974, Bingham and Barr 1979, Hunter et al. 1983). Leaching has sometimes been omitted in studies that deal primarily with far-field phenomena (e.g., Cranwell et al. 1982, Hunter 1983).

Leaching is not an initiating event. Leaching might well occur before any other release or transport event or process; however, its occurrence does not necessarily begin to move waste out of the repository. Furthermore, leaching is not even necessary for the transport of waste in some cases. Only if some other event or processes occurs, such as ground-water flow or drilling, is leaching important. Leaching is retained for examination during scenario analysis, however.

Nuclear Criticality

The WIPP repository will contain large amounts of U-233, U-235, and Pu-239; conceivably a critical mass of one or more of these isotopes could form. Although the formation of a critical mass would not immediately increase releases of waste from the repository, two effects would occur: the inventory would be altered by fission as well as decay, and the temperature in the repository would rise more than expected. Because any releases to the accessible environment could differ substantially in content, a change in inventory might require different transport calculations from those required by the expected inventory. Thermomechanical calculations might be required to determine whether the additional heat would pose a threat to waste isolation.

Studies that have examined the possible occurrence of criticality in stored nuclear waste are not directly usable in deciding whether criticality could occur at the WIPP site, because none have had access to the final WIPP inventory. Allen (1978) calculated minimum critical masses for over 400 combinations of various high-level-waste types, ages, and actinide mixtures and rock types, but none of the actinide mixtures was similar to the WIPP inventory. Blyckert and Carter (1980) calculated k-effective for a variety of arrays of 55-gallon drums of Pu-contaminated wastes, but the minimum Pu loading used was 200 g Pu-239/55-gallon drum. Only a very small percentage of the drums in the WIPP inventory will contain as much as 200 g of fissile material. Cohen (1984) examined the occurrence of criticality after TRU waste has been assumed to leave the WIPP repository in a brine solution and to become reconcentrated in an aquifer, apparently by sorption. When the final WIPP inventory is published, nuclear criticality can be examined to determine whether scenarios including it should be developed.

Waste/Rock Interaction and Waste Effects

Bingham and Barr (1979) and the DOE (1980a) considered several effects of interaction between TRU waste and the host rock. One mechanism considered was the potential for radiation to store energy in the crystal structure of the host rock or backfill, which could later be released either by annealing or by dissolution. Annealing was thought to require temperature increases that cannot be attained locally in the repository, and dissolution was thought to be unlikely. Even if dissolution were to occur, Bingham and Barr (1979) thought the consequences would be minor. The consequences they suggested, slight rises in temperature, radiolysis, and phase changes, are likely to be negligible in comparison with more direct effects of the waste, which will be extensively studied in experiments conducted during the Test Phase of the WIPP Project (Bertram-Howery and Hunter 1989, DOE 1989a). The DOE (1980a), Neill et al. (1979), and Lappin et al. (1989) also considered the effects of gas generation by radiolysis, bacterial degradation, thermal decomposition and dewatering, and chemical corrosion. These too will be studied during the Test Phase.

Pending the results of experiments designed to assess directly gas generation by the waste and the interactions between waste and rock, these phenomena are retained for future scenario development.

4. SUMMARY

Events and processes considered by previous workers for the development of scenarios for the release of nuclear waste from a repostory in bedded salt have been reexamined in the light of 40 CFR 191 (EPA, 1985). Four criteria have been used to determine whether individual events and processes should be dismissed or retained for future scenario development: physical unreasonableness, low probability, negligible consequence, and regulatory guidelines. Most events and processes considered by earlier workers have been dismissed using one or more of these criteria. The following events and processes have been retained: normal flow of ground water, climatic change, drilling of exploratory boreholes, solution mining, seal performance, the effects of drilling into a brine pocket beneath the repository, leaching of the solid waste, nuclear criticality, waste/rock interaction, and waste effects. Table 3 shows whether each event or process considered has been retained or dismissed and gives the number of the page on which a discussion of it can be found in the text.

Table 3. Disposition in this report of all events and processes considered by earlier workers

	Discussed and Dismissed in This Report (basis*, page)	Retained for Consequence Analysis (page)
Dissolution Other Than Leaching	PU, NC, 9	
Migration of Brine Aquifer	NC, 10	
Breccia-Pipe Formation	PU, LP, NC, 10	
Migration of Intracrystalline Brine Inclusions	PU, NC, 12	
Induced Diapirism	PU, 13	
Diffusion out of the Repository	PU, 13	
Exhumation, Sedimentation	NC, 14	
Faulting	PU, LP, 14	
Glaciation	NC, RG, 14	
Igneous Intrusion	LP, 15	
Meteorite Impact	LP, 15	
Sabotage, Warfare	RG, 16	
Subsidence	NC, 16	
Thermal Effects	NC, 17	
Ground-Water Flow		18
Climatic Change		19
Drilling into Repository		20
Effects of Brine Pocket		27
Effects of Mining for Resources		27
Seal Performance		29
Leaching		29
Nuclear Criticality		29
Waste/Rock Interaction		30
Waste Effects (e.g., gas generation, radiolysis)		30

* PU - Physical Unreasonableness
LP - Low Probability
NC - Negligible Consequence
RG - Regulatory Guidelines

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WIPP Project Office (Carlsbad)
Attn: J. Tillman
P.O. Box 3090
Carlsbad, NM 88221

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Research & Waste Management Division
Attn: W. R. Bibb, Director
P. O. Box E
Oak Ridge, TN 37831

U. S. Department of Energy (2)
Idaho Operations Office
Fuel Processing and Waste
  Management Division
785 DOE Place
Idaho Falls, ID 83402

U. S. Department of Energy (2)
Deputy Assistant Secretary for
  Environment, EH-20
Attn: Raymond P. Berube
  John Tseng
1000 Independence Avenue SW
Washington, DC 20585

U. S. Department of Energy (4)
  Albuquerque Operations Office
Attn: Bruce G. Twining
  J. E. Bickel
  R. Marquez, Public Affairs
  G. Runkle
P.O. Box 5400
Albuquerque, NM 87185

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P. O. Box 5400
Albuquerque, NM 87185

U. S. Department of Energy (5)
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  M. Duff--------DP-123
  A. Follett-----DP-122
  C. H. George---DP-124
  J. Mathur------DP-123
Washington, DC 20545

U.S. Department of Energy
Richland Operations Office
Nuclear Fuel Cycle & Production
  Division
Attn: R. E. Gerton
P.O. Box 500
Richland, WA 99352

U.S. Department of Energy
Savannah River Operations Office
Defense Waste Processing
  Facility Project Office
Attn: W. D. Pearson
P.O. Box A
Aiken, SC 29802

U.S. Environmental Protection Agency
Attn: D. J. Egan, Jr.
Mark Cotton
Office of Radiation Programs
(ANR-460)
Washington, DC 20460

U.S. Geological Survey
Conservation Division
Attn: W. Melton
P.O. Box 1857
Roswell, NM 88201

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Division of Waste Management
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Hubart Miller
Jacob Philip
NRC Library
Mail Stop 623SS
Washington, DC 20555

U.S. Geological Survey
Branch of Regional Geology
Attn: R. Snyder
MS913, Box 25046
Denver Federal Center
Denver, CO 80225

U.S. Geological Survey (2)
Water Resources Division
Attn: Kathy Peter
Suite 200
4501 Indian School, NE
Albuquerque, NM 87110

STATE AGENCIES

Environmental Evaluation Group (3)
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Albuquerque, NM 87109

NM Department of Energy & Minerals
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P.O. Box 2770
Santa Fe, NM 87501

New Mexico Bureau of Mines
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J. Hawley
Socorro, NM 87801

Kirkland Jones, Department Director
New Mexico Environmental Improvement
Division
P.O. Box 968
1190 St. Francis Drive
Santa Fe, NM 87503-0968

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R. E. Westerman
S. Bates
H. C. Burkholder
Battelle Boulevard
Richland, WA 99352

Savannah River Laboratory (6)
Attn: N. Bibler
E. L. Albenisius
M. J. Plodinec
G. G. Wicks
C. Jantzen
J. A. Stone
Aiken, SC 29801

Savannah River Plant
Attn: Richard G. Baxter
Building 704-S
Aiken, SC 29808

INTERA Technologies, Inc. (4)
Attn: G. E. Grisak
J. F. Pickens
A. Haug
A. M. LeVenue
Suite #300
6850 Austin Center Blvd.
Austin, TX 78731

IT Corporation (3)
Attn: R. F. McKinney
J. Myers
Barbara Deschler
Regional Office - Suite 700
5301 Central Avenue, NE
Albuquerque, NM 87108

Charles R. Hadlock
Arthur D. Little, Inc.
Acorn Park
Cambridge, MA 02140-2390

RE/SPEC, Inc.
Attn: W. Coons
P. F. Gnirk
P.O. Box 14984
Albuquerque NM 87191

Rockwell International
Attn: C. E. Wickland
Rocky Flats Plant
Golden, CO 80401

Science Applications
International Corporation
Attn: Howard R. Pratt,
Senior Vice President
10260 Campus Point Drive
San Diego, CA 92121

E G & G Idaho (2)
1955 Fremont Street
Attn: C. Atwood
C. Hertzler
Idaho Falls, ID 83415

George Dymmel
SAIC
101 Convention Center Dr.
Las Vegas, NV 89109

INTERA Technologies, Inc.
Attn: Wayne Stensrud
P.O. Box 2123
Carlsbad, NM 88221

IT Corporation (2)
Attn: D. E. Deal
P.O. Box 2078
Carlsbad, NM 88221

Los Alamos Scientific Laboratory
Attn: B. Erdal, CNC-11
Los Alamos, NM 87545

Oak Ridge National Laboratory (4)
Attn: R. E. Blanko
E. Bondietti
C. Claiborne
G. H. Jenks
Box 2009
Oak Ridge, TN 37831

RE/SPEC, Inc. (7)
Attn: L. L. Van Sambeek
D. B. Blankenship
G. Callahan
T. Pfeifle
J. L. Ratigan
P. O. Box 725
Rapid City, SD 57709

Science Applications
International Corporation
Attn: Michael B. Gross
Ass't. Vice President
Suite 1250
160 Spear Street
San Francisco, CA 94105

K. K. Wahi
GRAM Incorporated
1709 Moon, NE
Albuquerque, NM 87112

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W. C. Moffitt
W. P. Poirer
W. R. Chiquelin
V. F.Likar
D. J. Moak
R. F. Kehrman
P. O. Box 2078
Carlsbad, NM 88221

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Attn: E. Peterson
P. Lagus
Box 1620
La Jolla, CA 92038

Don Wood
Westinghouse Hanford Company
P.O. Box 1970
Richland, WA 99352

UNIVERSITIES

University of Arizona
Attn: J. G. McCray
Department of Nuclear Engineering
Tucson, AZ 85721

Pennsylvania State University
Materials Research Laboratory
Attn: Della Roy
University Park, PA 16802

University of New Mexico (2)
Geology Department
Attn: D. G. Brookins
Library
Albuquerque, NM 87131

Texas A&M University
Center of Tectonophysics
College Station, TX 77840

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Las Cruces, NM 88001

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P.O. Box 1629
Santa Fe, NM 87503

Pannell Library
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New Mexico Junior College
Lovington Highway
Hobbs, NM 88240

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General Library
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Albuquerque, NM 87131

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509 N. Ship Street
Hobbs, NM 88248

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Martin Speere Memorial Library
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Socorro, NM 87810

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Attn: Lee Hubbard, Head Librarian
Carlsbad Municipal Library
101 S. Halagueno St.
Carlsbad, NM 88220

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Department of Civil and
Mineral Engineering
University of Minnesota
500 Pillsbury Dr. SE
Minneapolis, MN 55455

Dr. John D. Bredehoeft
Western Region Hydrologist
Water Resources Division
U.S. Geological Survey (M/S 439)
345 Middlefield Road
Menlo Park, CA 94025

Dr. Rodney C. Ewing
Department of Geology
University of New Mexico
200 Yale, NE
Albuquerque, NM 87131

Dr. Frank L. Parker
Department of Environmental
Engineering
Vanderbilt University
Nashville, TN 37235

Dr. Christopher G. Whipple
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303

Ina Alterman
Board on Radioactive Waste
Management
GF462
2101 Constitution Avenue
Washington, D. C. 20418

Dr. John O. Blomeke
Route 3
Sandy Shore Drive
Lenoir City, TN 37771

Dr. Karl P. Cohen
928 N. California Avenue
Palo Alto, CA 94303

Dr. Fred M. Ernsberger
250 Old Mill Road
Pittsburgh, PA 15238

Dr. George M. Hornberger
Department of Environmental Sciences
Clark Hall
University of Virginia
Charlottesville, VA 22903

Dr. D'Arcy A. Shock
233 Virginia
Ponca City, OK 74601

Dr. Peter B. Myers, Staff
Director
National Academy of Sciences
Committee on Radioactive
Waste Management
2101 Constitution Avenue
Washington, DC 20418

PERFORMANCE ASSESSMENT PEER REVIEW PANEL

G. Ross Heath
College of Ocean
and Fishery Sciences
University of Washington
Seattle, WA 98195

Thomas H. Pigford
Department of Nuclear Engineering
4153 Etcheverry Hall
University of California
Berkeley, CA 94270

Patrick A. Domenico
Geology Department
Texas A & M
College Station
TX 77843-3115

Thomas A. Cotton
4429 Butterworth Place, NW
Washington, DC 20016

C. John Mann
Department of Geology
245 Natural History Bldg.
1301 West Green Street
University of Illinois
Urbana, IL 61801

Benjamin Ross
Disposal Safety, Inc.
Suite 600
1629 K Street NW
Washington, DC 20006

Neville Cook
Rock Mechanics Engineering
Mine Engineering Department
University of California
Berkeley, CA 94270

Robert J. Budnitz
Future Resources Associates, Inc.
2000 Center Street, Suite 418
Berkeley, CA 94704

Charles D. Hollister
Dean for Studies
Woods Hole Oceanographic
Institute
Woods Hole, MA 02543

FOREIGN ADDRESSES

Studiecentrum Voor Kernenergie
Centre D'Energie Nucleaire
Attn: Mr. A. Bonne
SCK/CEN
Boeretang 200
B-2400 Mol
BELGIUM

Dr. D. K. Mukerjee
Ontario Hydro Research Lab
800 Kipling Avenue
Toronto, Ontario, CANADA
M8Z 5S4

Mr. Jean-Pierre Olivier
OECD Nuclear Energy Agency
Division of Radiation Protection
and Waste Management
38, Boulevard Suchet
75016 Paris, FRANCE

Atomic Energy of Canada, Ltd. (2)
Whiteshell Research Estab.
Attn: Peter Haywood
John Tait
Pinewa, Manitoba, CANADA
ROE 1L0

Mr. D. Alexandre, Deputy Director
ANDRA
31, Rue de la Federation
75015 Paris, FRANCE

Claude Sombret
Centre D'Etudes Nucleaires
De La Vallee Rhone
CEN/VALRHO
S.D.H.A. BP 171
30205 Bagnols-Sur-Ceze
FRANCE

Bundesministerium fur Forschung
und Technologie
Postfach 200 706
5300 Bonn 2
FEDERAL REPUBLIC OF GERMANY

Hahn-Meitner-Institut fur
Kernforschung
Attn: Werner Lutze
Glienicker Strasse 100
100 Berlin 39
FEDERAL REPUBLIC OF GERMANY

Kernforschug Karlsruhe
Attn: K. D. Closs
Postfach 3640
7500 Karlsruhe
FEDERAL REPUBLIC OF GERMANY

D. R. Knowles
British Nuclear Fuels, plc
Risley, Warrington, Cheshire WA3 6AS
1002607 GREAT BRITAIN

Netherlands Energy Research
Foundation ECN (2)
Attn: Tuen Deboer, Mgr.
L. H. Vons
3 Westerduinweg
P.O. Box 1
1755 ZG Petten, THE NETHERLANDS

Bundesanstalt fur Geowissenschaften und Rohstoffe
Attn: Michael Langer
Postfach 510 153
3000 Hannover 51
FEDERAL REPUBLIC OF GERMANY

Institut fur Tieflagerung (4)
Attn: K. Kuhn
Theodor-Heuss-Strasse 4
D-3300 Braunschweig
FEDERAL REPUPLIC OF GERMANY

Physikalisch-Technische
Bundesanstalt
Attn: Peter Brenneke
Postfach 33 45
D-3300 Braunschweig
FEDERAL REPUBLIC OF GERMANY

Shingo Tashiro
Japan Atomic Energy Research
Institute
Tokai-Mura, Ibaraki-Ken
319-11 JAPAN

Svensk Karnbransleforsorjning AB
Attn: Fred Karlsson
Project KBS
Karnbranslesakerhet
Box 5864
10248 Stockholm, SWEDEN

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