Overview of Performance Assessment for the Waste Isolation Pilot Plant

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Abstract: The Waste Isolation Pilot Plant (WIPP) has been developed by the U.S. Department of Energy for the geologic (deep underground) disposal of transuranic waste. Compliance with the containment requirements is demonstrated by means of performance assessment (PA). The term PA signifies an analysis that 1) identifies the features, processes and events (FEPs) that might affect the disposal system; 2) examines the effects of these FEPs on the performance of the disposal system; 3) estimates the cumulative releases of radionuclides caused by all significant FEPs; and 4) accounts for uncertainty in the parameters of the PA models. Modifying the WIPP PA is a reoccurring process, which ensures confidence in the PA results. The updated WIPP PA demonstrates that the results continue to lie entirely below the specified limits and the WIPP therefore continues to be in compliance with the containment requirements. Analysis of the results shows that the total releases are dominated by radionuclide releases that could occur during an inadvertent penetration of the repository by a future drilling operation. The natural and engineered barrier systems of the WIPP provide robust and effective containment of transuranic waste even if the repository is penetrated by multiple borehole intrusions.

Keywords: WIPP, performance assessment, transuranic waste, geological disposal.

1. INTRODUCTION

The Waste Isolation Pilot Plant (WIPP), located in southeastern New Mexico, consists of a deep underground mined facility located in a bedded salt formation (Figure 1) and has been developed by the U.S. Department of Energy (DOE) for the geologic disposal of transuranic waste. Containment of transuranic waste at the WIPP is regulated by the U.S. Environmental Protection Agency (EPA). The DOE demonstrates compliance with the containment requirements by means of performance assessment (PA) calculations. After the original compliance certification in 1996, the application is updated with new information as part of a recertification process that occurs at five-year intervals following receipt in 1999 of the first shipment of waste at the site. The EPA requires a PA to demonstrate that potential cumulative releases of radionuclides to the accessible environment over a 10,000-year period after disposal are less than specified limits based on the nature of the materials disposed. The PA is to determine the effects of all significant features, processes and events (FEPs) that may affect the disposal system, consider the associated uncertainties of the FEPs, and estimate the probable cumulative releases of radionuclides.

2. CONTAINMENT REQUIREMENTS

The methodology employed in WIPP PA derives from the EPA's standard for the geologic disposal of radioactive waste, Environmental Radiation Protection Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes (40 CFR Part 191) [1], which is divided into three subparts. 40 CFR Part 191 Subpart A applies to a disposal facility prior to decommissioning and establishes standards for the annual radiation doses to members of the public from waste management and storage operations. 40 CFR Part 191 Subpart B applies after decommissioning and sets probabilistic limits on cumulative releases of radionuclides to the accessible environment for 10,000 years. 40 CFR Part 191 Subpart B also sets limits on radiation doses to members of the public in the accessible environment for 10,000 years of undisturbed repository performance. 40 CFR Part 191 Subpart C limits radioactive contamination of groundwater for 10,000 years after disposal. For the WIPP to be certified and recertified, the DOE must demonstrate, within a reasonable expectation, that the WIPP will continue to comply with the requirements of 40 CFR Part 191 Subparts B and C.

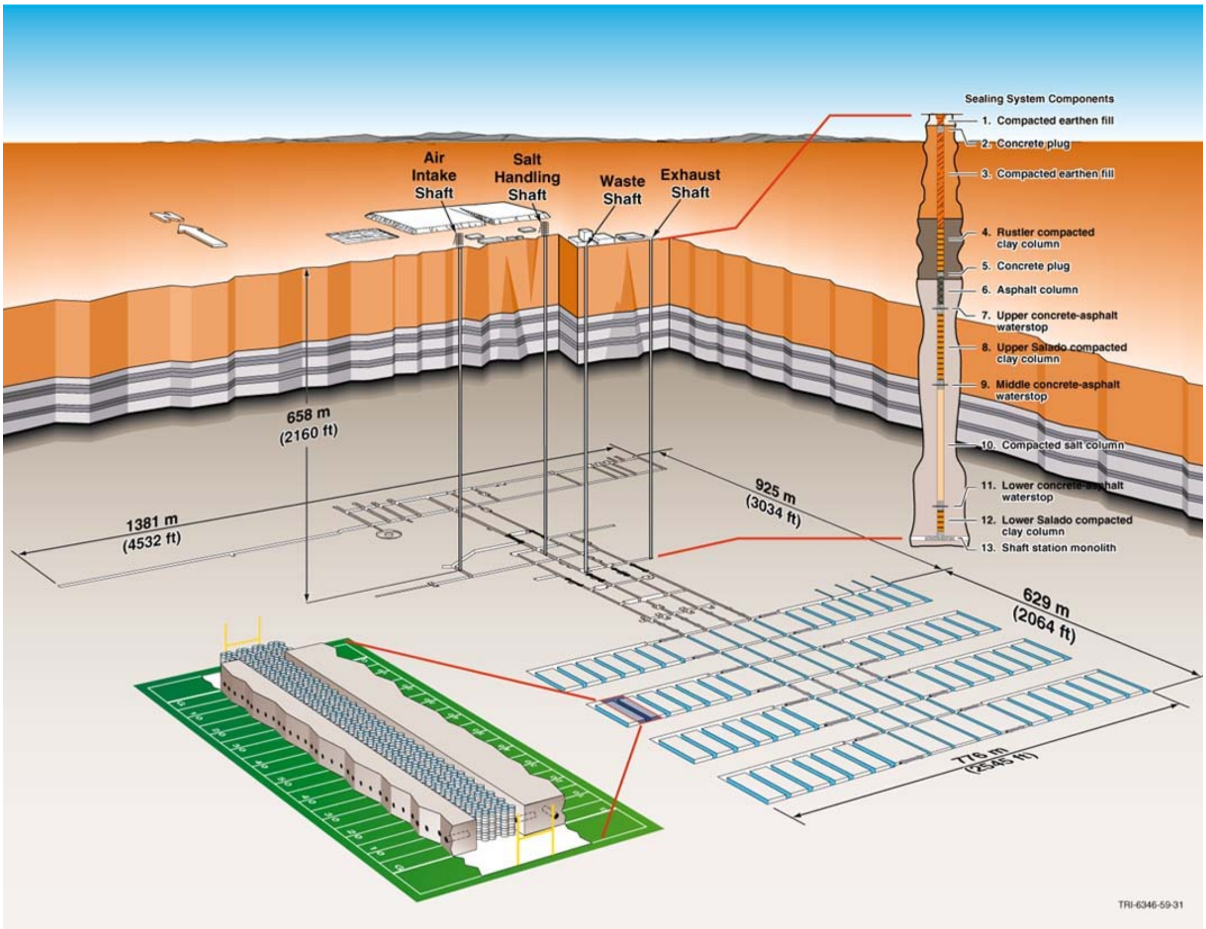

Figure 1. WIPP Layout.

The following is the central requirement in 40 CFR Part 191 Subpart B, and the primary determinant of the PA methodology [1].

§ 191.13 Containment Requirements:

(a) 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).

(b) Performance assessments need not provide complete assurance that the requirements of 191.13(a) will be met. Because of the long time period involved and the nature of the events

and processes 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. Instead, what is required is a reasonable expectation, on the basis of the record before the implementing agency, that compliance with 191.13(a) will be achieved.

Section 191.13(a) refers to "quantities calculated according to Table 1 (Appendix A)," which means a normalized radionuclide release to the accessible environment based on the type of waste being disposed, the initial waste inventory, and the size of release that may occur [1]. Table 1 of Appendix A specifies allowable releases (i.e., release limits) for individual radionuclides.

PAs are the basis for addressing the containment requirements. To help clarify the intent of 40 CFR Part 191, the EPA promulgated 40 CFR Part 194 [2], Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the Part 191 Disposal Regulations. There, an elaboration on the intent of section 191.13 is prescribed.

§ 194.34 Results of performance assessments.

(a) The results of performance assessments shall be assembled into "complementary, cumulative distributions functions" (CCDFs) that represent the probability of exceeding various levels of cumulative release caused by all significant processes and events.

(b) Probability distributions for uncertain disposal system parameter values used in performance assessments shall be developed and documented in any compliance application.

(c) Computational techniques, which draw random samples from across the entire range of the probability distributions developed pursuant to paragraph (b) of this section, shall be used in generating CCDFs and shall be documented in any compliance application.

(d) The number of CCDFs generated shall be large enough such that, at cumulative releases of 1 and 10, the maximum CCDF generated exceeds the 99^{th} percentile of the population of CCDFs with at least a 0.95 probability.

(e) Any compliance application shall display the full range of CCDFs generated.

(f) Any compliance application shall provide information which demonstrates that there is at least a 95% level of statistical confidence that the mean of the population of CCDFs meets the containment requirements of § 191.13 of this chapter.

The methodology for WIPP PA uses information about the disposal system and waste to evaluate performance over the 10,000-year regulatory time period. To accomplish this task, the FEPs with potential to affect the future of the WIPP are first defined. Next, scenarios that describe potential future conditions in the WIPP are formed from logical groupings of retained FEPs. The scenario development process results in a probabilistic characterization for the likelihood of different futures that could occur at the WIPP. Using the retained FEPs, models are developed to estimate the radionuclide releases from the repository. Finally, uncertainty in model parameters is characterized probabilistically.

3. OVERVIEW OF PERFORMANCE ASSESSMENT

The term PA signifies an analysis that (1) identifies the features, processes and events (FEPs) that might affect the disposal system; (2) examines the effects of these FEPs on the performance of the disposal system; and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant FEPs. PA is designed to address three primary questions about the WIPP:

Q1: What FEPs could take place at the WIPP site over the next 10,000 years?
Q2: How likely are the various FEPs to take place at the WIPP site over the next 10,000 years?
Q3: What are the consequences of the various FEPs that could take place at the WIPP site over the next 10,000 years?

In addition, accounting for uncertainty in the parameters of the PA models leads to a further question:

Q4: How much confidence should be placed in answers to the first three questions?

These questions give rise to a methodology for quantifying the probability distribution of possible radionuclide releases from the WIPP repository over the next 10,000 years and characterizing the uncertainty in that distribution due to imperfect knowledge about the parameters contained in the models used to predict releases.

The WIPP PA involves three basic entities: (1) a probabilistic characterization of different futures that could occur at the WIPP site over the next 10,000 years, (2) models for both the physical processes that take place at the WIPP site and the estimation of potential radionuclide releases that may be associated with these processes, and (3) a probabilistic characterization of the uncertainty in the models and parameters that underlies the WIPP PA.

3.1. History

The foundations of PA are a thorough understanding of the disposal system and the possible future interactions of the repository, waste, and surrounding geology. The confidence in the results of WIPP PA is based in part on the strength of the original research done during site characterization, experimental results used to develop and confirm parameters and models, and robustness of the facility design.

PA calculations were included in the 1996 Compliance Certification Application (CCA) [3], and in a subsequent Performance Assessment Verification Test (PAVT) [4,5,6]. Based in part on the CCA and PAVT calculations, the EPA certified that the WIPP met the containment criteria in the regulations and was approved for disposal of transuranic waste in May 1998 [7]. The PA is updated with new information as part of a recertification process that occurs at five-year intervals following receipt in 1999 of the first shipment of waste at the site. PA calculations were also an integral part of the 2004 Compliance Recertification Application (CRA-2004) [8]. During their review of the CRA-2004, the EPA requested an additional PA calculation, referred to as the CRA-2004 Performance Assessment Baseline Calculation (PABC) [9], be conducted with modified assumptions and parameter values [10].

Since the CRA-2004 PABC, additional PA calculations were completed for and documented in the 2009 Compliance Recertification Application (CRA-2009). The CRA-2009 PA resulted from continued review of the CRA-2004 PABC, including a number of technical changes and corrections, as well as updates to parameters and improvements to the WIPP PA computer codes [11]. The EPA then requested that additional information, which was received between the commencement of the CRA-2009 PA (December 2007) and the submittal of the CRA-2009 (March 2009), be included in an additional PA calculation [12], referred to as the CRA-2009 Performance Assessment Baseline Calculation (PABC-2009). The PABC-2009 [13] is the current completed PA.

3.2. Undisturbed Repository Performance

An evaluation of undisturbed repository performance, which is defined to exclude human intrusion and unlikely disruptive natural events, is required by regulation. Evaluations of past and present natural geologic processes in the region indicate that none has the potential to breach the repository within 10,000 years. Disposal system behavior is dominated by the coupled processes of rock deformation surrounding the excavation, fluid flow, and waste degradation. Each of these processes can be described independently, but the extent to which they occur is affected by the others.

Rock deformation immediately around the repository begins as soon as excavation creates a disturbance in the stress field. Stress relief results in some degree of brittle fracturing and the formation of a disturbed rock zone (DRZ), which surrounds excavations in all deep mines including the WIPP repository. For the WIPP, the DRZ is characterized by an increase in permeability and porosity, and it may ultimately extend a few meters (m) from the excavated region. Salt will also deform by creep processes resulting from deviatoric stress, causing the salt to move inward and fill voids. Salt creep will continue until the deviatoric stress is dissipated and the system is once again at stress equilibrium.

The ability of salt to creep, thereby healing fractures and filling porosity, is one of its fundamental advantages as a medium for geologic disposal of radioactive waste, and one reason it was recommended by the National Academy of Sciences [14]. Salt creep provides the mechanism for crushed salt compaction in the shaft seal system, yielding properties approaching those of intact salt within 200 years. Salt creep will also cause the DRZ surrounding the shaft to heal rapidly around the concrete components of the seal system. In the absence of elevated gas pressure in the repository, salt creep would also substantially compact the waste and heal the DRZ around the disposal region. Fluid pressures can become large enough through the combined effect of salt creep reducing pore volumes, and gas generation from waste degradation processes, to maintain significant porosity (greater than 20%) within the disposal room throughout the performance period.

Overall, the behavior of the undisturbed disposal system will result in extremely effective isolation of the radioactive waste. Concrete, clay, and asphalt components of the shaft seal system will provide an immediate and effective barrier to fluid flow through the shafts, isolating the repository until salt creep has consolidated the compacted crushed salt components and permanently sealed the shafts. Some quantity of brine will be present in the repository under most conditions and may contain actinides mobilized as both dissolved and colloidal species. Gas generation by corrosion and microbial degradation is expected to occur, and will result in elevated pressures within the repository. Magnesium oxide is emplaced in the waste-disposal region as an engineered barrier and reacts with some of the gas that is generated. These pressures are expected to not significantly exceed lithostatic because the more brittle anhydrite layers fracture and the pressure then decreases. Fracturing due to high gas pressures may enhance gas and brine migration from the repository. Brine flowing out of the waste disposal region through anhydrite layers may transport actinides as dissolved and colloidal species. However, the quantity of actinides that may reach the accessible environment boundary through the interbeds during undisturbed repository performance is insignificant and has no effect on the compliance determination. No migration of radionuclides is expected to occur vertically.

3.3. Disturbed Repository Performance

The WIPP PA is required by the performance standards to consider scenarios that include intrusions into the repository by inadvertent and intermittent drilling for resources. The probability of these intrusions is based on a future drilling rate. This rate was calculated using a method which analyzes the past record of drilling events. Future drilling practices are assumed to be the same as current practices, also consistent with regulatory criteria. These practices include the type and rate of drilling, emplacement of casing in boreholes, and the procedures implemented when boreholes are plugged and abandoned.

Human intrusion by drilling may cause releases from the disposal system through five mechanisms:

1. Cuttings, which include material intersected by the rotary drilling bit
2. Cavings, which include material eroded from the borehole wall during drilling
3. Spallings, which include solid material carried into the borehole during rapid depressurization of the waste disposal region

4. Direct brine flows, which include contaminated brine that may flow to the surface during drilling
5. Actinide transport by long-term groundwater flow, which includes the contaminated brine that may flow through a borehole after it is plugged and abandoned

The first four mechanisms immediately follow an intrusion event and are collectively referred to as direct releases. The fifth mechanism, actinide transport by long-term groundwater flow in the Culebra Formation (hereafter referred to as the Culebra), begins when concrete plugs are assumed to degrade in an abandoned borehole and may continue throughout the regulatory period (Figure 2).

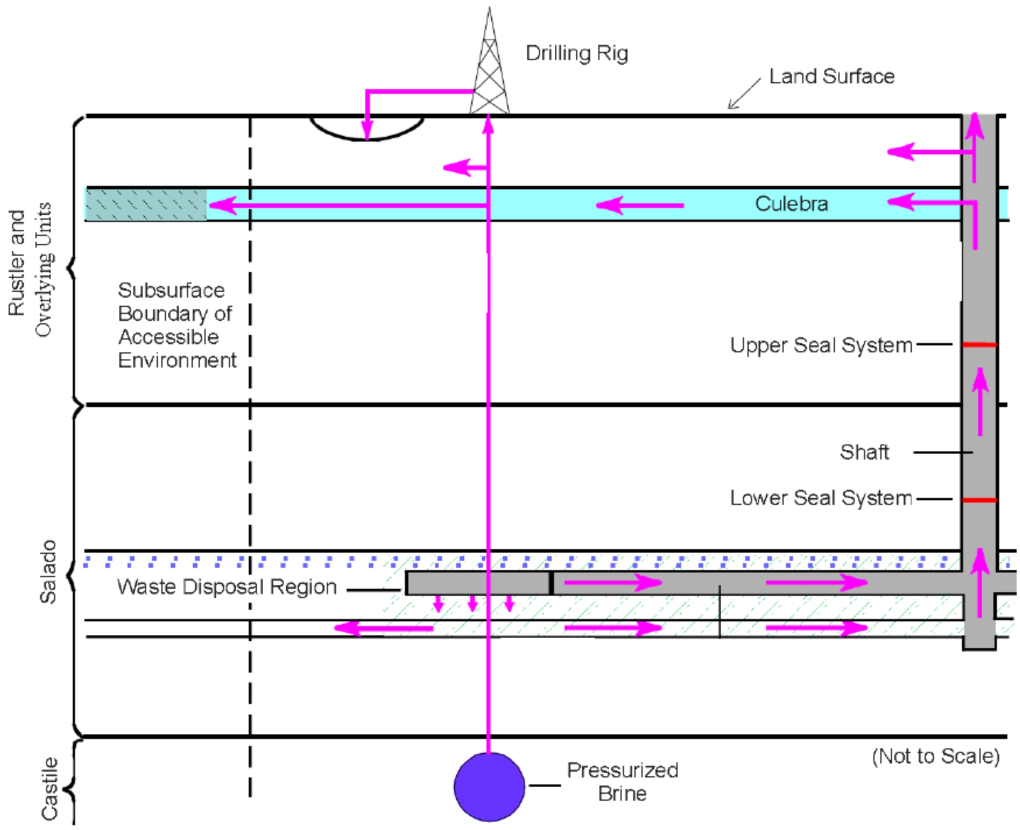

Figure 2. Possible Release Mechanisms after Human Intrusion.

Repository conditions prior to an intrusion will be the same as those for an undisturbed repository and all processes active in the undisturbed repository will continue to occur following intrusion. An intrusion provides a pathway for radionuclides to reach the ground surface and enter the geological units above the repository. Therefore, additional processes may occur in the disturbed condition that do not in the undisturbed condition. These processes include the mobilization of radionuclides as dissolved and colloidal species in repository brine and groundwater flow, and subsequent actinide transport in the overlying units. Flow and transport in the Culebra are of particular interest because it is the most transmissive unit above the repository. Thus, the Culebra is a potential pathway for lateral migration of contaminated brine in the event of a drilling intrusion accompanied by significant flow up the intrusion borehole.

3.3.1. Cuttings

In a rotary drilling operation, the volume of material brought to the surface as cuttings is calculated as the cylinder defined by the thickness of the unit and the diameter of the drill bit. The quantity of radionuclides released as cuttings is therefore a function of the volume of the intruded waste and its activity. The intersected waste activity may vary depending on the type of waste intersected.

3.3.2. Cavings

The volume of particulate material eroded from the borehole wall by the drilling fluids and brought to the surface as cavings may be affected by the drill bit diameter, effective shear resistance of the intruded material, rotational speed of the drill bit, viscosity of the drilling fluid and rate at which it is circulated in the borehole, and other properties related to the drilling process. The most important of these parameters, after drill bit diameter, is the effective shear resistance of the intruded material. In the absence of data describing the reasonable and realistic future properties of degraded waste and backfill, a conservative parameter value based on the properties of fine-grained sediment is used. Other properties are assigned fixed values consistent with current practice. The quantity of radionuclides released as cavings depends on the volume of eroded material and its activity.

3.3.3. Spallings

Unlike releases from cuttings and cavings, which occur with every modeled borehole intrusion, spalling releases will occur only if pressure in the waste-disposal region exceeds the hydrostatic pressure in the borehole. At lower pressures, below about 8 megapascals (MPa), fluid in the waste-disposal region will not flow toward the borehole. At higher pressures, gas flow toward the borehole may be sufficiently rapid to cause additional solid material to enter the borehole. If spalling occurs, the volume of spalled material will be affected by the physical properties of the waste, such as its tensile strength and particle diameter. The quantity of radionuclides released as spallings depends on the volume of spalled waste and its activity.

3.3.4. Direct Brine Flows

Radionuclides may be released to the accessible environment if repository brine enters the borehole during drilling and flows to the ground surface. The quantity of radionuclides released by direct brine flow depends on the volume of brine reaching the ground surface and the concentration of radionuclides contained in the brine. As with spallings, direct brine releases (DBRs) will not occur if repository pressure is below the hydrostatic pressure in the borehole. Furthermore, DBRs will not occur unless there is mobile brine present in the repository. At higher repository pressures, mobile brine present in the repository will flow toward the borehole. If the volume of brine flowing from the repository into the borehole is small, it will not affect the drilling operation, and flow may continue until the driller installs casing in the borehole.

3.3.5. Actinide Mobilization

Actinides may be mobilized in repository brine as dissolved and colloidal species. The solubilities of actinides depend on their oxidation states, with the more reduced forms (for example, III and IV oxidation states) being less soluble than the oxidized forms (V and VI). Conditions within the repository will be strongly reducing because of large quantities of metallic iron in the steel containers and the waste, and—in the case of plutonium—only the lower-solubility oxidation states will persist. Microbial activity will also help create reducing conditions. Solubilities also vary with pH. Magnesium oxide is emplaced in the waste-disposal region to ensure conditions that reduce uncertainty and establish low actinide solubilities. Magnesium oxide reacts with carbon dioxide and buffers pH, lowering actinide solubilities in WIPP brines. Solubilities in the PA are based on the chemistry of brines that might be present in the waste-disposal region, reactions of these brines with the magnesium oxide engineered barrier, and strongly reducing conditions produced by anoxic corrosion of steels and other iron-based alloys. The colloidal concentrations are directly proportional to the dissolved species concentrations.

3.3.6. Long-Term Groundwater Flow

Long-term releases to the ground surface or groundwater in the overlying units may occur after the borehole has been plugged and abandoned. In keeping with regulatory criteria, borehole plugs are assumed to have properties consistent with current practice in the area. Thus, boreholes are assumed to have concrete plugs emplaced at various locations. Initially, concrete plugs effectively limit fluid flow in the borehole. However, under most circumstances, these plugs cannot be expected to remain fully effective indefinitely. For the purposes of PA, discontinuous borehole plugs above the repository are assumed to degrade 200 years after emplacement. From then on, the borehole is assumed to fill with a silty-sand-like material containing degraded concrete, corrosion products from degraded casing, and material that sloughs into the hole from the walls. If sufficient brine is available in the repository, and if pressure in the repository is higher than in the overlying units, brine may flow up the borehole following plug degradation.

Site characterization activities in the units above the Salado have focused on the Culebra. These activities have shown that the direction of groundwater flow in the Culebra varies somewhat regionally, but in the area that overlies the repository, flow is southward. These characterization and modeling activities conducted in the units above the Salado confirm that the Culebra is the most transmissive unit above the Salado. The Culebra is the unit into which actinides are likely to be introduced from long-term flow up an abandoned borehole.

Field tests have shown that the Culebra is best characterized as a double-porosity medium for estimating contaminant transport in groundwater. Groundwater flow and advective transport of dissolved or colloidal species and particles occurs primarily in a small fraction of the rock's total porosity and corresponds to the porosity of open and interconnected fractures and vugs. Diffusion and slower advective flow occur in the remainder of the porosity, which is associated with the low-permeability dolomite matrix. Transported species, including actinides (if present), will diffuse into this porosity.

Diffusion from the advective porosity into the dolomite matrix will retard actinide transport through two mechanisms. Physical retardation occurs simply because actinides that diffuse into the matrix are no longer transported with the flowing groundwater. Transport is interrupted until they diffuse back into the advective porosity. Chemical retardation also occurs within the matrix as actinides are sorbed onto dolomite grains. The relationship between sorbed and liquid concentrations is assumed to be linear and reversible. The distribution coefficients that characterize the extent to which actinides will sorb on dolomite were based on experimental data.

3.3.7. Intrusion Scenarios

Human intrusion scenarios evaluated in the PA include both single intrusion events and combinations of multiple boreholes. Two different types of boreholes are considered: those that penetrate a pressurized brine reservoir in the underlying Castile Formation (hereafter referred to as the Castile), and those that do not. The presence of a brine reservoir under the repository is speculative, but on the basis of current information cannot be ruled out. A pressurized brine reservoir was encountered within the controlled area to the north of the disposal region, and other pressurized brine reservoirs associated with regions of deformation in the Castile have been encountered elsewhere in the general area.

The primary consequence of penetrating a pressurized reservoir is to provide an additional source of brine beyond that which might flow into the repository from the surrounding rocks. Direct releases at the ground surface resulting from the first repository intrusion would be unaffected by additional Castile brine, even if it flowed to the surface, because brine moving straight up a borehole will not significantly mix with waste. However, the presence of Castile brine could significantly increase radionuclide releases in two ways. First, the volume of contaminated brine that could flow to the surface may be greater for a second or subsequent intrusion into a repository that has already been connected by a previous borehole to a Castile reservoir. Second, the volume of contaminated brine that may flow up an abandoned borehole after plug degradation may be greater for combinations of two or more boreholes that intrude the same panel if one of the boreholes penetrates a pressurized reservoir. Both processes are modeled in PA.

4. MODIFICATIONS TO PERFORMANCE ASSESSMENT

Since the PA conducted for the original certification (CCA), many modifications and updates to the WIPP PA have occurred. The inventory information of the waste that is bound for disposal in WIPP has been updated numerous times to include the data generated from the waste characterization effort. Several conceptual models were updated based on new information and updated modeling strategies. A large number of parameters used in the calculations have been updated based on new or revised information. Computer codes have been improved to increase the accuracy and speed of the calculations while reducing the chance of possible mistakes. Errors found in the calculations have been corrected. These modifications are pooled together as part of the recertification process and ensure confidence in the PA results.

5. RESULTS

The results from the PABC-2009 are summarized in this section. Total releases are calculated by totaling the releases from each release pathway: cuttings and cavings releases, spallings releases, DBRs, and long-term releases (there were no undisturbed releases to contribute to the total release). As discussed above in Section 2, the key metric for regulatory compliance is the overall mean CCDF. To quantitatively determine the sufficiency of the sample size, a confidence interval is computed about the overall mean CCDF. Figure 3 shows the 95 percent confidence limits (CLs) about the overall mean for total releases for the PABC-2009. As seen in Figure 3, the overall mean CCDF and CLs lie below and to the left of the release limits and therefore demonstrate that the WIPP continues to comply with the containment requirements.

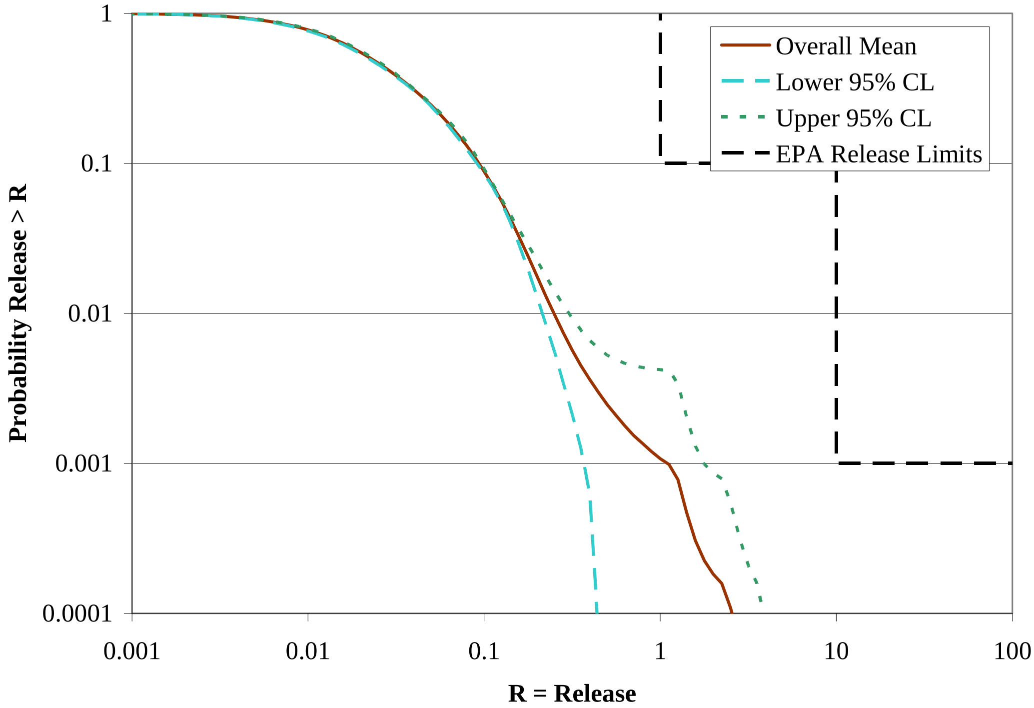

Figure 3. Confidence interval on overall mean CCDF for total normalized releases in EPA units, PABC-2009

Figure 4 shows the overall mean CCDFs for each component of total releases for the PABC-2009. Releases from cuttings and cavings dominate the mean CCDF at high probabilities, while DBRs dominate the mean CCDF at low probabilities in the PABC-2009. Spallings and long-term releases from the Culebra are less important as they are about two orders of magnitude below the total release.

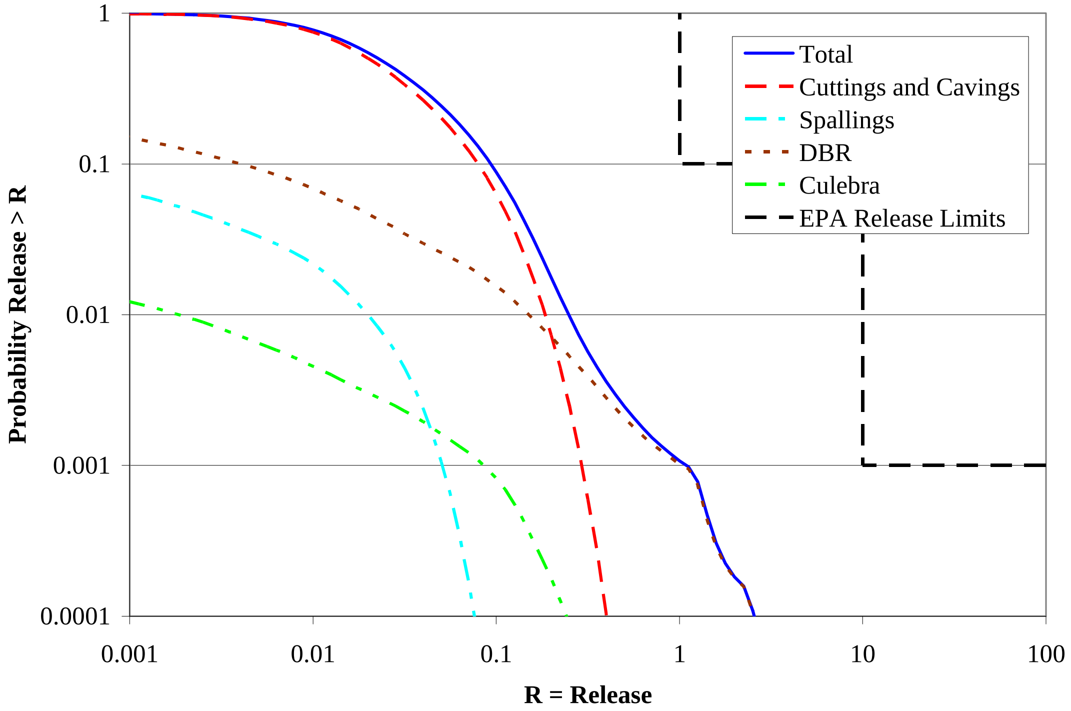

Figure 4. Overall mean CCDFs for components of total normalized releases in EPA units, PABC-2009.

The changes in the WIPP PA have changed the relative importance of the individual components. In the CCA, the dominate release mechanisms were cuttings, cavings and spallings. In the CCA, the releases due to groundwater transport through the Culebra were so low that the mean CCDF did not even appear on the graph. Including the updates and modifications to WIPP PA increased the relative importance of DBRs and releases from the Culebra while decreasing the importance of spallings releases. None of the updates and modifications have changed the overall mean CCDF for total releases such that the WIPP is no longer in compliance with the containment requirements.

6. CONCLUSION

The WIPP PA structure is governed by the corresponding regulations. Human intrusion by drilling may cause releases from the disposal system through five mechanisms. The first four mechanisms immediately follow an intrusion event and are collectively referred to as direct releases. The fifth mechanism, actinide transport by long-term groundwater flow, begins when concrete plugs are assumed to degrade in an abandoned borehole and may continue throughout the regulatory period. Modifying the WIPP PA is a reoccurring process, which ensures confidence in the PA results. The WIPP PA demonstrates that the results continue to lie entirely below the specified limits and the WIPP therefore continues to be in compliance with the containment requirements. Analysis of the results shows that the total releases are dominated by radionuclide releases that could occur on the surface during an inadvertent penetration of the repository by a future drilling operation. The natural and engineered barrier systems of the WIPP provide robust and effective containment of transuranic waste even if the repository is penetrated by multiple borehole intrusions.

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