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COMPLIANCE RESULTS OF THE 2009 WASTE ISOLATION PILOT PLANT PERFORMANCE ASSESSMENT BASELINE CALCULATION

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The U.S. Department of Energy (DOE) has developed the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico for the geologic disposal of transuranic waste. Performance assessment (PA) is the analysis methodology used to demonstrate that WIPP radionuclide release probabilities fall below limits designated by the U.S. Environmental Protection Agency (EPA), ensuring the protection of the public and environment. The most recent WIPP PA demonstrates that cumulative releases continue to lie entirely below specified limits. Therefore, WIPP continues to be in compliance with containment requirements. Analysis of the results shows that 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.

I. INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) consists of a deep underground mined facility located in a bedded salt formation (Figure 1) in southeastern New Mexico. Containment of transuranic waste at the WIPP is regulated by the U.S. Environmental Protection Agency (EPA). The U.S. Department of Energy (DOE) demonstrates compliance with containment requirements by means of performance assessment (PA) calculations.

Performance assessment is built upon a solid, and continually improving, understanding of the disposal system and the possible future interactions of the repository, waste, and surrounding geology. 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 has led to an overall confidence in PA results. Performance assessment begins with a determination of the features, events, and processes (FEPs) that could occur at the WIPP site during the 10,000 years following facility closure. Screened-in FEPs are described by conceptual models that, taken together, provide an overall descriptive model of the facility. 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 repository. Using the retained FEPs, process models are developed that provide quantitative descriptions of WIPP conceptual models. Performance assessment utilizes these process models, with corresponding numerical implementations, to calculate probabilities of cumulative radionuclide releases to the accessible environment over a 10,000 year regulatory period. Uncertainties associated with parameters used in the calculation of cumulative releases are quantified and included in computed results. Within this framework, PA is designed to address three primary questions about the WIPP:

1. What FEPs could take place at the WIPP site over the next 10,000 years?
2. How likely are the various FEPs to take place at the WIPP site over the next 10,000 years?
3. 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 used in PA models leads to a further question:

4. How much confidence should be placed in the answers to questions 1 - 3?

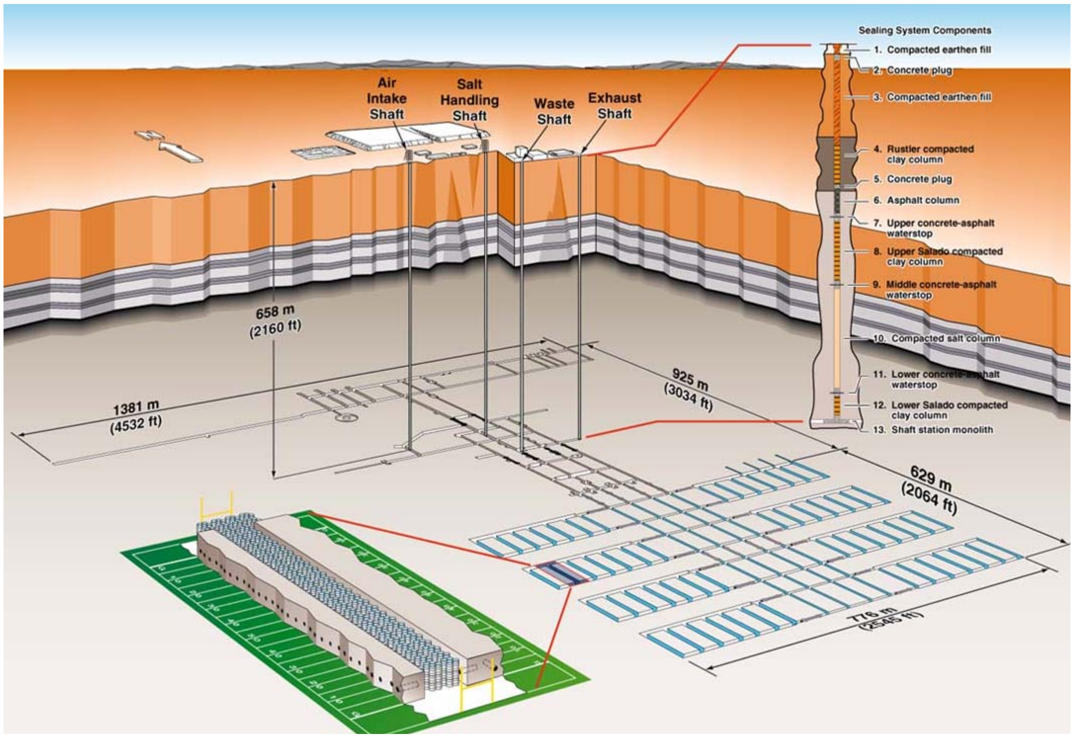

Figure 1. WIPP Layout.

Conceptual and process models, their numerical realizations, and the FEPS that underlay them, are maintained and updated with new information as part of the WIPP recertification process. This process occurs at five-year intervals following receipt in 1999 of the first shipment of waste at the site. During the recertification process for the facility, the EPA requires a performance assessment to demonstrate that potential cumulative releases of radionuclides to the accessible environment over the 10,000-year regulatory period after disposal are less than specified limits based on the nature of the materials disposed. Results obtained via performance assessments are compared to regulatory release limits. This comparison comprises one of the fundamental analyses used during WIPP recertification decisions.

PA calculations were included in the 1996 Compliance Certification Application (CCA) (Ref. 1), and in a subsequent Performance Assessment Verification Test (PAVT) (Refs. 2,3, and 4). 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 (Ref. 5). PA calculations were also an integral part of the 2004 Compliance Recertification Application (CRA-2004) (Ref. 6). 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) (Ref. 7), be conducted with modified assumptions and parameter values (Ref. 8).

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 (Ref. 9). 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 (Ref. 10), referred to as the CRA-2009 Performance Assessment Baseline Calculation (PABC-2009). The PABC-2009 (Ref. 11) is the current completed PA.

II. CONTAINMENT REQUIREMENTS

The methodology employed in WIPP PA derives from the EPA's standard for the geologic disposal of radioactive waste. Termed the Environmental Radiation Protection Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and

Transuranic Radioactive Wastes (40 CFR Part 191) (Ref. 12), this standard 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. It also sets limits on radiation doses to members of the public in the accessible environment for 10,000 years of undisturbed repository performance. Appendix A to Subpart B contains a table, referred to as Table 1 in the containment requirements, listing release limits for each radionuclide. A given radionuclide release is normalized based on the type of waste being disposed, the initial waste inventory, and the size of releases that may occur. The central requirement in 40 CFR Part 191 Subpart B is the primary determinant of the PA methodology.

> *§ 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.*

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 repository will continue to comply with the requirements of 40 CFR Part 191 Subparts B and C. Performance assessments are the basis for the demonstration of compliance.

To help clarify the intent of 40 CFR Part 191, the EPA promulgated 40 CFR Part 194 (Ref. 13), 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 distribution 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 99th 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.*

Accordingly, the outcome of a performance assessment is a set of CCDFs that quantify release probabilities and their associated uncertainties.

III. UNDISTURBED PERFORMANCE

An evaluation of undisturbed repository performance, which is defined to be the performance of the repository in the absence of 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 have the potential to breach the repository within 10,000 years. Disposal system behavior is dominated by the coupled processes of rock deformation around the excavation, fluid flow, and waste degradation. Each of these processes can be described independently, but the extent to which they occur is influenced by the coupling between them.

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 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 (Ref. 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 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 will substantially compact the waste and heal the DRZ around the disposal region. Fluid pressures can become large enough through the combined effects of pore volume reduction due to salt creep, 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. Therefore, no migration of radionuclides is expected to occur vertically.

IV. DISTURBED PERFORMANCE

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 occurring is based on a future drilling rate. This rate is calculated from an analysis of the historical record of drilling events. Future drilling practices are assumed to be the same as current practices, and this assumption is 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

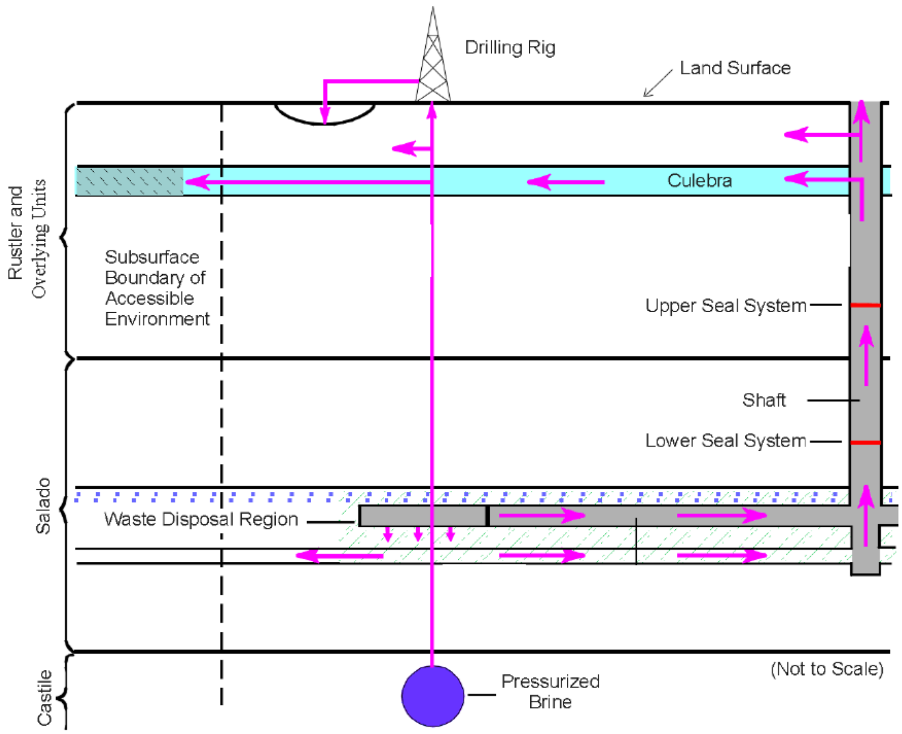

Figure 2. Possible Release Mechanisms after Human Intrusion.

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 brines 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).

Repository conditions prior to an intrusion event are the same as those in the 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 are not present in the undisturbed case. 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.

In a rotary drilling operation, the volume of material brought to the surface as cuttings is calculated to be the cylinder defined by the thickness of the unit being penetrated and the diameter of the drill bit. The volume of particulate material eroded from the borehole wall by the drilling fluids and brought to the surface as cavings is a function of 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 quantity of radionuclides released as cuttings and cavings depends on the volume of eroded material and its activity.

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.

Radionuclides may be released to the accessible environment if repository brine enters the borehole during drilling and flows to the ground surface. 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. 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.

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 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 used in performance assessment 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.

Long-term releases to the ground surface or groundwater in the overlying units may occur after the borehole has been plugged and abandoned. 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 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.

Human intrusion scenarios evaluated in performance assessment 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 cannot be ruled out on the basis of current information. 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 rock.

V. PA MODIFICATIONS

Since the performance assessment conducted for the original compliance certification application of 1996, many modifications and updates to the WIPP PA framework have been implemented. The inventory information of the waste that is bound for disposal in WIPP has been updated numerous times to include additional data generated through waste characterization efforts. Updates to several conceptual models have gone through adjudicated peer reviews, and have subsequently been included in performance assessment so that new information and refinements to modeling strategies can be leveraged in PA calculations. 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 likelihood of error. In fact, continued refinement of the PA methodology has resulted in corrections of errors discovered in calculated results. Updated information and methodology refinements are pooled together and implemented during the recertification process, enabling continual improvements in PA results. No new FEPS have been screened in or out since the original certification application.

VI. RESULTS

The results from the PABC-2009 are presented and summarized in this section. In the results that follow, total releases are calculated by totaling the releases from each release pathway, namely cuttings and cavings releases, spallings releases, direct brine releases, and long-term releases through the Culebra. There was no contribution to total releases due to releases occurring in the undisturbed repository condition. As discussed above in Section II, the key metric for regulatory compliance is the overall mean CCDF. To quantitatively demonstrate the sufficiency of sample size, a confidence interval is computed about the overall mean CCDF. Figure 3 shows the 95 percent confidence limits about the overall mean for total releases for the PABC-2009. As seen in that figure, the overall mean CCDF and its confidence limits lie below and to the left of the regulatory release limits. As a result, WIPP continues to comply with the containment requirements.

Figure 4 shows the overall mean CCDFs for each component of total releases found in the PABC-2009. As seen in that figure, cuttings and cavings releases are the most significant contributors to the overall mean CCDF at high probabilities. At lower probabilities, direct brine releases provide the most significant contribution to the overall mean CCDF. Spallings and long-term releases from the Culebra are less important as they are roughly two orders of magnitude below the overall mean for total releases.

Refinements to WIPP performance assessment have changed the relative importance of individual release components. In the original compliance application, the dominant release mechanisms were cuttings and cavings, as well as spallings. Releases due to groundwater transport through the Culebra were so low that the mean CCDF did not even appear on the graph. Continual updating and modification to WIPP PA have increased the relative importance of direct brine releases and releases from the Culebra, while decreasing the importance of spallings releases. None of the updates and modifications implemented in PA have changed the overall mean CCDF for total releases enough to make WIPP noncompliant with containment requirements.

VII. CONCLUSIONS

Federal regulations outlining the necessary criteria for the safe geologic disposal of radioactive waste underlay the performance assessment framework employed in support of WIPP recertification. Calculations that include intrusion scenarios into the repository due to inadvertent and intermittent drilling for resources are required to determine WIPP performance under disturbed conditions. 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. Refining the WIPP performance assessment methodology is a continual process, ensuring confidence and ever-increasing accuracy in PA results. The most recent WIPP performance assessment, (PABC-2009), demonstrates that total releases from the repository continue to lie entirely below specified regulatory limits. WIPP, therefore, continues to be in compliance with containment requirements. Analysis of the results shows that 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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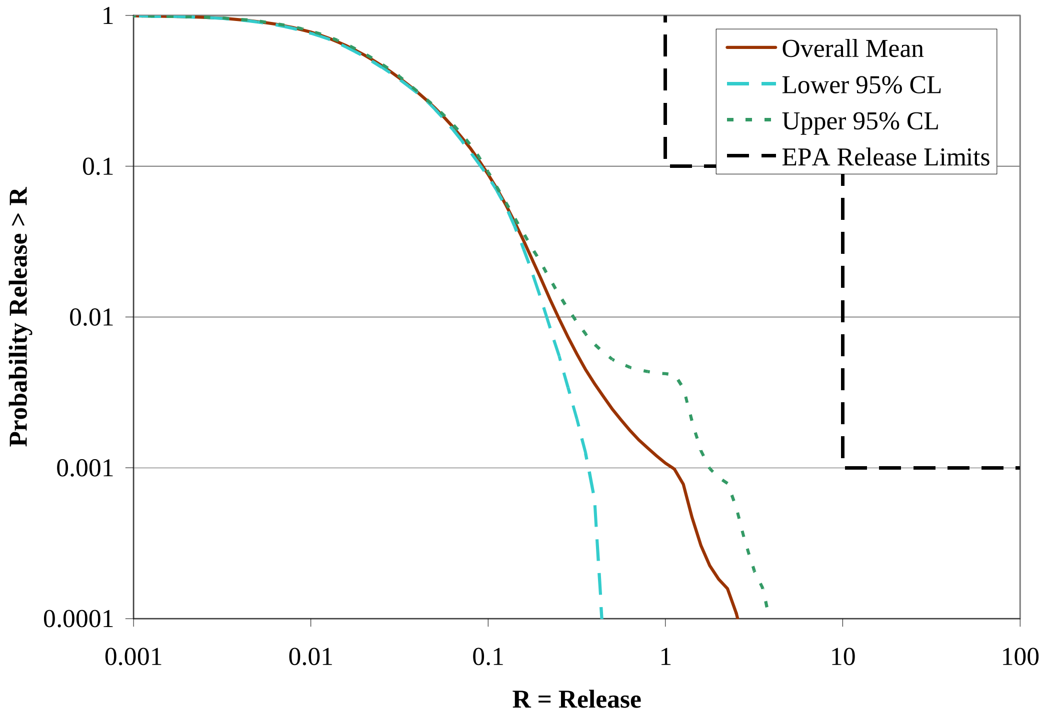

Figure 3. Confidence interval on overall mean CCDF for total normalized releases in EPA units, PABC-2009

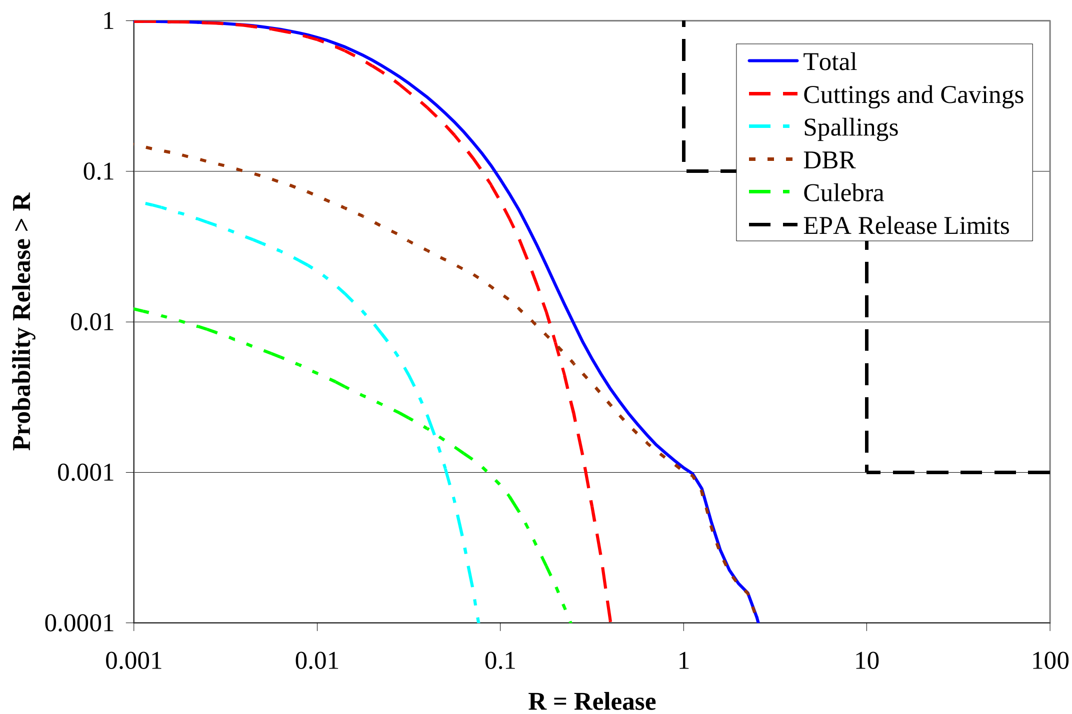

Figure 4. Overall mean CCDFs for components of total normalized releases in EPA units, PABC-2009.

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