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Comparisons of Release Probabilities Obtained in Recent WIPP Performance Assessments

R. Chris Camphouse, Daniel J. Clayton, and Moo Y. Lee

Sandia National Laboratories: 4100 National Parks Highway, Carlsbad, NM 88220, USA, rccamph@sandia.gov

The U.S. Department of Energy has developed the Waste Isolation Pilot Plant in southeastern New Mexico for the geologic disposal of transuranic waste. Performance assessment is the analysis methodology used to demonstrate that WIPP radionuclide release probabilities fall below limits designated by the U.S. Environmental Protection Agency, 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?

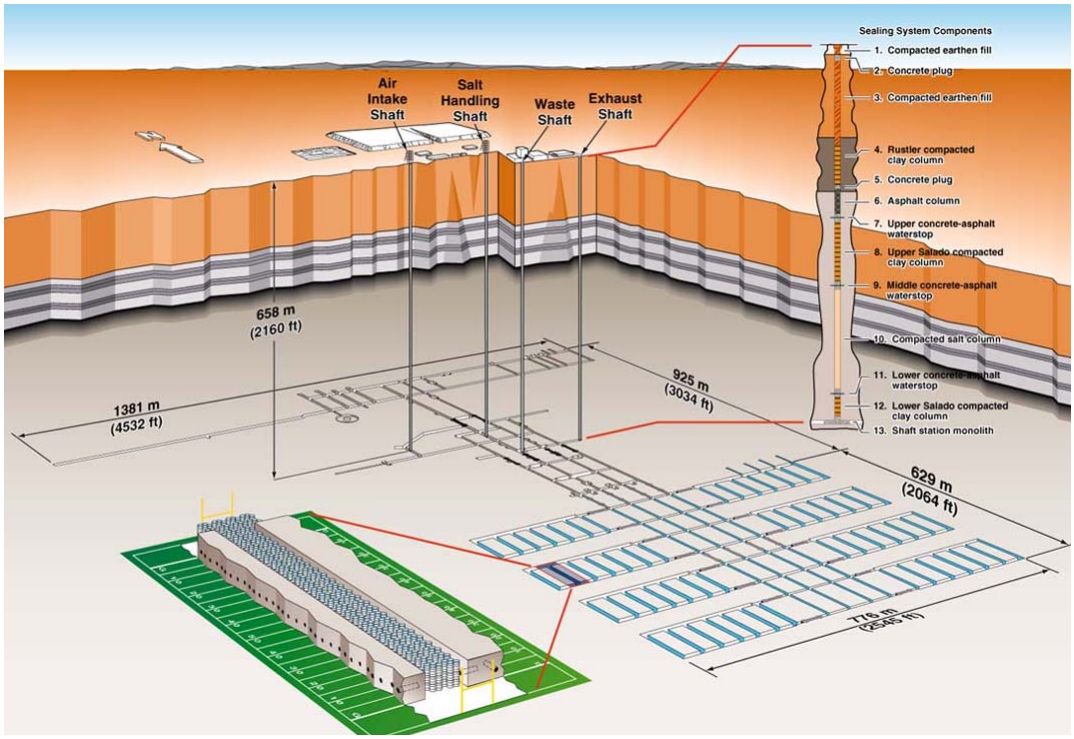

Figure 1. WIPP Layout.

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. No new FEPs have been screened in or out since the original certification application. 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.

A series of performance assessment analyses have recently been conducted to support the most recent WIPP recertification. The DOE conducted a performance assessment supporting the 2009 Compliance Recertification Application (CRA-2009) that incorporated modeling, parameter, and assumption changes occurring since the prior recertification calculation of 2004. During the documentation and review phases of the CRA-2009, additional waste inventory information became available. In addition, recommended model refinements, and improvements to the data used therein, were implemented. The impacts of these modifications were studied in an updated performance assessment calculation referred to as the CRA-2009 Performance Assessment Baseline Calculation (PABC-2009). Changes incorporated in this revised calculation included:

- the use of an updated waste inventory;
- incorporations of additional experimental results and published information in the uncertainty distribution for actinide solubilities;
- the incorporation of additional data, as well as a revised conceptual model, used to generate transmissivity information for groundwater flow;
- updated drilling rate parameters.

II. 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.

III. 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

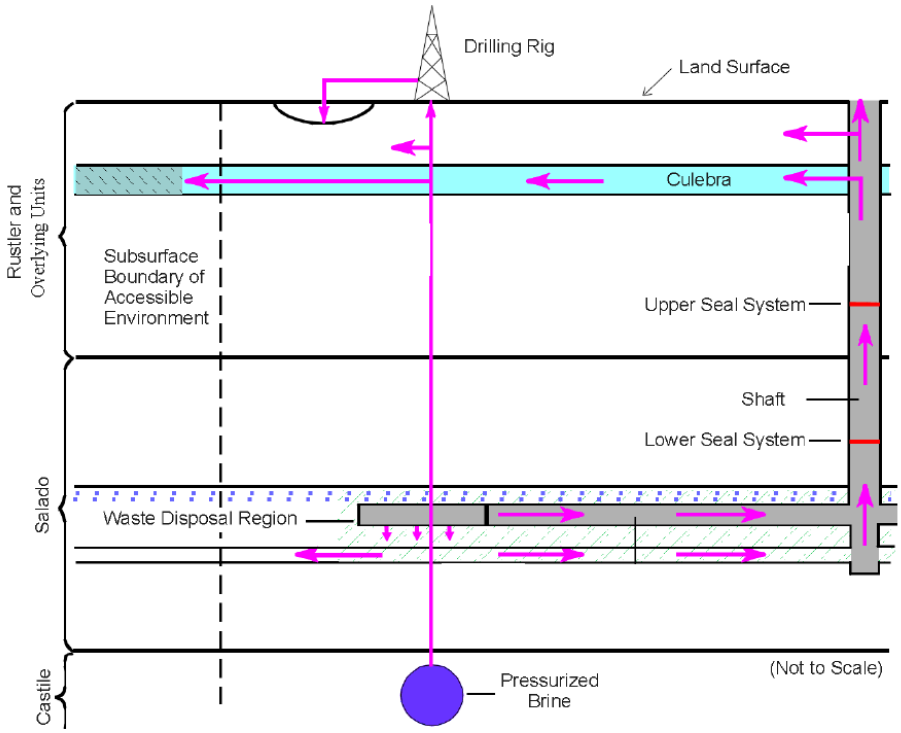

Figure 2. Possible Release Mechanisms after Human Intrusion.

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.

IV. PABC-2009 MODIFICATIONS

Following the completion of the CRA-2009 performance assessment, several changes were implemented for the PABC-2009. First, waste inventory parameters were updated to agree with the most recently available inventory information. This resulted in a slight decrease in the normalized waste inventory implemented in the PABC-2009 when compared to that used in the CRA-2009. Moreover, the amount of cellulose, plastic, and rubber materials in the inventory decreased from CRA-2009 to PABC-2009. Second, radionuclide solubility limits were increased, resulting in an increase in total mobilized concentration. Third, geologic transmissivity fields were updated to incorporate an increase in transmissivity near the repository due to mining. Finally, the matrix distribution coefficient lower limit

was significantly decreased, resulting in smaller retardation and consequent increased radionuclide transport.

V. RESULTS

The results from the PABC-2009 are presented in this section and compared to those obtained in the CRA-2009 PA. 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. The key metric for regulatory compliance is the overall mean complementary cumulative distribution function (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 and the CRA-2009 PA. As seen in that figure, cuttings and cavings releases are the most significant contributors to the overall mean CCDF at high probabilities. Release probabilities for cuttings decreased slightly in the PABC-2009 due to the slightly lower normalized waste inventory used in that calculation. At lower probabilities, direct brine releases provide the most significant contribution to the overall mean CCDF. The increase in radionuclide solubilities used in the PABC-2009 resulted in an increase in direct brine releases when compared to the CRA-2009 PA results. 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. Spallings release probabilities decreased in the PABC-2009 due to slightly lower repository pressures observed in the PABC-2009 calculations. A reduction in repository pressure translates into smaller spallings volumes as they depend directly on repository pressure. Probabilities of release from the Culebra increased in the PABC-2009. In the CRA-2009 PA, radionuclide releases from the Culebra were so small as to not appear on the plot at all for the chosen axes. Increased radionuclide solubilities and increases in transmissivity due to mining contributed to the increases seen in PABC-2009 Culebra 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. 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.

VI. CONCLUSIONS

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. 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 to the surface 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.

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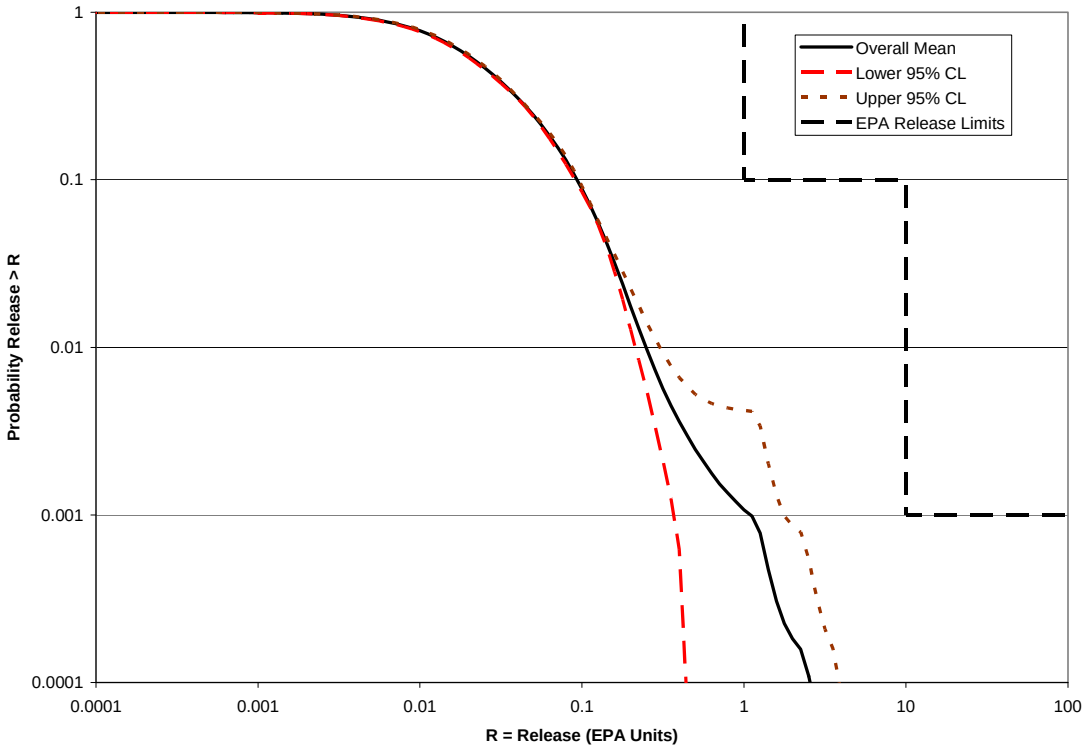

Figure 3. Confidence interval on overall mean CCDF for total normalized releases in EPA units, PABC-2009

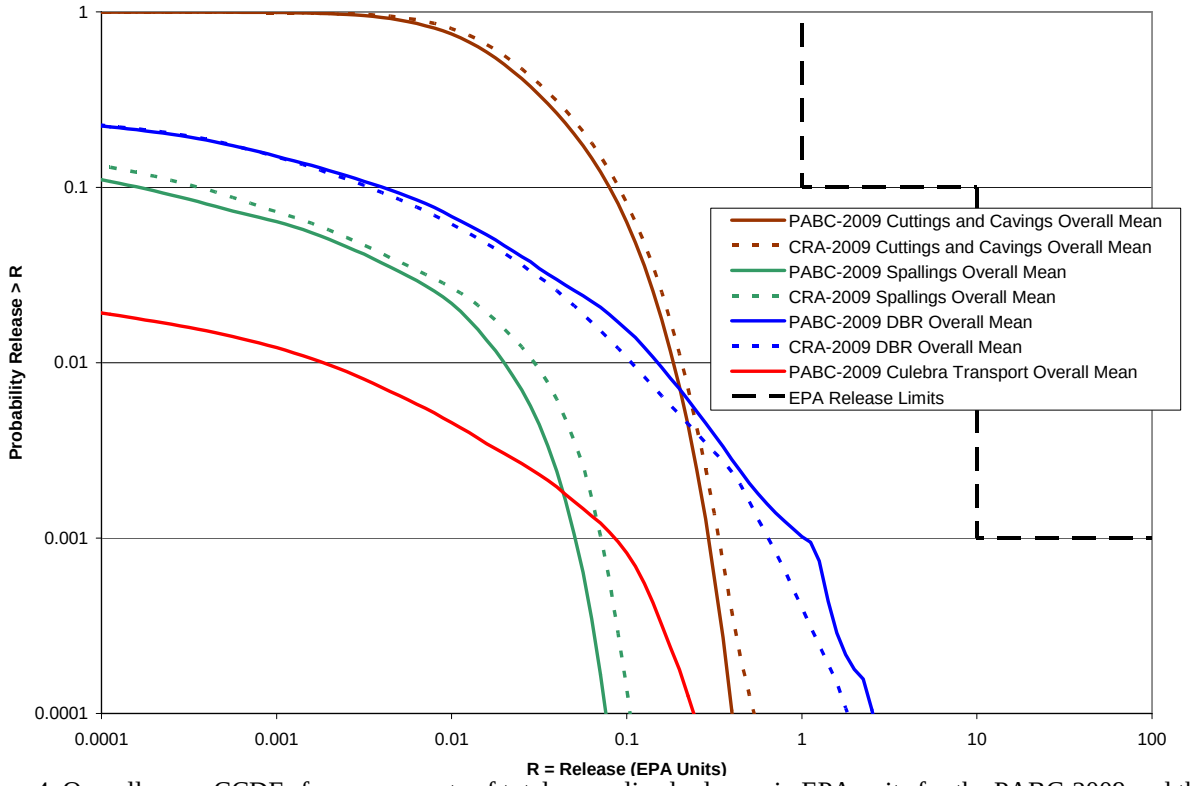

Figure 4. Overall mean CCDFs for components of total normalized releases in EPA units for the PABC-2009 and the CRA-2009 PA

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