### ***PA-8.4.4.1 Partial Mining Results***

***Under partial-mining conditions, only the $^{234}U$ species was transported beyond the LWB in any significant amount during the course of the 10,000-year simulation (Kanney 2003). Table PA-27 shows the eight vectors that resulted in releases greater than one billionth of the 1 kg source. Sensitivity analysis indicates that releases of $^{234}U$ are associated with the (VI) oxidation state. This result is reasonable because the matrix distribution coefficients for uranium in the (IV) state are much lower than for the (VI) state (see Section PA-5.2 and Attachment PAR, Table PAR-35).***

***Table PA-27. Releases of $^{234}U$ at LWB in Partial Mining Conditions***

| Replicate | Vector | $^{234}U$ Release at LWB (fraction of 1 kg source) |
|---|---|---|
| 3 | 54 | 0.479 |
| 3 | 84 | 0.177 |
| 3 | 38 | 0.0815 |
| 2 | 10 | 0.0711 |
| 1 | 58 | 0.0541 |
| 3 | 23 | $1.40 \times 10^{-3}$ |
| 1 | 8 | $2.36 \times 10^{-4}$ |
| 3 | 71 | $7.12 \times 10^{-8}$ |

### ***PA-8.4.4.2 Full Mining Results***

***Under full-mining conditions, only the $^{234}U$ species was transported beyond the LWB in significant amounts during the course of the 10,000-year simulation. Table PA-28 shows the 18 vectors that resulted in releases greater than one billionth of the source of 1 kg. Sensitivity analysis indicates that releases of $^{234}U$ in the full mining conditions are also associated with the U(VI) oxidation state.***

***Two vectors showed releases of $^{239}Pu$ greater $1 \times 10^{-9}$ kg. Replicate 2, vector 71 computed a release of $6.15 \times 10^{-6}$ kg; replicate R1, vector 92 showed a release of $2.03 \times 10^{-9}$ kg. No releases of $^{230}Th$ or $^{241}Am$ exceeded $1 \times 10^{-9}$ kg.***

### ***PA-8.4.4.3 Additional Information***

***More detailed information on the results of the Culebra transport calculations can be found in the Analysis Package for the Culebra Transport Calculations: Compliance Recertification Application (Kanney 2003).***

**Table PA-28. Releases of $^{234}U$ at LWB in Full-Mining Conditions**

| Replicate | Vector | $^{234}U$ Release at LWB (fraction of 1 kg source) |
|---|---|---|
| 2 | 15 | 0.987 |
| 3 | 38 | 0.987 |
| 1 | 58 | 0.889 |
| 1 | 65 | 0.766 |
| 3 | 54 | 0.712 |
| 2 | 10 | 0.209 |
| 3 | 27 | 0.0269 |
| 1 | 90 | 0.0127 |
| 2 | 30 | 0.0123 |
| 1 | 31 | $6.18 \times 10^{-3}$ |
| 3 | 65 | $4.72 \times 10^{-3}$ |
| 3 | 66 | $1.80 \times 10^{-4}$ |
| 2 | 53 | $1.66 \times 10^{-5}$ |
| 3 | 67 | $1.59 \times 10^{-7}$ |
| 1 | 67 | $1.03 \times 10^{-8}$ |
| 3 | 42 | $4.53 \times 10^{-9}$ |
| 2 | 33 | $1.98 \times 10^{-9}$ |
| 2 | 24 | $1.61 \times 10^{-9}$ |

## PA-8.5 Direct Releases

Direct releases occur at the time of a drilling intrusion, and include cuttings and cavings; spallings; and DBRs. This section presents analysis of the volume released by each mechanism.

### PA-8.5.1 Cuttings and Cavings Volumes

Cuttings and cavings releases are solid waste material that is removed from the repository by the cutting of the drill bit and additional material that is sheared off the borehole wall by the circulation of the drilling fluid. Figure PA-77 shows the CCDFs for the total volume removed to the surface from cuttings and cavings for replicate R1. Figure PA-78 compares statistics for the CCDFs for cuttings and cavings volume for each replicate, and shows that the three replicates produced very similar results.

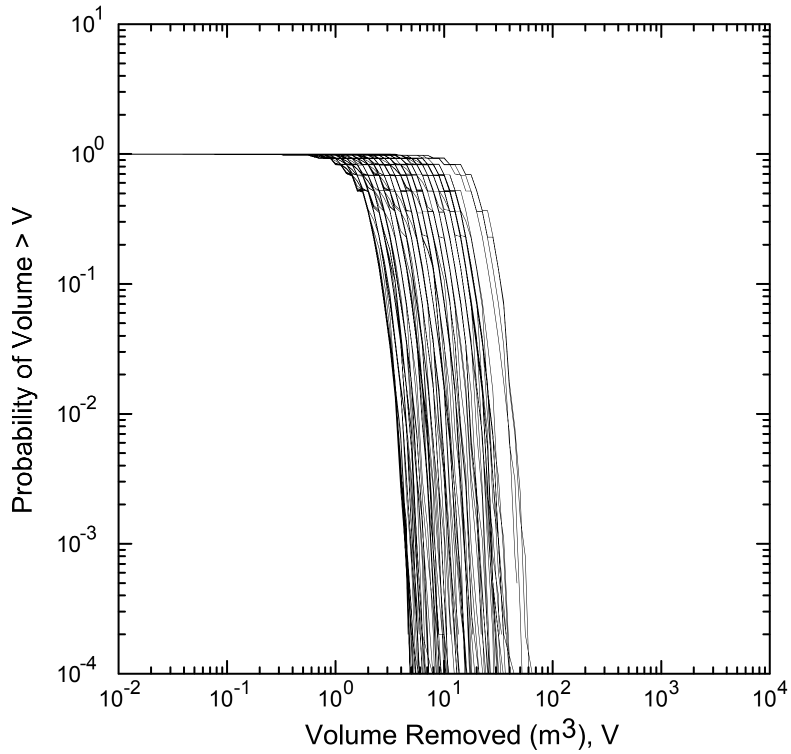


*Figure PA-77. Total Volume Removed by Cuttings and Cavings, Replicate R1.*

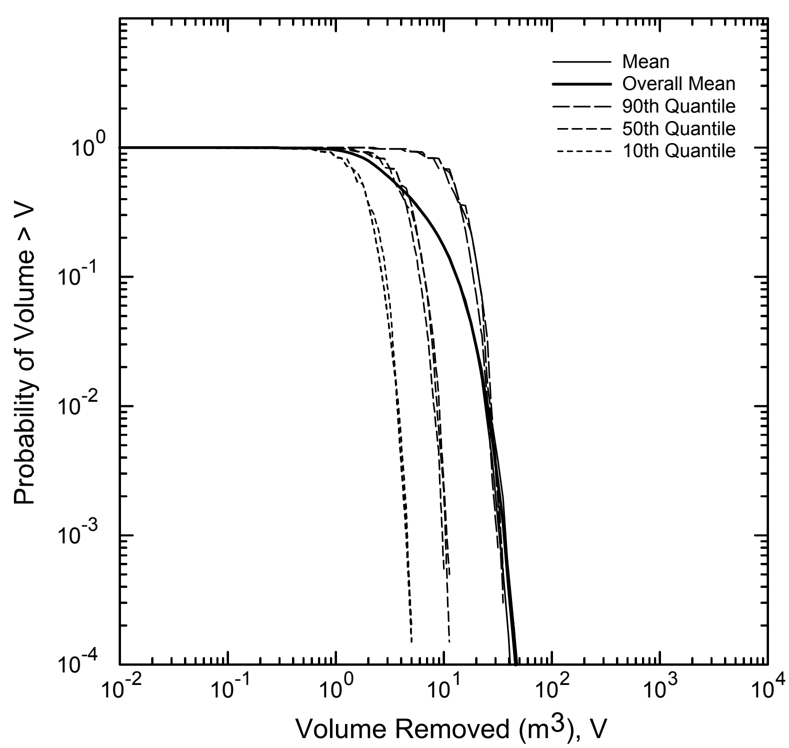


*Figure PA-78. Statistics for Volumes Removed by Cuttings and Cavings, All Replicates.*

***Figure PA-79 shows that the uncertainty in cuttings and cavings volume arises primarily from the uncertainty in the shear strength of the waste (WTAUFAIL, see Table PA-17). The uncertainty in drill string angular velocity (DOMEGA) affects the calculation of cavings volume (Section PA-4.5), but is much less significant (Dunagan 2003a).***

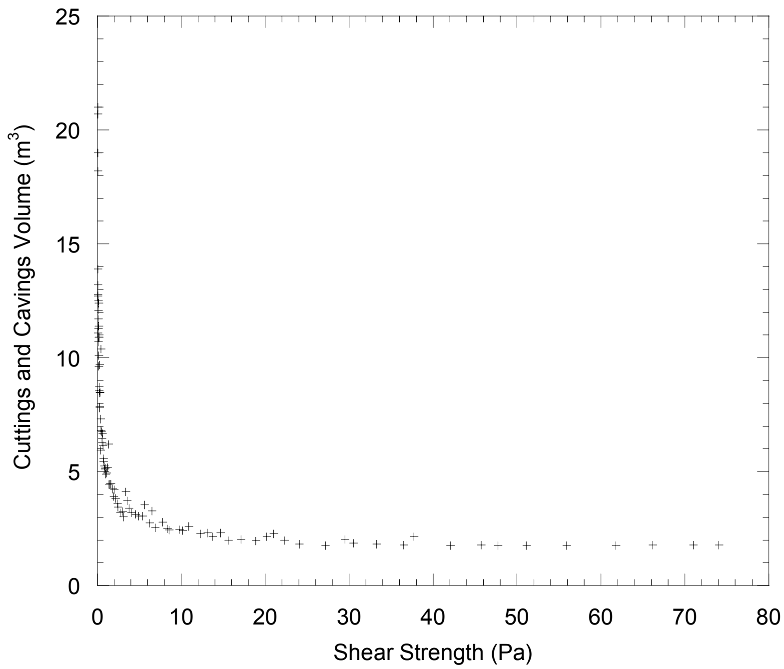


***Figure PA-79. Sensitivity of Mean Cuttings and Cavings Volume to Waste Shear Strength.***

### *PA-8.5.2 Spall Volumes*

***The volume of solid waste material released to the surface due to the spallings mechanism is calculated with the code DRSPALL. As outlined in Section PA-4.6.4, the code was run for each of 50 vectors in an LHS for DRSPALL, and for four values of repository pressure (10, 12, 14, and 14.8 MPa). Figure PA-80 shows the distribution of spall volumes for each value of repository pressure, ordered by increasing spall volume at 14.8 MPa. The maximum volume is 12.062 $m^3$ occurring at repository pressure of 14.8 MPa. At repository pressure at or below 10 MPa, no spallings occurred.***

***The distributions presented in Figure PA-80 are the volumes that could be removed by a single intrusion. As outlined in Section PA-4.6.4, the uncertainty in these volumes arises from four variables that are uncertain in the DRSPALL calculations: waste permeability; waste porosity; waste tensile strength; and waste particle diameter. Figure PA-81 and Figure PA-82 show the relationship between the spall volumes (SPALVOL) for the scenario with initial pressure of 14.8 MPa and the particle diameter (PARTDIAM) and the ratio of waste permeability to waste porosity (PERMPOR, from the term $k'/\phi$ in Equation (145)). Figure PA-81 and Figure PA-82 show that large spall volumes result from combinations of low values of particle diameter and low values for the ratio of waste permeability to waste porosity, and that uncertainty in these two parameters dominates the uncertainty in the spall volume from a single intrusion.***

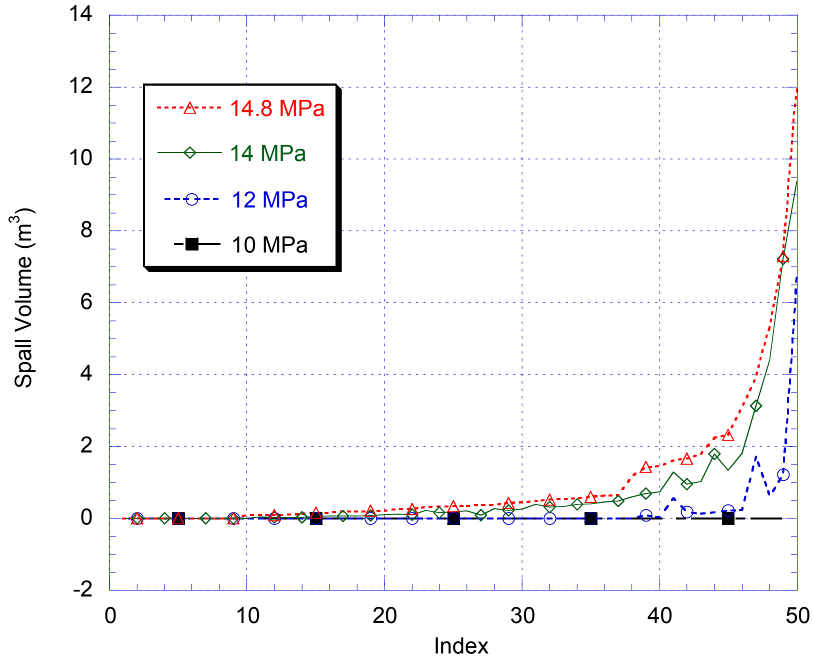


***Figure PA-80. Spall Volume for a Single Intrusion (Ranked by Increasing Volume in the 14.8 MPa Scenario).***

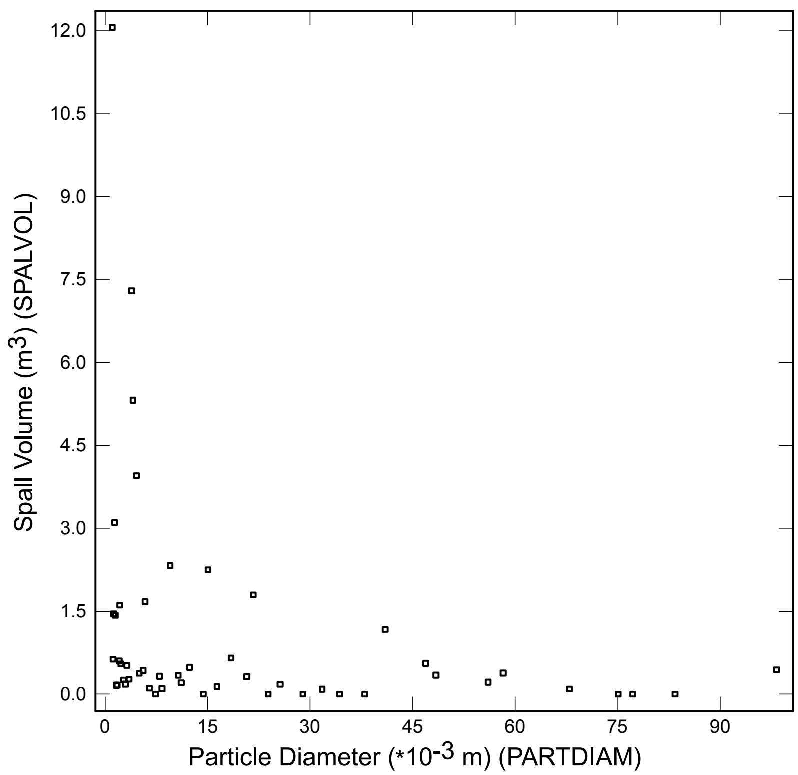


***Figure PA-81. Sensitivity of Spall Volume for a Single Intrusion to Particle Diameter, 14.8 MPa Scenario.***

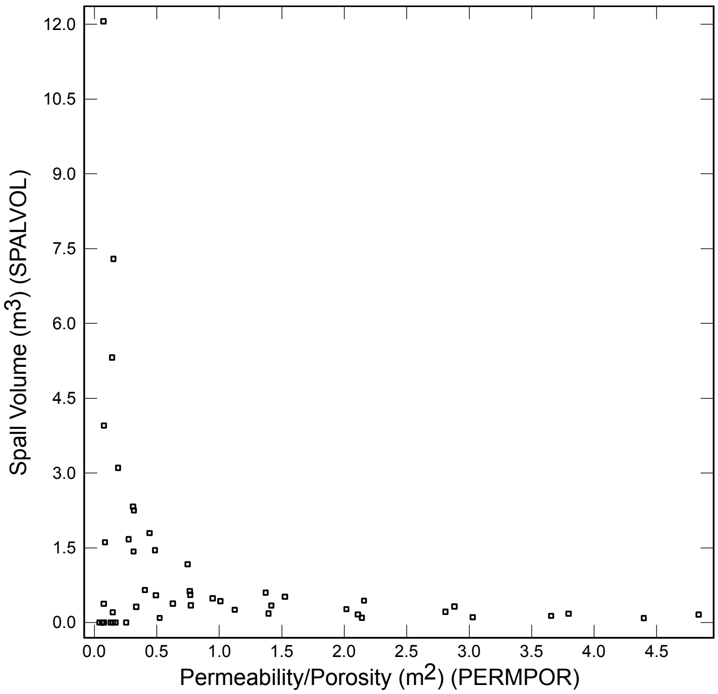


***Figure PA-82. Sensitivity of Spall Volume for a Single Intrusion to Waste Permeability / Waste Porosity , 14.8 MPa Scenario.***

***The code CCDFGF stochastically generates futures for the repository and constructs the distribution of total volume removed by spallings for all intrusions (see Section PA-6.5 and Section PA-6.8). Figure PA-83 shows the CCDFs for the volume of material released ($m^3$) by spallings for replicate R1. Figure PA-84 compares statistics for the distribution of CCDFs for spall volume among the three replicates, and shows that the three replicates produce similar results. The median ($50^{th}$ quantile) and $10^{th}$ quantile CCDFs do not plot on the scale of Figure PA-84 due to the large number of observations with spall volumes less than 0.01 $m^3$.***

***The distribution of spall volumes arises from the uncertain parameters used in the calculation of repository pressure (see Section PA-4.2) and the uncertain volume removed by a single intrusion (Figure PA-80). Section PA-7.1.1 and Section PA-8.3.1 identified three uncertain variables in the space for subjective uncertainty $S_{su}$ that are primarily responsible for the uncertainty in repository pressure: borehole permeability (BHPERM); the indicator for microbial action (WMICDFLG); and the initial pressure in the Castile brine reservoir (BPINTPRS). Thus, these three variables may correlate to uncertainty in the total volume released by spalling.***

***In addition, the variable RNDSPALL (Table PA-17) in the LHS for the CRA-2004 PA (Equation (254)) assigns vectors from the LHS for DRSPALL (Section PA-4.6.4) to vectors in the LHS for the CRA-2004 PA. The variable RNDSPALL creates a mapping between the uncertain spall volumes in Figure PA-80 and the CCDFs in Figure PA-83. Thus, the spall volume (SPALVOL) for the 14.8 MPa scenario can be included in the sensitivity analysis for total spall volumes.***

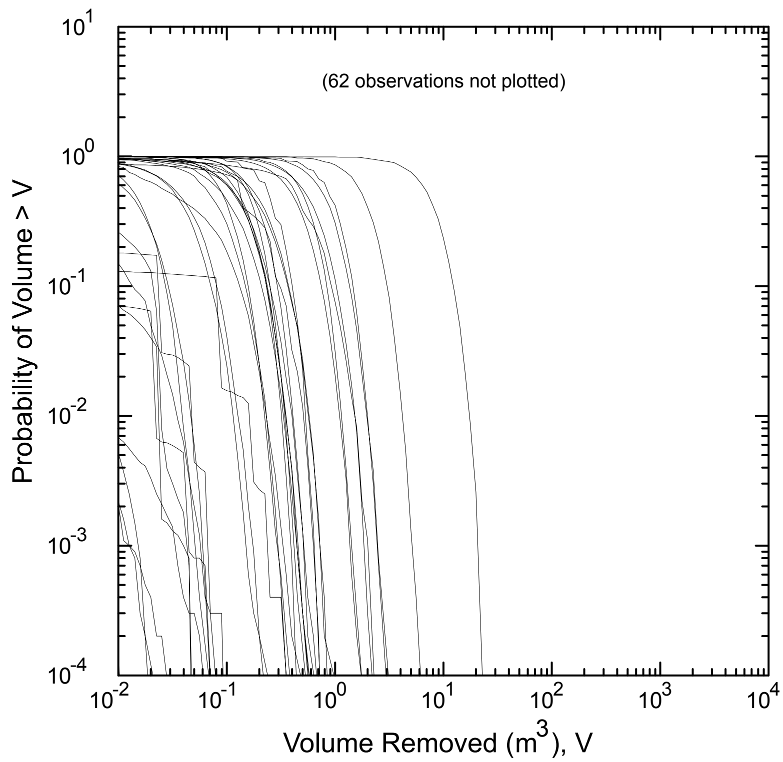


***Figure PA-83. Total Volume Removed by Spallings, Replicate R1.***

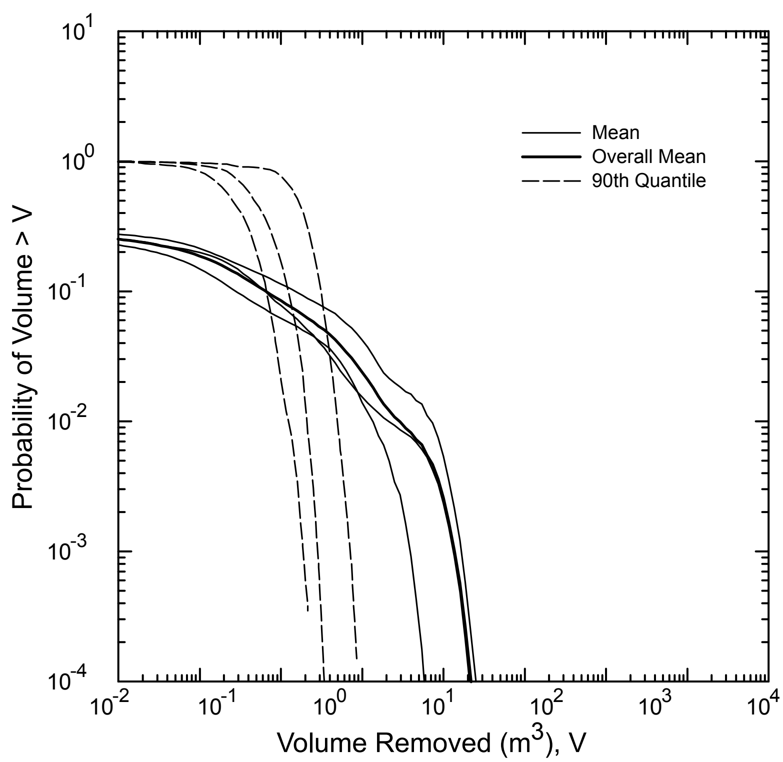


***Figure PA-84. Statistics for Total Spall Volume, All Replicates.***

*Figure PA-85 demonstrates that the uncertainty in mean total spall volume arises primarily from the uncertainty in the indicator for microbial action (WMICDFLG) and the uncertainty in the spall volume from a single intrusion (SPALVOL). The indicator for microbial action (WMICDFLG) partitions the vectors into two sets of equal size: a set of vectors where microbial action occurs (WMICDFLG = 1 or 2) and a set where no microbial action is present (WMICDFLG = 0). Figure PA-80 shows that no spall releases are possible unless pressure exceeds 10 MPa. Figure PA-85 shows that when no microbial action is present, no spallings releases occur even when the spall volume from a single intrusion could be non-zero. Therefore, when no microbial action is present, repository pressure does not exceed the threshold for spall releases. In contrast, when microbial action is present (WMICDFLG = 1 or 2), Figure PA-85 shows that the uncertainty in total mean spall releases arises primarily from the uncertainty in the spall volume from a single release (SPALVOL).*

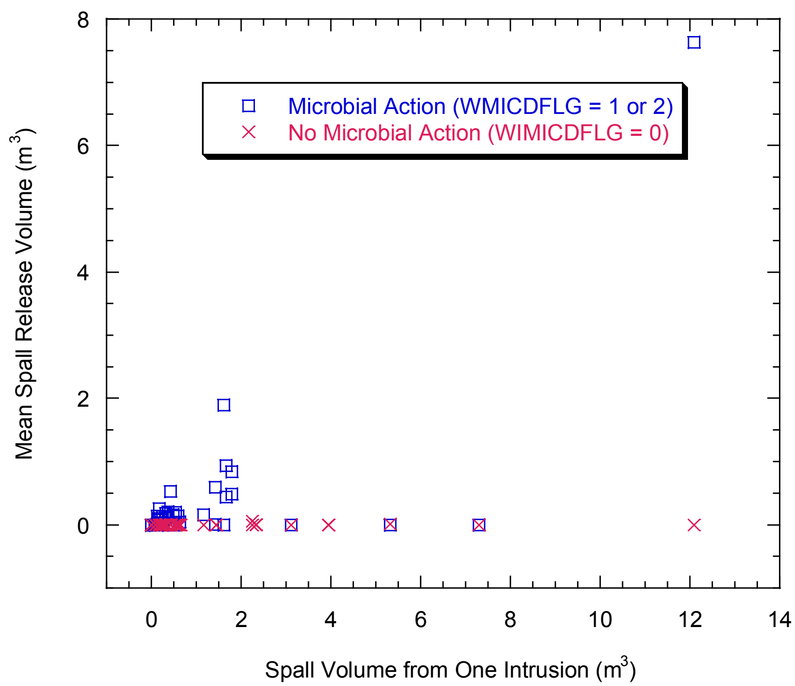


*Figure PA-85. Sensitivity of Mean Total Spall Volume, Replicate R1.*

### *PA-8.5.3 Direct Brine Release Volumes*

*DBRs to the surface can occur during or shortly after a drilling intrusion. For each element of the LHS, the code BRAGFLO (Section PA-4.7) calculates volumes of brine released for a total of 78 combinations of intrusion time, intrusion location, and initial conditions (Section PA-6.7.5) Initial conditions for the DBR calculations are computed by BRAGFLO for five scenarios (S1 through S5; see Section PA-6.7) Results from the S1 scenario represent undisturbed repository conditions; results from the S2 through S5 scenarios represent repository conditions that result after a drilling intrusion.*

*For replicate R1, only about eight percent of the 7,800 DBR calculations (100 vectors × 78 combinations) resulted in direct brine flow to the surface. The maximum DBR release is*

***approximately 115 $m^3$. Only intrusions into a lower panel (see Section PA-4.7.1) resulted in significant brine volume releases. In the S1 scenario, the lower panel represents an undisturbed panel at the south end of the repository. In the S2 and S3 scenarios, the lower panel represents any panel that has a previous E1 intrusion; in the S4 and S5 scenarios, the lower panel has a previous E2 intrusion.***

***Figure PA-86 shows probability plots of DBR volumes for Scenarios S1 through S5, lower intrusion, at the discrete times for which DBR is calculated. A probability plot displays the percentage of the vectors on the x-axis where release volumes are less than the value on the y-axis. Figure PA-86a shows DBR volumes for scenario S1 representing the initial intrusion at various times. Figure PA-86b and Figure PA-86c show DBR volumes for Scenarios S2 and S3, which represent a subsequent intrusion (at various times) into a panel that had an E1 intrusion at 350 years and 1,000 years, respectively. Figure PA-86d and Figure PA-86e show DBR volumes for Scenarios S4 and S5, which represent a subsequent intrusion (at various times) into a panel that had an E2 intrusion at 350 years and 1,000 years, respectively. Release volumes are larger and occur more frequently in the S2 and S3 scenarios, because the lower panel has much higher saturations after an E1 intrusion (Section PA-8.3.2).***

***Sensitivity analysis determined that DBR volume from a single intrusion is most sensitive to the initial pressure and brine saturation in the intruded panel (Stein 2003). The analysis is illustrated below for scenario S2; similar conclusions follow from analysis of the other scenarios. The initial pressure and brine saturation in the DBRs calculations are transferred from the Salado Flow calculations as described in Section PA-4.7.2. Thus, the uncertain parameters that are most influential to the uncertainty in pressure and brine saturation in the Salado Flow calculations (see Section PA-7.1 and Section PA-8.3) are also most influential in the uncertainty in DBR volumes.***

***The combination of relatively high pressure and brine saturation in the intruded panel is required for direct brine release to the surface. Figure PA-87 shows a scatter plot of pressure in the waste panel vs. DBR volumes for Scenario S2, lower intrusion with symbols indicating the value of the mobile brine saturation (defined as brine saturation $S_b$ from the solution of Equation (25) minus residual brine saturation $S_{br}$ in the waste (see Table PA-2)). The figure clearly shows that there are no releases until pressures exceed 8 MPa as indicated by the vertical line. Above 8 MPa, a significant number of vectors have zero releases, but these vectors have mobile brine saturations less than zero and thus no brine is available to be released. When mobile brine saturation approaches 1, relative permeability to gas becomes small enough that no gas flows into the well, and in these circumstances DBR releases end after three days (Equation (211)). Thus, in vectors with high mobile brine saturations, DBR releases increase proportionally with increases in pressure, as evidenced by the linear relationship between DBR volume and pressure for mobile brine saturation between 0.8 and 1.0. For vectors with mobile saturations between 0.2 and 0.8, both gas and brine can flow in the well, and the rate of gas flow can be high enough that the ending time of DBR releases may be as long as 11 days. Although brine may be flowing at slower rates in these vectors than in vectors with high mobile saturations, brine flow may continue longer and thus result in larger DBR volumes.***

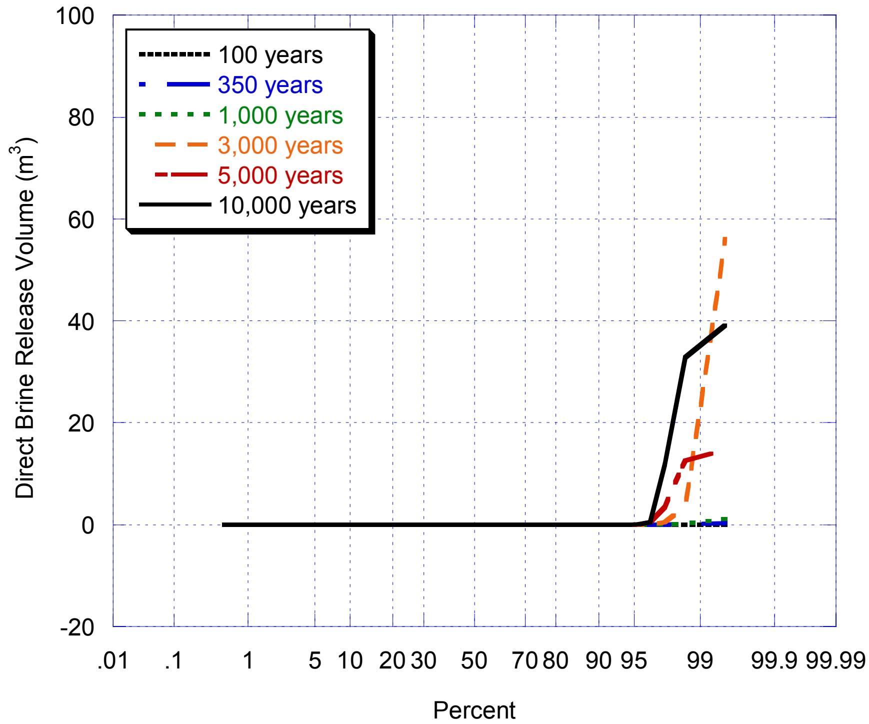


*Figure PA-86a. DBRs for Initial Intrusions into Lower Panel (Scenario S1), Replicate R1.*

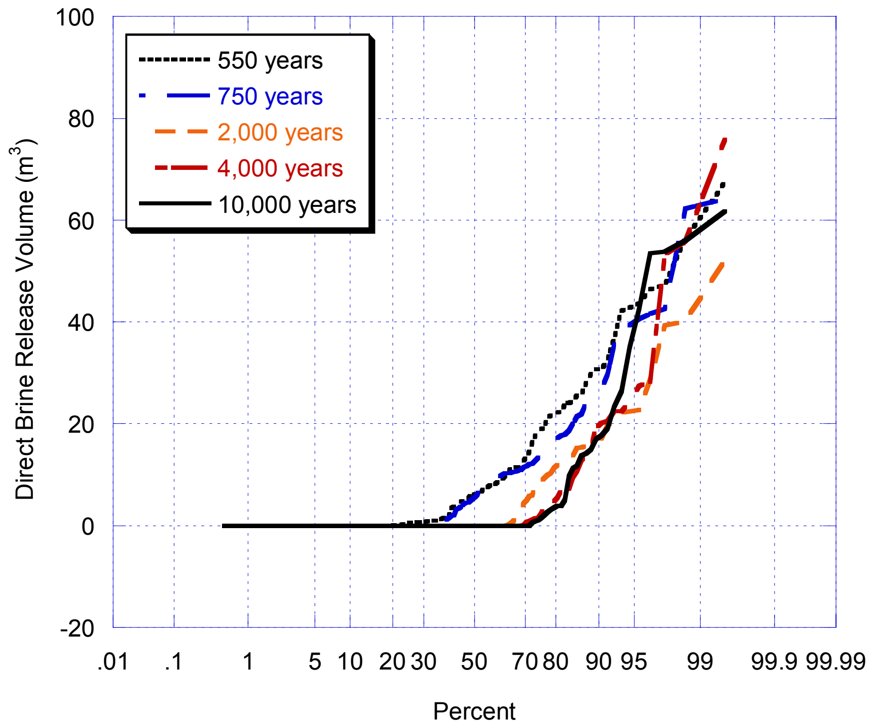


*Figure PA-86b. DBRs for Subsequent Intrusions into Lower Panel After an E1 Intrusion at 350 Years (Scenario S2), Replicate R1.*

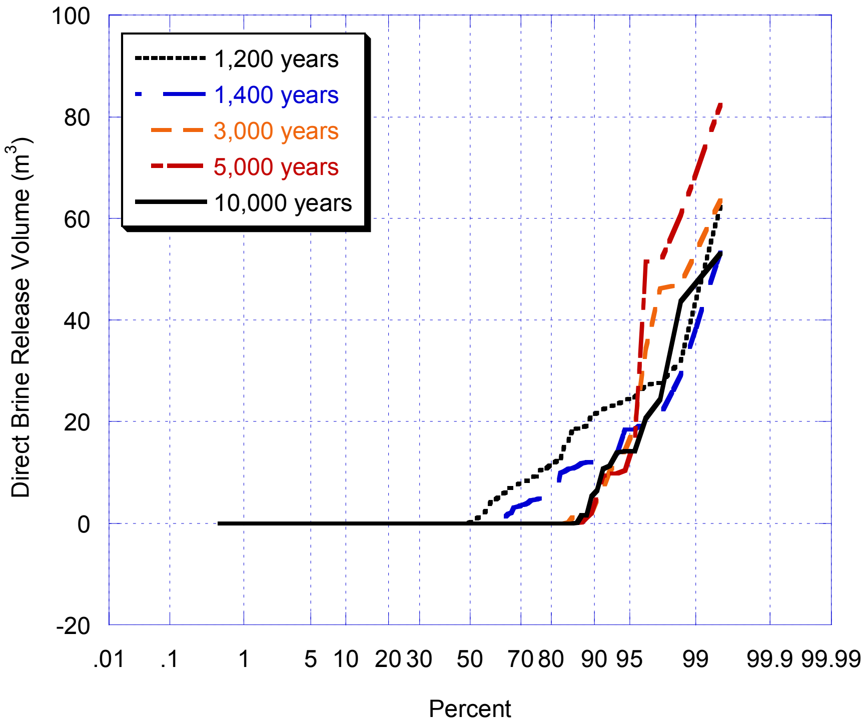


***Figure PA-86c. DBRs for Subsequent Intrusions into Lower Panel After an E1 Intrusion at 1,000 Years (Scenario S3), Replicate R1.***

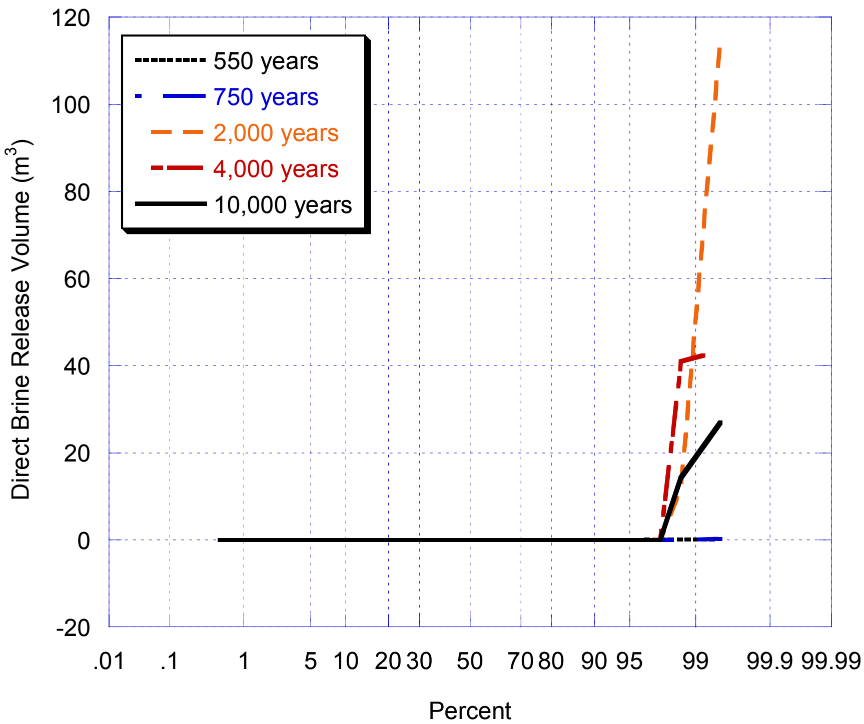


***Figure PA-86d. DBRs for Subsequent Intrusions into Lower Panel After an E2 Intrusion at 350 Years (Scenario S4), Replicate R1.***

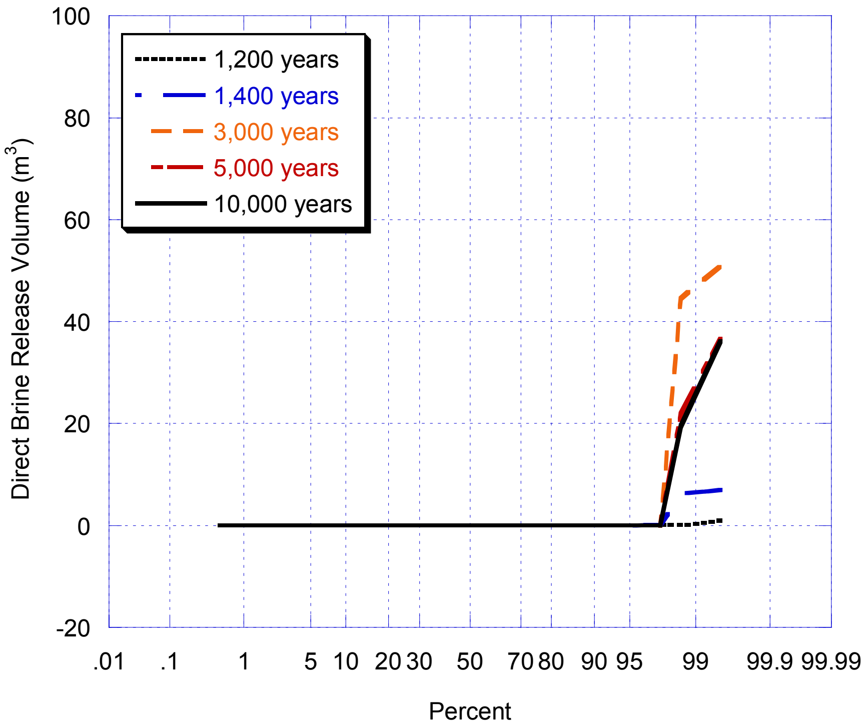


*Figure PA-86e. DBRs for Subsequent Intrusions into Lower Panel After an E2 Intrusion at 1,000 Years (Scenario S5), Replicate R1.*

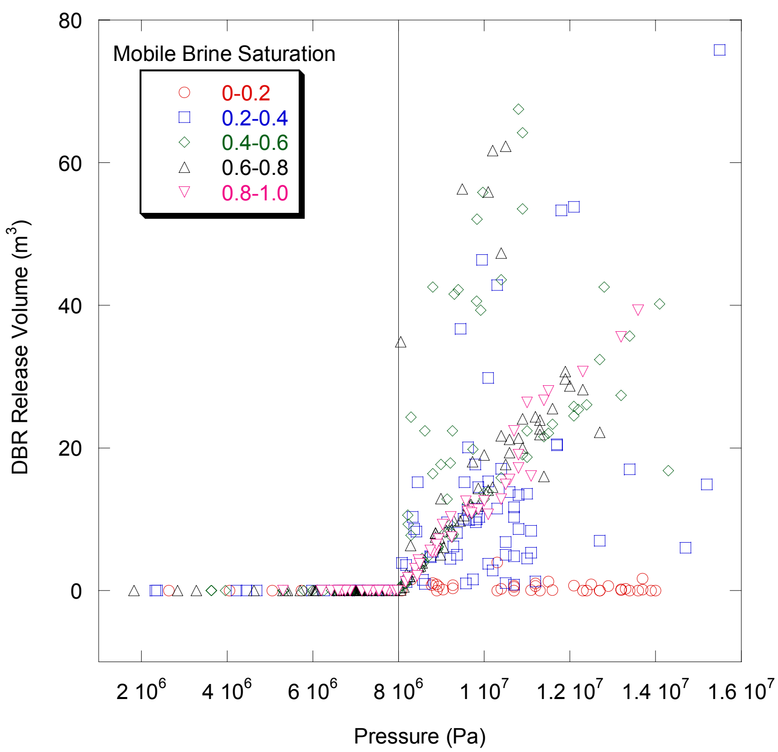


*Figure PA-87. Sensitivity of DBR Volumes to Pressure, Replicate R1, Scenario S2, Lower Panel.*

***Figure PA-88 plots pressure against mobile brine saturation for the S2 scenario for all intrusion times with symbols indicating the range of DBR volumes. It is clear from Figure PA-88 that not all the variability in DBRs can be explained by pressure and saturation alone.***

***Borehole permeability can also be an important parameter controlling the volume of direct brine released. Borehole permeability is not a direct input to the DBR calculations, but this parameter affects conditions in the repository as modeled in the 10,000-year BRAGFLO calculations, which are used as initial conditions of the DBR model. Figure PA-89 shows a scatter plot of the log of borehole permeability against DBR volume for Scenario S2, lower intrusion with symbols indicating intrusion times. As borehole permeability decreases direct brine releases tend to increase, especially at late intrusion times (4,000 and 10,000 years). Helton et al. (1998) identified this same relationship in analysis of the CCA PA. Low values of borehole permeability tend to result in higher pressures following an E1 intrusion (Figure PA-53), which in turn lead to higher DBRs from subsequent intrusions.***

***The distributions presented in Figure PA-86 are for volumes of brine that could be released by a single intrusion. The code CCDFGF stochastically generates futures for the repository, specifying drilling times and locations, and constructs the distribution of total brine volume released (see Section PA-6.5 and Section PA-6.8). Figure PA-90 shows the CCDFs for the total brine volume released for replicate R1. Figure PA-91 compares the statistics for the CCDFs for total brine volume released among the three replicates, and shows that the three replicates produced similar results. Due to the number of observations which do not plot on the scale of Figure PA-90, the 10^th^ quantiles do not appear on Figure PA-91.***

***Table PA-29 summarizes a stepwise regression analysis for mean total DBR volume. The uncertain parameters most important to uncertainty in total DBR volumes are those related to repository pressure (the indicator for microbial action (WMICDFLG) and the rate of steel corrosion (WGRCOR)) and brine saturation (the probability of an intrusion into the Castile brine reservoir (PBRINE), the pressure in the Castile brine reservoir (BPINTPRS), the permeability of the DRZ around the panel closures (DRZPCPRM), and the residual brine saturation in the waste (WRBRNSAT)). The linear regression model is not very effective at explaining the uncertainty in the total DBRs. The lack of resolution is due to the large number of vectors in which no direct brine releases occur; this conclusion was reached after analysis of the CCA PA (Helton et al. 1998).***

#### ***PA-8.5.4 Additional Information***

***Dunagan (2003b) provides additional information about the cuttings and cavings releases calculated for the CRA-2004 PA. Additional information about the spallings releases is found in Lord et al. (2003) and Lord and Rudeen (2003). Stein (2003) provides detailed analysis of direct brine releases in the CRA-2004 PA.***

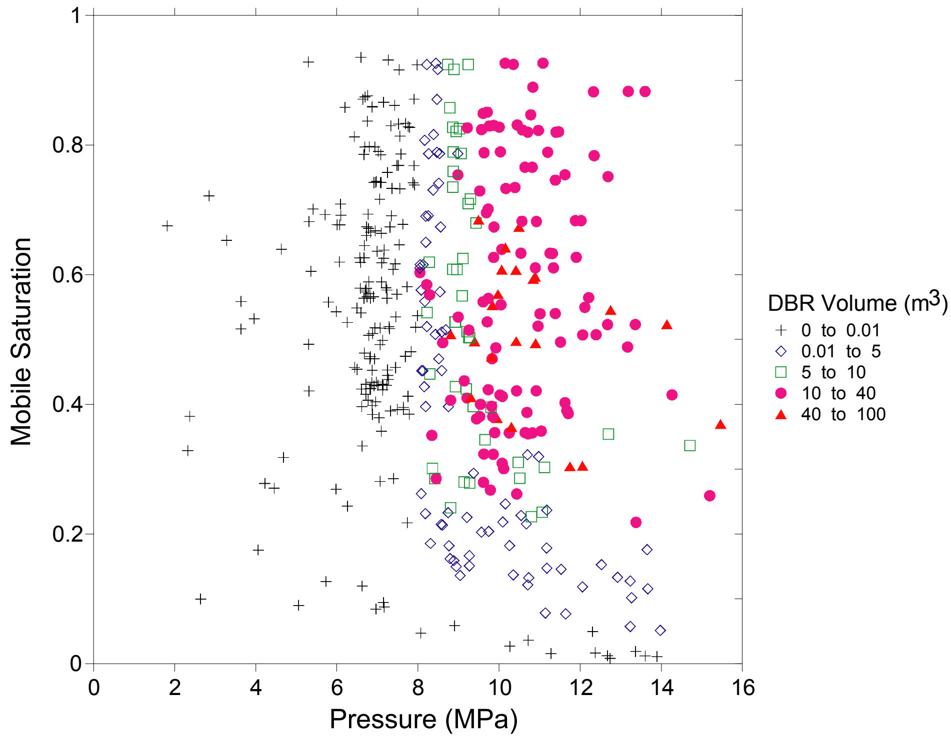


*Figure PA-88. Sensitivity of DBR Volumes to Pressure and Mobile Brine Saturation, Replicate R1, Scenario S2, Lower Panel.*

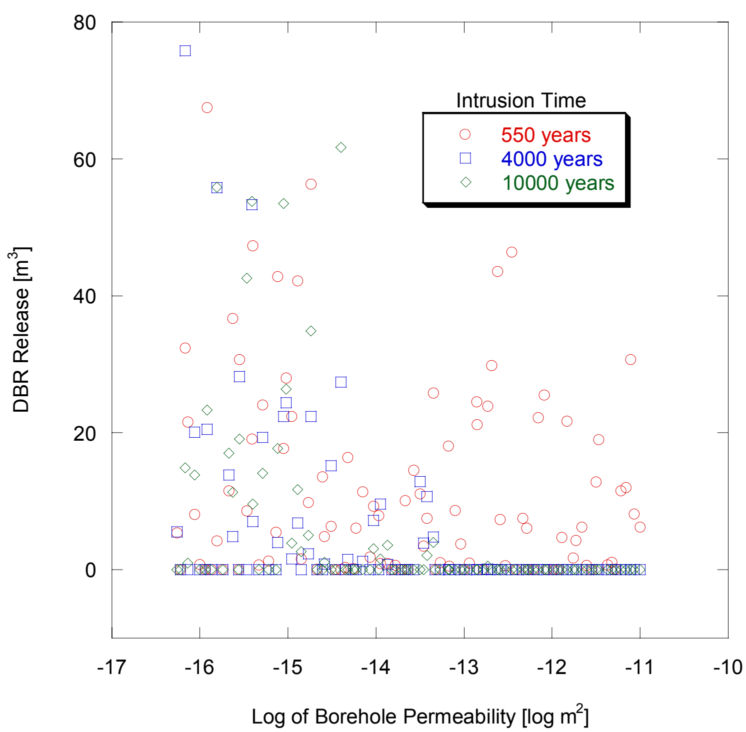


*Figure PA-89. Sensitivity of DBR Volumes to Borehole Permeability, Replicate R1, Scenario S2, Lower Panel.*

### *Table PA-29. Stepwise Regression Analysis for Mean Total DBR Volume*

| Step[1] | Expected Normalized Release | | |
|---|---|---|---|
| | Variable[2] | SRRC[3] | $R^2$ [4] |
| 1 | WMICDFLG | –0.583 | 0.239 |
| 2 | PBRINE | –0.385 | 0.378 |
| 3 | BPINTPRS | 0.389 | 0.515 |
| 4 | WGRCOR | –0.190 | 0.553 |
| 5 | DRZPCPRM | 0.176 | 0.585 |
| 6 | WRBRNSAT | –0.168 | 0.613 |

[1] Steps in stepwise regression analysis
[2] Variables listed in order of selection in regression analysis
[3] Standardized Rank Regression Coefficient in final regression model
[4] Cumulative $R^2$ value with entry of each variable into regression model

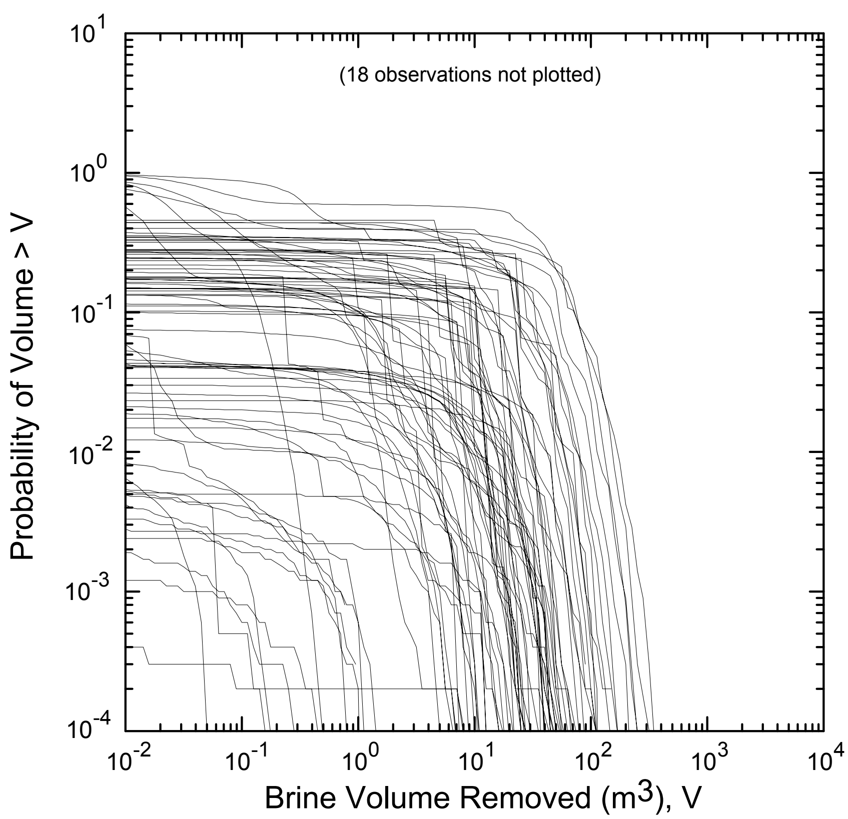


*Figure PA-90. Total DBRs Volumes, Replicate R1.*

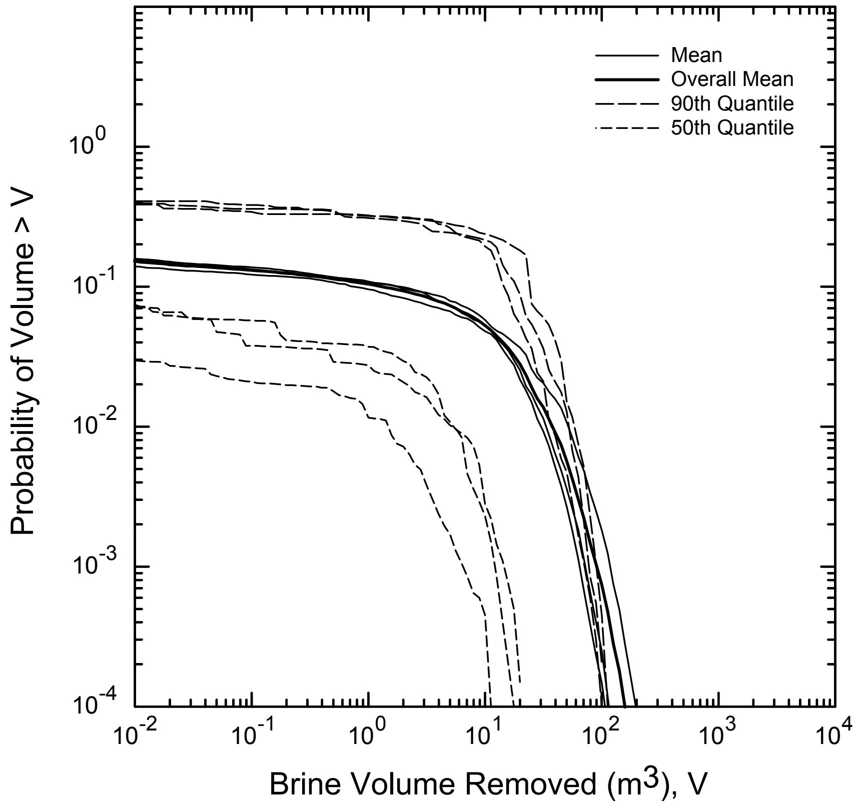


***Figure PA-91. Statistics for Total DBR Volumes, All Replicates.***

# *PA-9.0 NORMALIZED RELEASES*

***This section presents total normalized releases, followed by discussion of each of the four categories of releases that constitute the total release: cuttings and cavings; spallings; DBRs; and transport releases. Finally, this section concludes with a discussion of the sensitivity of total releases to uncertainty in parameter values.***

## *PA-9.1 Total Releases*

***Figures PA-92, PA-93, and PA-94 show the CCDFs for total releases for replicates R1, R2, and R3 of the CRA-2004 PA. Each CCDF lies below and to the left of the limits specified in 40 CFR § 191.13(a). Thus, the WIPP continues to comply with the containment requirements of 40 CFR Part 191. The consistent increase in total releases at a probability of approximately 0.003 results from unlikely cuttings and cavings releases, as discussed in Section PA-9.6.1.***

***To compare the distributions of CCDFs among replicates and to demonstrate sufficiency of the sample size, mean and quantile CCDFs are computed. At each value for normalized release R on the abscissa, the CCDFs for a single replicate define 100 values for probability. The arithmetic mean of these 100 probabilities is the mean probability that release exceeds R; the curve defined by the mean probabilities for each value of R is the mean CCDF. The quantile CCDFs are defined analogously.***

***Figure PA-95 compares the mean, median, 90$^{th}$ and 10$^{th}$ quantiles for each replicate's distribution of CCDFs for total releases. Figure PA-95 shows that each replicate's distribution is quite similar, and shows qualitatively that the sample size of 100 in each replicate is sufficient to generate a stable distribution of outcomes.***

***Each of the mean and quantiles CCDFs in Figure PA-95 is an estimate of the true mean CCDF of the population of CCDFs. The overall mean CCDF is computed as the arithmetic mean of the three mean CCDFs from each replicate, and is an estimate of the true mean CCDF. To quantitatively determine the sufficiency of the sample size, a confidence interval is computed about the overall mean CCDF using Student's t-distribution. Figure PA-96 shows 95 percent confidence intervals about the overall mean, and provides quantitative confirmation of the sufficiency of the sample size, by displaying the overall mean together with the 0.95 confidence interval of the Student's t-distribution estimated from the individual means of the three independent replicates.***

***Figure PA-97, Figure PA-98, and Figure PA-99 show the mean CCDFs for each component of total releases, for replicates R1, R2, and R3, respectively. In each replicate, the location of the mean CCDF for total releases is dominated by the cuttings and cavings releases. The mean predicted released from spallings and direct brine are an order of magnitude less than mean releases for cuttings and cavings; therefore, these categories of releases make relatively little contribution to the location of the mean CCDF for total releases. Release by subsurface transport in the Salado or Culebra make essentially no contribution to total releases.***

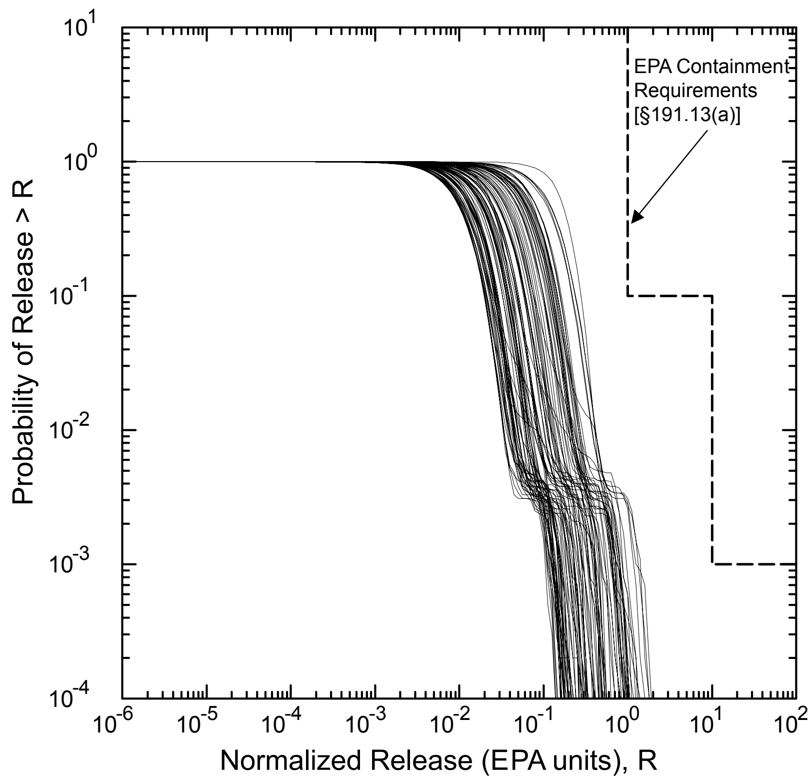


***Figure PA-92. Total Normalized Releases, Replicate R1.***

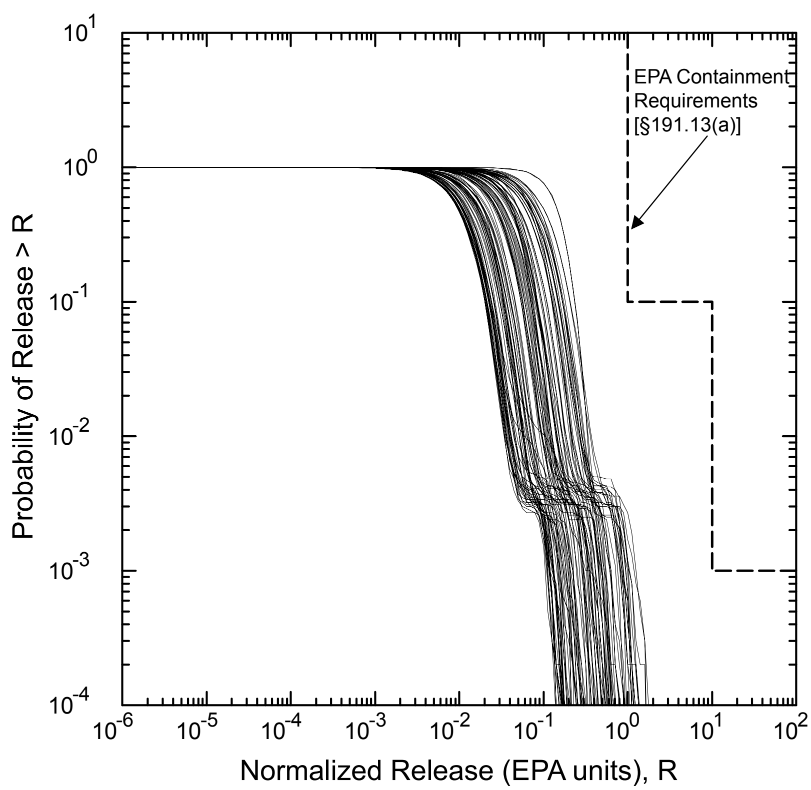


***Figure PA-93. Total Normalized Releases, Replicate R2.***

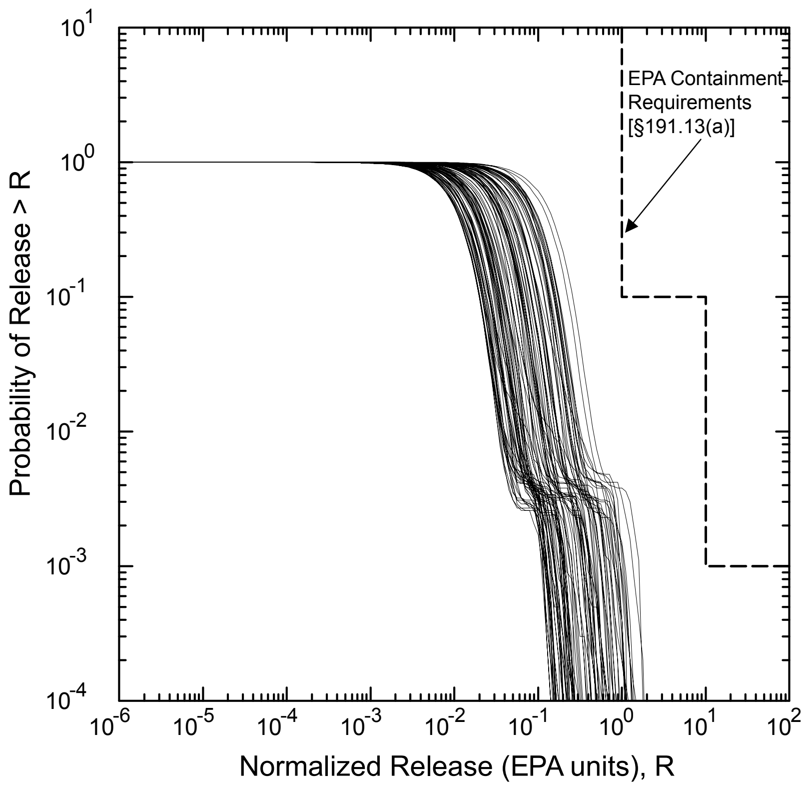


***Figure PA-94. Total Normalized Releases, Replicate R3.***

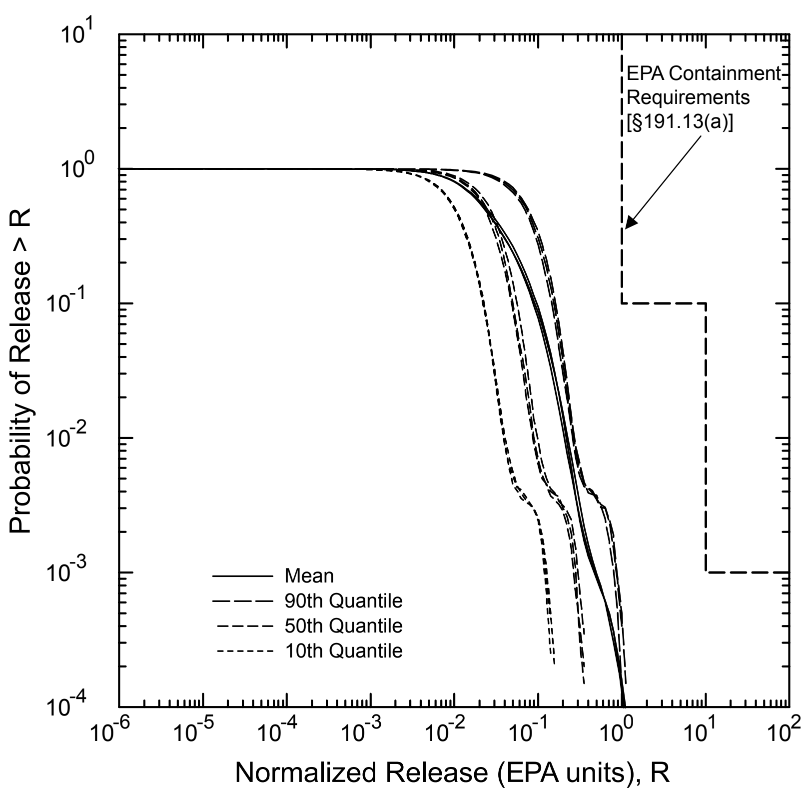


***Figure PA-95. Mean and Quantiles CCDFs for Total Normalized Releases, All Replicates.***

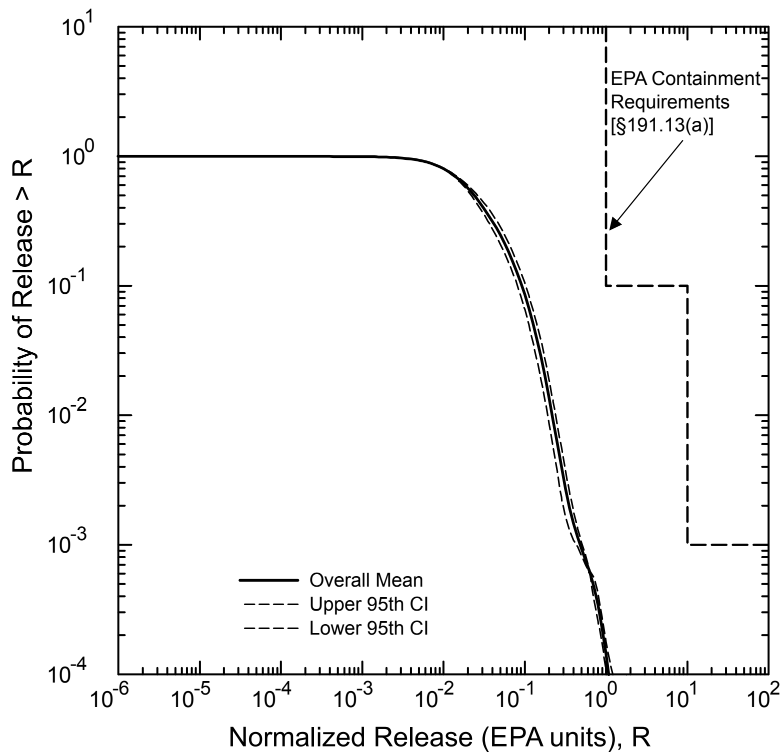


***Figure PA-96. Confidence Interval on Overall Mean CCDF for Total Normalized Releases.***

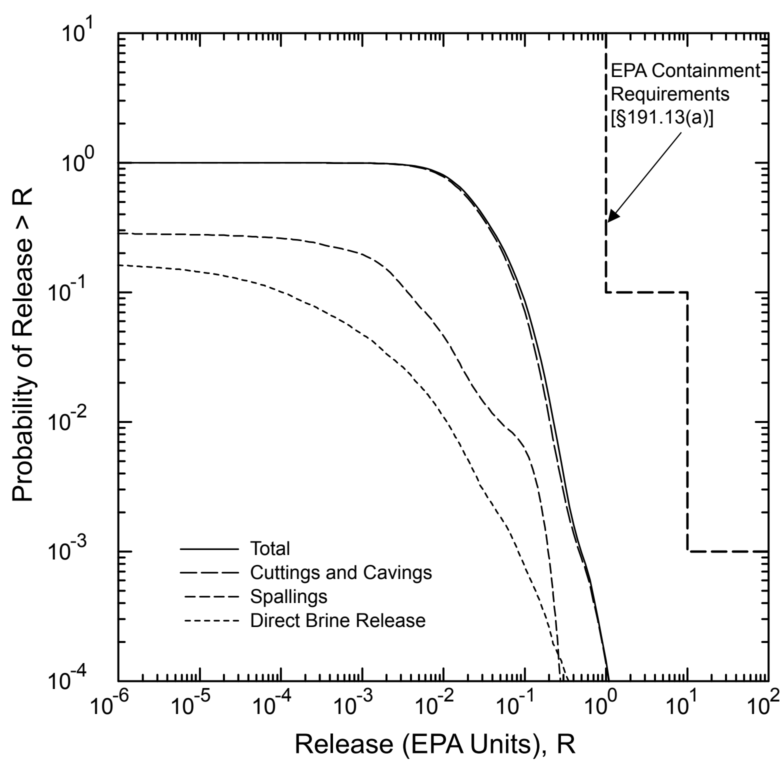


***Figure PA-97. Mean CCDFs for Components of Total Normalized Releases, Replicate R1.***

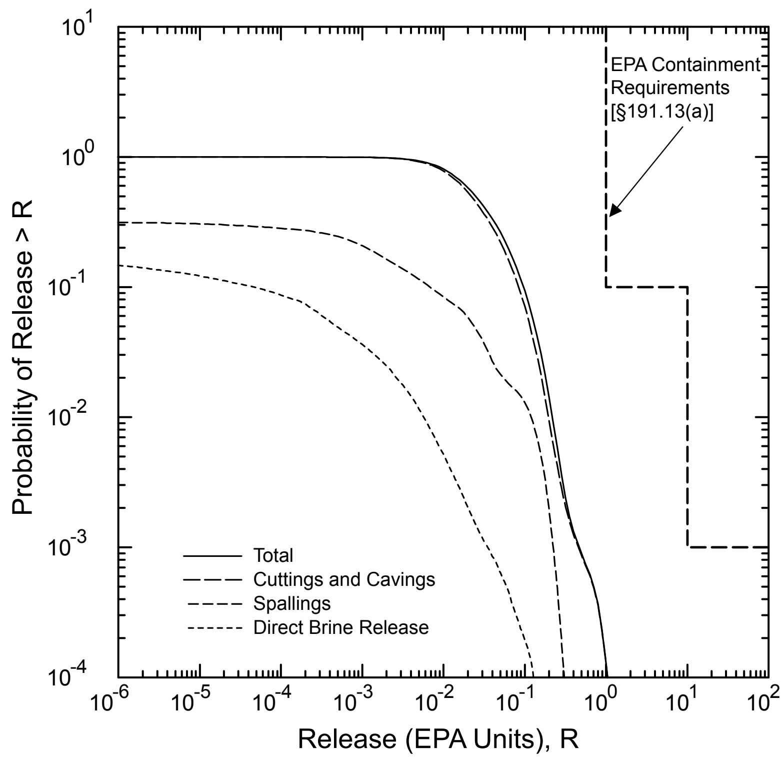


***Figure PA-98. Mean CCDFs for Components of Total Normalized Releases, Replicate R2.***

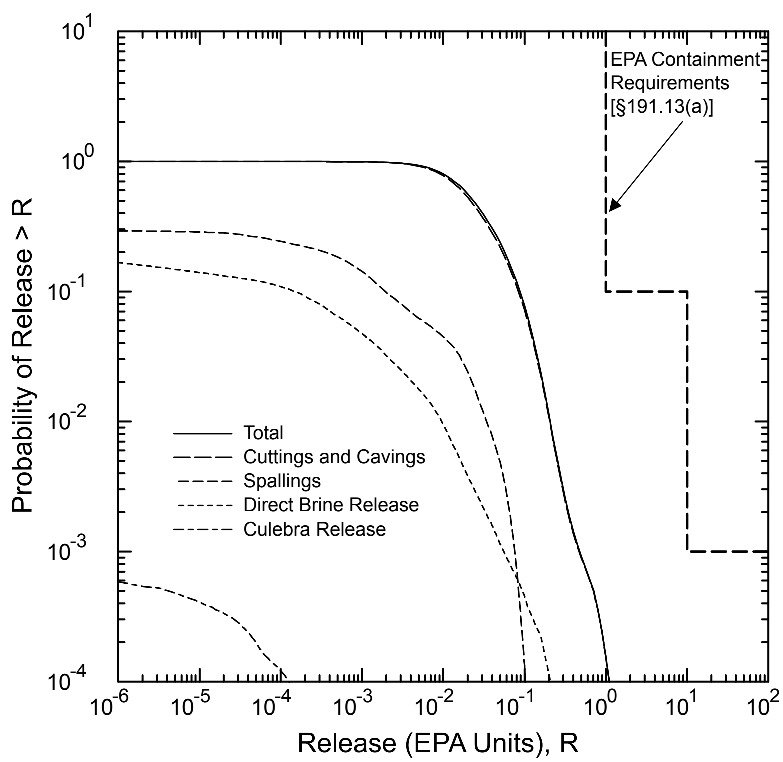


***Figure PA-99. Mean CCDFs for Components of Total Normalized Releases, Replicate R3.***