SANDIA NATIONAL LABORATORIES
WASTE ISOLATION PILOT PLANT

ANALYSIS REPORT FOR CUTTINGS, CAVINGS, AND SPALLINGS IN THE 2026 COMPLIANCE RECERTIFICATION APPLICATION PERFORMANCE ASSESSMENT: INTERIM STATE REPOSITORY

REVISION 1

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JULY 2026

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Executive Summary

The Waste Isolation Pilot Plant (WIPP) was initially certified as a repository consisting of 10 panels, which were excavated for the long-term storage and placement of transuranic waste (U.S. EPA, 1998). However, due to operational constraints, the entire volume of the 10 panels is no longer available for waste disposal. In March 2024, the U.S. Department of Energy (DOE) submitted the Replacement Panels Planned Change Request (RPPCR) to the U.S. Environmental Protection Agency (EPA) for approval of waste emplacement in two new panels. These panels, referred to as replacement panels, are located to the west of the existing operations area. The EPA approved the RPPCR in July 2025 (U.S. EPA, 2025).

The addition of the two replacement panels is not expected to provide adequate space for the disposal of the allowable waste volume designated for WIPP under the Land Withdrawal Act (LWA); thus, the 12-panel configuration is regarded as an interim state of the repository. The DOE may pursue approval for waste disposal in seven additional panels to accommodate the full allowable volume of waste. This hypothetical 19-panel configuration is considered the anticipated final state of the repository.

The DOE demonstrates compliance with containment requirements as outlined in the Certification Criteria of Title 40 CFR Part 191.13 through performance assessment (PA). PA calculations estimate the probability and consequences of potential radionuclide releases from the repository to the accessible environment over a regulatory period of 10,000 years following facility closure. WIPP PA models are utilized to support the periodic recertification of WIPP.

The 2026 Compliance Recertification Application (CRA-2026) represents the fifth recertification application submitted to the EPA. A PA has been carried out by Sandia National Laboratories to support the DOE's submission of the CRA-2026. The results presented in the CRA-2026 PA are compared to those from the RPPCR PA, the most recent regulatory submission.

This analysis report documents the direct solids releases component of the CRA-2026 PA for the interim state repository and describes the effects of changes introduced in the CRA-2026 PA that influence the CUTTINGS_S model. Compared to the RPPCR, the primary effect is an increase in spallings concentrations driven by updates to the waste inventory, while spallings volumes remain similar between analyses. Cuttings and cavings results are unchanged. Overall, the CRA-2026 PA exhibits behavior consistent with the RPPCR, with no substantive changes to the underlying direct-release models.

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NOTES FOR REVISION 1

Revision 1 of this report expands the description of sampled and constant parameters for spallings calculations, providing more details on waste mechanical properties and drilling conditions. Additional figures and tables provide more granular statistics and visualizations by scenario, location, and replicate. Additional replicate-specific results are included for completeness.

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1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP), located in southeastern New Mexico, has been developed by the U.S. Department of Energy (DOE) for the geologic disposal of transuranic (TRU) waste. The containment of TRU waste at WIPP is regulated by the U.S. Environmental Protection Agency (EPA) under Title 40 of the Code of Federal Regulations (CFR), Part 191.

The DOE demonstrates compliance with the containment requirements of 40 CFR 191.13 by means of performance assessment (PA) as described in the Certification Criteria of Title 40 CFR Part 194. Sandia National Laboratories (SNL) conducts PAs at the request of the DOE. The PA calculations estimate the probability and consequences of potential radionuclide releases from the repository to the accessible environment over a regulatory period of 10,000 years following facility closure. The PA models are continuously maintained and updated with new information, which typically leads to refinement and modifications in both the models and their parameters. Additionally, planned changes to the repository and its components necessitate updates to the WIPP PA models.

All previous WIPP certifications have been based on a repository consisting of 10 panels. In March 2024, the DOE submitted the Replacement Panels Planned Change Request (RPPCR) to seek EPA approval for waste emplacement in two new panels, referred to as replacement panels, located to the west of the existing operations area (Bollinger, 2024). The EPA approved the RPPCR in July 2025 (U.S. EPA, 2025).

The addition of the two replacement panels is not expected to provide sufficient space for the disposal of the allowable waste volume designated for WIPP under the Land Withdrawal Act (LWA). The 12-panel configuration is thus regarded as an interim state of the repository. The DOE may seek approval for waste disposal in up to seven additional panels to accommodate the full allowable volume of waste. This 19-panel configuration is considered the anticipated final state of the repository.

The CRA-2026 is the fifth recertification application for the WIPP submitted by the DOE for EPA approval. The PA executed by SNL in support of the CRA-2026 PA is described in AP-214 (Hansen et al., 2025). This analysis report documents the direct solids releases in the CRA-2026 PA for the interim state repository.

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2.0 CHANGES SINCE THE RPPCR

Several changes are incorporated in the CRA-2026 PA relative to the RPPCR that may impact direct solids releases. These changes include:

- The repository design.
- Parameters related to repository dimensions.
- MgO hydration parameters.
- The Salado flow and transport computational grid.
- The waste inventory.
- A new lower bound on capillary pressure in the anhydrite marker beds.
- Revisions to the porosity-permeability parameter distribution.

Changes listed above are discussed in more detail in the sections that follow.

2.1 Repository Design

This analysis represents the 12-panel interim state repository consisting of ten original and two replacement panels. Figure 1 depicts the interim state repository. The RPPCR considered the anticipated final repository state, which included a total of 19 waste panels and the entire allowable inventory volume.

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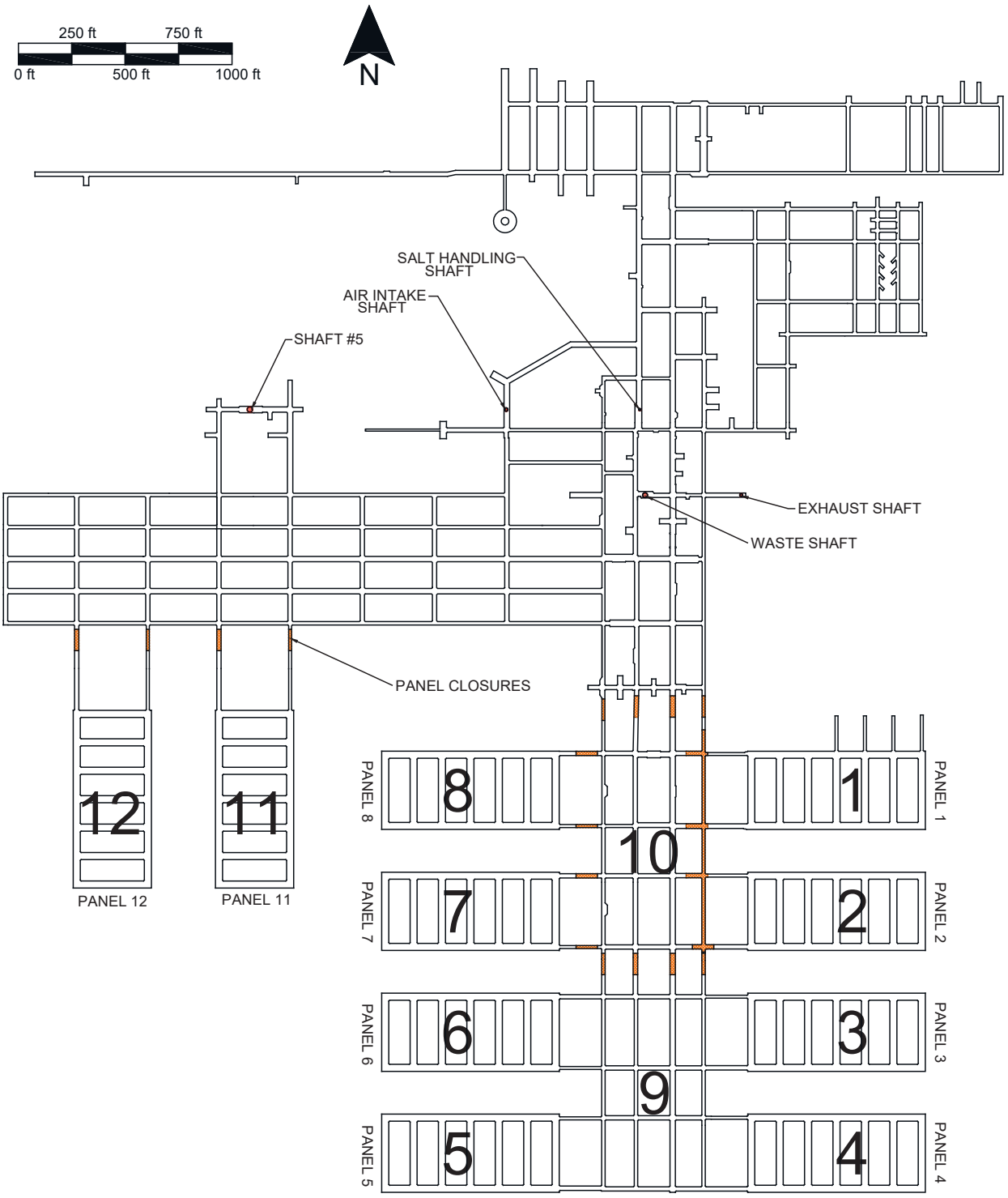


Figure 1. Interim State Repository Layout

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2.2 Parameters Related to Repository Dimensions

The repository design (Section 2.1) requires changes to several parameters describing repository dimensions. Brunell (2025) revises four parameters to align with the dimensions used in the development of the Salado flow and transport grid (Section 2.4). The parameters include:

- the waste storage volume (REFCON:VREPOS).
- the area of the berm placed over the waste panels (REFCON:ABERM).
- the area allocated for contact-handled (CH) waste disposal (REFCON:AREA_CH).
- the fraction of the repository volume occupied by CH waste (REFCON:FVW).

Although not listed in AP-214 as an anticipated change (Hansen et al., 2025), the area for emplaced remote-handled (RH) waste (REFCON:AREA_RH) is revised by King (2025a) due to the reduced inventory volume used in the CRA26_IS PA calculation (see Section 2.5). The updated values are provided in Table 1.

Table 1. Changed Repository Parameters

Material	Property	RPPCR Value	CRA-2026 IS Value	Units
REFCON	VREPOS	853,284.89	560,722.29	m^3
REFCON	ABERM	1,268,303	750,000	m^2
REFCON	AREA_CH	216,952	141,511	m^2
REFCON	FVW	0.197	0.279	-
REFCON	AREA_RH	15,760	3,528	m^2

2.3 MgO Hydration Parameters

The rate of hydration of MgO to form brucite, $Mg(OH)_2$, in the Salado flow model is specified for humid (WAS_AREA:BRUCITEH), Castile brine inundated (WAS_AREA:BRUCITEC), and Salado brine inundated (WAS_AREA:BRUCITES) conditions. Although changes to the MgO hydration rate parameters were not anticipated in AP-214 (Hansen et al., 2025), Nemer (2025) recommends new parameter distributions for the Castile and Salado brine inundated conditions. King (2025b) redefines the recommended distributions to be compatible with the WIPP PA code LHS.

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2.4 Updates to the Salado Flow and Transport Computational Grid

Dimensions in the computational grid for the Salado flow (BRAGFLO) and transport (NUTS) calculation are changed to be consistent with the interim state repository dimensions (Section 2.1). Day (2025a) modifies the computational grid based on as-built excavation footprint dimensions within the existing repository, plans for future excavations, and the planned change for alternative panel closure locations for Panels 1 and 2 (Knerr, 2020). The Salado flow and transport computational grid is shown in Figure 2.

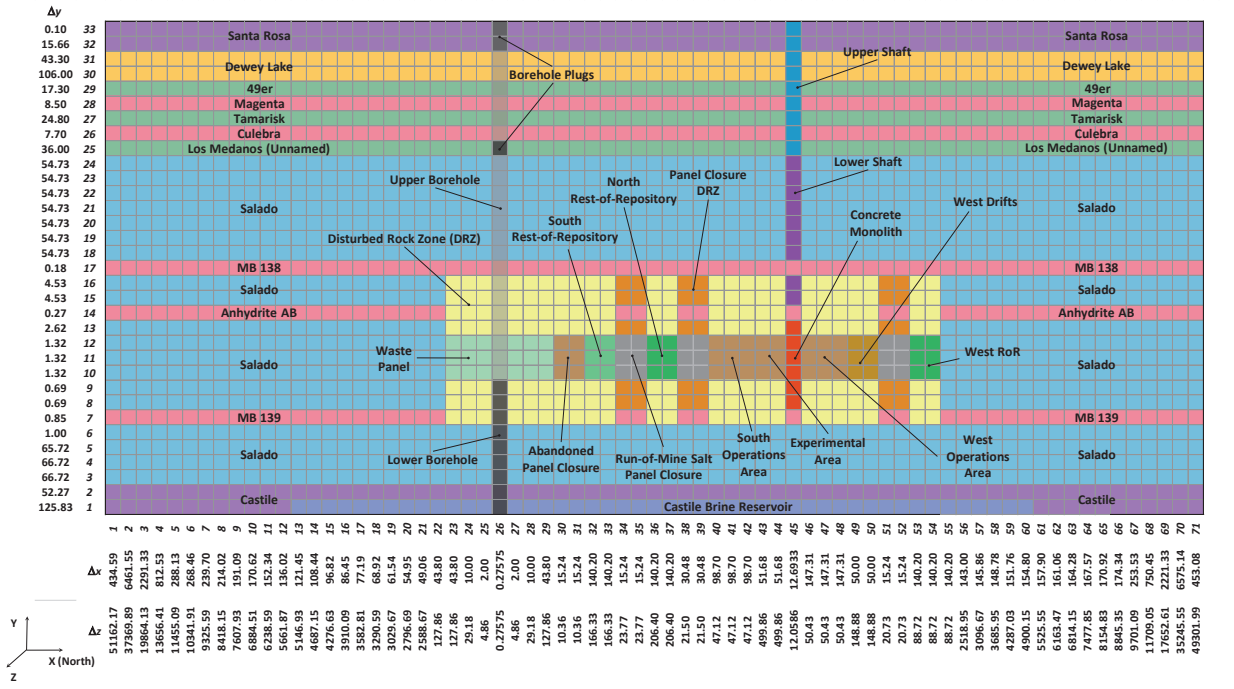


Figure 2. CRA26_IS Salado Flow and Transport Computational Grid

2.5 Waste Inventory

The LWA establishes a statutory limit on the volume of waste that can be disposed of in the WIPP repository, set at 175,564 m^3 (6,200,000 ft^3). Current assessments indicate that the interim state repository will accommodate less waste than the LWA volume. Ward (2025) provided an assessment of the projected waste storage capacity at 157,837.92 m^3, which includes 156,247.12 m^3 of Contact-Handled (CH) waste and 1,584.80 m^3 of Remote-Handled (RH) waste. Based on information collected up to December 31, 2023, the Interim State Performance Assessment Inventory Report – 2024 (ISPAIR-2024; Van Soest, 2025) offers an inventory estimate scaled to the waste volume specified by Ward (2025). Kicker (2025) conducted a screening analysis of the inventory estimates for the ISPAIR-2024 to define the inventory-related input parameters for the PA calculations.

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2.6 Lower Bound on Capillary Pressure in the Anhydrite Marker Beds

To improve the numerical stability of the Salado flow model when using the modified van Genuchten-Parker capillary pressure function in the anhydrite marker beds, Version 8.00 of the PA code BRAGFLO introduces a new capillary pressure model that incorporates a lower bound on capillary pressure (WIPP PA, 2025). This lower bound is applied when brine saturations exceed one minus the residual gas saturation. Day (2025b) sets the lower bound on capillary pressure to 1 atm (101,325 Pa), with the PO_MIN property of the S_MB139, S_ANH_AB, and S_MB138 materials, and applied the new capillary pressure model by setting the CAP_MOD property to 6 for the same materials.

2.7 Porosity-Permeability Parameter Distribution

King (2025b) redefines the distribution for the parameter representing the relationship between porosity and permeability in a run-of-mine salt panel closure system during the secondary time duration (PCS_T2:POR2PERM). Initially defined as a truncated normal distribution, this parameter is revised, along with the MgO hydration parameters, to a cumulative distribution characterized by discrete data points. This change constitutes a deviation from AP-214 (Hansen et al., 2025).

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3.0 CONCEPTUAL APPROACH FOR THE CRA-2026

This section describes the conceptual basis used to calculate direct solids releases for the CRA26_IS analysis. The code CUTTINGS_S represents releases resulting from drilling intrusions into the repository using three solid-volume removal mechanisms:

- Cuttings, representing material removed directly by the drill bit;
- Cavings, representing shear-induced erosion of waste from the borehole wall; and
- Spallings, representing gas-driven expulsion of waste into and up through the borehole when repository pressures exceed waste tensile strength.

CUTTINGS_S integrates scenario-specific intrusion conditions obtained from BRAGFLO with spallings response functions generated by DRSPALL. Together, these models characterize the waste removal mechanisms due to drilling, the conditions under which they occur, and the subsequent use of these results in the overall PA framework.

3.1 Cuttings and Cavings

The solid material extracted from the repository and transported to the surface by the drilling fluid during borehole drilling is categorized into cuttings and cavings. For the CRA26_IS, cuttings and cavings were computed using the same conceptual and numerical models as those employed in the RPPCR; these models are detailed in the CUTTINGS_S design document (WIPP PA, 2021).

CUTTINGS_S calculates the base area of the cylinder of cuttings and cavings removed as a result of a drilling intrusion into the repository. The area of cuttings removed and transported to the surface in the drilling mud corresponds to the drill bit area A_{cut}. The cuttings area A_{cut} and uncompacted volume V_{cut} removed are expressed by Equations 1 and 2:

$$A_{cut} = \frac{\pi D^2}{4} \qquad (1)$$

$$V_{cut} = A_{cut} H = \left(\frac{\pi D^2}{4}\right) H \qquad (2)$$

where D = 0.31115 m is the drill bit diameter (BOREHOLE:DIAMMOD) and H = 3.96 m is the uncompacted repository height (BLOWOUT:HREPO) (WIPP PA, 2021). Since both the drill bit diameter D and the repository height H are treated as constant parameters, both the drill bit area A_{cut} and cuttings volume V_{cut} are fixed quantities for the CRA26_IS.

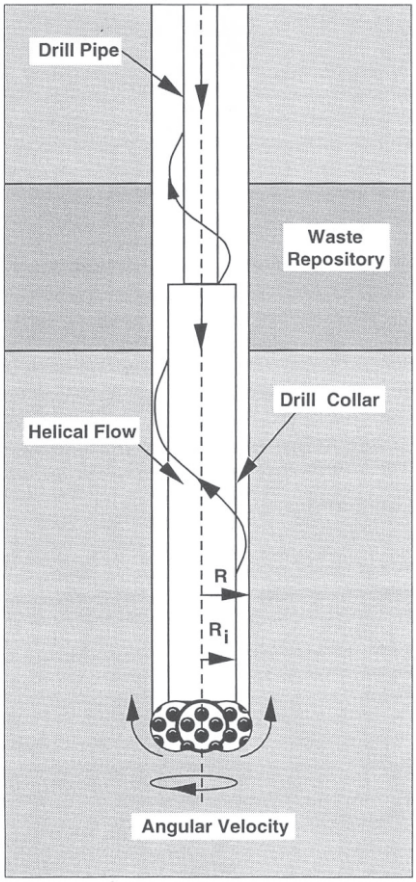
WIPP PA estimates cavings removal using a model that considers the effect of shear stress on the material adjacent to the borehole edge. Specifically, it is assumed that material around the borehole edge shears off until the shear stress on the borehole wall equals the shear strength of the waste, which represents the maximum shear stress at which erosion can occur. This process is modeled as radially symmetric, treating the cavings area as an annulus surrounding the initial cuttings area (Figure 3).

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The final eroded diameter, D_f, of the borehole determines the volume V of uncompacted waste that will be removed to the surface by circulating drilling fluid. This total combined volume of cuttings and cavings removed is represented by Equation 3:

$$V = V_{cut} + V_{cav} = \frac{\pi D_f^2 H}{4} \quad (3)$$

Where V_{cav} is the volume (m^3) of waste removed as cavings. Different models are used to determine the eroded diameter of a borehole, depending on whether flow in the vicinity of the drill collar is laminar or turbulent. For an in-depth discussion of these models, as well as a more comprehensive discussion of the conceptual model for cavings, refer to WIPP PA (2021).



From Helton et al. (1998).

Figure 3. Detail of Rotary Drill String Adjacent to the Drill Bit

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3.2 Spallings

This section outlines the methodology employed by CUTTINGS_S to calculate spalling volumes released to the surface during WIPP drilling intrusion scenarios. The conceptual model for spallings is documented by Lord et al. (2006; Section 3) and implemented in the code DRSPALL. Spallings volumes are calculated based on pressure conditions in the repository waste areas. Time-dependent spallings volumes are determined by interpolating the spallings volumes calculated by DRSPALL to the time-dependent repository pressures calculated by BRAGFLO. DRSPALL uses sampled parameter values from the LHS code but has no dependencies on outputs of other PA codes (Lord and Rudeen, 2003). It is for this reason that DRSPALL is not typically run during a PA calculation. Both the RPPCR and the CRA26_IS use DRSPALL outputs from a previous analysis (Kirchner et al., 2014; 2015).

Spallings consist of waste that enters the borehole due to the release of waste-generated gas escaping into the borehole, which is at a lower pressure than the gas. As in previous analyses, calculation of spallings releases for the CRA26_IS is divided into five steps (Lord et al., 2003):

1. Characterization of the subjective uncertainty when calculating spallings volumes.
2. Calculation of spallings volumes using DRSPALL to account for subjective uncertainty in waste properties.
3. Interpolation of DRSPALL volumes in CUTTINGS_S to derive spallings volumes for drilling intrusion scenarios.
4. Calculation of spallings concentrations using PRECCDFGF (WIPP PA, 2022b).
5. Calculation of spallings releases, incorporating stochastic uncertainty regarding the future of the repository using CCDFGF (WIPP PA, 2022a).

The work presented in this report is limited to Step 3 and Step 4. For each vector, the code DRSPALL computes the spallings volume generated for four initial repository pressures: P_1 = 10 MPa, P_2 = 12 MPa, P_3 = 14 MPa, and P_4 = 14.8 MPa. The lower limit P_1 is established as a threshold, as repository pressures at or below 10 MPa do not yield spallings. The upper limit P_4 corresponds to lithostatic pressure; repository pressures exceeding this value result in repository fracture (Lord et al., 2003).

For each vector within a specific combination of intrusion scenario, time, and location, the initial repository pressure P is determined using data from prior BRAGFLO calculations (Day and King, 2025). If V_i (where i = 1, 2, 3, or 4) denotes the volume calculated by DRSPALL corresponding to pressure P_i, CUTTINGS_S computes the spallings volume V_{spall} as a function of P for a given vector using the formula presented in Equation 4 (WIPP PA, 2021):

$$V_{spall}(P) = \begin{cases} V_1, & P \le P_1 \\ V_i + \dfrac{P - P_i}{P_{i+1} - P_i}(V_{i+1} - V_i), & P_i \le P \le P_{i+1}, i = 1, 2, \text{or } 3 \\ V_4, & P \ge P_4 \end{cases} \quad (4)$$

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3.3 CUTTINGS_S and Integrated PA Components

Building on the conceptual framework outlined above, the following section details the specific implementation of these mechanisms within the CUTTINGS_S model for the CRA26_IS analysis.

Spallings volumes are provided through pre-calculated DRSPALL response surfaces. DRSPALL computes spallings volumes as a function of repository pressure and sampled waste properties (porosity, permeability, tensile strength, and particle size). These volumes are not recalculated during the PA but are interpolated within CUTTINGS_S.

Repository pressure, brine saturation, porosity, and other state variables for each intrusion scenario are obtained from BRAGFLO. CUTTINGS_S uses these BRAGFLO outputs to determine the conditions present at the time and location of each drilling intrusion and to map those conditions onto the DRSPALL pressure–volume functions.

3.4 Intrusion Scenarios

As described by Day and King (2025), the five BRAGFLO Salado flow scenarios capture the long-term behavior of the repository under three different conditions: undisturbed (E0); intersected by a borehole that continues down to a hypothetical pressurized brine reservoir below the repository (E1); and intersected by a borehole that does not intersect pressurized regions below the repository (E2).

CUTTINGS_S uses the standard WIPP PA drilling scenarios S1-DBR through S5-DBR (Table 2). These scenarios differ by whether a prior intrusion has occurred, the timing between intrusions, the spatial location within the repository grid (L, M, U, and O), and whether the intrusion intersects a pressurized brine pocket. In total, CUTTINGS_S evaluates 31,200 calculations across these scenarios. The “-DBR” suffix differentiates them from the BRAGFLO Salado flow scenarios.

Scenario S1-DBR represents an intrusion into an undisturbed repository. CUTTINGS_S computes cuttings, cavings, and spallings releases at the four drilling locations (L, M, U, and O). Initial conditions for each calculation are taken from the BRAGFLO S1-BF outputs at the time of intrusion.

Scenarios S2-DBR through S5-DBR model a second intrusion occurring after an earlier E1 or E2 event. For the second intrusion, CUTTINGS_S again evaluates releases at the four drilling locations, which correspond to same-panel, connected-panel, adjacent-panel, and nonadjacent-panel intrusions, respectively. Initial conditions for each calculation are taken from the BRAGFLO scenario at the time of the second intrusion.

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Table 2. Intrusion Scenarios Used in Calculating Direct Brine and Spallings Releases

Scenario	Description
S1-DBR	Initially undisturbed repository (E0 conditions). Intrusion at the L, M, U, or O location at 100; 350; 1,000; 3,000; 5,000; or 10,000 years: 24 combinations.
S2-DBR	Initial E1 intrusion at 350 years followed by a second intrusion at the L, M, U, or O location at 550; 750; 2,000; 4,000; or 10,000 years: 20 combinations.
S3-DBR	Initial E1 intrusion at 1,000 years followed by a second intrusion at the L, M, U, or O location at 1,200; 1,400; 3,000; 5,000; or 10,000 years: 20 combinations.
S4-DBR	Initial E2 intrusion at 350 years followed by a second intrusion at the L, M, U, or O location at 550; 750; 2,000; 4,000; or 10,000 years: 20 combinations.
S5-DBR	Initial E2 intrusion at 1,000 years followed by a second intrusion at the L, M, U, or O location at 1,200; 1,400; 3,000; 5,000; or 10,000 years: 20 combinations.

NOTE: The S*x*-DBR (*x*=1-5) scenarios utilize the S*x*-BF scenario results (waste area pressures and saturations) as initial conditions for subsequent intrusions at the times specified in the last column.

3.5 Direct Brine Release Calculations

Using data from previously executed BRAGFLO calculations, CUTTINGS_S computes volume-weighted averages of gas pressure, brine pressure, gas saturation, rock permeability to brine, and waste room porosity for each scenario-vector-location-intrusion combination (WIPP PA, 2021). These results serve as initial conditions for the CRA26_IS DBR calculations. For a detailed discussion of the implementation and results of these calculations, refer to Zeitler (2025).

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4.0 METHODOLOGY FOR CALCULATING CUTTINGS, CAVINGS, AND SPALLINGS

This section documents the implementation of the conceptual approach described in Section 3.0 and identifies the parameters used to compute cuttings, cavings, and spallings in the CRA26_IS analysis. CUTTINGS_S version 6.04 was used to calculate cuttings and cavings areas and spallings volumes for each replicate, vector, scenario, intrusion location, and intrusion time. CUTTINGS_S reads both sampled and constant parameters from the LHS parameter files and the PA parameter database and applies these values consistently across all calculations. Sampled parameters introduce variability in cavings and spallings behavior, while constant parameters provide fixed geometric, hydraulic, and mechanical specifications for drilling conditions and waste material properties.

CUTTINGS_S obtains scenario-specific repository conditions from BRAGFLO and interpolates DRSPALL-generated spallings volumes to the BRAGFLO pressures using the sampled waste property values. Together, these parameter sets and state-variable inputs define the model response for each replicate and scenario. The specific methodology, parameter sets, and data transfers among BRAGFLO, DRSPALL, and CUTTINGS_S are described in the subsections that follow.

4.1 Execution Procedure

CUTTINGS_S relies on input files generated from scenario specific BRAGFLO simulation results and pressure-dependent DRSPALL response surfaces. For each replicate, the following steps are applied:

1. Load BRAGFLO results for each scenario/time/location combination.
2. Sample uncertain parameters (Section 4.2.2) via the LHS code to generate replicate-specific realizations of shear strength, drill-string angular velocity, and waste properties relevant to spallings.
3. Compute cuttings and cavings volumes based on drill bit geometry, repository height, and sampled erosion related parameters (Section 4.2.1).
4. Interpolate DRSPALL spallings volumes from the pressure-dependent response surfaces.
5. Record outputs for subsequent use in PRECCDFGF and CCDFGF.

Additional details on file structures and run-control scripts are provided in Long (2025).

4.2 Parameters

CUTTINGS_S utilizes both sampled uncertain parameters and constant parameters to evaluate cuttings, cavings, and spallings releases. The parameters used in the CRA26_IS analysis are summarized in Table 3 through Table 6 and are consistent with those used in previous WIPP PA calculations unless otherwise noted.

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4.2.1 Cuttings and Cavings

Two parameters governing cavings behavior are sampled by the LHS code: the effective shear strength of the waste (BOREHOLE:TAUFAIL) and the drill-string angular velocity (BOREHOLE:DOMEGA). These variables control the erosion response adjacent to the borehole wall and therefore determine the computed cavings area for each realization. Constant parameters such as drill bit diameter, drill collar diameter, repository height, drilling fluid properties, and waste roughness are taken directly from the PA parameter database. Although several of these parameters are represented as distributions in the database, CUTTINGS_S uses the median values as constants, consistent with the sensitivity analysis results documented in Lord et al. (2003).

Table 3. Sampled Uncertain Parameters for Cavings Calculations

Material	Property	Description	Distribution	Range	Units
BOREHOLE	TAUFAIL	Effective shear strength for erosion of the waste	Uniform	1.60 to 77.0	Pa
BOREHOLE	DOMEGA	Drill string angular velocity	Cumulative	4.2 to 23.0	rad/s

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Table 4. Constant Parameters for Cuttings and Cavings Calculations

Material	Property	Description	Value	Units
BLOWOUT	PARTDIA	Waste particle diameter [a]	0.0028	m
BLOWOUT	HREPO	Height of repository at burial time	3.96	m
BOREHOLE	DIAMMOD	Modern or current drill bit diameter	0.31115	m
BOREHOLE	COLDIA	Drill collar diameter	0.2032	m
DRILLMUD	DNSFLUID	Density of brine used as drilling fluid (mud) [a]	1210	kg/m^3
DRILLMUD	VISCO	Viscosity of brine used as drilling fluid (mud) [a]	9.17e-3	Pa·s
DRILLMUD	YLDSTRSS	Yield stress point of brine used as drilling fluid (mud) [a]	4.40	Pa
DRILLMUD	SHEARRT	Shear rate of the drilling fluid (mud)	1020	s^{-1}
DRILLMUD	MUDFLWRT	Drilling fluid (mud) flow rate	0.09935	$m^3/(m·s)$
WAS_AREA	ABSROUGH	Absolute roughness of waste material [a]	0.025	m
REFCON	SECYR	Seconds to year conversion	3.168877e-8	year/s
REFCON	PI	Reference constant π	3.141593	-

[a] This parameter corresponds to a distribution where the "Value" column lists the median value of the distribution, which is treated by CUTTINGS_S as constant.

4.2.2 Spallings

Spallings calculations rely on both sampled and constant parameters describing waste mechanical properties, brine and gas flow behavior, wellbore geometry, and drilling conditions. Four parameters governing waste properties local to the intrusion are sampled by LHS for each replicate (Table 5): particle diameter (SPALLMOD:PARTDIAM), waste permeability (SPALLMOD:REPIPERM), waste porosity (SPALLMOD:REPIPOR), and waste tensile strength (SPALLMOD:TENSLSTR). These parameters influence the DRSPALL-generated spallings volumes by modifying the pressure threshold for spall initiation and the rate at which material is expelled during a blowout.

A larger set of constant parameters is used to provide geometric, hydraulic, and mechanical context for spallings calculations (Table 6). These include drill bit and drill pipe dimensions, drilling-damaged zone and disturbed rock zone properties, brine and gas viscosities, stress terms, flow resistance coefficients, and material roughness values. DRSPALL uses these constants to compute spallings volumes at the four pressure points used in CUTTINGS_S interpolation.

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CUTTINGS_S then applies the sampled waste property values and the scenario-specific BRAGFLO pressures to interpolate the spallings volume for each vector, time, and location.

Table 5. Sampled Uncertain Parameters for Spallings Calculations

Material	Property	Description	Distribution	Range	Units
SPALLMOD	PARTDIAM	Particle diameter of disaggregated waste	Loguniform	0.001 to 0.1	m
SPALLMOD	REPIPERM	Waste permeability to gas local to intrusion borehole	Loguniform	2.4E-14 to 2.4E-12	m^2
SPALLMOD	REPIPOR	Waste porosity at time of drilling intrusion	Uniform	0.35 to 0.66	-
SPALLMOD	TENSLSTR	Tensile strength of waste	Uniform	120000.0 to 170000.0	Pa

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Table 6. Constant Parameters for Spallings Calculations

Material	Property	Description	Value	Units
BOREHOLE	DIAMMOD	Modern or current drill bit diameter	0.31115	m
BOREHOLE	COLDIA	Drill collar diameter	0.2032	m
BRINESAL	COMPRES	Brine compressibility	3.1e-10	Pa^{-1}
DRILLMUD	DNSFLUID	Brine Density	1210	kg/m^3
DRILLMUD	VISCO	Viscosity of drilling mud	0.00917	Pa·s
H2	VISCO	Viscosity of hydrogen gas	8.93389e-6	Pa·s
REFCON	GRAVACC	Standard gravitational acceleration	9.80665	m/s^2
REFCON	PI	Reference constant π	3.141593	-
SPALLMOD	ANNUROUG	Absolute wall roughness of wellbore annulus	5e-5	m
SPALLMOD	BIOTBETA	Biot's beta for waste	1.0	-
SPALLMOD	COHESION	Cohesion of waste	1.4e5	Pa
SPALLMOD	DDZPERM	Permeability of drilling-damaged zone (DDZ)	1e-14	m^2
SPALLMOD	DDZTHICK	Thickness of drilling-damaged zone (DDZ)	0.16	m
SPALLMOD	DRILRATE	Drill penetration rate through Salado	4.445e-3	m/s
SPALLMOD	DRZPERM	DRZ Permeability for DRSPALL	1e-15	m^2
SPALLMOD	DRZTCK	Thickness of DRZ above waste room in DRSPALL model	0.85	m
SPALLMOD	FFSTRESS	Isotropic in-situ stress in waste area	1.49e7	Pa
SPALLMOD	FRCHBETA	Forchheimer Beta	1.15e-06	m^{-2}
SPALLMOD	FRICTANG	Friction angle of waste	45.8	deg
SPALLMOD	MUDPRATE	Typical volumetric mud pumping rate for drilling in Salado	0.020181	m^3/s
SPALLMOD	MUDSOLMX	Solids volume fraction in drill mud that causes choking of flow	0.615	-
SPALLMOD	MUDSOLVE	Exponent on mud slurry viscosity power law	-1.5	-
SPALLMOD	PIPEID	Inner diameter of drill pipe (where OD = 0.1143 m)	0.09718	m

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Table 6. Constant Parameters for Spallings Calculations (cont.)

SPALLMOD	PIPEROUG	Absolute wall roughness of drill pipe	5e-5	m
SPALLMOD	POISRAT	Poisson's ratio for waste	0.38	-
SPALLMOD	REFPRS	Atmospheric pressure at sea level	1.0177e5	Pa
SPALLMOD	REPOSTCK	Repository thickness	0.0	m
SPALLMOD	REPOSTOP	Elevation of roof in excavated area	384.7	m
SPALLMOD	REPOTRAD	Repository outer radius	19.2	m
SPALLMOD	SALTDENS	Density of solid cuttings from the Salado	2180.0	kg/m^3
SPALLMOD	SHAPEFAC	Shape factor for disaggregated waste particles	0.1	-
SPALLMOD	STPDVOLR	Mud ejection rate that turns off drilling	1000.0	m^3/s
SPALLMOD	STPPVOLR	Mud ejection rate that turns off mud pump	1000.0	m^3/s
SPALLMOD	SURFELEV	Elevation of land surface at WIPP site	1037.3	m

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5.0 RESULTS

The results obtained from the CUTTINGS_S calculations for Replicate 1 in the CRA26_IS analysis are summarized in this section, highlighting key findings related to the quantities of cuttings, cavings, and spallings generated during the simulated drilling intrusions. These results are then compared to those from the RPPCR analysis (Kicker, 2023). Results for the other two replicates show similar trends (Section 9.0).

Box and whisker plots are used in this section to display results. Boxes extend from the 25th percentile to the 75th percentile, also known as the interquartile range. Whiskers extend from the 25th percentile to the 25th percentile minus 1.5 times the interquartile range and from the 75th percentile to the 75th percentile plus 1.5 times the interquartile range. Outliers are defined as data points beyond the extent of the whiskers. Outliers are plotted as diamonds. The black center line in the box is the median value; the mean value is denoted with a white square.

5.1 Cuttings and Cavings

The results obtained for the CRA26_IS are consistent with those from the RPPCR. There were no changes to parameters associated with the cuttings and cavings processes in the CRA26_IS and therefore no changes to the cuttings and cavings input files used in CUTTINGS_S. Furthermore, cuttings and cavings volumes are independent of repository conditions so there are no changes between the RPPCR and the CRA26_IS. A summary of statistics for cavings is presented in Table 7, which highlights the mean and maximum cavings areas, as well as the number of vectors without cavings. Note that since the cavings statistics are identical between the CRA26_IS and the RPPCR, the values listed in Table 7 apply to both analyses. The cumulative frequencies of nonzero cavings areas for Replicate 1 for the RPPCR and CRA26_IS is illustrated in Figure 4, showing identical results. Results for Replicates 2 and 3, while not shown here, exhibit similarly identical results.

Table 7. Cavings Area Statistics

Analysis	Mean Cavings Area (m^2)	Mean Non-Zero Cavings Area (m^2)	Maximum Cavings Area (m^2)	Number of Realizations Without Cavings
CRA26_IS	0.011	0.021	0.110	49
RPPCR	0.011	0.021	0.110	49

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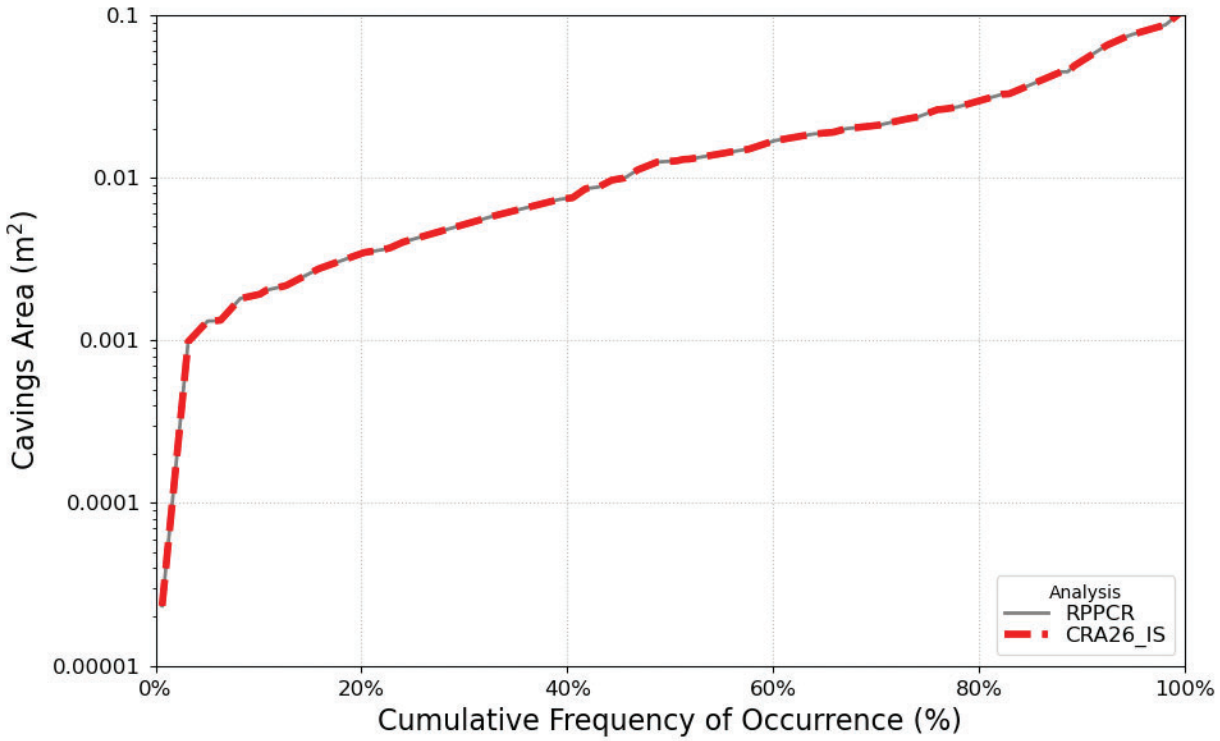


Figure 4. Cumulative Frequency of Cavings Area, Replicate 1

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5.2 Spallings Volume

Spallings releases are calculated by multiplying the estimated spallings volumes by the concentrations of radionuclides present in Contact Handled (CH) waste at the time of intrusion. This methodology ensures that the assessment accurately reflects the radionuclide concentrations relevant to the specific conditions in the repository during each intrusion event.

Results for three replicates were calculated for the CRA26_IS and RPPCR analyses. Only results from Replicate 1, including means, statistics, and sensitivity analyses, will be presented in this section. Results for Replicate 2 and Replicate 3 are presented in Section 9.0. Results in this section are discussed for scenarios S1-DBR, S2-DBR, and S4-DBR. Results from S3-DBR and S5-DBR are not examined individually because the only difference between them and S2-DBR and S4-DBR, respectively, is in the timing of drilling intrusions. Results for S3-DBR and S5-DBR are provided without commentary in Section 8.1 and Section 8.2, respectively.

Section 5.3 discusses the spallings concentrations, which are based on the average activity per volume of CH-TRU waste. While the spallings volumes remain generally consistent across analyses, the spallings concentrations increase from the RPPCR to the CRA26_IS. For consistency with previous analyses, in calculating average non-zero spallings volumes and rates, non-zero volumes are defined as volumes that are greater than 10^{-7} m^3.

5.2.1 Summary

The spallings volume calculations for the RPPCR and the CRA26_IS utilize DRSPALL solids release volumes as outlined by Kirchner et al. (2014; 2015). Individual borehole spallings releases are influenced by repository conditions, particularly the pressures present in the waste areas.

The intrusion scenarios and times employed in the calculation of spallings release volumes are presented in Table 2; these same scenarios are also used for calculating DBR volumes. Time-dependent spallings volumes are determined by interpolating the spallings volumes calculated by DRSPALL to align with the time-dependent repository pressures derived from BRAGFLO. Summary statistics of spallings volumes are provided in Table 8 and shown in Figure 5 and Figure 6 for the CRA26_IS and RPPCR. Note that the statistics presented in Kicker (2023) for the RPPCR are based on data from all three replicates, while the values in Table 8 are derived from a single replicate.

The mean nonzero spallings volume remain relatively consistent across analyses, with the highest occurring in the undisturbed scenario S1-DBR, with volumes of 1.76 m^3 for the RPPCR and 2.06 m^3 for the CRA26_IS. Among the subsequent intrusion scenarios S2-DBR through S5-DBR, S5-DBR has the highest mean nonzero volume of 1.73 m^3 in CRA26_IS and 1.48 m^3 in the RPPCR, while S3-DBR shows the lowest mean at 1.10 m^3 in the CRA26_IS and 1.08 m^3 in the RPPCR.

The percentage of realizations with nonzero spallings volume remains relatively consistent across analyses. Scenario S2-DBR, involving an early-time intrusion into a brine pocket, shows the highest percentage of realizations with nonzero spallings for both RPPCR (33.75%) and CRA26_IS (34.80%). For each analysis, scenario S1-DBR has the lowest percentage across all scenarios (13.83% for RPPCR and 11.54% for CRA26_IS). The percentage of non-zero

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realizations decreased slightly from RPPCR to CRA26_IS in the O locations. The decreased brine saturation (discussed in Day and King 2025) contributes to lower brine pressure, ultimately leading to smaller spallings volumes in this area.

Comparison of Table 8 (Replicate 1) with Table 14 and Table 15 (Replicates 2 and 3) shows no significant departures in the behavior of the spallings results. Replicate 1 generally exhibits higher mean spallings volumes and larger non-zero release volumes than Replicates 2 and 3, which show similar values to one another. These differences represent normal variability among replicates and do not indicate any changes in model behavior.

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Table 8. Spallings Volume Summary, Replicate 1

Scenario	Mean Spallings Volume (m^3) RPPCR	Mean Spallings Volume (m^3) CRA26_IS	Fraction of Sim. with Nonzero Releases RPPCR	Fraction of Sim. with Nonzero Releases CRA26_IS	Mean of Non-Zero Spallings Releases (m^3) RPPCR	Mean of Non-Zero Spallings Releases (m^3) CRA26_IS
S1-DBR	**0.24**	**0.24**	**13.83%**	**11.54%**	**1.76**	**2.06**
L	0.28	0.28	15.67%	13.33%	1.80	2.13
M	0.28	0.28	15.67%	13.33%	1.80	2.12
U	0.27	0.27	14.00%	12.83%	1.90	2.09
O	0.14	0.12	10.00%	6.67%	1.43	1.75
S2-DBR	**0.39**	**0.41**	**33.75%**	**34.80%**	**1.16**	**1.18**
L	0.54	0.60	48.60%	50.60%	1.12	1.18
M	0.54	0.59	48.20%	50.60%	1.12	1.17
U	0.33	0.33	25.20%	26.60%	1.30	1.26
O	0.15	0.12	13.00%	11.40%	1.18	1.08
S3-DBR	**0.36**	**0.38**	**33.25%**	**34.75%**	**1.08**	**1.10**
L	0.44	0.51	45.20%	49.20%	0.98	1.04
M	0.44	0.51	44.80%	49.20%	0.98	1.04
U	0.37	0.36	27.60%	27.60%	1.32	1.29
O	0.19	0.15	15.40%	13.00%	1.25	1.13
S4-DBR	**0.20**	**0.20**	**15.20%**	**13.15%**	**1.33**	**1.52**
L	0.21	0.23	17.20%	15.00%	1.23	1.54
M	0.21	0.23	17.20%	15.00%	1.22	1.53
U	0.24	0.23	16.20%	14.80%	1.50	1.57
O	0.15	0.11	10.20%	7.80%	1.43	1.36
S5-DBR	**0.28**	**0.28**	**18.85%**	**15.90%**	**1.48**	**1.73**
L	0.30	0.32	20.80%	18.20%	1.43	1.76
M	0.30	0.32	20.80%	18.20%	1.42	1.76
U	0.33	0.32	20.00%	18.00%	1.66	1.76
O	0.19	0.14	13.80%	9.20%	1.39	1.57
All	**0.29**	**0.30**	**22.63%**	**21.63%**	**1.30**	**1.38**
L	0.35	0.38	28.96%	28.65%	1.22	1.34
M	0.35	0.38	28.81%	28.65%	1.22	1.34
U	0.31	0.30	20.35%	19.69%	1.50	1.53
O	0.16	0.13	12.38%	9.50%	1.33	1.34

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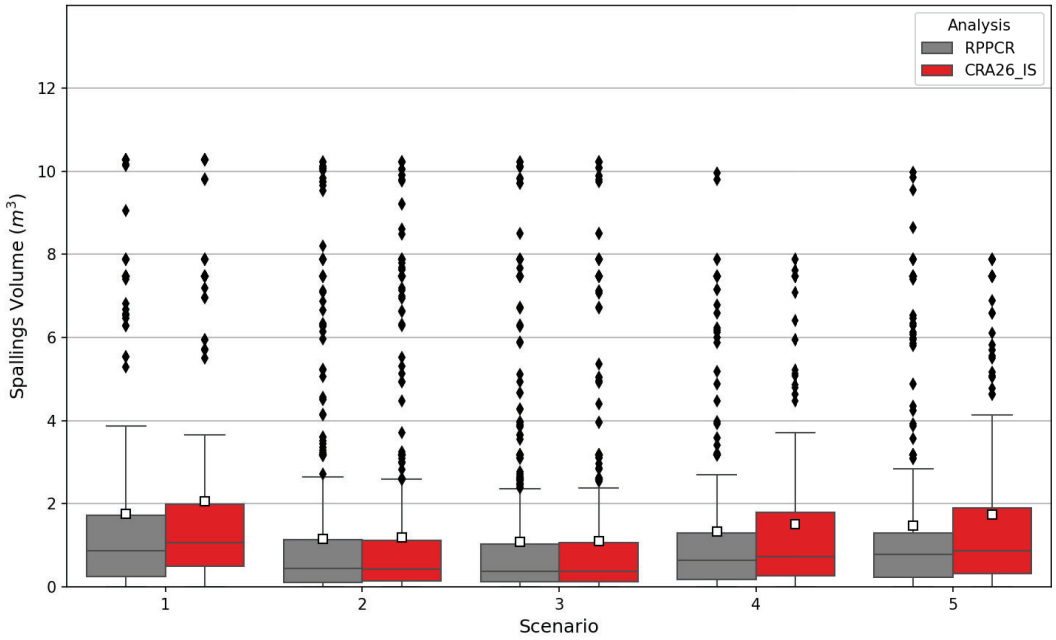


Figure 5. Non-Zero Spallings Volume by Intrusion Scenario, Replicate 1

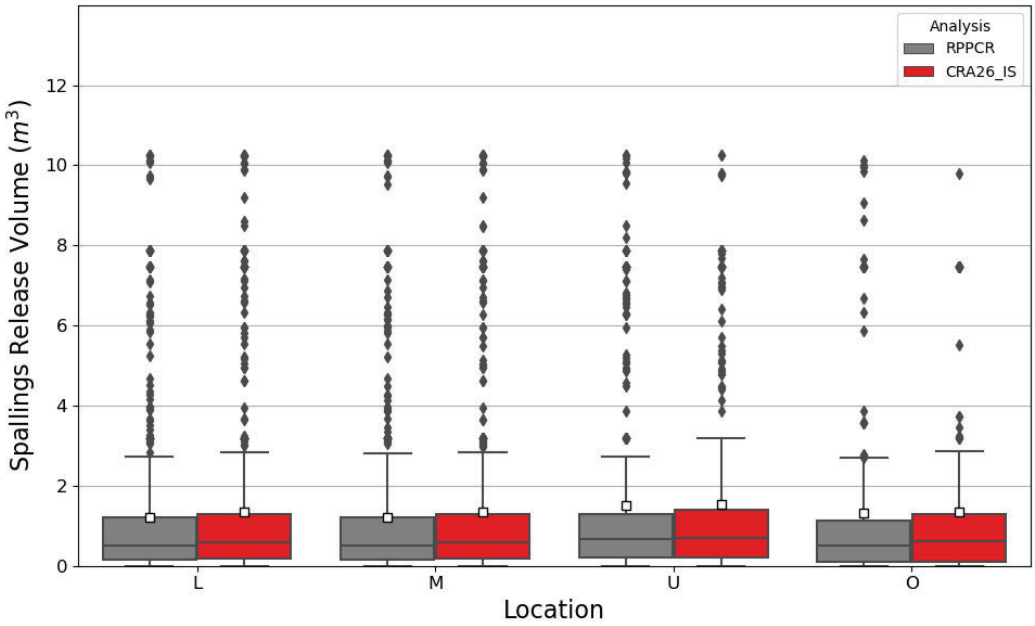


Figure 6. Non-Zero Spallings Release Volume by Intrusion Location, Replicate 1

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5.2.2 Scenario S1-DBR

The S1-DBR scenario models spallings volumes resulting from an intrusion into a previously undisturbed repository (Table 2). Summary statistics for the mean spallings volume, the fraction of simulations with non-zero releases, and the mean volume of non-zero releases are provided in Table 9, with non-zero spallings volumes shown in Figure 7 by intrusion location and time.

Although small numerical differences occur at individual intrusion times and locations, the mean S1-DBR spallings volumes remain effectively consistent between the RPPCR and CRA26_IS analyses. For S1-DBR, the fraction of simulations producing non-zero spallings releases decreases from the RPPCR to the CRA26_IS analysis, while the mean of the non-zero releases increases. This reflects fewer realizations exceeding the spallings threshold, but slightly larger releases in those that do.

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Table 9. S1-DBR Spallings Volume Summary, Replicate 1

Intrusion Location and Time (yr)	Mean Spallings Volume (m^3)	Mean Spallings Volume (m^3)	Fraction of Sim. with Nonzero Releases	Fraction of Sim. with Nonzero Releases	Mean of Non-Zero Spallings Releases (m^3)	Mean of Non-Zero Spallings Releases (m^3)
	RPPCR	CRA26_IS	RPPCR	CRA26_IS	RPPCR	CRA26_IS
Lower	**0.28**	**0.28**	**15.67%**	**13.33%**	**1.8**	**2.13**
100	0.00	0.00	0.00%	0.00%	-	-
350	0.00	0.00	0.00%	2.00%	-	0.02
1,000	0.17	0.20	17.00%	14.00%	1.01	1.39
3,000	0.48	0.46	24.00%	20.00%	1.98	2.32
5,000	0.53	0.53	25.00%	21.00%	2.11	2.51
10,000	0.52	0.51	28.00%	23.00%	1.85	2.24
Middle	**0.28**	**0.28**	**15.67%**	**13.33%**	**1.8**	**2.12**
100	0.00	0.00	0.00%	0.00%	-	-
350	0.00	0.00	0.00%	2.00%	-	0.02
1,000	0.17	0.19	17.00%	14.00%	1.00	1.38
3,000	0.47	0.46	24.00%	20.00%	1.97	2.32
5,000	0.53	0.53	25.00%	21.00%	2.11	2.51
10,000	0.52	0.51	28.00%	23.00%	1.85	2.24
Upper	**0.27**	**0.27**	**14.00%**	**12.83%**	**1.9**	**2.09**
100	0.00	0.00	0.00%	0.00%	-	-
350	0.00	0.00	0.00%	0.00%	-	-
1,000	0.14	0.17	14.00%	14.00%	1.01	1.22
3,000	0.44	0.43	21.00%	20.00%	2.09	2.13
5,000	0.51	0.51	23.00%	21.00%	2.21	2.44
10,000	0.51	0.50	26.00%	22.00%	1.94	2.29
Other	**0.14**	**0.12**	**10.00%**	**6.67%**	**1.43**	**1.75**
100	0.00	0.00	0.00%	0.00%	-	-
350	0.00	0.00	0.00%	0.00%	-	-
1,000	0.08	0.10	7.00%	4.00%	1.12	2.44
3,000	0.17	0.13	13.00%	8.00%	1.32	1.69
5,000	0.27	0.19	16.00%	12.00%	1.71	1.61
10,000	0.33	0.28	24.00%	16.00%	1.39	1.72
S1-DBR	**0.24**	**0.24**	**13.83%**	**11.54%**	**1.76**	**2.06**

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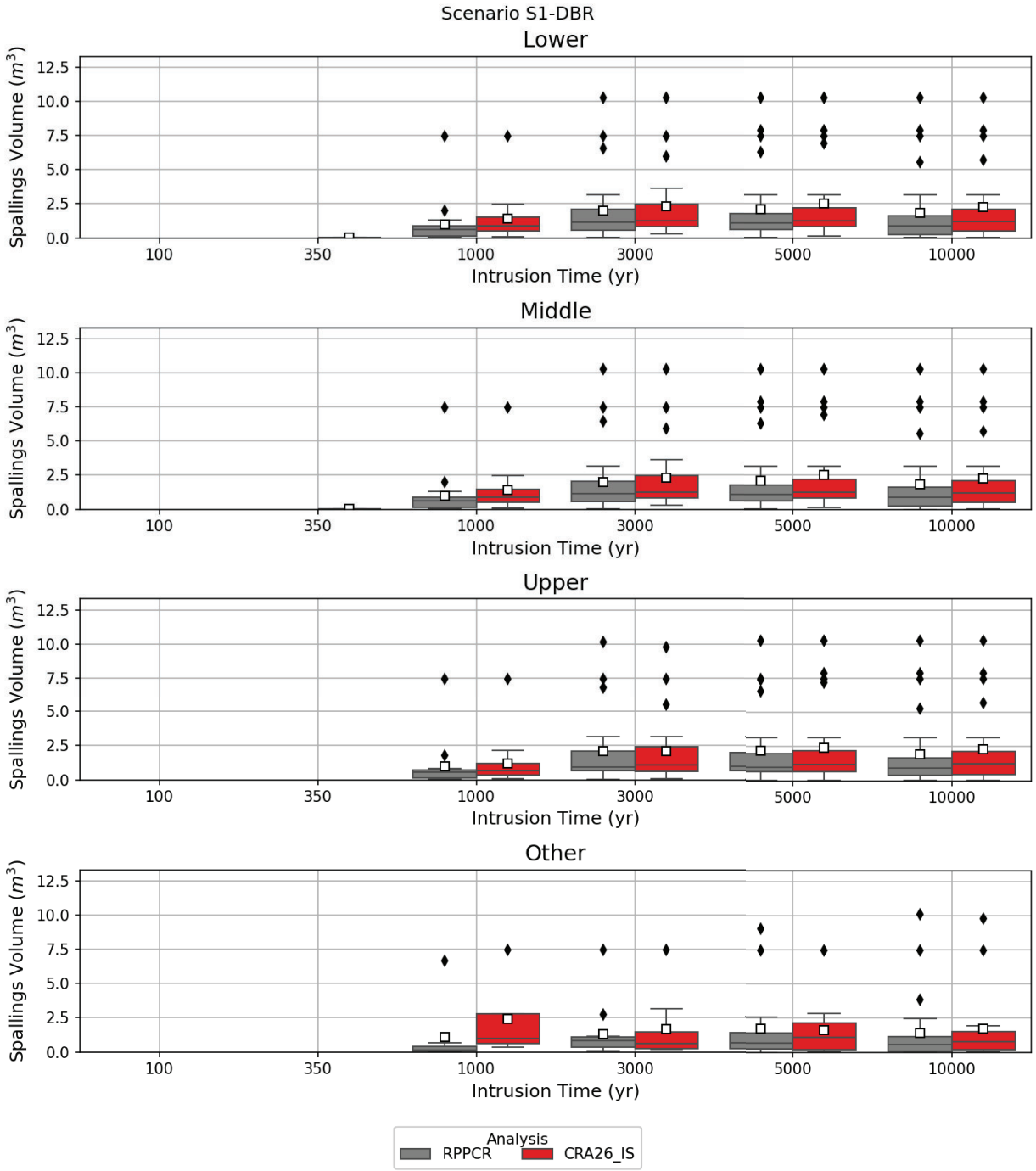


Figure 7. S1-DBR Spallings Volumes, All Non-Zero Releases, Replicate 1

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5.2.3 Scenario S2-DBR

The S2-DBR scenario models spallings volumes resulting from a repository that has been previously intruded by a wellbore intersecting a pressurized brine pocket in the Castile formation (Table 2). Summary statistics for S2-DBR are provided in Table 10, with RPPCR values shown for comparison. Non-zero spallings volumes are plotted in Figure 8 by intrusion location and time.

Relative to the RPPCR, the mean spallings volume increases in the L and M intrusion locations, remains unchanged in the U location, and decreases in the O location, producing a small overall increase at the scenario level. The fraction of simulations with non-zero spallings releases also increases slightly, reflecting higher-pressure repository conditions associated with the prior E1 intrusion. Among simulations with non-zero releases, the mean spallings volume increases modestly overall, with increases in the L and M regions dominating and small decreases in the U and O locations.

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Table 10. S2-DBR Spallings Volume Summary, Replicate 1

Intrusion Location and Time (yr)	Mean Spallings Volume (m^3)	Mean Spallings Volume (m^3)	Fraction of Sim. with Nonzero Releases	Fraction of Sim. with Nonzero Releases	Mean of Non-Zero Spallings Releases (m^3)	Mean of Non-Zero Spallings Releases (m^3)
	RPPCR	CRA26_IS	RPPCR	CRA26_IS	RPPCR	CRA26_IS
Lower	**0.54**	**0.60**	**48.60%**	**50.60%**	**1.12**	**1.18**
550	0.08	0.21	33.00%	36.00%	0.25	0.57
750	0.40	0.48	54.00%	57.00%	0.75	0.85
2,000	0.88	0.88	60.00%	59.00%	1.46	1.49
4,000	0.84	0.79	56.00%	55.00%	1.49	1.43
10,000	0.52	0.63	40.00%	46.00%	1.30	1.36
Middle	**0.54**	**0.59**	**48.20%**	**50.60%**	**1.12**	**1.17**
550	0.08	0.20	32.00%	36.00%	0.25	0.57
750	0.40	0.48	53.00%	57.00%	0.75	0.84
2,000	0.87	0.88	60.00%	59.00%	1.45	1.48
4,000	0.83	0.78	56.00%	55.00%	1.49	1.42
10,000	0.52	0.62	40.00%	46.00%	1.29	1.36
Upper	**0.33**	**0.33**	**25.20%**	**26.60%**	**1.30**	**1.26**
550	0.00	0.01	5.00%	7.00%	0.08	0.17
750	0.05	0.09	10.00%	10.00%	0.50	0.91
2,000	0.37	0.37	33.00%	35.00%	1.12	1.05
4,000	0.64	0.64	39.00%	40.00%	1.64	1.59
10,000	0.57	0.57	39.00%	41.00%	1.47	1.39
Other	**0.15**	**0.12**	**13.00%**	**11.40%**	**1.18**	**1.08**
550	0.00	0.00	1.00%	2.00%	0.01	0.09
750	0.03	0.04	4.00%	4.00%	0.64	1.12
2,000	0.13	0.12	10.00%	7.00%	1.29	1.73
4,000	0.26	0.18	20.00%	16.00%	1.32	1.13
10,000	0.35	0.26	30.00%	28.00%	1.17	0.95
S2-DBR	**0.39**	**0.41**	**33.75%**	**34.80%**	**1.16**	**1.18**

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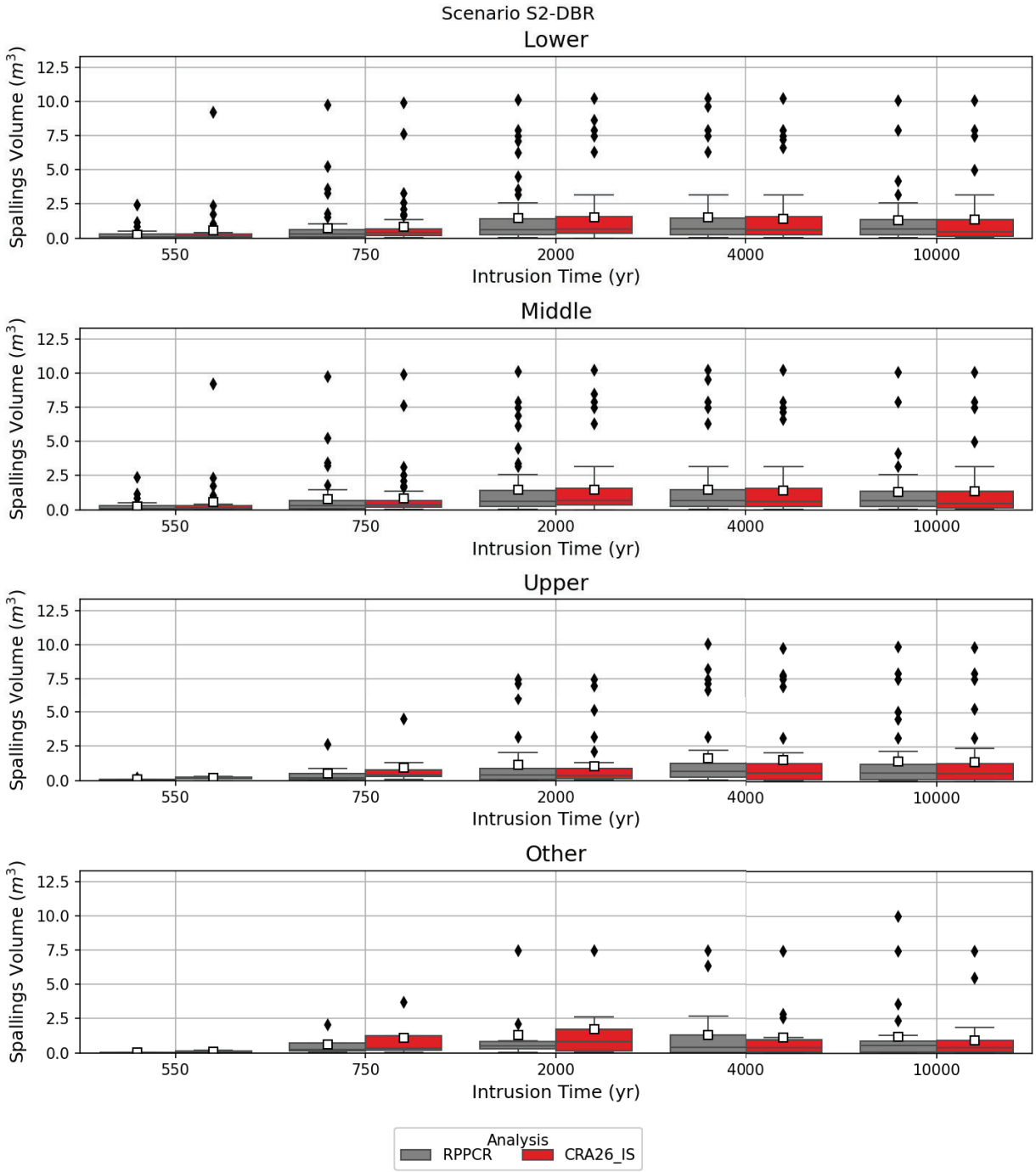


Figure 8. S2-DBR Spallings Volumes, All Non-Zero Releases, Replicate 1

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5.2.4 Scenario S4-DBR

The S4-DBR scenario models spallings volumes resulting from a repository that has been previously intruded by a wellbore that did not intersect a pressurized brine pocket in the Castile formation (Table 2). Summary statistics for S4-DBR are provided in Table 11, with RPPCR values shown for comparison. Non-zero spallings volumes are plotted in Figure 9 by intrusion location and time.

Relative to the RPPCR, the mean spallings volume increases in the L and M intrusion locations, decreases in the U and O locations, and remains effectively unchanged at the overall scenario level. The fraction of simulations with non-zero spallings releases decreases across all intrusion locations. Among simulations with non-zero releases, the mean spallings volume generally increases across locations, with only a small decrease in the O region. Fewer realizations exceed the spallings threshold in S4-DBR, but those that do tend to produce slightly larger release volumes, particularly in the L and M regions.

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Table 11. S4-DBR Spallings Volume Summary, Replicate 1

Intrusion Location and Time (yr)	Mean Spallings Volume (m^3)	Mean Spallings Volume (m^3)	Fraction of Sim. with Nonzero Releases	Fraction of Sim. with Nonzero Releases	Mean of Non-Zero Spallings Releases (m^3)	Mean of Non-Zero Spallings Releases (m^3)
	RPPCR	CRA26_IS	RPPCR	CRA26_IS	RPPCR	CRA26_IS
Lower	**0.21**	**0.23**	**17.20%**	**15.00%**	**1.23**	**1.54**
550	0.02	0.03	7.00%	8.00%	0.25	0.41
750	0.06	0.10	11.00%	10.00%	0.56	1.00
2,000	0.27	0.28	21.00%	18.00%	1.30	1.55
4,000	0.44	0.39	23.00%	20.00%	1.90	1.97
10,000	0.27	0.35	24.00%	19.00%	1.12	1.84
Middle	**0.21**	**0.23**	**17.20%**	**15.00%**	**1.22**	**1.53**
550	0.02	0.03	7.00%	8.00%	0.24	0.41
750	0.06	0.10	11.00%	10.00%	0.54	0.98
2,000	0.27	0.28	21.00%	18.00%	1.28	1.54
4,000	0.44	0.39	23.00%	20.00%	1.89	1.96
10,000	0.27	0.35	24.00%	19.00%	1.12	1.84
Upper	**0.24**	**0.23**	**16.20%**	**14.80%**	**1.50**	**1.57**
550	0.00	0.02	6.00%	6.00%	0.07	0.25
750	0.05	0.10	10.00%	10.00%	0.51	0.96
2,000	0.31	0.27	18.00%	18.00%	1.72	1.52
4,000	0.48	0.41	22.00%	21.00%	2.18	1.96
10,000	0.37	0.36	25.00%	19.00%	1.49	1.91
Other	**0.15**	**0.11**	**10.20%**	**7.80%**	**1.43**	**1.36**
550	0.00	0.00	1.00%	2.00%	0.01	0.09
750	0.03	0.04	4.00%	4.00%	0.64	1.12
2,000	0.13	0.12	10.00%	7.00%	1.29	1.73
4,000	0.25	0.17	13.00%	11.00%	1.96	1.54
10,000	0.32	0.19	23.00%	15.00%	1.39	1.28
S4-DBR	**0.20**	**0.20**	**15.20%**	**13.15%**	**1.33**	**1.52**

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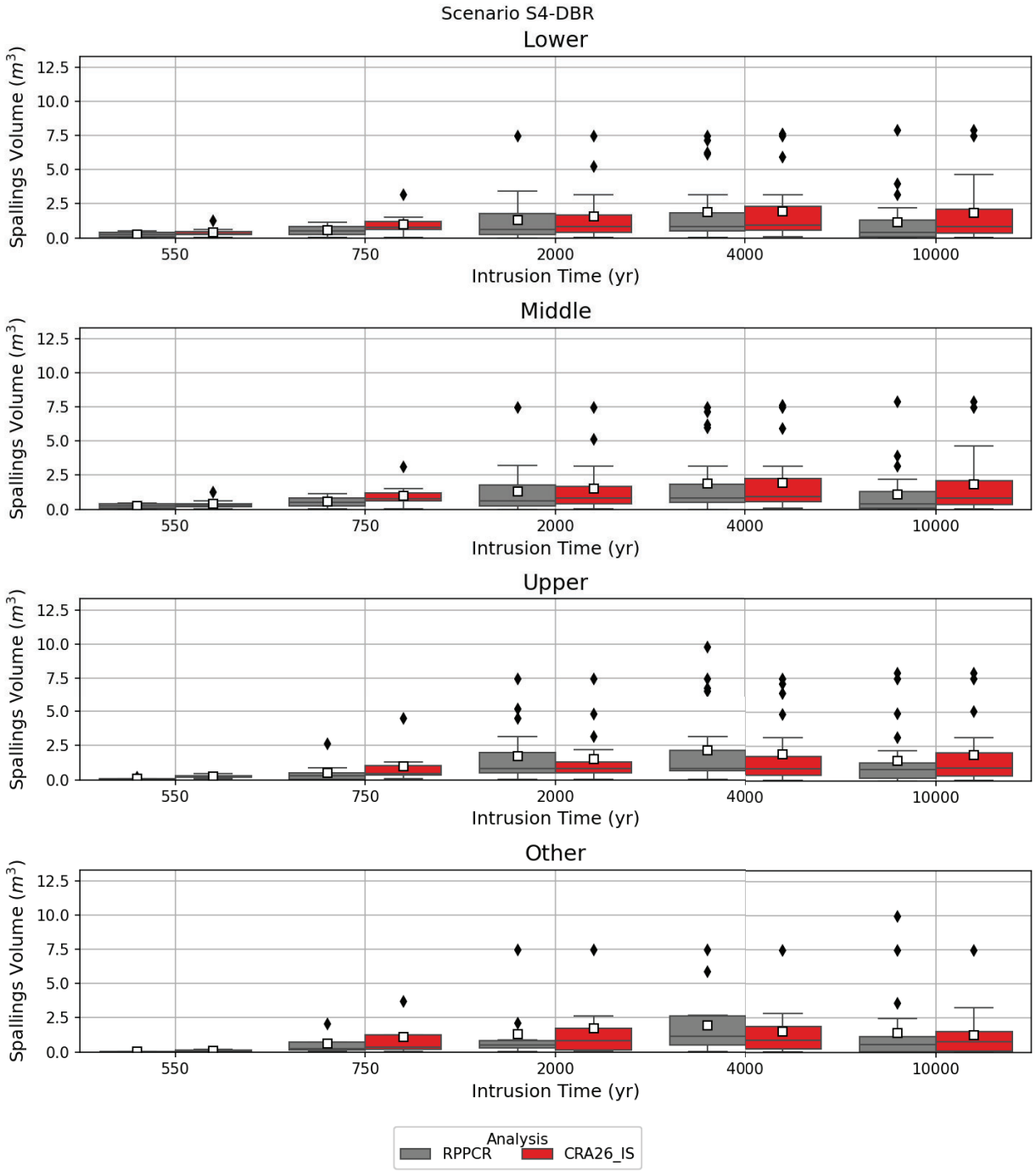


Figure 9. S4-DBR Spallings Volumes, All Non-Zero Releases, Replicate 1

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5.3 Spallings Concentration

In the PA calculations for spallings releases, radionuclide concentrations are determined using the PRECCDFGF code (WIPP PA, 2022b), which processes output from the EPAUNI model (Kim and Kicker, 2025) based on WIPP waste inventory data (Section 2.5). EPAUNI calculates the volume-weighted average concentration of radionuclides across all Contact Handled Transuranic (CH-TRU) waste streams. The spallings concentration, expressed in EPA units per cubic meter of waste, is illustrated in Figure 10, which depicts concentration trends over the 10,000-year regulatory period. The figure illustrates that the CRA26_IS inventory consistently exhibits higher radionuclide concentrations over time than the RPPCR inventory. Although the total inventory volume in the CRA26_IS is lower than that used in the RPPCR, as discussed in Kim and Kicker (2025), the elevated concentrations can be attributed to the increased levels of ^{239}Pu in the CRA26_IS inventory compared to the RPPCR inventory. The higher radionuclide concentrations in the CRA26_IS inventory combined with overall similar mean spallings volumes may lead to greater spallings releases over the assessment period compared to the RPPCR.

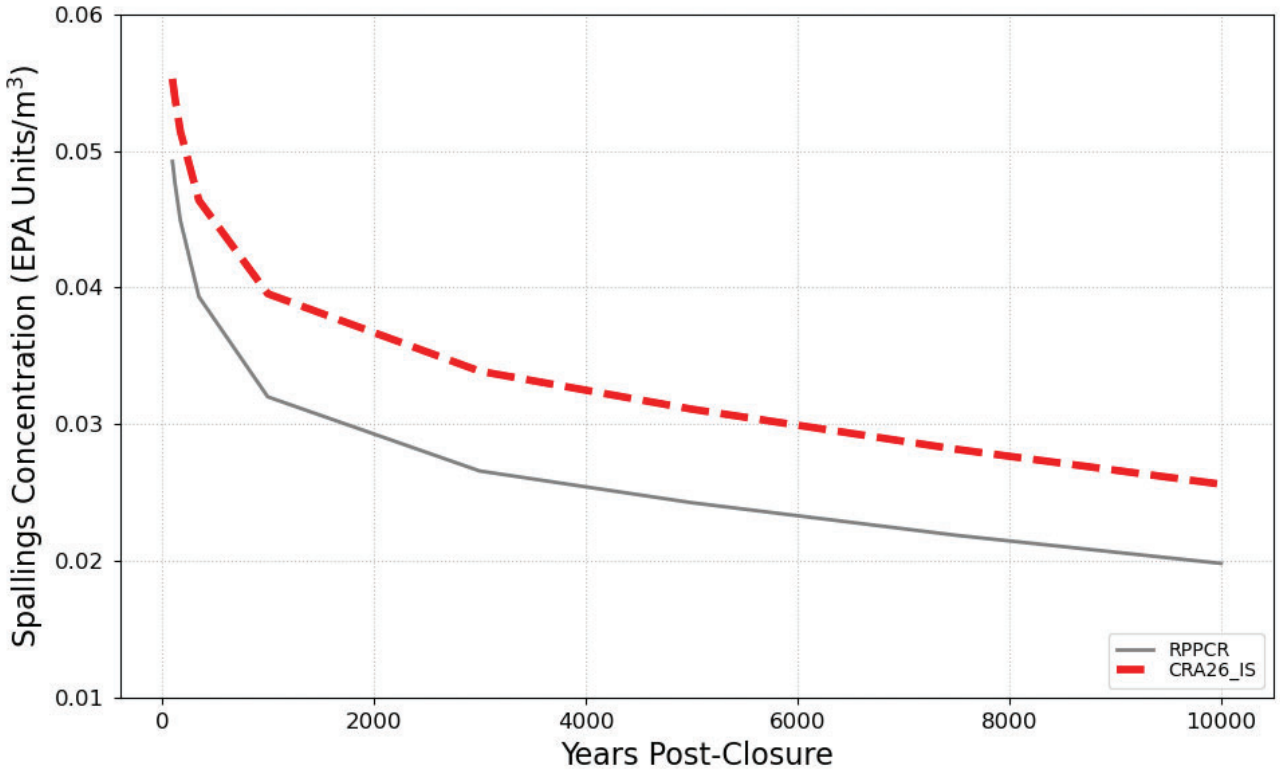


Figure 10. Spallings Release Concentration from Closure to 10,000 Years

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6.0 SUMMARY

The CUTTINGS_S results for the CRA26_IS analysis remain consistent with those from the RPPCR. Because no changes were made to the conceptual models or parameters for cuttings and cavings, these components of the direct-release model are unchanged from the RPPCR and do not vary across replicates.

For spallings, the CRA26_IS results exhibit behavior that is generally consistent with that observed in the RPPCR. Within Replicate 1, mean spallings volumes show only small differences between the two analyses and maintain clear spatial patterns. In the E1 scenarios (S2-DBR and S3-DBR), mean volumes increase in the L and M regions, remain similar or show minor shifts in the U region, and decrease in the O region. The E2 scenarios (S4-DBR and S5-DBR) show no change at the scenario-level mean but follow the same spatial pattern of increases in the L and M regions and decreases in the U and O regions. The spallings results do not meaningfully change across replicates.

The fraction of simulations with non-zero spallings releases also follows the expected scenario-dependent behavior. In scenarios S2-DBR and S3-DBR, this fraction increases slightly from the RPPCR to CRA26_IS, while in S4-DBR and S5-DBR it decreases across all locations. For simulations producing non-zero releases, mean spallings volumes increase modestly across all scenarios, with the largest increases occurring in the L and M regions.

Overall, the CRA26_IS spallings results are consistent with the RPPCR in trends, scenario ordering, spatial behavior, and replicate-to-replicate variability. The only substantive difference between analyses is the higher radionuclide concentrations in the CRA26_IS inventory, which lead to correspondingly higher spallings releases even though spallings volumes remain similar.

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7.0 REFERENCES

Bollinger, M. 2024. Letter to Lee Veal, Subject: Planned Change Request for the Use of Replacement Panels 11 and 12. March 12, 2024. CBFO:ERCD:MG:SV:24-0168. Carlsbad, NM: U.S. DOE, Carlsbad Field Office.

Brunell, S. 2025. Update to CRA-2026 PA Input Parameters Due to Revised WIPP Repository Dimensions. EIMS-0004799007. Carlsbad, NM: Sandia National Laboratories.

Day, B. 2025a. BRAGFLO Grid Development for CRA-2026. EIMS-0004447000. Carlsbad, NM: Sandia National Laboratories.

Day, B. 2025b. Recommendation and Justification for Implementing a Lower Bound on Capillary Pressure in Marker Bed Materials S_MB139, S_ANH_AB, and S_MB138 Using the CAP_MOD and PO_MIN Parameters for CRA-2026. EIMS-0004430534. Carlsbad, NM: Sandia National Laboratories.

Day, B., and S. King. 2025. Analysis Report for Salado Flow in the 2026 Compliance Recertification Application Performance Assessment: Interim State Repository. Carlsbad, NM: Sandia National Laboratories.

Hansen, C., S. Brunell, B. Day, S. King, and J. Wilgus. 2025. Analysis Plan for the 2026 WIPP Compliance Recertification Application Performance Assessment. AP-214. EIMS-0004440569. Carlsbad, NM: Sandia National Laboratories.

Helton, J., J. Bean, J. Berglund, F. Davis, K. Economy, J. Garner, J. Johnson, R. MacKinnon, J. Miller, D. O'Brien, J. Ramsey, J. Schreiber, A. Shinta, L. Smith, D. Stoelzel, C. Stockman, and P. Vaughn. 1998. Uncertainty and Sensitivity Analysis Results Obtained in the 1996 Performance Assessment for the Waste Isolation Pilot Plant. SAND98-0365. Albuquerque, NM: Sandia National Laboratories.

Kicker, D. 2023. Analysis Report for Cuttings, Cavings, and Spallings in the Replacement Panels Planned Change Request (RPPCR). ERMS 579723. Carlsbad, NM: Sandia National Laboratories.

Kicker, D. 2025. Analysis Report for Radionuclide Inventory Screening in the 2026 Compliance Recertification Application Performance Assessment: Interim State Repository. EIMS-0004832100. Carlsbad, NM: Sandia National Laboratories.

Kim, S. and D. Kicker. 2025. Analysis Report for Inventory EPA Units in the 2026 Compliance Recertification Application Performance Assessment: Interim State Repository. Rev. 1. EIMS-0004940556 Carlsbad, NM: Sandia National Laboratories.

King, S. 2025a. Area for RH Waste Disposal for the Interim State CRA-2026 PA Calculation. EIMS-0004801801. Carlsbad, NM: Sandia National Laboratories.

King, S. 2025b. Constructed Cumulative Distributions for Approximation of Truncated Normal Distributions. EIMS-0004799476. Carlsbad, NM: Sandia National Laboratories.

Kirchner, T., A. Gilkey, and J. Long. 2014. Summary Report on the Migration of the WIPP PA Codes from VMS to Solaris. Rev. 1. Carlsbad, NM: Sandia National Laboratories.

Information Only

Kirchner, T., A. Gilkey, and J. Long. 2015. Addendum to the Summary Report on the Migration of the WIPP PA Codes. Carlsbad, NM: Sandia National Laboratories.

Knerr, R. 2020. Letter to Lee Ann Veal, Subject: Planned Change Request for Alternative Panel Closure Locations for Panels 1 and 2. November 2, 2020. CBFO:OEP:MRB:VV:20-0280:UFC 54.86.00. Carlsbad, NM: U.S. DOE, Carlsbad Field Office.

Long, J. 2025. Computational Code Execution and File Management in the 2026 Compliance Recertification Application Performance Assessment: Interim State Repository. EIMS-0004900878. Carlsbad, NM: Sandia National Laboratories.

Lord, D., and D. Rudeen. 2003. Sensitivity Analysis Report: Parts I and II: DRSPALL Version 1.00: Report for Conceptual Model Peer Review July 7–11. ERMS 524400. Carlsbad, NM: Sandia National Laboratories.

Lord, D., D. Rudeen, and C. Hansen. 2003. Analysis Package for DRSPALL: Compliance Recertification Application: Part I — Calculation of Spall Volumes. Carlsbad, NM: Sandia National Laboratories.

Lord, D., D. Rudeen, J. Schatz, A. Gilkey, and C. Hansen. 2006. DRSPALL: Spallings Model for the Waste Isolation Pilot Plant 2004 Recertification. SAND2004-0730. Albuquerque, NM: Sandia National Laboratories.

Nemer, M. 2025. MgO Hydration Rates for the CRA-2026 Under AP-208. EIMS-0004445255. Albuquerque, NM: Sandia National Laboratories.

U.S. Department of Energy (U.S. DOE). 2019. Title 40 CFR Part 191 Subparts B and C Compliance Recertification Application for the Waste Isolation Pilot Plant. DOE/WIPP 2019-3609. Carlsbad, NM: U.S. Department of Energy, Carlsbad Field Office.

U.S. Environmental Protection Agency (U.S. EPA). 1998. 40 CFR Part 194: Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the Disposal Regulations: Certification Decision. Federal Register, vol. 63 (May 18, 1998): 27354 – 27406. Washington, DC.

U.S. Environmental Protection Agency (U.S. EPA). 2025. Letter from Abigale Tardif to Mark Bollinger, Subject: EPA's Review and Approval of DOE's RPPCR for Waste Panels 11 and 12 at WIPP. July 31, 2025. Washington, DC: U.S. EPA.

Van Soest, G. 2025. Interim State Performance Assessment Inventory Report – 2024. Revision 0. INV-IPA-24. Carlsbad, NM: Los Alamos National Laboratory.

Ward, A. 2025. Letter to Bill McInroy, Subject: Performance Assessment Inventory for Analysis of a 12-Panel Repository Configuration. March 18, 2025. CBFO:ERCD:AW:RS:25-0197. Carlsbad, NM: U.S. DOE, Carlsbad Field Office.

WIPP PA. 2021. Design Document and User's Manual for CUTTINGS_S Version 6.04. ERMS 574596. Carlsbad, NM: Sandia National Laboratories.

WIPP PA. 2022a. Design Document and User's Manual for CCDFGF Version 8.01. ERMS 577625. Carlsbad, NM: Sandia National Laboratories.

Information Only

WIPP PA. 2022b. Design Document and User's Manual for PRECCDFGF Version 3.01. ERMS 577631. Carlsbad, NM: Sandia National Laboratories.

WIPP PA. 2025. Design Document and User's Manual for BRAGFLO Version 8.00. EIMS 0004430695. Carlsbad, NM: Sandia National Laboratories.

Zeitler, T. 2025. Analysis Report for Direct Brine Releases in the 2026 Compliance Recertification Application Performance Assessment: Interim State Repository. Carlsbad, NM: Sandia National Laboratories.

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8.0 APPENDIX A – ADDITIONAL REPLICATE 1 RESULTS

Additional results for Replicate 1 are provided in this appendix.

8.1 Scenario S3-DBR

Table 12. S3-DBR Spallings Volume Summary, Replicate 1

Intrusion Location and Time (yr)	Mean Spallings Volume (m^3)	Mean Spallings Volume (m^3)	Fraction of Sim. with Nonzero Releases	Fraction of Sim. with Nonzero Releases	Mean of Non-Zero Spallings Releases (m^3)	Mean of Non-Zero Spallings Releases (m^3)
	RPPCR	CRA26_IS	RPPCR	CRA26_IS	RPPCR	CRA26_IS
Lower	**0.44**	**0.51**	**45.20%**	**49.20%**	**0.98**	**1.04**
1,200	0.14	0.28	39.00%	43.00%	0.36	0.66
1,400	0.38	0.48	49.00%	56.00%	0.77	0.86
3,000	0.68	0.68	56.00%	57.00%	1.21	1.19
5,000	0.57	0.63	48.00%	48.00%	1.19	1.31
10,000	0.45	0.50	34.00%	42.00%	1.34	1.18
Middle	**0.44**	**0.51**	**44.80%**	**49.20%**	**0.98**	**1.04**
1,200	0.14	0.28	38.00%	43.00%	0.36	0.66
1,400	0.37	0.48	49.00%	56.00%	0.76	0.86
3,000	0.67	0.68	55.00%	57.00%	1.22	1.19
5,000	0.57	0.63	48.00%	48.00%	1.18	1.30
10,000	0.45	0.50	34.00%	42.00%	1.33	1.18
Upper	**0.37**	**0.36**	**27.60%**	**27.60%**	**1.32**	**1.29**
1,200	0.16	0.18	16.00%	14.00%	1.01	1.31
1,400	0.19	0.20	16.00%	17.00%	1.16	1.18
3,000	0.40	0.36	32.00%	33.00%	1.26	1.08
5,000	0.57	0.52	38.00%	37.00%	1.51	1.40
10,000	0.50	0.52	36.00%	37.00%	1.39	1.41
Other	**0.19**	**0.15**	**15.40%**	**13.00%**	**1.25**	**1.13**
1,200	0.10	0.11	8.00%	6.00%	1.19	1.76
1,400	0.10	0.11	9.00%	6.00%	1.17	1.87
3,000	0.17	0.13	13.00%	10.00%	1.30	1.34
5,000	0.26	0.18	18.00%	17.00%	1.43	1.06
10,000	0.34	0.20	29.00%	26.00%	1.16	0.77
S3-DBR	**0.36**	**0.38**	**33.25%**	**34.75%**	**1.08**	**1.10**

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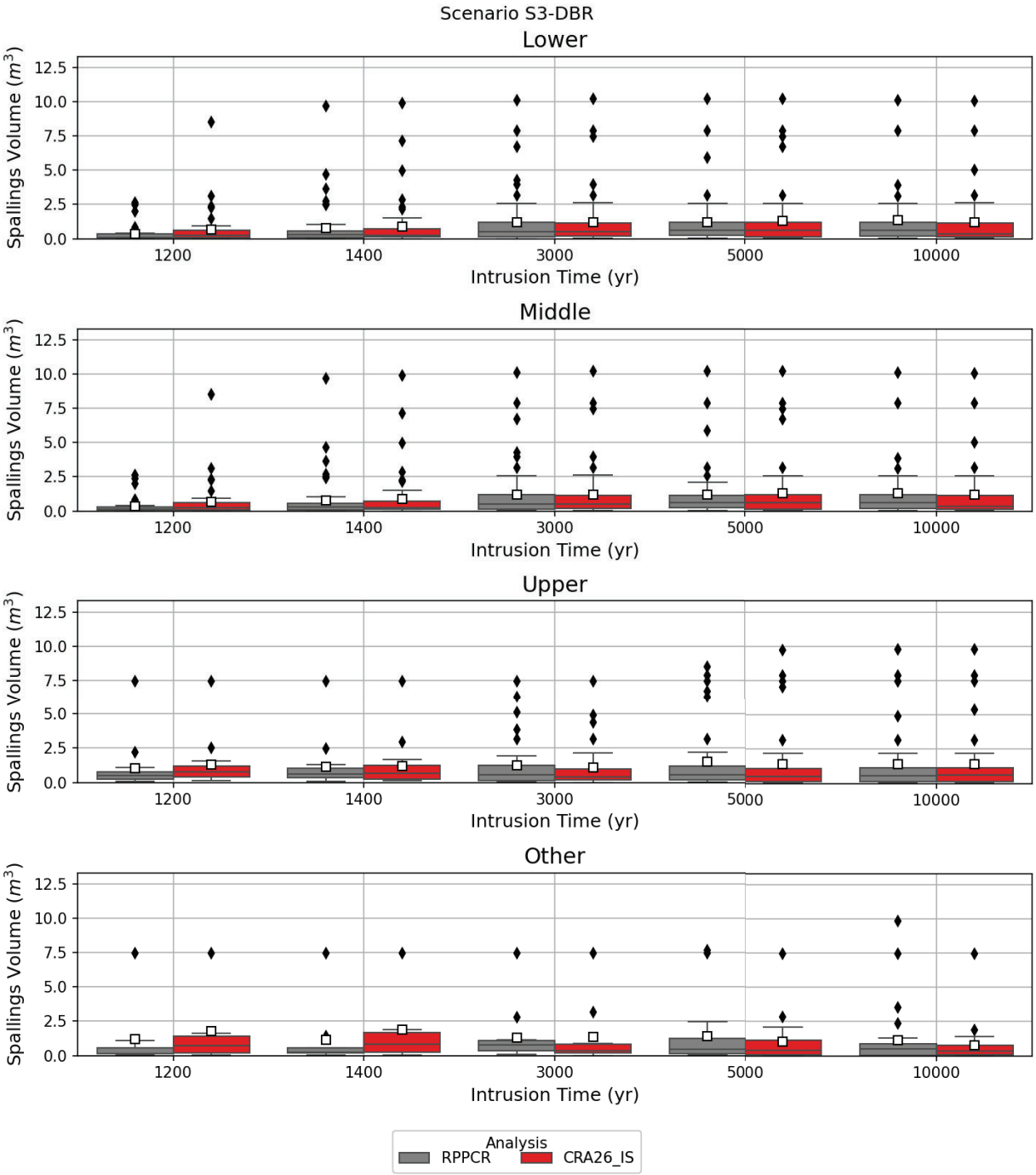


Figure 11. S3-DBR Spallings Volumes, All Non-Zero Releases, Replicate 1

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8.2 Scenario S5-DBR

Table 13. S5-DBR Spallings Volume Summary, Replicate 1

Intrusion Location and Time (yr)	Mean Spallings Volume (m^3)	Mean Spallings Volume (m^3)	Fraction of Sim. with Nonzero Releases	Fraction of Sim. with Nonzero Releases	Mean of Non-Zero Spallings Releases (m^3)	Mean of Non-Zero Spallings Releases (m^3)
	RPPCR	CRA26_IS	RPPCR	CRA26_IS	RPPCR	CRA26_IS
Lower	0.3	0.32	20.80%	18.20%	1.43	1.76
1,200	0.2	0.26	18.00%	16.00%	1.13	1.63
1,400	0.23	0.28	18.00%	17.00%	1.25	1.62
3,000	0.39	0.35	23.00%	20.00%	1.69	1.73
5,000	0.41	0.37	23.00%	19.00%	1.77	1.95
10,000	0.27	0.35	22.00%	19.00%	1.22	1.84
Middle	0.3	0.32	20.80%	18.20%	1.42	1.76
1,200	0.2	0.26	18.00%	16.00%	1.12	1.62
1,400	0.22	0.27	18.00%	17.00%	1.22	1.61
3,000	0.38	0.35	23.00%	20.00%	1.67	1.73
5,000	0.4	0.37	23.00%	19.00%	1.75	1.95
10,000	0.27	0.35	22.00%	19.00%	1.21	1.84
Upper	0.33	0.32	20.00%	18.00%	1.66	1.76
1,200	0.18	0.2	16.00%	14.00%	1.11	1.41
1,400	0.21	0.24	17.00%	17.00%	1.22	1.42
3,000	0.42	0.37	21.00%	20.00%	2.01	1.83
5,000	0.48	0.42	21.00%	20.00%	2.3	2.1
10,000	0.37	0.36	25.00%	19.00%	1.48	1.91
Other	0.19	0.14	13.80%	9.20%	1.39	1.57
1,200	0.1	0.11	8.00%	6.00%	1.19	1.76
1,400	0.1	0.11	9.00%	6.00%	1.17	1.87
3,000	0.17	0.13	13.00%	8.00%	1.32	1.68
5,000	0.27	0.18	16.00%	11.00%	1.67	1.61
10,000	0.32	0.19	23.00%	15.00%	1.39	1.29
S5-DBR	0.28	0.28	18.85%	15.90%	1.48	1.73

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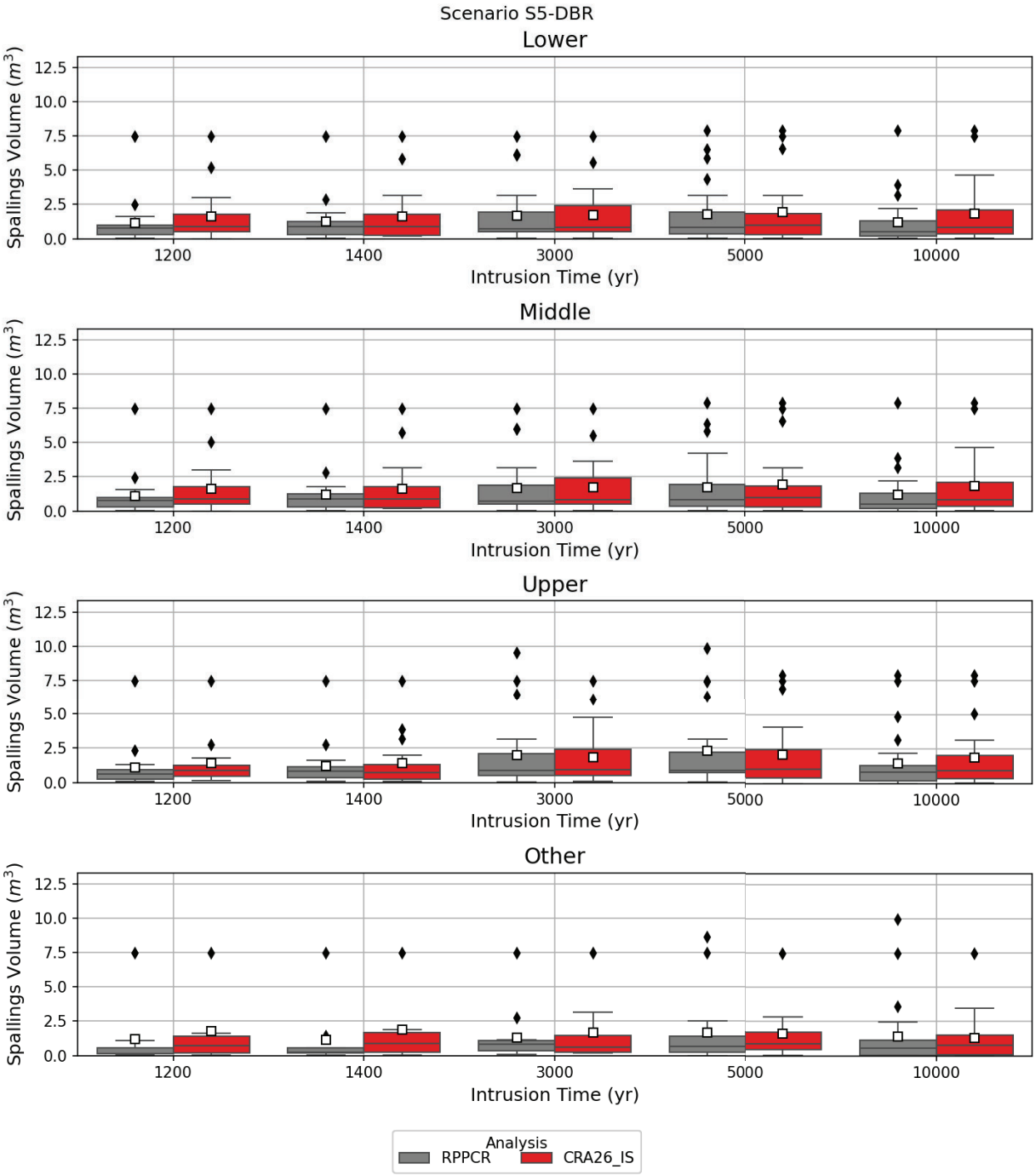


Figure 12. S5-DBR Spallings Volumes, All Non-Zero Releases, Replicate 1

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9.0 APPENDIX B – RESULTS FROM REPLICATE 2 AND REPLICATE 3

In this appendix, select Replicate 2 and Replicate 3 results are presented.

Table 14. Spallings Volume Summary, Replicate 2

Scenario	Mean Spallings Volume (m^3) RPPCR	Mean Spallings Volume (m^3) CRA26_IS	Fraction of Sim. with Nonzero Releases RPPCR	Fraction of Sim. with Nonzero Releases CRA26_IS	Mean of Non-Zero Spallings Releases (m^3) RPPCR	Mean of Non-Zero Spallings Releases (m^3) CRA26_IS
S1-DBR	**0.12**	**0.10**	**16.08%**	**13.42%**	**0.73**	**0.73**
L	0.14	0.13	17.83%	15.83%	0.80	0.83
M	0.14	0.13	17.83%	15.83%	0.80	0.83
U	0.12	0.10	17.00%	15.67%	0.73	0.66
O	0.06	0.03	11.67%	6.33%	0.49	0.43
S2-DBR	**0.27**	**0.32**	**34.85%**	**35.70%**	**0.76**	**0.89**
L	0.41	0.50	49.00%	52.40%	0.83	0.95
M	0.41	0.49	48.80%	52.20%	0.83	0.95
U	0.17	0.20	26.60%	28.20%	0.65	0.70
O	0.08	0.08	15.00%	10.00%	0.52	0.82
S3-DBR	**0.25**	**0.30**	**34.10%**	**36.05%**	**0.74**	**0.83**
L	0.36	0.45	45.20%	50.20%	0.79	0.90
M	0.36	0.45	44.80%	50.20%	0.80	0.89
U	0.20	0.22	30.00%	32.00%	0.68	0.68
O	0.09	0.09	16.40%	11.80%	0.55	0.74
S4-DBR	**0.11**	**0.08**	**16.80%**	**13.75%**	**0.64**	**0.60**
L	0.13	0.11	18.00%	16.40%	0.71	0.65
M	0.13	0.11	17.80%	16.40%	0.71	0.64
U	0.12	0.09	18.00%	16.20%	0.68	0.57
O	0.06	0.03	13.40%	6.00%	0.42	0.43
S5-DBR	**0.14**	**0.11**	**22.05%**	**18.60%**	**0.65**	**0.59**
L	0.17	0.14	23.80%	21.80%	0.72	0.65
M	0.17	0.14	23.80%	21.80%	0.71	0.65
U	0.16	0.12	24.40%	22.60%	0.65	0.55
O	0.07	0.03	16.20%	8.20%	0.44	0.42
ALL	**0.17**	**0.18**	**24.44%**	**23.12%**	**0.72**	**0.77**
L	0.24	0.26	30.27%	30.73%	0.78	0.84
M	0.24	0.26	30.12%	30.69%	0.79	0.84
U	0.16	0.15	22.96%	22.65%	0.68	0.64
O	0.07	0.05	14.42%	8.38%	0.49	0.60

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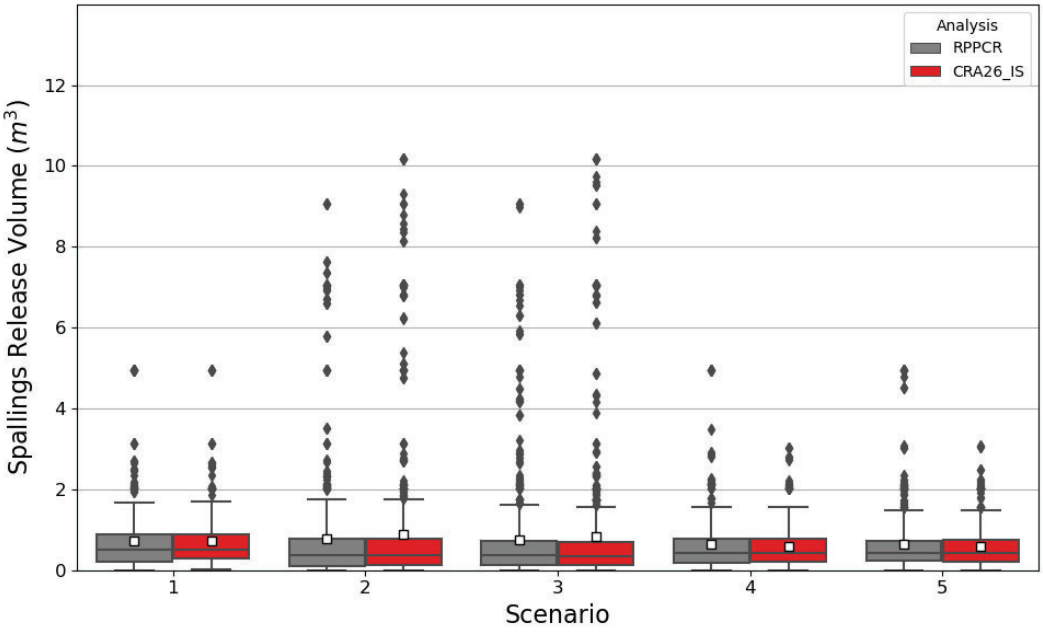


Figure 13. Non-Zero Spallings Volume by Intrusion Scenario, Replicate 2

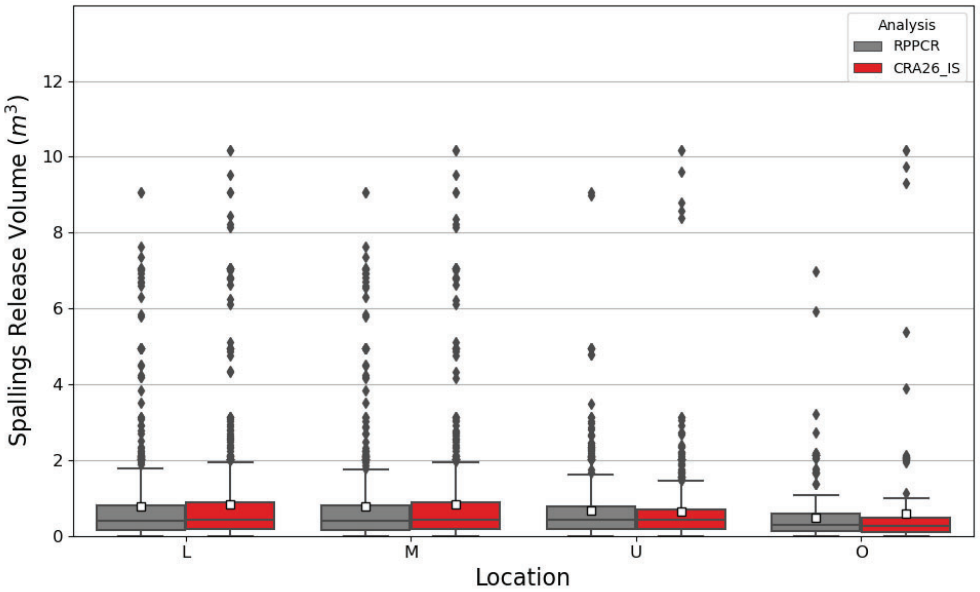


Figure 14. Non-Zero Spallings Volume by Intrusion Location, Replicate 2

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Table 15. Spallings Volume Summary, Replicate 3

Scenario	Mean Spallings Volume (m^3) RPPCR	Mean Spallings Volume (m^3) CRA26_IS	Fraction of Sim. with Nonzero Releases RPPCR	Fraction of Sim. with Nonzero Releases CRA26_IS	Mean of Non-Zero Spallings Releases (m^3) RPPCR	Mean of Non-Zero Spallings Releases (m^3) CRA26_IS
S1-DBR	**0.20**	**0.11**	**15.29%**	**12.25%**	**1.33**	**0.90**
L	0.25	0.15	18.00%	14.33%	1.40	1.05
M	0.25	0.15	18.00%	14.33%	1.40	1.05
U	0.22	0.12	16.00%	14.00%	1.40	0.86
O	0.08	0.02	9.17%	6.33%	0.89	0.33
S2-DBR	**0.34**	**0.35**	**32.45%**	**33.65%**	**1.04**	**1.04**
L	0.49	0.56	46.80%	50.80%	1.05	1.11
M	0.49	0.56	46.60%	50.60%	1.05	1.11
U	0.28	0.23	25.20%	25.40%	1.11	0.90
O	0.09	0.04	11.20%	7.80%	0.83	0.57
S3-DBR	**0.30**	**0.26**	**32.05%**	**32.85%**	**0.93**	**0.79**
L	0.40	0.42	43.80%	47.40%	0.92	0.88
M	0.40	0.42	43.60%	47.20%	0.92	0.89
U	0.29	0.18	28.20%	27.20%	1.04	0.66
O	0.10	0.03	12.60%	9.60%	0.78	0.28
S4-DBR	**0.16**	**0.07**	**15.55%**	**12.00%**	**1.01**	**0.57**
L	0.18	0.09	17.80%	14.00%	0.99	0.62
M	0.18	0.09	17.80%	14.00%	0.99	0.61
U	0.20	0.09	17.20%	14.60%	1.15	0.60
O	0.08	0.01	9.40%	5.40%	0.81	0.27
S5-DBR	**0.20**	**0.09**	**19.95%**	**16.45%**	**0.99**	**0.56**
L	0.23	0.11	22.80%	19.20%	0.99	0.59
M	0.22	0.11	22.80%	19.20%	0.98	0.59
U	0.24	0.12	22.60%	19.20%	1.08	0.64
O	0.09	0.02	11.60%	8.20%	0.79	0.22
All	**0.24**	**0.17**	**22.76%**	**21.09%**	**1.04**	**0.82**
L	0.31	0.26	29.38%	28.58%	1.05	0.92
M	0.31	0.26	29.31%	28.50%	1.05	0.92
U	0.25	0.15	21.62%	19.85%	1.14	0.74
O	0.09	0.02	10.73%	7.42%	0.82	0.33

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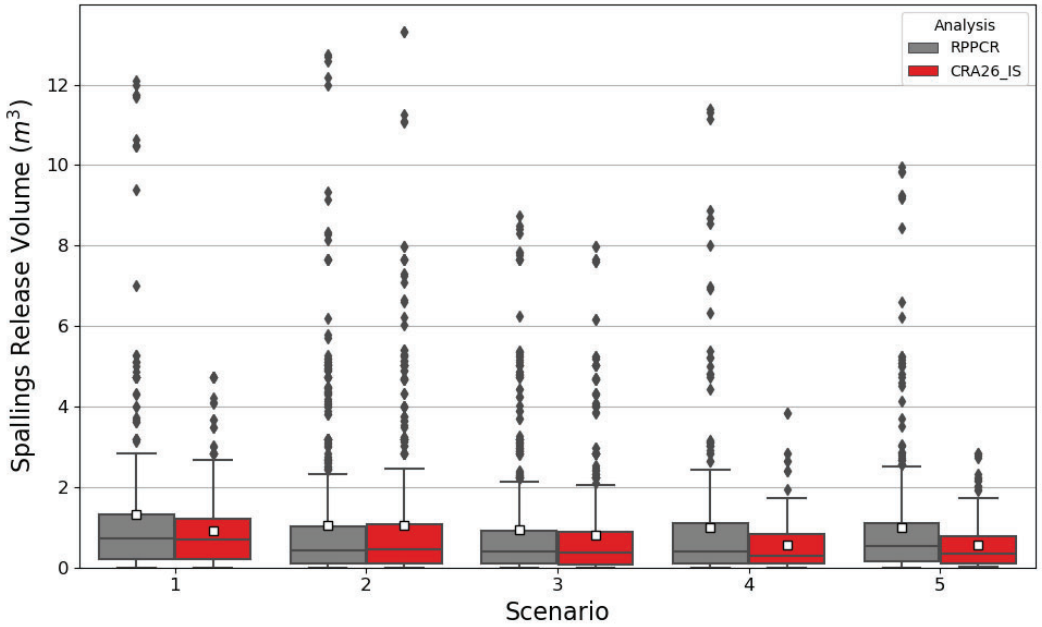


Figure 15. Non-Zero Spallings Volume by Intrusion Scenario, Replicate 3

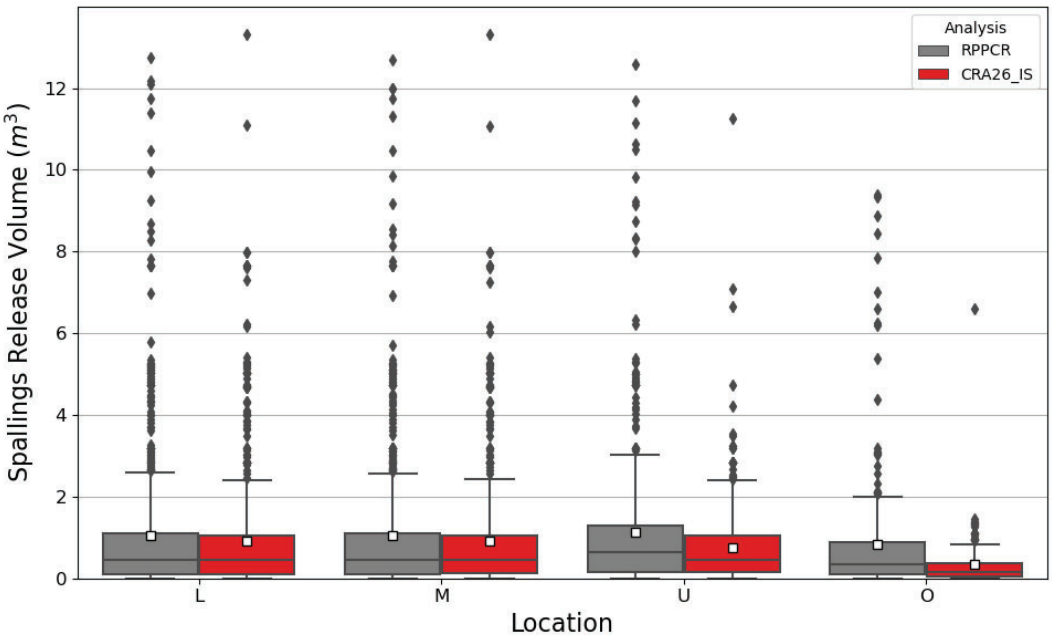


Figure 16. Non-Zero Spallings Volume by Intrusion Location, Replicate 3

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Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This research is funded by WIPP programs administered by the Office of Environmental Management (EM) of the U.S. Department of Energy.







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