Sandia National Laboratories
Waste Isolation Pilot Plant

Analysis Package for Cuttings, Cavings, and Spallings: 2014 Compliance Recertification Application Performance Assessment (CRA-2014 PA)
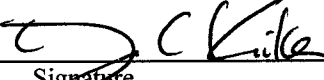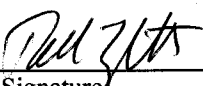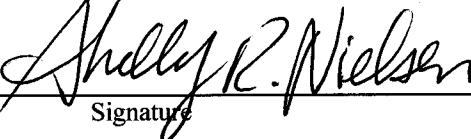
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1   Introduction

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 (deep underground) disposal of transuranic (TRU) waste. Containment of TRU waste at the WIPP is regulated by the U.S. Environmental Protection Agency (EPA) according to the regulations set forth in Title 40 of the Code of Federal Regulations (CFR), Part 191. The DOE demonstrates compliance with the containment requirements according to the Certification Criteria in Title 40 CFR Part 194 by means of performance assessment (PA) calculations performed by Sandia National Laboratories (SNL). WIPP PA calculations estimate the probability and consequence of potential radionuclide releases from the repository to the accessible environment for a regulatory period of 10,000 years after facility closure. The models used in PA are maintained and updated with new information as part of an ongoing process. Improved information regarding important WIPP features, events, and processes typically results in refinements and modifications to PA models and the parameters used in them. Planned changes to the repository and/or the components therein also result in updates to WIPP PA models. WIPP PA models are used to support the repository recertification process that occurs at five-year intervals following the receipt of the first waste shipment at the site in 1999.

PA calculations were included in the 1996 Compliance Certification Application (CCA) (U.S. DOE 1996), and in a subsequent Performance Assessment Verification Test (PAVT) (MacKinnon and Freeze 1997a, 1997b and 1997c). Based in part on the CCA and PAVT PA calculations, the EPA certified that the WIPP met the regulatory containment criteria. The facility was approved for disposal of TRU waste in May 1998 (U.S. EPA 1998). PA calculations were an integral part of the 2004 Compliance Recertification Application (CRA-2004) (U.S. DOE 2004). During their review of the CRA-2004, the EPA requested an additional PA calculation, referred to as the CRA-2004 Performance Assessment Baseline Calculation (PABC) (Leigh et al. 2005), be conducted with modified assumptions and parameter values (Cotsworth 2005). Following review of the CRA-2004 and the CRA-2004 PABC, the EPA recertified the WIPP in March 2006 (U.S. EPA 2006).

PA calculations were completed for the second WIPP recertification and documented in the 2009 Compliance Recertification Application (CRA-2009). The CRA-2009 PA resulted from continued review of the CRA-2004 PABC, including a number of technical changes and corrections, as well as updates to parameters and improvements to the PA computer codes (Clayton et al. 2008). To incorporate additional information which was received after the CRA-2009 PA was completed, but before the submittal of the CRA-2009, the EPA has requested an additional PA calculation, referred to as the 2009 Compliance Recertification Application Performance Assessment Baseline Calculation (PABC-2009) (Clayton et al. 2010), be undertaken which included updated information (Cotsworth 2009). Following the completion and submission of the PABC-2009, the WIPP was recertified in 2010 (U.S. EPA 2010).

The Land Withdrawal Act (U.S. Congress 1992) requires that the DOE apply for WIPP recertification every five years following the initial 1999 waste shipment. The 2014 Compliance Recertification Application (CRA-2014) is the third WIPP recertification application submitted by the DOE for EPA approval. The PA executed by SNL in support of the CRA-2014 is detailed in AP-164 (Camphouse 2013a). The CRA-2014 PA includes a number of technical changes and

parameter refinements, as well as a redesigned WIPP panel closure system. Results found in the CRA-2014 PA are compared to those obtained in the PABC-2009 in order to assess repository performance in terms of the current regulatory baseline. This analysis package consists of the direct solids releases component of the CRA-2014 PA analysis.

2 Cuttings, Cavings, and Spallings

The PA code CUTTINGS_S calculates the cuttings and cavings areas removed for a set of vectors, scenarios, times, and locations. Cuttings are the solid waste material removed directly by the drill bit intruding into the repository, while cavings are the solid waste material eroded from the walls of the borehole by shear stresses from the circulating drill fluid. CUTTINGS_S also calculates spallings volumes, which are a function of repository pressure. A spallings event is a special case of the drilling intrusion in which the repository contains gas at high pressure that causes (1) localized shear failure of the waste material surrounding the borehole and (2) entrainment of the failed waste material into and up the borehole, carried ultimately to the land surface.

CUTTINGS_S receives inputs from the PA code BRAGFLO, in which BRAGFLO scenarios S1-BF to S5-BF are used to initialize the flow field properties necessary for the calculation of direct brine releases (DBRs). This requires that results obtained on the BRAGFLO grid be mapped appropriately to the DBR grid. Code CUTTINGS_S is used to transfer the appropriate scenario results obtained with BRAGFLO to the DBR grid. These transferred flow results are used as initial conditions in the calculation of DBRs. As a result, intrusion scenarios used in the calculation of cuttings, cavings, and spallings correspond to those used in the calculation of DBRs.

2.1 CUTTINGS_S and WIPP PA Intrusion Scenarios

WIPP PA considers five different intrusion scenarios for the calculation of DBRs (Table 1). While CUTTINGS_S uses these standard DBR scenarios as a basis for its calculations, it does so to provide initial conditions for subsequent intrusions in the DBR calculations, rather than modeling the intrusion scenario itself. Thus, in CUTTINGS_S, scenario S1-DBR corresponds to an initial intrusion into the repository, while scenarios S2-DBR through S5-DBR are used to model an intrusion into a repository that has already been penetrated. Two types of intrusions, denoted as E1 and E2, are considered. An E1 intrusion assumes the borehole passes through a waste-filled panel and into a pressurized brine pocket that may exist under the repository in the Castile formation. An E2 intrusion assumes that the borehole passes through the repository but does not encounter a brine pocket. The times at which intrusions are assumed to occur for each scenario are outlined in the last column of Table 1; six intrusion times are modeled for scenario S1-DBR, while five times are modeled for each of scenarios S2-DBR through S5-DBR. Intrusions are assumed to take place in three locations: the southwest waste panel (identified in the CUTTINGS_S output files as location "L"), or in other parts of the repository that are higher in elevation, referred to as North Rest-of-Repository (identified in the CUTTINGS_S output files as location "U") and South Rest-of-Repository (identified in the CUTTINGS_S output files as location "M"). Further details regarding the locations of repository sub-regions are provided by Camphouse (2013b).

CUTTINGS_S does not calculate the radioactivity of the material removed; this calculation is performed using CCDFGF, which accounts for stochastic uncertainty in the future of the repository (WIPP PA 2003a). The releases associated with cuttings, cavings, and spallings for the CRA-2014 PA can be found in Zeitler (2013).

Table 1. PA intrusion scenarios used in calculating direct solids releases

Scenario	First Intrusion Time (year) and Type	Intrusion Times – Subsequent (year)
S1-DBR	None	100, 350, 1000, 3000, 5000, 10000
S2-DBR	350, E1	550, 750, 2000, 4000, 10000
S3-DBR	1000, E1	1200, 1400, 3000, 5000, 10000
S4-DBR	350, E2	550, 750, 2000, 4000, 10000
S5-DBR	1000, E2	1200, 1400, 3000, 5000, 10000

NOTES: For the first intrusions in each scenario, the repository conditions are obtained from BRAGFLO intrusion scenarios. An E1 intrusion scenario is defined as an intrusion into the repository that creates a pathway to a pressurized brine pocket below the repository. An E2 intrusion scenario is defined as an intrusion into the repository that does not create a pathway to a pressurized brine pocket below the repository.

2.2 Cuttings and Cavings

The solid material removed from the repository and carried to the surface by the drilling fluid during the process of drilling a borehole is divided into cuttings and cavings. Cuttings are removed directly by the drill bit, while cavings are eroded from the walls of the borehole by shear stresses from the circulating drill fluid. For the CRA-2014 PA, cuttings and cavings were computed using the same conceptual and numerical models as the PABC-2009; these models are described in the CUTTINGS_S design document (WIPP PA 2004).

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 is given by

$$A_{cut} = \pi D^2 / 4, \tag{1}$$

$$V_{cut} = A_{cut} H = \left(\pi D^2 / 4\right) H, \tag{2}$$

where $D = 0.31115$ m is the drill bit diameter and $H = 3.96$ m is the uncompacted repository height (WIPP PA 2004). Since 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 CRA-2014 PA.

WIPP PA estimates cavings removal with a model based on the effect of shear stress on the material located adjacent to the edge of the borehole. In particular, material around the edge of the borehole is assumed to shear off until the shear stress on the borehole wall is equal to the shear strength of the waste, which is the maximum shear stress at which erosion of the waste can occur. The process is assumed to be radially symmetric, so that the cavings area is treated as an

annulus formed around the initial cuttings area. For a more detailed discussion of the conceptual model of cavings, see WIPP PA (2004).

2.3 Spallings

Spallings consist of waste that enters the borehole through the release of waste-generated gas escaping into the borehole, which is at a lower pressure than the gas. Calculation of spallings releases for the CRA-2014 PA is divided into four 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 calculate spallings volumes in scenarios for drilling intrusions; and

(4) calculation of spallings releases accounting for stochastic uncertainty in the future of the repository using CCDFGF (WIPP PA 2003a).

This section discusses the process used by CUTTINGS_S to calculate spalling volumes for the WIPP drilling intrusion scenarios. For the CRA-2014 PA, no changes were made to the DRSPALL model (WIPP PA 2003b).

Additionally, for each vector the code DRSPALL calculates the spallings volume produced for each of 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 has been selected as a lower bound as repository pressures below 10 MPa do not yield spallings. Thus, for pressures below P_1, the borehole has a higher pressure than the repository, and therefore the gas will not flow into the borehole (WIPP PA 2004). The upper limit P_4 corresponds to lithostatic pressure; repository pressures above this value lead to repository fracture.

For each vector in a given combination of intrusion scenario, time, and location, the initial repository pressure P is determined using data from previously executed BRAGFLO calculations (Camphouse 2013b). If V_i ($i = 1, 2, 3,$ or 4) denotes the volume calculated by DRSPALL corresponding to pressure P_i, CUTTINGS_S calculates the spallings volume V_{spall} as a function of P for a given vector using the formula (WIPP PA 2004):

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

2.4 Direct Brine Release Calculations

Using data from previously executed BRAGFLO calculations, CUTTINGS_S calculates the volume-weighted averages for gas pressure, brine pressure, gas saturation, permeability of rock

to brine, and waste room porosity for each user specified zone of the repository. The resulting averages are used as initial conditions for the CRA-2014 PA direct brine release (DBR) calculations. For a discussion of the implementation and results of these calculations, see Malama (2013).

3 Methodology for Calculating Cuttings, Cavings, and Spallings

Analysis plan AP-164 (Camphouse 2013a) explains the methodology used to calculate direct releases (cuttings and cavings, spallings, and DBRs) for the analysis reported here and identifies three separate cases in which CUTTINGS_S is executed (Camphouse 2013a, Section 2.3.1 and Table 2-14):

- CRA14-BL — This case is used to compare the impact of a baseline set of changes relative to the PABC-2009. The changes considered include replacement of the Option D panel closure with the revised panel closure design, additional excavation in the WIPP experimental area, updated waste inventory parameters, updated radionuclide solubilities and their associated uncertainty, and updated drilling rate and plugging pattern parameters. A single replicate (Replicate 1) will be executed for case CRA14-BL.

- CRA14-TP — In addition to the changes in case CRA14-BL, this case incudes refinements to parameter TAUFAIL (waste shear strength), and to parameter PBRINE (the probability of encountering a pressurized brine pocket during a drilling intrusion). A single replicate (Replicate 1) will be executed for case CRA14-TP.

- CRA14-0 — This case includes all changes from previous cases as well as refinements to the steel corrosion rate and a water balance that includes MgO hydration. Three replicates (Replicate 1, Replicate 2, and Replicate 3) will be executed for case CRA14-0.

CUTTINGS_S calculates the quantity of material brought to the surface from a radioactive waste disposal repository as a consequence of an inadvertent human intrusion through drilling, either as cuttings and cavings or as spallings releases and DBRs (WIPP PA 2004). The amount of material removed by cuttings and cavings is reported in terms of the cross-sectional area (m^2), while the amount of material removed by spallings is reported as a volume (m^3), consistent with the output from CUTTINGS_S.

3.1 CUTTINGS_S Calculations

The CRA-2014 PA used CUTTINGS_S version 6.02. For cases CRA14-BL and CRA14-TP, one replicate of 100 vectors each was executed. CUTTINGS_S calculates an area for cuttings and cavings and a spallings volume for each combination of replicate, vector, scenario, drilling location, and intrusion time. In both the CRA14-BL and CRA14-TP cases, a total of 7,800 areas (1 replicate × 100 vectors × 3 drilling locations × 26 intrusion times) and 7,800 volumes were determined. For the CRA14-0 case, which included three replicates of 100 vectors each, a total of 23,400 areas (3 replicates × 100 vectors × 3 drilling locations × 26 intrusion times) and 23,400 volumes were determined. Details of the run control procedure are provided by Long (2013).

3.2 Parameters

The code LHS samples two parameters for CUTTINGS_S calculations (Kirchner 2013): the effective shear strength for erosion of the waste (BOREHOLE:TAUFAIL) and the drill string angular velocity (BOREHOLE:DOMEGA). The ranges sampled for these variables are shown in Table 2.

Table 2. Sampled uncertain parameters retrieved from the PA parameter database for cavings calculations

Material	Property	Description	Distribution	Range	PA
BOREHOLE	TAUFAIL	Effective shear strength for erosion of the waste	Loguniform	0.05 to 77.0 Pa	PABC-2009; CRA-2014 Case CRA14-BL
			Uniform	2.22 to 77.0 Pa	CRA-2014 Cases CRA14-TP and CRA14-0
BOREHOLE	DOMEGA	Drill string angular velocity	Cumulative	4.2 to 23.0 rad/s	PABC-2009; CRA-2014 Cases CRA14-BL, CRA14-TP, and CRA14-0

In addition to these uncertain parameters, CUTTINGS_S uses a set of constant parameters, listed in Table 3, retrieved from the PA parameter database. Although five of these parameters (BLOWOUT:PARTDIA, all of the DRILLMUD parameters, and WAS_AREA:ABSROUGH) are stored in the PA parameter database as quantities with an associated probability distribution, CUTTINGS_S only uses a single value for each of these parameters. Treating these parameters as constants is a reasonable simplification of the problem based on the results of a sensitivity analysis (Lord et al. 2003). For these parameters, the median value of the distribution is then used as the constant value for CUTTINGS_S. The values in Table 3 have not changed from the PABC-2009 PA, and they apply to all cases in the CRA-2014 PA.

Table 3. Constant parameters retrieved from the PA parameter database for cuttings and cavings calculations

Material	Property	Value	Description
BLOWOUT	PARTDIA	2.80000E–03 m	Waste particle diameter[a]
BLOWOUT	HREPO	3.96000E+00 m	Height of repository at burial time
BOREHOLE	DIAMMOD	3.11150E–01 m	Modern or current drill bit diameter
BOREHOLE	COLDIA	2.03200E–01 m	Drill collar diameter
DRILLMUD	DNSFLUID	1.21000E+03 kg/m^3	Density of brine used as drilling fluid (mud)[a]
DRILLMUD	VISCO	9.17000E–03 Pa · s	Viscosity of brine used as drilling fluid (mud)[a]
DRILLMUD	YLDSTRSS	4.40000E+00 Pa	Yield stress point of brine used as drilling fluid (mud)[a]
DRILLMUD	SHEARRT	1020 s^{-1}	Shear rate of the drilling fluid (mud)
DRILLMUD	MUDFLWRT	0.09935 m^3/(m ·s)	Drilling fluid (mud) flow rate
WAS_AREA	ABSROUGH	2.50000E–02 m	Absolute roughness of waste material[a]
REFCON	SECYR	3.16888E–08 year/s	Seconds to year conversion
REFCON	PI	3.14159E+00	Reference constant π

[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.

Several assumptions were made when determining the CUTTINGS_S parameter values. The major assumptions affecting parameter values are:

- Based upon regulatory guidance in 40 CFR 194 (EPA 1996), future drilling practices will be the same as they are at present.

- The diameter of the intrusion borehole is constant at 12.25 inches (0.31115 m). Since the most common bit size used to reach the depth of the repository is 11 inches (Hansen et al. 2003), this assumption can be considered conservative.

Additional assumptions have also been made about the waste shear strength parameter (BOREHOLE:TAUFAIL); these are discussed in the following section.

3.3 The BOREHOLE:TAUFAIL Parameter

For WIPP PA calculations performed between the 1996 Performance Assessment Verification Test (PAVT) (MacKinnon and Freeze 1997a, 1997b, 1997c) and the PABC-2009, as well as for Case CRA14-BL of the CRA-2014 PA, the distribution for BOREHOLE:TAUFAIL was chosen based on the extreme values found in the literature for the waste shear strength of marine clays (Herrick et al. 2007). This assumption can be considered conservative since degraded surrogate waste materials yield higher shear strengths than naturally occurring marine clays (Hansen and Leigh 2003).

Experiments to directly measure the erosion resistance of surrogate degraded wastes material have been developed by Herrick et al. (2012). The hydrodynamic shear strength of a material can only be measured in the laboratory by flume testing. Flume testing is typically performed in a channel in which the fluid is horizontal, mimicking a stream or ocean current. However, in a WIPP intrusion event, the drill bit would penetrate the degraded waste and the drilling mud would flow up the borehole in a predominantly vertical direction. In order to simulate this, a flume was designed and built so that the eroding fluid enters a vertical channel from the bottom and flows up past a specimen of surrogate waste material held in a cylindrical sample holder. Based on experimental results that realistically simulate the effect of a drilling intrusion on an accepted surrogate waste material, the distribution for BOREHOLE:TAUFAIL was revised in Cases CRA14-TP and CRA14-0 of the CRA-2014 PA.

The principal parameters of the probability distribution function for the waste shear strength parameter BOREHOLE:TAUFAIL are shown in Table 4; the cumulative distribution function is plotted in Figure 1.

Table 4. Principal parameters for the BOREHOLE:TAUFAIL distribution

Attribute	PABC-2009 PA and CRA-2014 PA (Case CRA14-BL)	CRA-2014 PA (Cases CRA14-TP and CRA14-0)
Distribution type	Loguniform	Uniform
Minimum (Pa)	0.05	2.22
Maximum (Pa)	77.00	77.00
Mean (Pa)	10.5	39.61
Median (Pa)	1.96	39.61
Standard deviation (Pa)	17.1	21.59

NOTE: The statistical parameters associated with various distribution types, including both loguniform and uniform, are described by Tierney (1996) with details provided in Appendix A (see worksheet *TAUFAIL*).
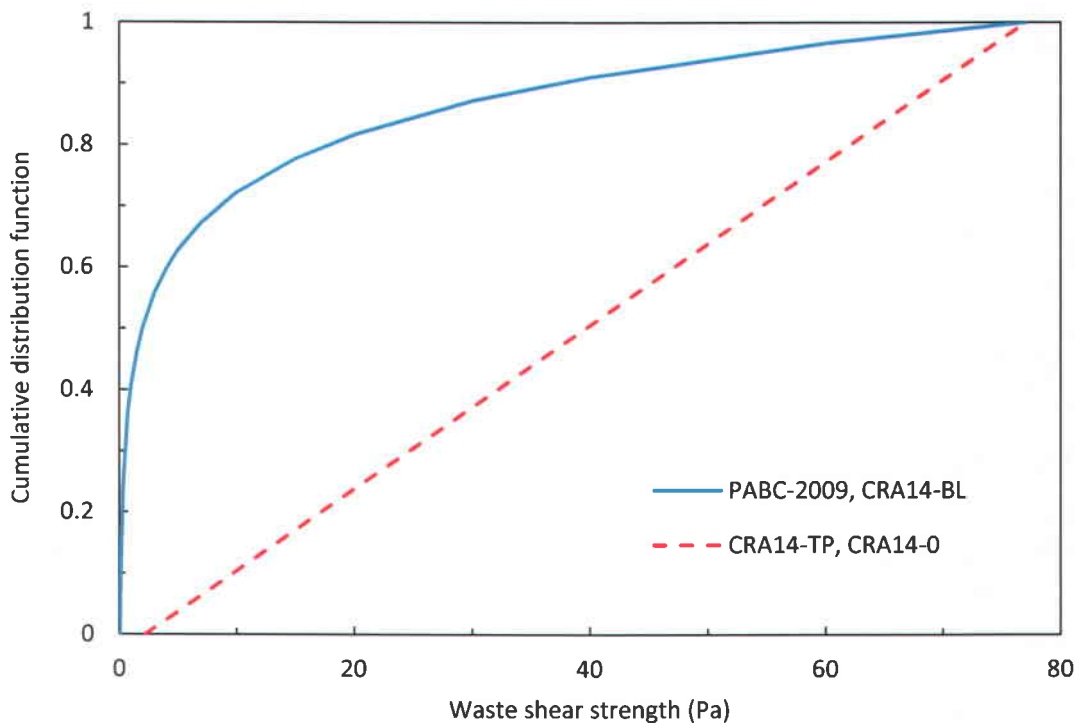
NOTE: Calculation details are provided in Appendix A (see worksheet *TAUFAIL*).

Figure 1. Cumulative distribution function for the waste shear strength parameter BOREHOLE:TAUFAIL in the PABC-2009 and CRA-2014 PA.

4   Results

The results from CUTTINGS_S are summarized in this section. A Microsoft Office Professional Plus 2010 Microsoft Excel® spreadsheet was developed to analyze the CUTTINGS_S output and is documented in Appendix A.

4.1   Cuttings and Cavings

Since the drill bit diameter, D (see Borehole Property DIAMMOD in Table 3) is treated as a constant in both the CRA-2009 PABC and the CRA-2014 PA, the cuttings area, A_{cut}, is the same for all vectors ($A_{cut} = 0.0760$ m^2, Eq. 1).

CUTTINGS_S reports the combined area for cuttings and cavings $A = A_{cut} + A_{cav}$, where A_{cav} is the cavings area. Consequently, the cuttings area A_{cut} must be subtracted from the reported area to determine the cavings area A_{cav} for a given vector. (If $A = A_{cut}$, then no cavings occurs for the given vector.) The results obtained for Case CRA14-BL of the CRA-2014 PA are the same as for the PABC-2009, because there have been no changes to either the models or the parameters underlying the calculation of cuttings and cavings areas (Ismail 2010). However, for Cases CRA14-TP and CRA14-0 of the CRA-2014 PA, parameter BOREHOLE:TAUFAIL has changed, which impacts the cavings area. The summary of statistics for cavings is shown in Table 5 for both the PABC-2009 and CRA-2014.

**Table 5.** Cavings area statistics for the PABC-2009 and CRA-2014 PA

Replicate	Cavings Area (m²)		Vectors with no Cavings	Cavings Area (m²)		Vectors with no Cavings
	Maximum	Mean		Maximum	Mean	
PABC-2009				CRA-2014 (Case CRA14-BL)		
R1	0.748	0.177	9	0.748	0.177	9
R2	0.785	0.175	10	—	—	—
R3	0.753	0.178	11	—	—	—
CRA-2014 (Case CRA14-TP)				CRA-2014 (Case CRA14-0)		
R1	0.090	0.010	50	0.090	0.010	50
R2	—	—	—	0.090	0.010	44
R3	—	—	—	0.075	0.010	50

NOTES: The PABC-2009 report for CUTTINGS_S reported the total area for cuttings and cavings, instead of the cuttings area. To obtain the cavings area, the cuttings area of 0.0760 m² was subtracted from the combined area reported for the PABC-2009 (Ismail 2010). Calculation details are provided in Appendix A (see worksheets *CUSP_CRA14-BL_R1*, *CUSP_CRA14-TP_R1*, *CUSP_CRA14-0_R1*, *CUSP_CRA14-0_R2*, and *CUSP_CRA14-0_R3*).

The cumulative frequency of nonzero cavings areas for Cases CRA14-BL, CRA14-TP (replicate 1 only), and CRA14-0 (replicates 1, 2, and 3) of the CRA-2014 PA and the PABC-2009 (replicate 1 only and replicates 1, 2, and 3) is shown in Figure 2. Figure 2 shows that the cumulative distributions of cavings areas are identical in Case CRA14-BL of the CRA-2014 PA and replicate 1 of the PABC-2009. The cumulative distribution of Case CRA14-BL and replicate 1 of the PABC-2009 is very similar to the cumulative distribution of the PABC-2009 (all three replicates). Figure 2 also shows that the cumulative distributions of cavings areas are identical in Case CRA14-TP and replicate 1 of Case CRA14-0 the CRA-2014 PA. The cumulative distributions of cavings areas from Cases CRA14-TP (replicate 1) and Case CRA14-0 (replicates 1, 2, and 3) are very similar, and are an approximate order of magnitude less than the cumulative distribution of cavings area from the PABC-2009. The probability distributions of cavings area from the CRA-2014 (Case CRA14-0) and the PABC-2009 are provided in Figure 3, which shows a shift in the mean cavings area as well as a decrease in the overall number of nonzero vectors for CRA-2014 compared to PABC-2009.

Previous sensitivity analyses have shown that the primary parameters influencing the results of CUTTINGS_S are the waste shear strength and the drill string angular velocity (Vugrin 2005). The cuttings and cavings area for Case CRA14-0 of the CRA-2014 PA is plotted against the waste shear strength (Figure 4) and plotted against the drill string angular velocity (Figure 5). While a strong inverse relationship can be seen to exist between waste shear strength and cuttings and cavings area in Figure 4, no correlation between cuttings and cavings area and drill string angular velocity is observed in Figure 5, as nearly identical values of the drill string angular velocity can lead to very different cuttings and cavings areas.

However, plotting cavings areas as a function of both waste shear strength and drill string angular velocity, as in Figure 6, shows that the drill string angular velocity can have a secondary effect on the cavings area, since, for a given waste shear strength, there is a trend towards larger cavings areas as the drill string angular velocity increases.
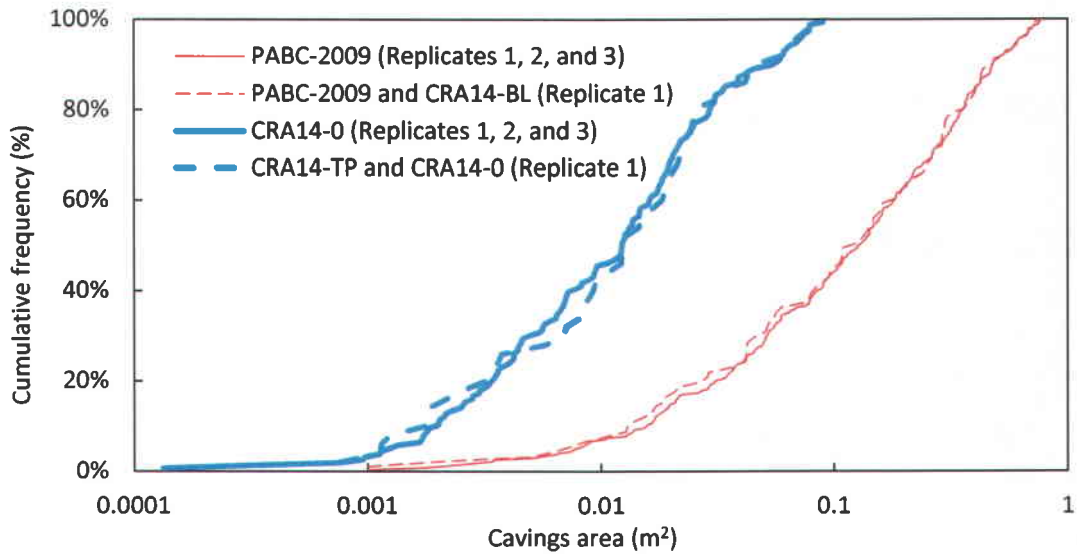
NOTE: Calculation details are provided in Appendix A (see worksheets *Cavings* and *Plots*).

Figure 2. Cumulative frequency of cavings area in the CRA-2014 PA and the PABC-2009.
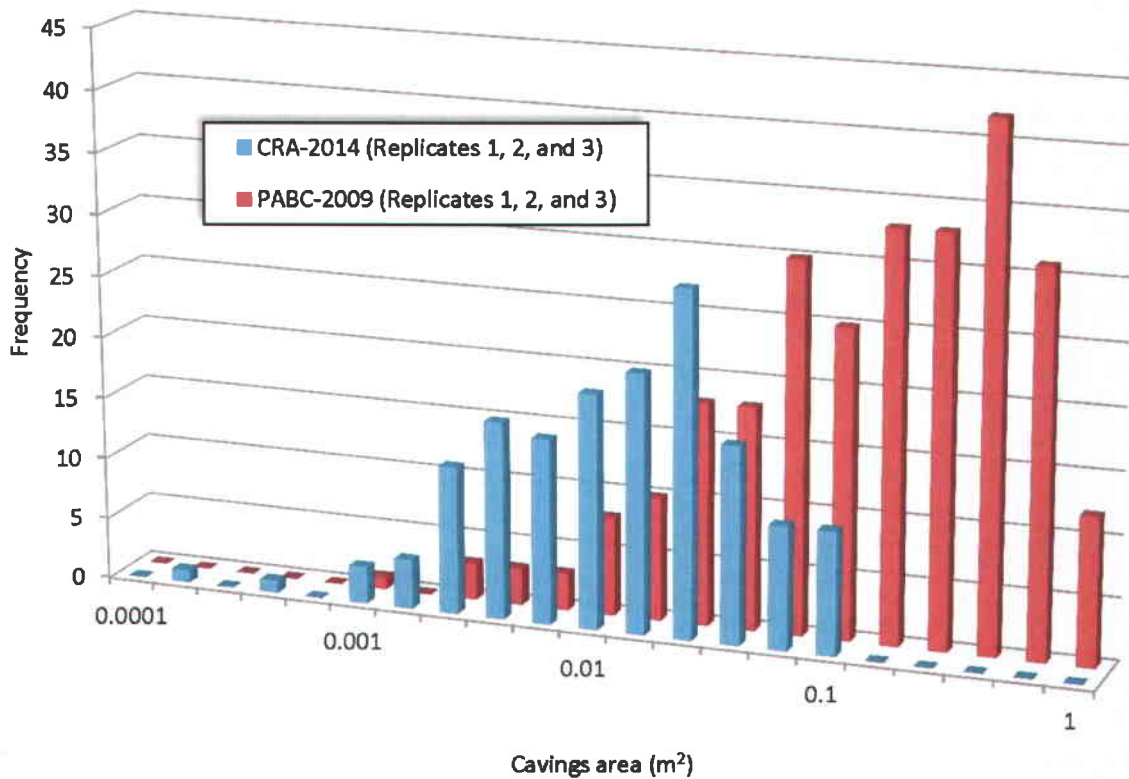
NOTE: Calculation details are provided in Appendix A (see worksheets *Cavings* and *Plots*).

Figure 3. Probability frequency of cavings area in the CRA-2014 PA (Case CRA14-0) and the PABC-2009.
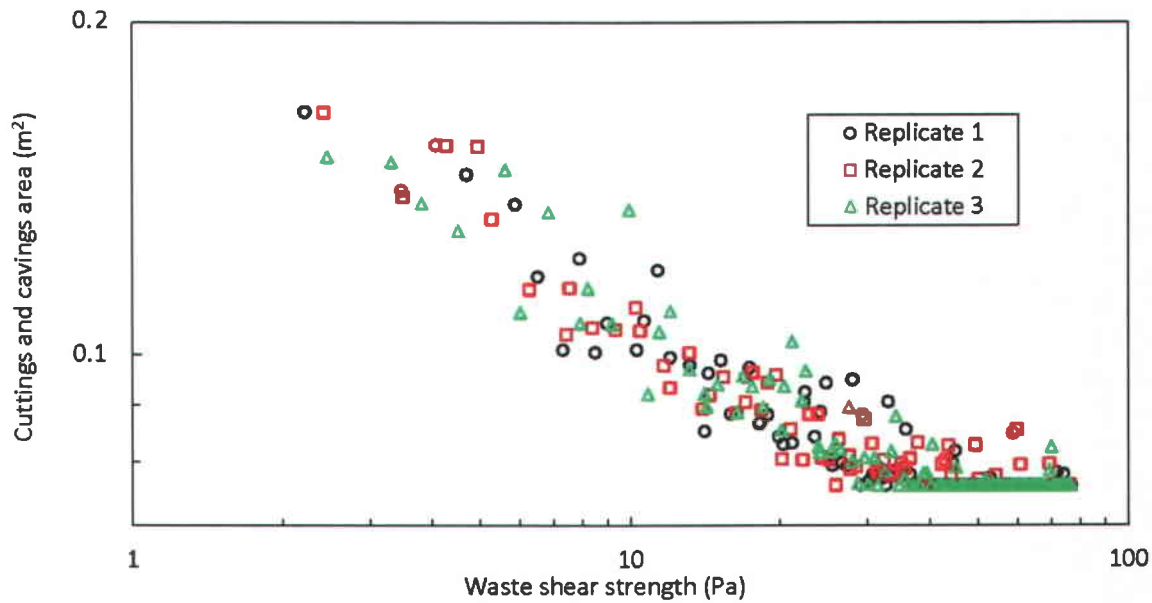
NOTES: The lower end of the cuttings and cavings area scale, 0.0760 m², corresponds to the limit of zero cavings; the nearly linear trend on the log-log plot indicates a power-law relationship for cuttings and cavings areas as a function of waste shear strength for values of BOREHOLE:TAUFAIL less than about 20 Pa. Calculation details are provided in Appendix A (see worksheets *CUSP_CRA14-0_R1*, *CUSP_CRA14-0_R2*, *CUSP_CRA14-0_R3*, and *Plots*).

Figure 4. Cuttings and cavings area as a function of waste shear strength for Case CRA14-0 of the CRA-2014 PA.
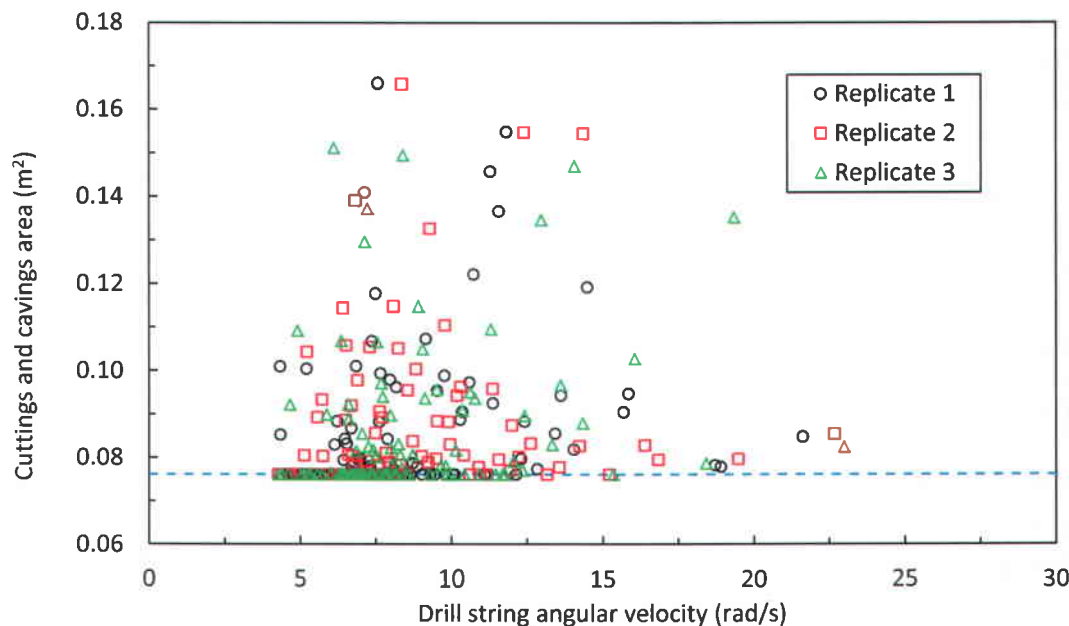
NOTES: The horizontal line indicates the constant cuttings area of 0.0760 m². Calculation details are provided in Appendix A (see worksheets *CUSP_CRA14-0_R1*, *CUSP_CRA14-0_R2*, *CUSP_CRA14-0_R3*, and *Plots*).

Figure 5. Cuttings and cavings area as a function of drill string angular velocity for Case CRA14-0 of the CRA-2014 PA.
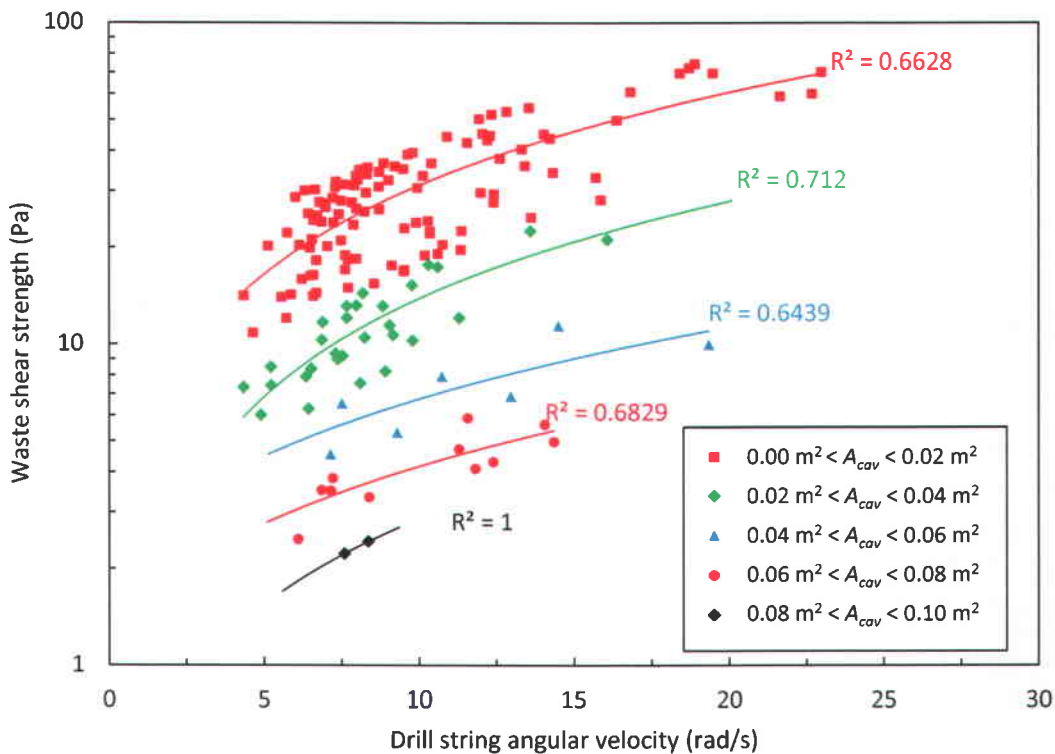
NOTE: Calculation details are provided in Appendix A (see worksheets *R1,R2,R3* and *Plots*).

Figure 6. Waste shear strength versus drill string angular velocity according to calculated nonzero cavings area for Case CRA14-0 of the CRA-2014 PA.

4.2 Spallings

The cumulative frequency of nonzero spallings volumes for Cases CRA14-BL, CRA14-TP (replicate 1 only), and CRA14-0 (replicates 1, 2, and 3) of the CRA-2014 PA and the PABC-2009 (replicate 1 only and replicates 1, 2, and 3) is shown in Figure 7. This figure provides a summary of all nonzero spallings data from all scenarios, repository regions, and times. Figure 7 shows that the cumulative distributions of spallings volumes are identical in Cases CRA14-BL and CRA14-TP of the CRA-2014 PA. The cumulative distribution of Cases CRA14-BL and CRA14-TP (which are only for replicate 1) is similar to the cumulative distribution of replicate 1 of the PABC-2009. While the cumulative distributions of spallings volumes from all three replicates of both the CRA-2014 PA (Case CRA14-0) and the PABC-2009 are similar, CRA-2014 spallings volumes less than about 0.1 m^3 occur at a lower frequency and CRA-2014 spallings volumes greater than about 0.1 m^3 occur at a higher frequency compared to the PABC-2009.

The change in spallings volumes between the CRA-2014 PA and the PABC-2009 is the result of changing repository pressures observed in BRAGFLO calculations for the CRA-2014 PA (Camphouse 2013b). The change in pressure within the repository may be attributable to several factors, including (1) the change in permeability and porosity resulting from the modified panel
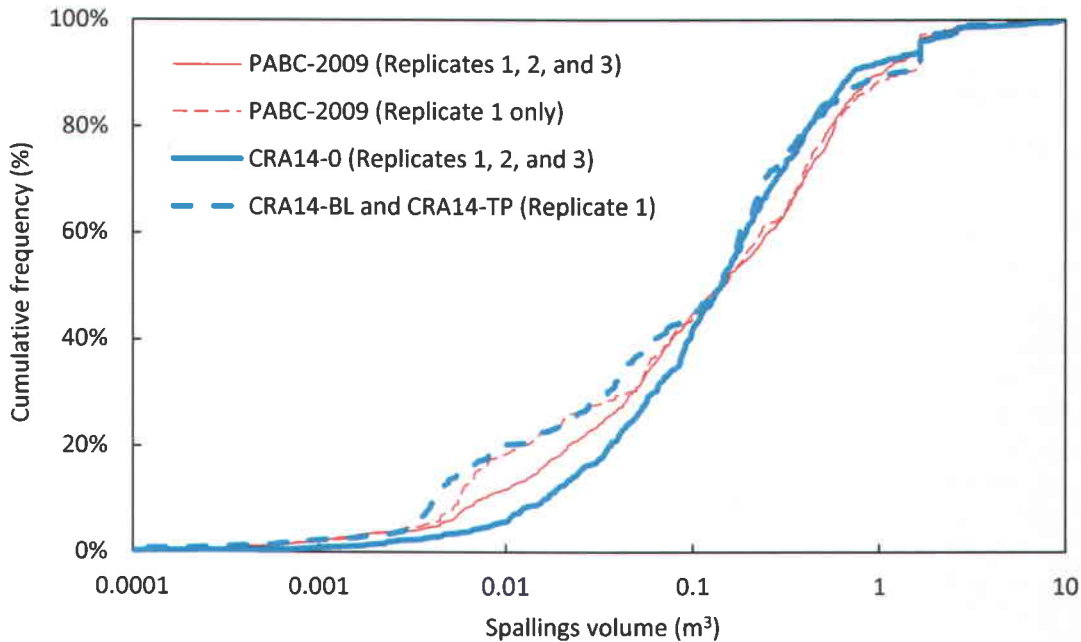
NOTE: Calculation details are provided in Appendix A (see worksheets *Spallings* and *Plots*).

Figure 7. Cumulative frequency of spallings volume in the CRA-2014 PA and the PABC-2009.

closure system consisting of 100 feet run of mine salt with barriers at each end, (2) additional excavation in the WIPP experimental area, (3) refinement of the corrosion rate of steel, and (4) refinement of the repository water balance to include MgO hydration. Because spallings volumes directly depend on repository pressure, an increase in repository pressure translates into larger spallings volumes. Since there is a minimum threshold pressure required to create spallings, an increase in repository pressure also increases the percentage of vectors with spallings.

4.2.1 Spallings Volumes by Scenario

Average and maximum statistics for the various calculations for each of the different intrusion scenarios considered by CUTTINGS_S are shown in Table 6 for both the CRA-2014 PA and the PABC-2009. The results for Replicate 1 of the PABC-2009 PA and Cases CRA14-BL and CRA14-TP are very similar for all five scenarios. Also, Replicate 1 of Case CRA14-0 is similar to Replicate 1 of the PABC-2009 for the maximum spallings value and the average nonzero spallings volume for all five scenarios. However, there is a decrease in the number of nonzero spallings in the CRA-2014 results (Case CRA14-0) compared to the PABC-2009 results across all scenarios. Replicates 2 and 3 of Case CRA14-0 also show a decrease in the maximum spallings value and the average nonzero spallings volume in scenarios S1-DBR, S4-DBR, and S5-DBR compared to the corresponding replicates in the PABC-2009. The additional excavation in the WIPP experimental area produces a slight reduction in the repository pressure. The refinement of the steel corrosion rate and the repository water balance results in further reduction of the repository pressure (Camphouse 2013b). Consequently, initial intrusions into a

Table 6. Summary of spallings releases by scenario

Attribute		S1-DBR	S2-DBR	S3-DBR	S4-DBR	S5-DBR	Total
				Scenarios			
CRA-2014 PA (Cases CRA14-BL and CRA14-TP)							
R1	Maximum [m^3]	1.67	9.27	8.62	1.67	1.67	9.27
	Average nonzero volume [m^3]	0.32	0.53	0.52	0.27	0.30	0.40
	Number of nonzero volumes	127	113	105	59	80	484
	Percent of nonzero volumes	7.1%	7.5%	7.0%	3.9%	5.3%	6.2%
CRA-2014 PA (Case CRA14-0)							
R1	Maximum [m^3]	1.67	9.69	9.13	1.67	1.67	9.69
	Average nonzero volume [m^3]	0.41	0.58	0.70	0.42	0.41	0.55
	Number of nonzero volumes	41	95	60	16	23	235
	Percent of nonzero volumes	2.3%	6.3%	4.0%	1.1%	1.5%	3.0%
R2	Maximum [m^3]	1.23	2.76	1.96	0.64	0.64	2.76
	Average nonzero volume [m^3]	0.28	0.31	0.23	0.22	0.25	0.27
	Number of nonzero volumes	41	98	64	23	26	252
	Percent of nonzero volumes	2.3%	6.5%	4.3%	1.5%	1.7%	3.2%
R3	Maximum [m^3]	0.96	6.14	4.91	0.48	0.43	6.14
	Average nonzero volume [m^3]	0.25	0.41	0.44	0.17	0.16	0.35
	Number of nonzero volumes	30	85	46	16	17	194
	Percent of nonzero volumes	1.7%	5.7%	3.1%	1.1%	1.1%	2.5%
Total	Maximum [m^3]	1.67	9.69	9.13	1.67	1.67	9.69
	Average nonzero volume [m^3]	0.32	0.43	0.45	0.26	0.28	0.39
	Number of nonzero volumes	112	278	170	55	66	681
	Percent of nonzero volumes	2.1%	6.2%	3.8%	1.2%	1.5%	2.9%
PABC-2009							
R1	Maximum [m^3]	2.24	8.29	7.97	1.67	1.67	8.29
	Average nonzero volume [m^3]	0.37	0.54	0.50	0.30	0.37	0.43
	Number of nonzero volumes	142	117	111	59	77	506
	Percent of nonzero volumes	7.9%	7.8%	7.4%	3.9%	5.1%	6.5%
R2	Maximum [m^3]	2.36	2.76	1.86	2.26	1.93	2.76
	Average nonzero volume [m^3]	0.32	0.39	0.37	0.50	0.47	0.39
	Number of nonzero volumes	168	122	122	57	84	553
	Percent of nonzero volumes	9.3%	8.1%	8.1%	3.8%	5.6%	7.1%
R3	Maximum [m^3]	4.91	6.23	2.62	1.47	1.49	6.23
	Average nonzero volume [m^3]	0.53	0.39	0.28	0.30	0.28	0.38
	Number of nonzero volumes	156	113	118	45	72	504
	Percent of nonzero volumes	8.7%	7.5%	7.9%	3.0%	4.8%	6.5%
Total	Maximum [m^3]	4.91	8.29	7.97	2.26	1.93	8.29
	Average nonzero volume [m^3]	0.40	0.44	0.38	0.37	0.38	0.40
	Number of nonzero volumes	466	352	351	161	233	1563
	Percent of nonzero volumes	8.6%	7.8%	7.8%	3.6%	5.2%	6.7%

NOTES: The notation R*r* stands for Replicate *r*. Calculation details for the CRA-2014 PA are provided in Appendix A (see worksheets *CUSP_CRA14-BL_R1, CUSP_CRA14-TP_R1, CUSP_CRA14-0_R1, CUSP_CRA14-0_R2, and CUSP_CRA14-0_R3*). The PABC-2009 results (except for the "Percent of nonzero volumes" and "Total") are provided by Ismail (2010).

previously undisturbed repository result in decreases to spallings volumes, as well as decreases to the number of nonzero spallings volumes.

4.2.2 Spallings Volumes by Location

Examining spallings releases as a function of intrusion location in Table 7 shows consistent behavior across analyses: releases are largest for intrusions into the intruded waste panel (Lower Region); intrusions into the South Rest-of-Repository and North Rest-of-Repository (Middle and Upper Regions) areas lead to releases that are smaller in magnitude. The spallings releases for Cases CRA14-BL and CRA14-TP of the CRA-2014 PA are similar to Replicate 1 of the PABC-2009 across all three intrusion locations.

The maximum volumes, the average nonzero volumes, and the number of nonzero volumes in the intruded waste panel (Lower Region) are similar for Case CRA14-0 of the CRA-2014 PA and the PABC-2009 across all replicates. The maximum and average volumes in the South Rest-of-Repository and North Rest-of-Repository areas for Case CRA14-0 of the CRA-2014 PA are lower than the PABC-2009 across all replicates. The number of nonzero volumes in the South Rest-of-Repository and North Rest-of-Repository is lower for Case CRA14-0 of the CRA-2014 PA compared to the corresponding regions of the PABC-2009 PA. The additional excavation in the WIPP experimental area and the refinement of the steel corrosion rate and the repository water balance produces a reduction in the repository pressure. The decrease in waste panel pressure translates to decreases in spallings volumes and the number of nonzero spallings volumes in the CRA-2014 PA. Further details regarding the locations of repository sub-regions and repository pressures are provided by Camphouse (2013b).

5 Summary

The results for cuttings, cavings, and spallings from the CRA-2014 PA have been compared to the cuttings, cavings, and spallings releases obtained in the PABC-2009 calculations. In the baseline case of the CRA-2014 PA (Case CRA14-BL), no changes have been found in the cuttings and cavings area, because none of the changes between the PABC-2009 and Case CRA14-BL of the CRA-2014 PA have affected the cuttings and cavings model. However, in Case CRA14-TP of the CRA-2014 PA (and subsequently in Case CRA14-0), the waste shear strength (parameter TAUFAIL) was modified to increase its lower limit. This resulted in a decrease in the amount of cavings produced (Figures 2 and 3) compared to the PABC-2009 PA.

The cumulative frequency of spallings volumes for both the CRA-2014 PA and the PABC-2009 are similar, with the cumulative distribution showing both increases and decreases in CRA-2014 spallings volumes compared to the PABC-2009. Spallings volumes directly depend on repository pressure. For undisturbed conditions, implementation of the modified panel closure system yields higher long-term waste panel pressure (on average) than was seen in the PABC-2009 (Camphouse 2013b). The additional excavation in the WIPP experimental area produces a slight reduction in the repository pressure. The refinement of the steel corrosion rate and the repository water balance results in further reduction of the repository pressure. Consequently, initial intrusions into a previously undisturbed repository result in decreases to spallings volumes, as well as decreases to the number of nonzero spallings volumes, in Case CRA14-0 of

Table 7. Summary of spallings releases as a function of intrusion location

Attribute		Intruded Waste Panel (Lower Region)	South Rest-of-Repository (Middle Region)	North Rest-of-Repository (Upper Region)
CRA-2014 PA (Cases CRA14-BL and CRA14-TP)				
R1	Maximum [m^3]	9.27	1.67	1.67
	Average nonzero volume [m^3]	0.49	0.32	0.36
	Number of nonzero volumes	202	160	122
	Percent of nonzero volumes	7.8%	6.2%	4.7%
CRA-2014 PA (Case CRA14-0)				
R1	Maximum [m^3]	9.69	1.67	1.67
	Average nonzero volume [m^3]	0.60	0.48	0.46
	Number of nonzero volumes	146	47	42
	Percent of nonzero volumes	5.6%	1.8%	1.6%
R2	Maximum [m^3]	2.76	0.74	0.74
	Average nonzero volume [m^3]	0.28	0.26	0.25
	Number of nonzero volumes	160	50	42
	Percent of nonzero volumes	6.2%	1.9%	1.6%
R3	Maximum [m^3]	6.14	0.96	0.49
	Average nonzero volume [m^3]	0.44	0.20	0.19
	Number of nonzero volumes	122	43	29
	Percent of nonzero volumes	4.7%	1.7%	1.1%
Total	Maximum [m^3]	9.69	1.67	1.67
	Average nonzero volume [m^3]	0.44	0.31	0.31
	Number of nonzero volumes	428	140	113
	Percent of nonzero volumes	5.5%	1.8%	1.4%
PABC-2009				
R1	Maximum [m^3]	8.29	2.24	2.21
	Average nonzero volume [m^3]	0.49	0.39	0.40
	Number of nonzero volumes	194	163	149
	Percent of nonzero volumes	7.5%	6.3%	5.7%
R2	Maximum [m^3]	2.76	2.41	1.63
	Average nonzero volume [m^3]	0.39	0.41	0.35
	Number of nonzero volumes	210	175	168
	Percent of nonzero volumes	8.1%	6.7%	6.5%
R3	Maximum [m^3]	6.23	4.89	4.85
	Average nonzero volume [m^3]	0.40	0.38	0.37
	Number of nonzero volumes	187	166	151
	Percent of nonzero volumes	7.2%	6.4%	5.8%
Total	Maximum [m^3]	8.29	4.89	4.85
	Average nonzero volume [m^3]	0.43	0.40	0.37
	Number of nonzero volumes	591	504	468
	Percent of nonzero volumes	7.6%	6.5%	6.0%

NOTES: The notation Rr stands for Replicate r. Calculation details for the CRA-2014 PA are provided in Appendix A (see worksheets *CUSP_CRA14-BL_R1a*, *CUSP_CRA14-TP_R1a*, *CUSP_CRA14-0_R1a*, *CUSP_CRA14-0_R2a, and CUSP_CRA14-0_R3a*). The PABC-2009 results (except for the "Percent of nonzero volumes" and "Total") are provided by Ismail (2010).

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the CRA-2014 PA. Note that Case CRA14-0 includes all changes associated with the CRA-2014 PA, including those changes from Cases CRA14-BL and CRA14-TP.

For E1 intrusion scenarios (i.e., an intrusion into the repository that creates a pathway to a pressurized brine pocket below the repository), results obtained for the South Rest-of-Repository region and the North Rest-of-Repository region do not change appreciably from those seen for the undisturbed repository according to BRAGFLO (Camphouse 2013b). The modified panel closure system effectively isolates impacts associated with borehole intrusion to the intruded panel. Changes included in the CRA-2014 PA yield an increase to the mean pressure in the intruded panel for a period of time after the intrusion as compared to results from the PABC-2009. The revised iron corrosion rate utilized in the CRA-2014 PA results in slower gas production due to iron corrosion (on average), resulting in a mean waste panel pressure curve in that eventually falls below that seen in the PABC-2009.

For intrusion scenarios that do not involve an encounter with a region of pressurized brine below the repository (i.e., an E2 intrusion), results obtained for the South Rest-of-Repository region and the North Rest-of-Repository region do not change appreciably from those seen for the undisturbed repository. The modified panel closure system effectively isolates impacts associated with borehole intrusion to the intruded panel. Changes included in the CRA-2014 PA yield a decrease to the mean pressure in the intruded panel as compared to results from the PABC-2009 according to BRAGFLO (Camphouse 2013b). The replacement of the Option D panel closure system with the modified panel closure system results in reduced mean pressure in the waste panel prior to the E2 intrusion. The refined water balance implementation sequesters water, reducing the amount that is freely available for gas production processes prior to the intrusion. The revised iron corrosion rate results in slower gas production due to iron corrosion (on average). As gas generation due to iron corrosion is the dominant gas production mechanism, the reduction (on average) in the rate of gas production due to iron corrosion yields a corresponding decrease in the rate of mean gas generation in the waste panel, further lowering waste panel mean pressure. Consequently, at the time of the E2 intrusion, the mean waste panel pressure is lower in the CRA-2014 PA than in the PABC-2009, and is also lower 200 years later when the borehole plugs fail. The decrease in waste panel pressure translates to decreases in spallings volumes and the number of nonzero spallings volumes in the CRA-2014 PA.

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Appendix A   Excel File for Analyzing CUTTINGS_S Results

This appendix provides information on the Microsoft Office Professional Plus 2010 Microsoft Excel® 2010 file used to analyze the results obtained from CUTTINGS_S as part of the CRA-2014 PA calculations. The Excel file, *cusp_cra14.xlsx*, was developed on a PC workstation running Windows 7 Enterprise and is included as a machine readable (CD ROM) supplement to this analysis package.

Appendix A.1   Inputs

Inputs for the Excel file, *cusp_cra14.xlsx*, include CUTTINGS_S output files *CUSP_CRA14BL_R1.TBL*, *CUSP_CRA14TP_R1.TBL*, *CUSP_CRA14_R1.TBL*, *CUSP_CRA14_R2.TBL*, and *CUSP_CRA14_R3.TBL* (located in the CMS library LIBCRA14_CUSP) and LHS output files *LHS2_CRA14BL_R1_CON.TRN*, *LHS2_CRA14TP_R1_CON.TRN*, *LHS2_CRA14_R1_CON.TRN*, *LHS2_CRA14_R2_CON.TRN*, and *LHS2_CRA14_R3_CON.TRN* (located in the CMS library LIBCRA14_LHS).

CUTTINGS_S output files for the PABC-2009 (*CUSP_PABC09_R1.TBL*, *CUSP_PABC09_R2.TBL*, and *CUSP_PABC09_R3.TBL*) were used as inputs to *cusp_cra14.xlsx* to develop PABC-2009 data summaries to compare to the CRA-2014 results and to verify the calculation method. These input files are located in the CMS library LIBPABC09_CUSP.

Appendix A.2   Verification

The file, *cusp_cra14.xlsx*, has been verified by comparison with hand calculations (for operations such as counting the number of vectors with no cavings). Other calculations, such as the average spallings statistics, were included for the same vectors as in the PABC-2009. The PABC-2009 results produced in *cusp_cra14.xlsx* were visually compared to the results presented in the CUTTINGS_S report for the PABC-2009 (Ismail 2010) to show that they were identical within the reported precision. The reproduction of the PABC-2009 results in *cusp_cra14.xlsx* provides verification that the calculation method to summarize the CRA-2014 PA results is correct.

Appendix A.3   Description

The calculations in the file process and summarize the output from CUTTINGS_S, including the tabulated results shown in Tables 4 through 7 and the graphical output shown in Figures 1 through 7. Excel file *cusp_cra14.xlsx* contains multiple worksheets described as follows:

- *CUSP_CRA14-BL_R1.* This worksheet calculates summary statistics for Replicate 1 obtained from CUTTINGS_S in support of Case CRA14-BL of the CRA-2014 PA, including spallings volumes by scenario.
  - Columns A through G contain input data and are taken directly from *CUSP_CRA14BL_R1.TBL* (located in the CMS library LIBCRA14_CUSP), which is the CUTTINGS_S output file for Case CRA14-BL, Replicate 1.
    - o Column A: SCN, scenario number.
      There are 5 scenarios for each replicate.
    - o Column B: CAV, borehole intrusion location (L, M, or U).
      L=lower, M=middle, and U=upper.

- o Column C: TIME, spalling scenario intrusion time (years)
- o Column D: VEC, vector number
  There are 100 vectors for each intrusion time.
- o Column E: DRILDIAM, drill bit diameter (m)
  DRILDIAM is constant at 0.31115 m for all scenarios and replicates.
- o Column F: AREA_C, combined area for cuttings and cavings (m^2)
- o Column G: VOL_S, spallings volume (m^3)

– Columns I and J contain input data and are taken directly from *LHS2_CRA14BL_R1_CON.TRN* (located in the CMS library LIBCRA141_LHS), which is an LHS output file for Case CRA14-BL, Replicate 1.
- o Column I: DOMEGA, drill string angular velocity (rad/s)
- o Column J: TAUFAIL, waste shear strength (Pa)

– Columns L and M contain calculations for Case CRA14-BL, Replicate 1 using standard Excel equations.
- o Column L: A_{cut}, cuttings area (m^2), which is the drill bit area
  $$A_{cut} = \frac{(DRILDIAM)^2 \times \pi}{4} = \frac{(0.31115)^2 \times \pi}{4} = 0.0760 \text{ m}^2$$
- o Column M: A_{cav}, cavings area (m^2)
  $$A_{cav} = AREA\_C - A_{cut}$$

– Columns O through Y contain calculations for Case CRA14-BL, Replicate 1 using standard Excel math and statistics formulas.
- o Column O: Maximum cavings area (m^2)
  Returns the maximum A_{cav} value from Column M.
- o Column P: Mean cavings area (m^2)
  Returns the mean A_{cav} value from Column M.
- o Column Q: Number of vectors with no cavings
  Counts the total number of A_{cav} values that equal 0. Only the first set of 100 vectors are included in the count, because each set of 100 vectors contain identical A_{cav} values. Also, any value less than 0.0000001 is considered to be zero.
- o Columns T through Y: Spallings volume information for each scenario
  Row 4 returns the maximum VOL_S value (m^3) from Column G for each scenario. Row 5 returns the average VOL_S value (m^3) from Column G (considering only values greater than 0) for each scenario. Row 6 counts the number of VOL_S values that are greater than 0 for each scenario. Row 7 calculates the percentage of VOL_S values that are greater than 0 for each scenario (number of VOL_S values greater than 0 divided by the total number of VOL_S values).

- • *CUSP_CRA14BL_R1a.* This worksheet calculates summary statistics for Replicate 1 obtained from CUTTINGS_S in support of Case CRA14-BL of the CRA-2014 PA, including spallings volumes by location.

- Columns A through G contain input data and are taken directly from *CUSP_CRA14BL_R1.TBL* (located in the CMS library LIBCRA14_CUSP), which is the CUTTINGS_S output file for Case CRA14-BL, Replicate 1. In this worksheet, the data are sorted (using the Data/Sort function) by Column B, which is the borehole intrusion location. Details for Columns A through G are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.
- Columns I and J contain calculations for Case CRA14-BL, Replicate 1 using standard Excel equations.
    - ○ Column I: A_{cut}, cuttings area (m^2), which is the drill bit area
      $$A_{cut} = \frac{(DRILDIAM)^2 \times \pi}{4} = \frac{(0.31115)^2 \times \pi}{4} = 0.0760 \text{ m}^2$$
    - ○ Column J: A_{cav}, cavings area (m^2)
      $$A_{cav} = \text{AREA\_C} - A_{cut}$$
- Columns L through O contain calculations for Case CRA14-BL, Replicate 1 using standard Excel math and statistics formulas.

  Row 4 returns the maximum VOL_S value (m^3) from Column G for each location. Row 5 returns the average VOL_S value (m^3) from Column G (considering only values greater than 0) for each location. Row 6 counts the number of VOL_S values that are greater than 0 for each location. Row 7 calculates the percentage of VOL_S values that are greater than 0 for each location (number of VOL_S values greater than 0 divided by the total number of VOL_S values).

- **CUSP_CRA14-TP_R1.** This worksheet calculates summary statistics for Replicate 1 obtained from CUTTINGS_S in support of Case CRA14-TP of the CRA-2014 PA, including spallings volumes by scenario.
    - Columns A through G contain input data and are taken directly from *CUSP_CRA14TP_R1.TBL* (located in the CMS library LIBCRA14_CUSP), which is the CUTTINGS_S output file for Case CRA14-TP, Replicate 1. This worksheet is structured the same as worksheet *CUSP_CRA14-BL_R1*. Details for Columns A through G are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.
    - Columns I and J contain input data and are taken directly from *LHS2_CRA14TP_R1_CON.TRN* (located in the CMS library LIBCRA14_LHS), which is an LHS output file for Case CRA14-TP, Replicate 1. Details for Columns I and J are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.
    - Columns L and M contain calculations for Case CRA14-TP, Replicate 1 using standard Excel equations. Details for Columns L and M are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.
    - Columns O through Y contain calculations for Case CRA14-TP, Replicate 1 using standard Excel math and statistics formulas. Details for Columns O through Y are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

- **CUSP_CRA14-TP_R1a.** This worksheet calculates summary statistics for Replicate 1 obtained from CUTTINGS_S in support of Case CRA14-TP of the CRA-2014 PA, including spallings volumes by location.

    – Columns A through G contain input data and are taken directly from *CUSP_CRA14TP_R1.TBL* (located in the CMS library LIBCRA14_CUSP), which is the CUTTINGS_S output file for Case CRA14-TP, Replicate 1. In this worksheet, the data are sorted (using the Data/Sort function) by Column B, which is the borehole intrusion location. Details for Columns A through G are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

    – Columns I and J contain calculations for Case CRA14-TP, Replicate 1 using standard Excel equations. Details for Columns I and J are provided above in the description for worksheet *CUSP_CRA14-BL_R1a*.

    – Columns L through O contain calculations for Case CRA14-TP, Replicate 1 using standard Excel math and statistics formulas. Details for Columns L through N are provided above in the description for worksheet *CUSP_CRA14-BL_R1a*.

- *CUSP_CRA14-0_R1.* This worksheet calculates summary statistics for Replicate 1 obtained from CUTTINGS_S in support of Case CRA14-0 of the CRA-2014 PA, including spallings volumes by scenario.

    – Columns A through G contain input data and are taken directly from *CUSP_CRA14_R1.TBL* (located in the CMS library LIBCRA14_CUSP), which is the CUTTINGS_S output file for Case CRA14-0, Replicate 1. This worksheet is structured the same as worksheet *CUSP_CRA14-BL_R1*. Details for Columns A through G are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

    – Columns I and J contain input data and are taken directly from *LHS2_CRA14_R1_CON.TRN* (located in the CMS library LIBCRA14_LHS), which is an LHS output file for Case CRA14-0, Replicate 1. Details for Columns I and J are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

    – Columns L and M contain calculations for Case CRA14-0, Replicate 1 using standard Excel equations. Details for Columns L and M are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

    – Columns O through Y contain calculations for Case CRA14-0, Replicate 1 using standard Excel math and statistics formulas. Details for Columns O through Y are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

- *CUSP_CRA14-0_R1a.* This worksheet calculates summary statistics for Replicate 1 obtained from CUTTINGS_S in support of Case CRA14-0 of the CRA-2014 PA, including spallings volumes by location.

    – Columns A through G contain input data and are taken directly from *CUSP_CRA14_R1.TBL* (located in the CMS library LIBCRA14_CUSP), which is the CUTTINGS_S output file for Case CRA14-0, Replicate 1. In this worksheet, the data are sorted (using the Data/Sort function) by Column B, which is the borehole intrusion location. Details for Columns A through G are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

    – Columns I and J contain calculations for Case CRA14-0, Replicate 1 using standard Excel equations. Details for Columns I and J are provided above in the description for worksheet *CUSP_CRA14-BL_R1a*.

   – Columns L through O contain calculations for Case CRA14-0, Replicate 1 using standard Excel math and statistics formulas. Details for Columns L through N are provided above in the description for worksheet *CUSP_CRA14-BL_R1a*.

- *CUSP_CRA14-0_R2.* This worksheet calculates summary statistics for Replicate 2 obtained from CUTTINGS_S in support of Case CRA14-0 of the CRA-2014 PA, including spallings volumes by scenario.
  - Columns A through G contain input data and are taken directly from *CUSP_CRA14_R2.TBL* (located in the CMS library LIBCRA14_CUSP), which is the CUTTINGS_S output file for Case CRA14-0, Replicate 2. This worksheet is structured the same as worksheet *CUSP_CRA14-BL_R1*. Details for Columns A through G are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.
  - Columns I and J contain input data and are taken directly from *LHS2_CRA14_R2_CON.TRN* (located in the CMS library LIBCRA14_LHS), which is an LHS output file for Case CRA14-0, Replicate 2. Details for Columns I and J are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.
  - Columns L and M contain calculations for Case CRA14-0, Replicate 2 using standard Excel equations. Details for Columns L and M are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.
  - Columns O through Y contain calculations for Case CRA14-0, Replicate 2 using standard Excel math and statistics formulas. Details for Columns O through Y are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

- *CUSP_CRA14-0_R2a.* This worksheet calculates summary statistics for Replicate 2 obtained from CUTTINGS_S in support of Case CRA14-0 of the CRA-2014 PA, including spallings volumes by location.
  - Columns A through G contain input data and are taken directly from *CUSP_CRA14_R2.TBL* (located in the CMS library LIBCRA14_CUSP), which is the CUTTINGS_S output file for Case CRA14-0, Replicate 2. In this worksheet, the data are sorted (using the Data/Sort function) by Column B, which is the borehole intrusion location. Details for Columns A through G are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.
  - Columns I and J contain calculations for Case CRA14-0, Replicate 2 using standard Excel equations. Details for Columns I and J are provided above in the description for worksheet *CUSP_CRA14-BL_R1a*.
  - Columns L through O contain calculations for Case CRA14-0, Replicate 2 using standard Excel math and statistics formulas. Details for Columns L through N are provided above in the description for worksheet *CUSP_CRA14-BL_R1a*.

- *CUSP_CRA14-0_R3.* This worksheet calculates summary statistics for Replicate 3 obtained from CUTTINGS_S in support of Case CRA14-0 of the CRA-2014 PA, including spallings volumes by scenario.
  - Columns A through G contain input data and are taken directly from *CUSP_CRA14_R3.TBL* (located in the CMS library LIBCRA14_CUSP), which is the CUTTINGS_S output file for Case CRA14-0, Replicate 3. This worksheet is

structured the same as worksheet *CUSP_CRA14-BL_R1*. Details for Columns A through G are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

  − Columns I and J contain input data and are taken directly from *LHS2_CRA14_R3_CON.TRN* (located in the CMS library LIBCRA14_LHS), which is an LHS output file for Case CRA14-0, Replicate 3. Details for Columns I and J are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

  − Columns L and M contain calculations for Case CRA14-0, Replicate 3 using standard Excel equations. Details for Columns L and M are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

  − Columns O through Y contain calculations for Case CRA14-0, Replicate 3 using standard Excel math and statistics formulas. Details for Columns O through Y are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

  − Rows 13 through 16 in Columns T through Y contain total spallings volume data for all three replicates.

- *CUSP_CRA14-0_R3a.* This worksheet calculates summary statistics for Replicate 3 obtained from CUTTINGS_S in support of Case CRA14-0 of the CRA-2014 PA, including spallings volumes by location.

  − Columns A through G contain input data and are taken directly from *CUSP_CRA14_R3.TBL* (located in the CMS library LIBCRA14_CUSP), which is the CUTTINGS_S output file for Case CRA14-0, Replicate 3. In this worksheet, the data are sorted (using the Data/Sort function) by Column B, which is the borehole intrusion location. Details for Columns A through G are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

  − Columns I and J contain calculations for Case CRA14-0, Replicate 3 using standard Excel equations. Details for Columns I and J are provided above in the description for worksheet *CUSP_CRA14-BL_R1a*.

  − Columns L through O contain calculations for Case CRA14-0, Replicate 3 using standard Excel math and statistics formulas. Details for Columns L through N are provided above in the description for worksheet *CUSP_CRA14-BL_R1a*.

  − Rows 13 through 16 in Columns M through O contain total spallings volume data for all three replicates.

- *R1,R2,R3.* This worksheet calculates summary statistics for Replicates 1, 2, and 3 obtained from CUTTINGS_S in support of Case CRA14-0 of the CRA-2014 PA, including cuttings and cavings data sorted by the cavings area.

  − Columns A through G contain input data and are taken directly from *CUSP_CRA14_R1.TBL*, *CUSP_CRA14_R2.TBL*, and *CUSP_CRA14_R3.TBL* (located in the CMS library LIBCRA14_CUSP), which are the CUTTINGS_S output files for Case CRA14-0, Replicates 1, 2, and 3, respectively. Note that in each replicate, every set of 100 vectors contain identical A_{cav} values. Therefore, only the first set of 100 vectors from each output file are included. In this worksheet, the data are sorted (using the Data/Sort function) by Column M, which

is the cavings area, A_{cav} (m^2). Details for Columns A through G are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

– Columns I and J contain input data and are taken directly from *LHS2_CRA14_R1_CON.TRN*, *LHS2_CRA14_R2_CON.TRN*, and *LHS2_CRA14_R3_CON.TRN*, which are LHS output files for Case CRA14-0, Replicates 1, 2, and 3, respectively. Details for Columns I and J are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

– Columns L and M contain calculations using standard Excel equations. Details for Columns L and M are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

– Column O provides the replicate number.

- • *TAUFAIL.* This worksheet calculates parameters for BOREHOLE:TAUFAIL, which is the waste shear strength (Pa). The distribution type, minimum and maximum values are stored in the WIPP PA parameter database and shown in Rows 5 through 7. The Expected Value (Pa), Variance (Pa^2), Standard Deviation (Pa), Median (Pa), and Distribution Function are calculated in Rows 8 through 30 based on the calculation approach provided by Tierney (1996). The calculations in this worksheet are consistent with Herrick and Kirchner (2013, Table 4).

- • *Cavings.* This worksheet calculates the cumulative frequency of cavings area for both the CRA-2014 PA and the PABC-2009.

– Column A contains data taken directly from worksheet *CUSP_CRA14-BL_R1*, cells M4 to M103, which are the calculated cavings area (A_{cav}) data (m^2) for Case CRA14-BL from the CRA-2014 PA. Only the first set of 100 vectors is included this data, because each set of 100 vectors contain identical A_{cav} values. In this worksheet, the data in Column A are sorted (using the Data/Sort function) from smallest to largest area. All rows containing no cavings area (note that any value of A_{cav} less than 0.0000001 is considered to be zero) were deleted so that only nonzero cavings areas are included.

– Column B provides a count of number of cavings areas, and Column C calculates the cumulative frequency of the rank-ordered cavings areas (cumulative frequency = rank / total number of cavings areas).

– Column E contains data taken directly from worksheet *CUSP_CRA14-TP_R1*, cells M4 to M103, which are the calculated cavings area (A_{cav}) data (m^2) for Case CRA14-TP from the CRA-2014 PA. Only the first set of 100 vectors is included this data, because each set of 100 vectors contain identical A_{cav} values. In this worksheet, the data in Column E are sorted (using the Data/Sort function) from smallest to largest area. All rows containing no cavings area (note that any value of A_{cav} less than 0.0000001 is considered to be zero) were deleted so that only nonzero cavings areas are included.

– Column F provides a count of number of cavings areas, and Column G calculates the cumulative frequency of the rank-ordered cavings areas (cumulative frequency = rank / total number of cavings areas).

– Column I contains data taken directly from cells M4 to M103 of worksheet *CUSP_CRA14-0_R1*, which are the calculated cavings area (A_{cav}) data (m^2) for

Replicate 1 of Case CRA14-0 of the CRA-2014 PA. Only the first set of 100 vectors is included this data, because each set of 100 vectors contain identical A_{cav} values. Column J contains the replicate number. In this worksheet, the data in Column I is sorted (using the Data/Sort function) from smallest to largest area. All rows containing no cavings area (note that any value of A_{cav} less than 0.0000001 is considered to be zero) were deleted so that only nonzero cavings areas are included.

− Column K provides a count of number of cavings areas, and Column L calculates the cumulative frequency of the rank-ordered cavings areas (cumulative frequency = rank / total number of cavings areas).

− Column N contains data taken directly from cells M4 to M103 of worksheets *CUSP_CRA14-0_R1*, *CUSP_CRA14-0_R2*, and *CUSP_CRA14-0_R3*, which are the calculated cavings area (A_{cav}) data (m^2) for Case CRA14-0 from the CRA-2014 PA, Replicates 1, 2, and 3, respectively. Only the first set of 100 vectors in each replicate is included this data, because each set of 100 vectors contain identical A_{cav} values. Column O calculates the log of the cavings area. Column P contains the replicate number. In this worksheet, the data in Columns N through P are sorted (using the Data/Sort function) by Column N (A_{cav}) from smallest to largest area. All rows containing no cavings area (note that any value of A_{cav} less than 0.0000001 is considered to be zero) were deleted so that only nonzero cavings areas are included.

− Column Q provides a count of number of cavings areas, and Column R calculates the cumulative frequency of the rank-ordered cavings areas (cumulative frequency = rank / total number of cavings areas).

− Column T contains data taken directly from cells M4 to M103 of worksheets *Verification_PABC09_R1*, *Verification_PABC09_R2*, and *Verification_PABC09_R3*, which are the calculated cavings area (A_{cav}) data (m^2) for the PABC-2009 PA, Replicates 1, 2, and 3, respectively. Only the first set of 100 vectors in each replicate is included this data, because each set of 100 vectors contain identical A_{cav} values. Column U calculates the log of the cavings area. Column V contains the replicate number. In this worksheet, the data in Columns T through V are sorted (using the Data/Sort function) by Column T (A_{cav}) from smallest to largest area. All rows containing no cavings area (note that any value of A_{cav} less than 0.0000001 is considered to be zero) were deleted so that only nonzero cavings areas are included.

− Column W provides a count of number of cavings areas, and Column X calculates the cumulative frequency of the rank-ordered cavings areas (cumulative frequency = rank / total number of cavings areas).

− Column Z contains data taken directly from cells M4 to M103 of worksheet *Verification_PABC09_R1*, which are the calculated cavings area (A_{cav}) data (m^2) for Replicate 1 the PABC-2009 PA. Only the first set of 100 vectors is included this data, because each set of 100 vectors contain identical A_{cav} values. Column AA contains the replicate number. In this worksheet, the data in Column Z is sorted (using the Data/Sort function) from smallest to largest area. All rows containing no cavings area (note that any value of A_{cav} less than 0.0000001 is

considered to be zero) were deleted so that only nonzero cavings areas are included.

- Column AB provides a count of number of cavings areas, and Column AC calculates the cumulative frequency of the rank-ordered cavings areas (cumulative frequency = rank / total number of cavings areas).
- Columns AE through AH contain a histogram data analysis of the cavings area data. Columns AE and AF contain bin range data. The bin range was selected based on the log of the cavings area (Column O for CRA-2014 data and Column U for PABC-2009) data. Selecting a bin range from -4.0 to 0.0 encompasses the log of the cavings area data. The probability frequency data (Columns AG and AH) were calculated using the Histogram function of Excel (select Data/Data Analysis/Histogram) and setting the input range as the log of the cavings area (Column O for CRA-2014 and Column U for PABC-2009) and setting the bin range from Column AE.

- **Spallings.** This worksheet calculates the cumulative frequency of spallings volume for both the CRA-2014 PA and the PABC-2009.
  - Columns A through G contain input data and are taken directly from *CUSP_CRA14-BL_R1.TBL* (located in the CMS library LIBCRA14_CUSP), which is the CUTTINGS_S output file for Case CRA14-BL, Replicate 1, from the CRA-2014 PA. In this worksheet, the data in Columns A through G are sorted (using the Data/Sort function) by Column G, which is the spallings volume, VOL_S (m^3). All rows containing no spallings volume (VOL_S = 0) were deleted so that only nonzero spallings volumes are included. Details for Columns A through G are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.
  - Column H provides a count of number of spallings volumes, and Column I calculates the cumulative frequency of the rank-ordered spallings volumes (cumulative frequency = rank / total number of spallings volumes).
  - Columns K through Q contain input data and are taken directly from *CUSP_CRA14-TP_R1.TBL* (located in the CMS library LIBCRA14_CUSP), which is the CUTTINGS_S output file for Case CRA14-TP, Replicate 1, from the CRA-2014 PA. In this worksheet, the data in Columns K through Q are sorted (using the Data/Sort function) by Column Q, which is the spallings volume, VOL_S (m^3). All rows containing no spallings volume (VOL_S = 0) were deleted so that only nonzero spallings volumes are included. Details for Columns K through Q are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.
  - Column R provides a count of number of spallings volumes, and Column S calculates the cumulative frequency of the rank-ordered spallings volumes (cumulative frequency = rank / total number of spallings volumes).
  - Columns U through AA contain input data and are taken directly from *CUSP_CRA14_R1.TBL*, *CUSP_CRA14_R2.TBL*, and *CUSP_CRA14_R3.TBL* (located in the CMS library LIBCRA14_CUSP), which are the CUTTINGS_S output files for Replicates 1, 2, and 3, respectively from Case CRA14-0 of the CRA-2014 PA. Column AB contains the replicate number. In this worksheet, the

data in Columns U through AB are sorted (using the Data/Sort function) by Column AA, which is the spallings volume, VOL_S (m^3). All rows containing no spallings volume (VOL_S = 0) were deleted so that only nonzero spallings volumes are included. Details for Columns U through AA are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

− Column AC provides a count of number of spallings volumes, and Column AD calculates the cumulative frequency of the rank-ordered spallings volumes (cumulative frequency = rank / total number of spallings volumes).

− Columns AF through AL contain input data and are taken directly from *CUSP_PABC09_R1.TBL, CUSP_PABC09_R2.TBL,* and *CUSP_PABC09_R3.TBL* (located in the CMS library LIBPABC09_CUSP), which are the CUTTINGS_S output files for Replicates 1, 2, and 3, respectively from the PABC-2009. Column AM contains the replicate number. In this worksheet, the data in Columns AF through AM are sorted (using the Data/Sort function) by Column AL, which is the spallings volume, VOL_S (m^3). All rows containing no spallings volume (VOL_S = 0) were deleted so that only nonzero spallings volumes are included. Details for Columns AF through AL are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

− Column AN provides a count of number of spallings volumes, and Column AO calculates the cumulative frequency of the rank-ordered spallings volumes (cumulative frequency = rank / total number of spallings volumes).

− Columns AQ through AW contain input data and are taken directly from *CUSP_PABC09_R1.TBL* (located in the CMS library LIBPABC09_CUSP), which is the CUTTINGS_S output file for Replicate 1 from the PABC-2009. Column AX contains the replicate number. In this worksheet, the data in Columns AQ through AW are sorted (using the Data/Sort function) by Column AW, which is the spallings volume, VOL_S (m^3). All rows containing no spallings volume (VOL_S = 0) were deleted so that only nonzero spallings volumes are included. Details for Columns AQ through AW are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

− Column AY provides a count of number of spallings volumes, and Column AZ calculates the cumulative frequency of the rank-ordered spallings volumes (cumulative frequency = rank / total number of spallings volumes).

• ***Plots.*** This worksheet generates the following plots (using the Insert/Charts-Scatter function):

   − Figure 1. This chart plots the Cumulative Distribution Function, F(X) (from worksheet *TAUFAIL*, columns C and F) versus the Waste Shear Strength (from worksheet *TAUFAIL*, columns B and E).

   − Figure 2. This chart plots the Cumulative Frequency (from worksheet *Cavings*, Columns C, G, L, Q, V, and AA) versus the Cavings Area (from worksheet *Cavings*, Columns A, E, I, N, S, and X) for the CRA-2014 PA (Cases CRA14-BL, CRA14-TP, and CRA14-0) and the PABC-2009.

   − Figure 3. This chart plots the Probability Frequency of cavings area (from worksheet *Cavings*, Columns AG and AH) versus the Cavings Area bin

range (from worksheet *Cavings*, Column AF) for the CRA-2014 PA (Case CRA14-0) and the PABC-2009.

- Figure 4. This chart plots the Cuttings and Cavings Area (from worksheets *CUSP_CRA14-0_R1*, *CUSP_CRA14-0_R2*, and *CUSP_CRA14-0_R3*, column F4 to F103) versus the Waste Shear Strength (from worksheets *CUSP_CRA14-0_R1*, *CUSP_CRA14-0_R2*, and *CUSP_CRA14-0_R3*, column J4 to J103) for each replicate.

- Figure 5. This chart plots the Cuttings and Cavings Area (from worksheets *CUSP_CRA14-0_R1*, *CUSP_CRA14-0_R2*, and *CUSP_CRA14-0_R3*, column F4 to F103) versus the Drill String Angular Velocity (from worksheets *CUSP_CRA14-0_R1*, *CUSP_CRA14-0_R2*, and *CUSP_CRA14-0_R3*, column I4 to I103) for each replicate.

- Figure 6. This chart plots the Waste Shear Strength (from worksheet *R1,R2,R3*, column J) versus the Drill String Angular Velocity (from worksheet *R1,R2,R3*, column I) for a range of cavings area (A_{cav}). Note that any value of A_{cav} less than 0.0000001 is considered to be zero.

- Figure 7. This chart plots the Cumulative Frequency (from worksheet *Spallings*, Columns I, S, AD, AO, and AZ) versus the Spallings Volume (from worksheet *Spallings*, Columns G, Q, AA, AL, and AW) for the CRA-2014 PA (Cases CRA14-BL, CRA14-TP, and CRA14-0) and the PABC-2009.

- *Verification_PABC09_R1.* This worksheet is used to verify the results of the CUTTINGS_S summary statistics for the CRA-2014 PA by comparison with PABC-2009 calculations. This worksheet calculates summary statistics for Replicate 1 obtained from CUTTINGS_S in support of the PABC-2009, including spallings volumes by scenario. The results were visually compared to the results presented in the CUTTINGS_S report for the PABC-2009 (Ismail 2010) to show that they were identical within the reported precision.
  - Columns A through G contain input data and are taken directly from *CUSP_PABC09_R1.TBL* (located in the CMS library LIBPABC09_CUSP), which is the CUTTINGS_S output file for Replicate 1. This worksheet is structured the same as worksheet *CUSP_CRA14-BL_R1*. Details for Columns A through G are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.
  - Columns L and M contain calculations for Replicate 1 using standard Excel equations. Details for Columns L and M are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.
  - Columns O through Y contain calculations for Replicate 1 using standard Excel math and statistics formulas. Details for Columns O through Y are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

- *Verification_PABC09_R1a.* This worksheet is used to verify the results of the CUTTINGS_S summary statistics for the CRA-2014 PA by comparison with PABC-2009 calculations. This worksheet calculates summary statistics for Replicate 1 obtained from CUTTINGS_S in support of the PABC-2009, including spallings volumes by

location. The results were visually compared to the results presented in the CUTTINGS_S report for the PABC-2009 (Ismail 2010) to show that they were identical within the reported precision.

- Columns A through G contain input data and are taken directly from *CUSP_PABC09_R1.TBL* (located in the CMS library LIBPABC09_CUSP), which is the CUTTINGS_S output file for Replicate 1. In this worksheet, the data are sorted (using the Data/Sort function) by Column B, which is the borehole intrusion location. Details for Columns A through G are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.
- Columns I and J contain calculations for Replicate 1 using standard Excel equations. Details for Columns I and J are provided above in the description for worksheet *CUSP_CRA14-BL_R1a*.
- Columns L through O contain calculations for Replicate 1 using standard Excel math and statistics formulas. Details for Columns L through O are provided above in the description for worksheet *CUSP_CRA14-BL_R1a*.

- *Verification_PABC09_R2.* This worksheet is used to verify the results of the CUTTINGS_S summary statistics for the CRA-2014 PA by comparison with PABC-2009 calculations. This worksheet calculates summary statistics for Replicate 2 obtained from CUTTINGS_S in support of the PABC-2009, including spallings volumes by scenario. The results were visually compared to the results presented in the CUTTINGS_S report for the PABC-2009 (Ismail 2010) to show that they were identical within the reported precision.

  - Columns A through G contain input data and are taken directly from *CUSP_PABC09_R2.TBL* (located in the CMS library LIBPABC09_CUSP), which is the CUTTINGS_S output file for Replicate 2. This worksheet is structured the same as worksheet *CUSP_CRA14-BL_R1*. Details for Columns A through G are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.
  - Columns L and M contain calculations for Replicate 2 using standard Excel equations. Details for Columns L and M are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.
  - Columns O through Y contain calculations for Replicate 2 using standard Excel math and statistics formulas. Details for Columns O through Y are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

- *Verification_PABC09_R2a.* This worksheet is used to verify the results of the CUTTINGS_S summary statistics for the CRA-2014 PA by comparison with PABC-2009 calculations. This worksheet calculates summary statistics for Replicate 2 obtained from CUTTINGS_S in support of the PABC-2009, including spallings volumes by location. The results were visually compared to the results presented in the CUTTINGS_S report for the PABC-2009 (Ismail 2010) to show that they were identical within the reported precision.

  - Columns A through G contain input data and are taken directly from *CUSP_PABC09_R2.TBL* (located in the CMS library LIBPABC09_CUSP), which is the CUTTINGS_S output file for Replicate 2. In this worksheet, the data

are sorted (using the Data/Sort function) by Column B, which is the borehole intrusion location. Details for Columns A through G are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

- − Columns I and J contain calculations for Replicate 2 using standard Excel equations. Details for Columns I and J are provided above in the description for worksheet *CUSP_CRA14-BL_R1a*.

- − Columns L through O contain calculations for Replicate 2 using standard Excel math and statistics formulas. Details for Columns L through O are provided above in the description for worksheet *CUSP_CRA14-BL_R1a*.

- • **Verification_PABC09_R3.** This worksheet is used to verify the results of the CUTTINGS_S summary statistics for the CRA-2014 PA by comparison with PABC-2009 calculations. This worksheet calculates summary statistics for Replicate 3 obtained from CUTTINGS_S in support of the PABC-2009, including spallings volumes by scenario. The results were visually compared to the results presented in the CUTTINGS_S report for the PABC-2009 (Ismail 2010) to show that they were identical within the reported precision.

  - − Columns A through G contain input data and are taken directly from *CUSP_PABC09_R3.TBL* (located in the CMS library LIBPABC09_CUSP), which is the CUTTINGS_S output file for Replicate 3. This worksheet is structured the same as worksheet *CUSP_CRA14-BL_R1*. Details for Columns A through G are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

  - − Columns L and M contain calculations for Replicate 3 using standard Excel equations. Details for Columns L and M are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

  - − Columns O through Y contain calculations for Replicate 3 using standard Excel math and statistics formulas. Details for Columns O through Y are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

  - − Rows 13 through 16 in Columns T through Y contain total spallings volume data for all three replicates.

- • **Verification_PABC09_R3a.** This worksheet is used to verify the results of the CUTTINGS_S summary statistics for the CRA-2014 PA by comparison with PABC-2009 calculations. This worksheet calculates summary statistics for Replicate 3 obtained from CUTTINGS_S in support of the PABC-2009, including spallings volumes by location. The results were visually compared to the results presented in the CUTTINGS_S report for the PABC-2009 (Ismail 2010) to show that they were identical within the reported precision.

  - − Columns A through G contain input data and are taken directly from *CUSP_PABC09_R3.TBL* (located in the CMS library LIBPABC09_CUSP), which is the CUTTINGS_S output file for Replicate 3. In this worksheet, the data are sorted (using the Data/Sort function) by Column B, which is the borehole intrusion location. Details for Columns A through G are provided above in the description for worksheet *CUSP_CRA14-BL_R1*.

- Columns I and J contain calculations for Replicate 3 using standard Excel equations. Details for Columns I and J are provided above in the description for worksheet *CUSP_CRA14-BL_R1a.*
- Columns L through O contain calculations for Replicate 3 using standard Excel math and statistics formulas. Details for Columns L through O are provided above in the description for worksheet *CUSP_CRA14-BL_R1a.*
- Rows 13 through 16 in Columns M through O contain total spallings volume data for all three replicates.