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Sandia National Laboratories
Waste Isolation Pilot Plant

Analysis Package for CUTTINGS_S: Compliance Recertification Application 2009
Revision 1

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1 Introduction

The Waste Isolation Pilot Plant (WIPP) is a deep geologic repository developed by the US Department of Energy (DOE) for the disposal of transuranic (TRU) radioactive 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), Parts 191 (EPA 1985) and 194 (EPA 1996). In December 2007 and January 2008, Sandia National Laboratories (SNL) completed a Performance Assessment (PA) of the WIPP. This PA supports the Compliance Recertification Application (CRA-2009) to be submitted by the DOE to the EPA to demonstrate continued compliance with the radiation protection regulations of 40 CFR 191 and 40 CFR 194. This new analysis has been termed the 2009 CRA Performance Assessment (CRA-2009 PA).

Analysis Plan AP-137 (Clayton 2008a) outlines the set of PA calculations required and identifies the changes that were made for the CRA-2009 PA. This analysis package documents that part of the CRA-2009 PA calculations performed by the code CUTTINGS_S. The revision made to AP-137, which followed the completion of the work described here, only affected the inventory comparison task and does not affect CUTTINGS_S or any of the other CRA-2009 analysis packages.

2 Background

Analysis plan AP-137 (Clayton 2008a) explains the methodology used to calculate direct releases for the CRA-2009 PA. Direct releases to the surface include cuttings and cavings releases, spallings releases, and direct brine releases (DBRs). The CUTTINGS_S code 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 material removed by cuttings and cavings is reported in terms of the cross-sectional area (in m^2), while the material removed by spallings is reported as a volume (in m^3).

2.1 *Cuttings and Cavings*

Cuttings and cavings are the solid material removed from the repository and carried to the surface by the drilling fluid during the process of drilling a borehole. 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. Cuttings and cavings were calculated with the same conceptual and numerical models used in the CRA-2004 PABC and documented in Dunagan and Vugrin (2005). With the exceptions outlined in Clayton (2008a), which include changes to chemistry parameters and maximum DBR duration, as well as error corrections for porosity parameters and the fraction of repository volume occupied by waste, the same constant parameter values and ranges of uncertain parameters were used for both the CRA-2004 PABC and the CRA-2009. None of the changes made had a direct impact on the results presented here.

The drill bit area, A, and uncompacted volume, V_{cut}, of cuttings removed and transported to the surface in the drilling mud is given by

$$A = \pi D^2 / 4$$

$$V_{cut} = AH_i = \pi D^2 H_i / 4,$$

where H_i is the initial, uncompacted repository height (m); A is the drill bit area (m^2); and D is the drill bit diameter (m) (WIPP PA 2004). Since the drill bit diameter D and the repository height H are constant parameters, both the drill bit area A and cuttings volume V_{cut} are fixed quantities for a particular set of calculations.

WIPP PA estimates cavings removal with a model based on the effect of shear stress on the borehole diameter. In particular, the borehole diameter is assumed to grow until the shear stress on the borehole wall is equal to the *shear strength* of the waste, which is the shear stress below which erosion of the waste ceases (WIPP PA 2004). For a more detailed discussion of the conceptual model of cavings, see WIPP PA (2004). CUTTINGS_S computes the cross-sectional area of cuttings and cavings; the volume of cuttings and cavings removed can easily be calculated in a post-processing step.

The code CUTTINGS_S calculates the base area of the cylinder of cuttings and cavings removed for a set of vectors, scenarios, times, and locations (see Table 1 through Table 3). Note that while the CRA-2009 PA considers six different intrusion scenarios (Clayton 2008a), scenario S6 is not explicitly considered by CUTTINGS_S. The scenarios are used as initial conditions for later intrusions; consequently, S1 serves as the initial condition for the first intrusion, while S2 through S5 correspond to subsequent intrusions. Further details regarding the drilling locations are provided in Stein (2003). CUTTINGS_S does not calculate the radioactivity of the material removed; this calculation is done when CCDFGF accounts for stochastic uncertainty in the future of the repository (WIPP PA 2003). The results from the CRA-2009 CCDFGF calculations can be found in Dunagan (2008).

Table 1 PA Scenario Descriptions

Scenario	Number of Drilling Intrusions	Intrusion Time(s) (Years)	Castile Brine Pocket Encountered
S1	0	N/A	N/A
S2	1	350	Yes
S3	1	1000	Yes
S4	1	350	No
S5	1	1000	No
S6	2	1000 and 2000	Only for intrusion at 2000 years

Table 2 Times for the Scenarios

Scenarios	Times
1	100, 350, 1000, 3000, 5000, 10000
2 & 4	550, 750, 2000, 4000, 10000
3 & 5	1200, 1400, 3000, 5000, 10000

Table 3 Drilling Locations and Abbreviations

Abbreviation	Drilling Location
L	Waste Panel
M	South Rest-of-Repository
U	North Rest-of-Repository

2.2 *Spallings*

Spallings consist of waste that enters the borehole through the release of waste-generated gas escaping into the borehole to lower pressure. Calculation of spallings releases for the CRA-2009 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 accounting for subjective uncertainty in waste properties; (3) interpolation of DRSPALL volumes in the code 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 the code CCDFGF (WIPP PA 2003). This section discusses the process used by CUTTINGS_S to calculate spall volumes for the WIPP drilling intrusion scenarios. For the CRA-2009 PA, since no changes were made to the DRSPALL model, the results from the CRA-2004 PABC were reused without alteration.

During the history of the WIPP PA, four different models have been used to calculate spallings releases. The CRA-2009 PA and (the CRA-2004 PABC) used CUTTINGS_S spall model 4. The initial repository pressure for a given scenario, time, location, and vector is interpolated using data from previously executed BRAGFLO calculations (Nemer and Clayton 2008). Additionally, for each vector the code DRSPALL calculates a spallings volume 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; repository pressures below 10 MPa do not yield spallings, as the borehole then has a higher pressure than the repository, and thus the gas will not flow into the borehole (WIPP PA 2004). If P denotes the interpolated pressure from BRAGFLO and V_i denotes the DRSPALL volume corresponding to the initial pressure P_i, CUTTINGS_S calculates a spallings volume in the following manner (WIPP PA 2004):

1. Find which pressures bracket the repository pressure:
    a. If $P < P_1$, set $i = 1$ and $P_{\text{Spall}} = P_1$.
    b. If $P > P_4$, set $i = 3$ and $P_{\text{Spall}} = P_4$.
    c. If $P_1 \le P \le P_4$, let i be such that $P_i \le P < P_{i+1}$. Let $P_{\text{Spall}}=P$.
2. $V = V_i + (P_{\text{Spall}} - P_i)/(P_{i+1} - P_i) \times (V_{i+1} - V_i)$

CUTTINGS_S calculates a spallings volume for each combination of vector, scenario, drilling location, and time. The intrusion scenarios are used as initial conditions for later intrusions; consequently, S1 serves as the initial condition for the first intrusion, while S2 through S5 correspond to subsequent intrusions.

2.3 *DBR 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 were used as initial conditions for CRA-2009 PA DBR calculations. For a discussion of the results of these calculations and how they were implemented into the CRA-2009 PA DBR calculations, see Clayton (2008b). The results are unchanged from the CRA-2004 PABC calculations.

3 Methodology

3.1 *Code Version*

The CRA-2009 and CRA-2004 PABC calculations both used CUTTINGS_S version 6.02 for the calculations described in Section 2. Version 6.02 has the capability to map DRSPALL vectors to PA vectors on a one-to-one basis. Both PA's used this option as there were 100 DRSPALL vectors per replicate in each set of calculations.

3.2 *MATSET*

The code MATSET records the values of constant parameters that CUTTINGS_S uses in the PA Parameter Database (PAPDB) and puts them into a binary input file for use by CUTTINGS_S. When MATSET is executed, a set of logicals are defined for the run control script. Two of these logicals, COMPUTATIONALCODENAME and COMPUTATIONALCODEVERSION, identify the code that will use the MATSET output file and the version number of that code, respectively. The log file EVAL_CUSP_CRA09_STEP1.LOG, stored in SCMS library LIBCRA09_CUSP in class CRA09-0, recorded that COMPUATIONALCODENAME and COMPUTATIONALCODEVERSION were set to "CUTTINGS_S" and "6.02" for the CUTTINGS_S calculations in the CRA-2009 PA.

3.3 *Parameters*

The code LHS (Kirchner 2008) is used to sample two uncertain parameters for CUTTINGS_S calculations. The sampled parameters are the effective shear strength for erosion of the waste (BOREHOLE:TAUFAIL) and the drill string angular velocity (BOREHOLE:DOMEGA) (Table 4).

Table 4 Sampled Uncertain Parameters for Cavings Calculations

Material	Property	Distribution	Range	Description
BOREHOLE	TAUFAIL	Loguniform	0.05 Pa to 77.0 Pa	Effective shear strength for erosion of the waste
BOREHOLE	DOMEGA	Empirical Cumulative	4.2 rad/s to 23.0 rad/s	Drill string angular velocity

In addition to the uncertain parameters, CUTTINGS_S uses a set of constant parameters retrieved from the PA parameter database (PA PDB). These parameters are listed in Table 5; Table 6 lists two additional drilling parameters whose values are specified in the CUTTINGS_S control input file.

Table 5 Constant Parameters retrieved for Cuttings and Cavings Calculations from the PAPDB

Material	Property	Value[1]	Description
BLOWOUT	PARTDIA	2.80000E–03 [m]	Waste particle diameter
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)
DRILLMUD	VISCO	9.17000E–03 [Pa · s]	Viscosity of brine used as drilling fluid (mud)
DRILLMUD	YLDSTRSS	4.40000E+00 [Pa]	Yield stress point of brine used as drilling fluid (mud)
WAS_AREA	ABSROUGH	2.50000E–02 [m]	Absolute roughness of waste material
REFCON	SECYR	3.16888E–08 [year/s]	Seconds to year conversion
REFCON	PI	3.14159E+00 [-]	Reference constant π

Table 6 Drilling Parameters Listed in the CUTTINGS_S Control File

Parameter Name	Value	Description
SHEARRT	1020 [1/s]	Shear rate w/in drilling fluid (mud)
MUDFLWRT	0.09935 [m^3/(m ·s)]	Drilling fluid (mud) flow rate

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 (31.115 centimeters). Since the most common bit size for the depth of the repository is 11 inches (Hansen et al. 2003), this assumption can be considered conservative.
- Waste shear strength (BOREHOLE:TAUFAIL) is based on properties of marine clays. This assumption is conservative since degraded surrogate waste materials yield higher shear strengths than naturally occurring marine clays (Hansen and Leigh 2003).

[1] For parameters listed in Table 5 stored in the PAPDB as uncertain distributions, this column lists the median values of the distributions pulled by MATSET for use by CUTTINGS_S as constants.

3.4 *CUTTINGS_S Calculations*

Three replicates of 100 vectors each were executed for the CUTTINGS_S calculations in the CRA-2009 PA. CUTTINGS_S calculates a cuttings and cavings area and a spallings volume for each combination of replicate, vector, scenario, drilling location, and intrusion time. A total of 23,400 (= 3 replicates × 100 vectors × 3 drilling locations × 26 intrusion times) areas and 23,400 volumes were calculated for the CRA-2009 PA. Details of the calculation procedure are provided in Long (2008).

4 Analysis Results

The CUTTINGS_S calculations resulted in direct release calculations for 7,800 separate combinations of vector, scenario, drilling location, and time per replicate. These results are input into the code CCDFGF to calculate a release for each combination of vector, scenario, drilling location, and intrusion time combination.

The data in the following sections has been obtained by analyzing the data in the files CUSP_CRA09_R1.TBL, CUSP_CRA09_R2.TBL, and CUSP_CRA09_R3.TBL, which are stored in the SCMS library LIBCRA09_CUSP in class CRA09-0.

4.1 *Cuttings and Cavings*

Results for the cuttings and cavings analysis are identical to those obtained for the CRA-2004 PABC. The minimum area calculated for each replicate was 0.0760 m^2. For vectors with this area, shear stresses were not large enough to cause cavings; the minimum area is therefore equal to the area of the drillbit that causes the cuttings. Nine vectors in replicate R1, ten in R2, and eleven in R3 had no cavings. The mean cuttings and cavings area was approximately 0.25 m^2 in each replicate; the largest observed cuttings and cavings area was 0.861m^2. On average, cavings contribute approximately 70% of the cuttings and cavings area; for the vectors with the largest areas, cavings are as much as 90% of the area. These summary statistics, presented in Table 7, are identical to the results obtained in the CRA-2004 PABC results (Vugrin 2005). Table 10 (in Appendix A) lists the individual areas calculated for each vector.

Table 7 CRA-2009 Cuttings & Cavings Area Statistics

Replicate	Min (m^2)	Max (m^2)	Mean (m^2)	Vectors w/o Cavings
R1	0.0760	0.824	0.253	9
R2	0.0760	0.861	0.251	10
R3	0.0760	0.829	0.254	11

Scatter plots, shown in Figure 1 through Figure 3, were developed to analyze the sensitivity of the cuttings and cavings area to the waste material shear strength (BOREHOLE:TAUFAIL) and the drill string angular velocity (BOREHOLE:DOMEGA). Figure 1 indicates an inverse relationship between the shear strength and the cutting and cavings area. This observation agrees with the cavings model because the shear strength of the material is the limiting shear stress below which the erosion of the waste ceases. No obvious correlations between cavings area and the angular velocity of the drill string can be established from Figure 2. Figure 3 suggests a small positive correlation between the cuttings and cavings area and the angular velocity of the drill string velocity, but this correlation is insignificant as shear strength is clearly the dominant parameter affecting cavings.

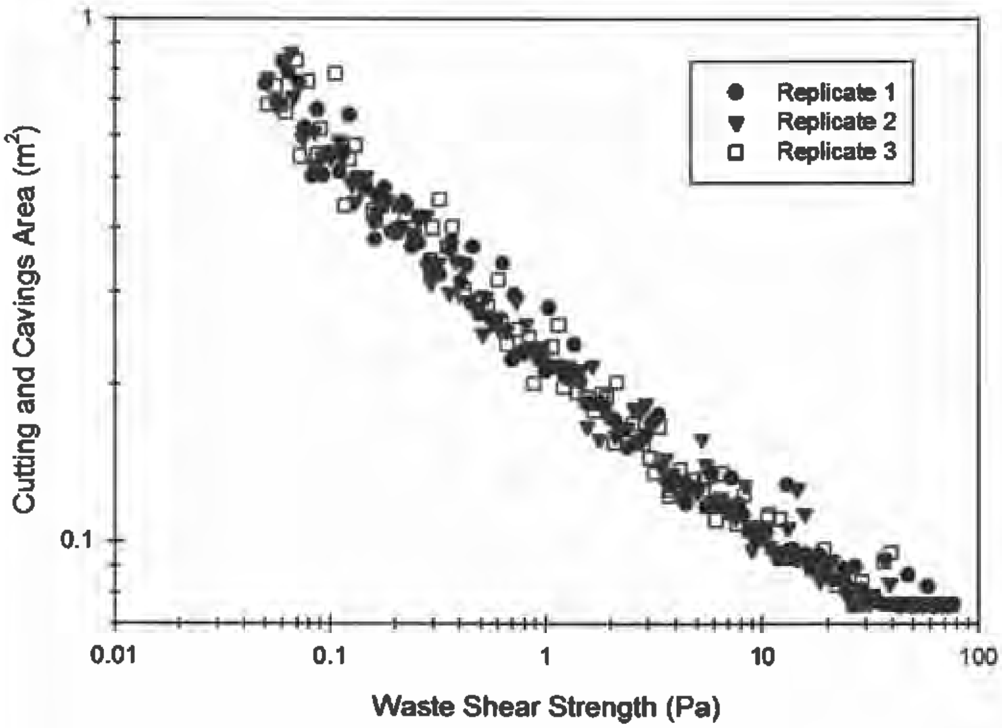

Figure 1 Scatter plot of Cuttings and Cavings Areas versus Shear Strength

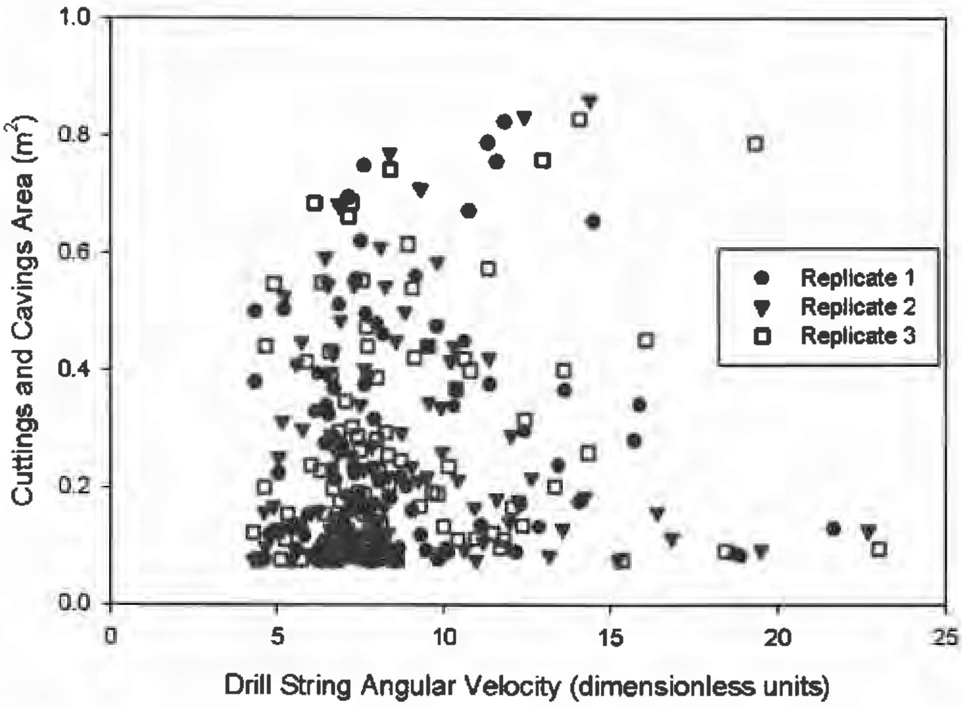

Figure 2 Scatter plot of Cuttings and Cavings Areas versus Drill String Angular Velocity

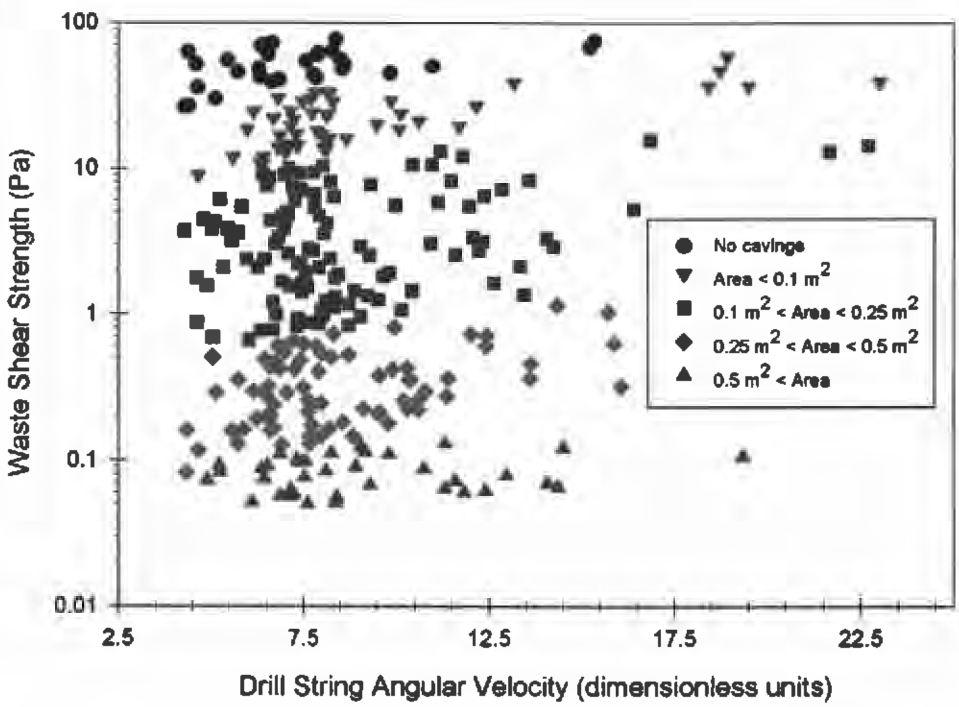

Figure 3 Scatter plot of Drill String Angular Velocity versus Shear Strength. Symbols indicate the range of cuttings and cavings areas in square meters.

4.2 *Spallings*

Spallings release volumes are quite modest (Appendix B, Table 11). Of the 7,800 spallings volumes calculated per replicate, more than 92% of each replicate's calculations resulted in no spallings. Only 34 vectors in replicate R1, 41 vectors in replicate R2, and 36 vectors in replicate R3 had spallings in at least one scenario (Table 12); for the other vectors, spallings do not contribute to the total releases, as compared to 34, 37, and 31 vectors in each of the three replicates for the CRA-2004 PABC. For each replicate, scenarios S2 and S3 resulted in the largest maximum spallings volume and largest number of nonzero spallings volumes per time intrusion. (Spallings were calculated at six different elapsed times for S1 times and five times for S2 and S3.) Scenarios S2 and S3 generally have the highest pressures because in these scenarios, the drill bit intrudes into a pressurized brine pocket (Nemer and Stein 2005). The resulting high pressures lead to more spallings events and larger spallings volumes.

Table 8 CRA-2009 PA versus CRA-2004 PABC Spallings Summary Statistics by Scenario

Scenario		Replicate R1		Replicate R2		Replicate R3	
		CRA-2009	CRA-2004 PABC	CRA-2009	CRA-2004 PABC	CRA-2009	CRA-2004 PABC
S1	**Maximum [m^3]**	2.52	1.67	2.52	1.04	5.33	3.14
	Average nonzero volume [m^3]	0.38	0.42	0.35	0.25	0.57	0.30
	# of nonzero volumes	158	115	177	109	183	125
S2	**Maximum [m^3]**	8.31	8.33	2.87	3.81	6.32	6.30
	Average nonzero volume [m^3]	0.60	0.61	0.43	0.40	0.49	0.57
	# of nonzero volumes	120	117	135	107	122	89
S3	**Maximum [m^3]**	7.99	8.04	2.13	2.14	3.15	2.68
	Average nonzero volume [m^3]	0.47	0.57	0.37	0.25	0.35	0.33
	# of nonzero volumes	129	103	138	100	133	75
S4	**Maximum [m^3]**	1.67	1.67	2.40	0.85	1.99	1.11
	Average nonzero volume [m^3]	0.30	0.37	0.53	0.27	0.36	0.31
	# of nonzero volumes	69	52	64	43	56	31
S5	**Maximum [m^3]**	1.67	1.67	2.20	0.80	3.00	2.27
	Average nonzero volume [m^3]	0.36	0.46	0.49	0.22	0.34	0.34
	# of nonzero volumes	91	68	93	62	91	47

Scenario		Replicate R1		Replicate R2		Replicate R3	
		CRA-2009	CRA-2004 PABC	CRA-2009	CRA-2004 PABC	CRA-2009	CRA-2004 PABC
All	Maximum [m^3]	8.31	8.33	2.77	3.81	6.32	6.30
	Average nonzero volume [m^3]	0.43	0.50	0.41	0.29	0.45	0.38
	# of nonzero volumes	564	455	607	421	585	367

Table 8 summarizes the statistics for CRA-2009 PA and CRA-2004 PABC spallings volumes calculated by CUTTINGS_S. For Scenario 1, the CRA-2009 maximum volumes are uniformly larger than the corresponding values in the CRA-2004 PABC. The remaining scenarios, however, show no such clear trend. Similarly, looking within replicates, we see that replicate 3 has uniformly larger values for the maximum volumes, but no uniform trend is found for replicates 1 and 2. Changes in the magnitude of the maximum nonzero volume, as explained in Section 2.2, are the result of changes in the pressure in the repository as calculated by BRAGFLO (WIPP PA 2004).

In contrast to the maximum spallings volumes, the average nonzero spallings volume shows consistent trends for both Replicates 1 and 2: for each scenario considered, the average volume decreased from the CRA-2004 PABC to the CRA-2009 in Replicate 1 and increased in Replicate 2. No consistent trend is observed for Replicate 3. In addition, the differences between the CRA-2004 PABC and CRA-2009 for maximum and average nonzero volume do not move together consistently: in many cases, the average increases while the maximum decreases, or vice versa.

The number of nonzero spallings volumes was fairly consistent across the three replicates for all scenarios. This is in contrast to the CRA-2004 PABC, in which consistency was observed for scenarios S1 and S2, but replicate R3 had substantially fewer nonzero volumes for scenarios S3, S4, and S5 than did replicates R1 and R2 (Table 8). Correcting the probability distribution for the porosity (Ismail 2007) ultimately leads to an increase in pressure within the repository for vectors with an increased porosity (Nemer and Clayton 2008). This increase in pressure can lead to greater spallings releases. The largest increases in the number of nonzero spallings vectors came in results for Scenario 1 in all three replicates. These increases are largely attributable to the increase in pressure in the repository as a result of the larger amounts of brine available; most of the nonzero spallings volumes occur for intrusions at later times. This explains the larger increases for Scenario 1 compared to the prior intrusion scenarios (2 through 5), in which the pressure has decreased substantially because of the prior intrusion. Consequently, more vectors have repository pressures greater than 10 MPa, which means that more vectors exceed the minimum pressure threshold required for spallings to occur (WIPP PA 2004). Similarly, Scenario 4 has fewer nonzero spallings volumes than Scenario 5 because the delayed intrusion time in Scenario 5 (1000 years versus 350 years for Scenario 4) allows the pressure to build over 10 MPa in more vectors than in Scenario 4.

Table 9 lists the summary spallings statistics by drilling location. For all replicates, the largest volume occurred with Lower intrusions, and the greatest number of nonzero spallings volumes also occurred with Lower intrusions. A Lower intrusion corresponds to an intrusion into the waste panel in which the highest pressures are observed (Nemer and Clayton 2008). Comparing the average nonzero spallings volumes as a function of location, the results are more consistent by replicate: in Replicate 1, average volumes decreased from the CRA-2004 PABC to the CRA-2009, while for the other replicates, average volumes increased.

Table 9 CRA-2009 PA versus CRA-2004 PABC Spallings Summary Statistics by Drilling Location

		Replicate R1		Replicate R2		Replicate R3	
Cavity		CRA-2009	CRA-2004 PABC	CRA-2009	CRA-2004 PABC	CRA-2009	CRA-2004 PABC
L	Maximum [m^3]	8.31	8.33	2.77	3.81	6.32	6.30
	Average nonzero volume [m^3]	0.49	0.55	0.41	0.28	0.46	0.37
	# of nonzero volumes	211	180	228	183	271	158
M	Maximum [m^3]	2.52	2.36	2.54	3.08	3.37	4.36
	Average nonzero volume [m^3]	0.41	0.45	0.44	0.29	0.46	0.42
	# of nonzero volumes	182	145	193	123	181	106
U	Maximum [m^3]	2.49	2.36	1.91	3.07	3.00	3.16
	Average nonzero volume [m^3]	0.39	0.49	0.38	0.28	0.41	0.33
	# of nonzero volumes	174	130	186	115	133	103

5 Conclusions

The CRA-2009 and CRA-2004 PABC cuttings and cavings areas are identical, as no changes affecting these results were made between the two sets of calculations. Approximately 10% of all vectors contribute cuttings but not cavings. The shear strength of the waste material is the dominant parameter affecting cavings. Lower strengths lead to more cavings, and conversely, higher strengths result in less cavings. The angular velocity of the drill string has a minor impact on cavings, with lower velocities tending to lead to less cavings and higher velocities yielding more cavings.

Spallings calculations by CUTTINGS_S show that spallings releases are very unlikely for most intrusions into the repository. Spallings cannot occur in the absence of repository pressures greater than 10 MPa; the pressures for most of the intrusion calculations do not reach this threshold. Approximately two-thirds of all vectors do not experience any spallings. Spallings are most likely to occur in scenarios S2 and S3, with a significant number observed in S1 as well, and the largest volumes are observed in scenarios S2 and S3. The greatest number of spallings and largest spallings volumes occurred with Lower intrusions, corresponding to waste panel intrusions in which the highest repository pressures are observed. In general, the maximum spallings volumes were roughly equal between the CRA-2009 and the CRA-2004 PABC, while the number of vectors with nonzero spallings volumes increased notably from the CRA-2004 PABC to the CRA-

2009. However, these changes had little effect overall on direct brine releases, which are markedly more responsive to changes in repository pressure and in cuttings and cavings volumes (which remain unchanged from the CRA-2004 PABC) than to changes in spallings volumes.

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Appendix A Cuttings and Cavings Results

This section contains the results of the cuttings and cavings calculations for the CRA-2009 PA (Table 10). This data can be found in the files CUSP_CRA09_R1.TBL, CUSP_CRA09_R2.TBL, and CUSP_CRA09_R3.TBL, and these files are stored in the SCMS library LIBCRA09_CUSP in the class CRA09-0. The statistics displayed in Table 10 were calculated with the spreadsheet CRA09_CUSP.XLS, and this file is stored in the SCMS library LIBCRA09_CUSP in the class ANALYSIS.

Since these calculations are independent of scenario, time, and location, the results are listed only by vector and replicate. Note that the minimum area observed is 0.0760 m^2, the area for which no cavings occur.

Table 10 CRA-2009 PA Cuttings and Cavings Areas as Calculated by CUTTINGS_S

Vector	R1 Area [m^2]	R2 Area [m^2]	R3 Area [m^2]
1	7.60E–02	1.35E–01	7.60E–02
2	7.48E–01	3.42E–01	1.54E–01
3	1.29E–01	1.26E–01	6.62E–01
4	1.35E–01	2.60E–01	3.46E–01
5	5.60E–01	2.36E–01	2.60E–01
6	3.29E–01	2.18E–01	5.47E–01
7	8.89E–02	4.20E–01	6.84E–01
8	9.75E–02	2.54E–01	8.26E–02
9	7.60E–02	1.06E–01	1.27E–01
10	3.41E–01	7.95E–02	1.31E–01
11	9.46E–02	4.49E–01	7.60E–02
12	7.60E–02	1.28E–01	4.40E–01
13	5.03E–01	5.26E–01	4.73E–01
14	8.88E–02	7.60E–02	1.22E–01
15	3.66E–01	1.12E–01	1.98E–01
16	3.38E–01	7.77E–02	7.85E–02
17	2.08E–01	7.95E–02	1.55E–01
18	1.21E–01	9.82E–02	1.05E–01
19	1.85E–01	1.21E–01	4.01E–01
20	2.80E–01	4.84E–01	1.10E–01
21	1.72E–01	7.60E–02	1.35E–01
22	8.65E–02	2.94E–01	4.31E–01
23	1.32E–01	4.28E–01	7.87E–01
24	2.39E–01	4.48E–01	1.23E–01
25	6.54E–01	8.33E–01	8.16E–02
26	2.23E–01	1.74E–01	2.93E–01
27	1.84E–01	1.14E–01	3.99E–01
28	3.63E–01	8.61E–01	1.33E–01
29	7.60E–02	4.02E–01	9.39E–02
30	6.19E–01	2.18E–01	1.78E–01
31	2.02E–01	7.60E–02	8.50E–02
32	5.55E–01	2.81E–01	1.89E–01
33	1.75E–01	2.90E–01	8.99E–02

Vector	R1 Area [m²]	R2 Area [m²]	R3 Area [m²]
34	3.93E–01	8.64E–02	4.20E–01
35	2.96E–01	7.60E–02	2.01E–01
36	8.97E–02	7.90E–02	1.54E–01
37	1.84E–01	2.19E–01	7.58E–01
38	8.34E–02	5.43E–01	4.41E–01
39	9.12E–02	8.44E–02	7.60E–02
40	2.13E–01	1.58E–01	9.55E–02
41	3.40E–01	1.64E–01	1.91E–01
42	8.23E–02	1.03E–01	9.53E–02
43	2.23E–01	1.66E–01	2.62E–01
44	8.46E–02	1.25E–01	3.87E–01
45	2.17E–01	7.60E–02	1.26E–01
46	7.87E–01	8.49E–02	2.37E–01
47	2.32E–01	4.39E–01	1.11E–01
48	2.73E–01	1.60E–01	1.37E–01
49	1.18E–01	4.98E–01	3.93E–01
50	4.37E–01	2.11E–01	7.60E–02
51	1.04E–01	1.66E–01	8.29E–01
52	8.24E–01	1.57E–01	4.19E–01
53	2.34E–01	3.45E–01	1.93E–01
54	5.00E–01	9.73E–02	1.89E–01
55	1.17E–01	1.66E–01	2.96E–01
56	9.66E–02	5.85E–01	1.26E–01
57	2.62E–01	7.60E–02	1.14E–01
58	1.82E–01	7.60E–02	1.07E–01
59	1.65E–01	1.19E–01	7.60E–02
60	6.71E–01	2.99E–01	1.10E–01
61	3.80E–01	3.37E–01	4.52E–01
62	1.02E–01	1.44E–01	8.95E–02
63	4.49E–01	5.92E–01	5.40E–01
64	1.13E–01	2.36E–01	2.06E–01
65	9.26E–02	7.60E–02	7.60E–02
66	1.18E–01	7.70E–01	2.26E–01
67	2.69E–01	1.40E–01	2.83E–01
68	5.11E–01	2.31E–01	4.13E–01
69	1.31E–01	9.30E–02	2.38E–01
70	1.71E–01	2.18E–01	1.35E–01
71	1.18E–01	2.13E–01	2.02E–01
72	9.30E–02	3.13E–01	1.66E–01
73	7.81E–02	9.25E–02	2.29E–01
74	1.27E–01	2.89E–01	4.41E–01
75	7.55E–01	1.13E–01	2.46E–01
76	4.75E–01	5.44E–01	5.54E–01
77	1.54E–01	7.60E–02	7.41E–01
78	1.60E–01	2.50E–01	9.30E–02
79	7.60E–02	5.44E–01	5.74E–01
80	6.93E–01	7.08E–01	3.17E–01

Vector	R1 Area [m²]	R2 Area [m²]	R3 Area [m²]
81	1.18E–01	9.16E–02	3.02E–01
82	4.79E–01	6.81E–01	1.68E–01
83	7.60E–02	1.80E–01	7.60E–02
84	1.52E–01	1.30E–01	1.45E–01
85	7.60E–02	8.36E–02	1.12E–01
86	3.16E–01	3.92E–01	2.55E–01
87	3.73E–01	4.10E–01	9.17E–02
88	7.70E–02	9.56E–02	9.69E–02
89	3.24E–01	3.84E–01	1.08E–01
90	4.95E–01	2.69E–01	7.60E–02
91	1.05E–01	1.29E–01	7.60E–02
92	9.48E–02	2.56E–01	2.87E–01
93	1.28E–01	1.84E–01	6.85E–01
94	7.60E–02	9.68E–02	7.60E–02
95	1.56E–01	1.41E–01	5.50E–01
96	8.12E–02	7.60E–02	3.68E–01
97	3.67E–01	1.79E–01	9.36E–02
98	7.60E–02	6.10E–01	8.39E–02
99	3.75E–01	4.16E–01	7.60E–02
100	4.60E–01	1.06E–01	6.15E–01

Appendix B Summary Statistics for Spallings Results

This section contains summary statistics of the spallings results from CUTTINGS_S for the CRA-2009 PA (Table 11). This data can be found by analyzing the data in the files CUSP_CRA09_R1.TBL, CUSP_CRA09_R2.TBL, and CUSP_CRA09_R3.TBL, and these files are stored in class CRA09-0 of the SCMS library LIBCRA09_CUSP. The statistics displayed in Table 8 and Table 9 were calculated in the spreadsheet CRA09SUMMARY.XLS, which is stored in class ANALYSIS of the SCMS library LIBCRA09_CUSP.

The number of nonzero spallings vectors and maximum spallings volume are listed by replicate, scenario, drilling location, and time. Table 12 also lists the vectors that did not have any spallings for all scenarios, times, and drilling locations. Spallings releases will not contribute to total releases for these vectors. The process used to create Table 11 and Table 12 is discussed in Appendix C.

Table 11 CRA-2009 PA CUTTINGS_S Spallings Statistics

			Replicate 1			Replicate 2			Replicate 3		
Scenario	Drilling Location	Time [yrs]	# of Vectors	Max. Vol. [m³]	Avg. Non-zero Vol. [m³]	# of Vectors	Max. Vol. [m³]	Avg. Non-zero Vol. [m³]	# of Vectors	Max. Vol. [m³]	Avg. Non-zero Vol. [m³]
S1	L	100	0	0	0	0	0	0	0	0	0
S1	L	350	0	0	0	0	0	0	0	0	0
S1	L	1000	3	0.5888	0.3757	3	0.5371	0.223	5	0.5152	0.1538
S1	L	3000	14	1.6654	0.3534	13	2.5197	0.4672	14	5.0234	0.8137
S1	L	5000	18	1.6654	0.3516	21	2.206	0.3398	22	5.3296	0.5309
S1	L	10000	21	2.5175	0.4406	24	1.847	0.3575	27	5.2166	0.5275
S1	M	100	0	0	0	0	0	0	0	0	0
S1	M	350	0	0	0	0	0	0	0	0	0
S1	M	1000	2	0.5999	0.576	3	0.2818	0.1402	3	0.4751	0.2244
S1	M	3000	14	1.6654	0.3283	13	2.0918	0.4171	12	4.8252	0.8294
S1	M	5000	17	1.6654	0.3386	20	1.9188	0.3303	19	5.3077	0.5593
S1	M	10000	21	2.5147	0.4263	24	1.7896	0.3458	25	5.2182	0.5623

			Replicate 1			Replicate 2			Replicate 3		
Sce-nario	Drilling Loca-tion	Time [yrs]	# of Vectors	Max. Vol. [m³]	Avg. Non-zero Vol. [m³]	# of Vectors	Max. Vol. [m³]	Avg. Non-zero Vol. [m³]	# of Vectors	Max. Vol. [m³]	Avg. Non-zero Vol. [m³]
S1	U	100	0	0	0	0	0	0	0	0	0
S1	U	350	0	0	0	0	0	0	0	0	0
S1	U	1000	2	0.5501	0.4886	2	0.1521	0.082	2	0.351	0.1869
S1	U	3000	10	1.6654	0.38	12	1.4495	0.3768	11	4.4987	0.6282
S1	U	5000	15	1.6654	0.3248	19	1.6611	0.3011	18	5.2571	0.5209
S1	U	10000	21	2.4851	0.4035	23	1.7359	0.3386	25	5.2157	0.5509
S2	L	550	12	0.7079	0.1637	12	0.8056	0.1752	10	1.8479	0.4633
S2	L	750	12	5.4135	0.7889	14	1.1444	0.2417	13	3.5948	0.3936
S2	L	2000	9	8.1969	1.5385	13	2.765	0.4258	11	6.3193	0.6777
S2	L	4000	11	8.3053	1.266	11	2.4182	0.6888	10	3.5286	0.4879
S2	L	10000	11	1.6675	0.2821	14	1.7496	0.4054	12	3.2621	0.5265
S2	M	550	0	0	0	0	0	0	0	0	0
S2	M	750	2	0.116	0.069	1	0.0172	0.0172	0	0	0
S2	M	2000	7	1.6654	0.6005	7	2.545	0.6478	8	4.4556	0.6624
S2	M	4000	11	2.0001	0.5509	13	2.2418	0.5434	12	3.881	0.4168
S2	M	10000	12	1.6695	0.4255	16	1.7107	0.3958	12	3.3329	0.5884
S2	U	550	0	0	0	0	0	0	0	0	0
S2	U	750	2	0.0889	0.0556	0	0	0	0	0	0
S2	U	2000	7	1.6654	0.5297	6	1.2987	0.4718	8	0.9001	0.2073
S2	U	4000	11	1.9978	0.4898	12	1.9102	0.502	12	2.9453	0.3562
S2	U	10000	13	1.6725	0.378	16	1.8106	0.4265	14	3.3703	0.5367
S3	L	550	16	1.2511	0.2466	17	1.8683	0.3314	14	2.6504	0.3826
S3	L	750	7	2.6736	0.6033	9	1.9286	0.3289	8	0.9729	0.1742
S3	L	2000	8	7.7382	1.4232	7	2.1279	0.6071	6	1.5389	0.3068
S3	L	4000	11	7.9922	0.9774	10	1.263	0.3981	9	1.8348	0.3440
S3	L	10000	11	0.7263	0.1317	12	0.8779	0.2647	11	3.0338	0.4587

			Replicate 1			Replicate 2			Replicate 3		
Sce-nario	Drilling Loca-tion	Time [yrs]	# of Vectors	Max. Vol. [m³]	Avg. Non-zero Vol. [m³]	# of Vectors	Max. Vol. [m³]	Avg. Non-zero Vol. [m³]	# of Vectors	Max. Vol. [m³]	Avg. Non-zero Vol. [m³]
S3	M	550	4	1.2586	0.5054	4	1.0535	0.3769	6	0.8514	0.2255
S3	M	750	4	1.6654	0.6205	4	1.66	0.604	8	0.9938	0.2071
S3	M	2000	8	1.6654	0.4383	8	1.9904	0.585	10	2.9947	0.3944
S3	M	4000	11	1.6654	0.3294	13	1.7479	0.387	11	1.5809	0.3055
S3	M	10000	12	1.6654	0.2865	13	1.3331	0.3038	11	3.1187	0.4921
S3	U	550	2	1.2173	0.8705	4	0.2401	0.0867	3	0.633	0.2407
S3	U	750	3	1.6654	0.7451	4	0.3666	0.1582	4	0.6812	0.2297
S3	U	2000	8	1.6654	0.3832	8	1.4024	0.4898	10	1.846	0.3460
S3	U	4000	11	1.6654	0.2893	12	1.5416	0.3812	10	1.5182	0.3378
S3	U	10000	13	1.6654	0.2493	13	1.4694	0.3434	12	3.1549	0.4623
S4	L	1200	0	0	0	0	0	0	0	0	0.0000
S4	L	1400	1	0.0567	0.0567	1	0.0185	0.0185	0	0	0.0000
S4	L	3000	4	0.2181	0.1089	5	2.396	0.7552	2	0.9927	0.5359
S4	L	5000	5	0.3283	0.1988	6	1.7705	0.6742	3	0.9355	0.3906
S4	L	10000	10	0.4867	0.1096	8	0.9048	0.3942	9	1.8701	0.3384
S4	M	1200	0	0	0	0	0	0	0	0	0.0000
S4	M	1400	2	0.101	0.0614	0	0	0	0	0	0.0000
S4	M	3000	5	1.6654	0.5976	6	2.2136	0.6403	5	1.72	0.4579
S4	M	5000	6	1.6654	0.5364	8	1.8404	0.5851	6	1.7129	0.3799
S4	M	10000	11	1.4973	0.2546	8	1.3688	0.4681	9	1.961	0.3796
S4	U	1200	0	0	0	0	0	0	0	0	0.0000
S4	U	1400	2	0.0779	0.0501	0	0	0	0	0	0.0000
S4	U	3000	5	1.6654	0.5038	5	1.0357	0.445	6	0.7821	0.2176
S4	U	5000	7	1.6654	0.4405	7	1.5079	0.59	6	1.0083	0.2929
S4	U	10000	11	1.6654	0.2746	10	1.4866	0.4137	10	1.9868	0.3558

			Replicate 1			Replicate 2			Replicate 3		
Sce-nario	Drilling Loca-tion	Time [yrs]	# of Vectors	Max. Vol. [m^3]	Avg. Non-zero Vol. [m^3]	# of Vectors	Max. Vol. [m^3]	Avg. Non-zero Vol. [m^3]	# of Vectors	Max. Vol. [m^3]	Avg. Non-zero Vol. [m^3]
S5	L	1200	4	1.1901	0.486	4	1.5749	0.5234	6	0.9024	0.2556
S5	L	1400	2	0.6708	0.3374	4	2.1214	0.709	4	0.9899	0.2732
S5	L	3000	5	0.4234	0.2336	5	2.192	0.8339	3	1.5788	0.5719
S5	L	5000	6	0.2559	0.128	7	1.3111	0.532	5	0.7891	0.2482
S5	L	10000	10	0.4896	0.1094	8	0.896	0.3814	8	1.8993	0.3860
S5	M	1200	4	1.2601	0.5071	4	1.0527	0.3756	6	0.8514	0.2252
S5	M	1400	4	1.6654	0.6139	4	1.6569	0.6033	8	0.9981	0.2032
S5	M	3000	6	1.6654	0.5742	7	2.0042	0.6526	6	3.0046	0.6310
S5	M	5000	8	1.6654	0.3917	9	1.7597	0.5248	7	1.0943	0.2598
S5	M	10000	11	1.5431	0.2599	8	1.3458	0.4556	8	1.9882	0.4324
S5	U	1200	2	1.2176	0.8709	3	0.2399	0.1147	3	0.633	0.2408
S5	U	1400	3	1.6654	0.7438	4	0.3665	0.1561	4	0.6773	0.2277
S5	U	3000	6	1.6654	0.5116	7	1.4095	0.5461	7	1.8436	0.4548
S5	U	5000	9	1.6654	0.3349	9	1.5521	0.4841	7	1.0349	0.2630
S5	U	10000	11	1.6654	0.276	10	1.4805	0.4072	9	2.0133	0.4000

Table 12 Vectors with No Spallings for All Scenarios, Times, and Drilling Locations

Replicate	Vectors with no Spallings
R1	1, 4, 5, 7, 9, 10, 11, 12, 13, 15, 16, 19, 20, 22, 23, 25, 26, 29, 33, 35, 39, 40, 41, 43, 45, 46, 47, 48, 49, 51, 52, 54, 55, 57, 58, 60, 61, 62, 63, 64, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 77, 78, 80, 82, 83, 84, 85, 88, 89, 90, 94, 95, 96, 97, 98, 99
R2	2, 4, 5, 6, 7, 8, 10, 11, 14, 15, 17, 19, 20, 21, 23, 24, 26, 28, 29, 30, 32, 33, 37, 38, 39, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 59, 61, 63, 64, 68, 69, 72, 73, 75, 77, 79, 81, 82, 83, 84, 85, 90, 93, 94, 95, 98, 99, 100
R3	1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 14, 18, 19, 20, 25, 26, 27, 29, 30, 31, 32, 33, 34, 35, 37, 38, 39, 41, 42, 43, 44, 45, 48, 50, 52, 53, 54, 56, 60, 61, 62, 63, 64, 65, 66, 70, 71, 73, 74, 76, 77, 78, 79, 80, 84, 86, 87, 88, 89, 91, 92, 95, 98, 100

Appendix C Analysis Tool for Spallings Statistics

This appendix documents the procedure used to create the tables in Appendix B.

Appendix C.1 Creation of the Tables

Table 11 and Table 12 were created as follows:

1) Files CUSP_CRA09_R1.TBL, CUSP_CRA09_R2.TBL, and CUSP_CRA09_R3.TBL were used as input to the Perl script cusp_analysis.pl, given below.

2) The number of nonzero vectors for each replicate was taken from the fourth column of the output files CUSP_CRA09_R1.TBL.scen, CUSP_CRA09_R2.TBL.scen, and CUSP_CRA09_R3.TBL.scen.

3) The maximum and average nonzero spallings volume for each replicate was taken from the fifth and sixth columns of the output files CUSP_CRA09_R1.TBL.scen, CUSP_CRA09_R2.TBL.scen, and CUSP_CRA09_R3.TBL.scen.

4) When a vector has spallings, a counter for that vector is incremented. After all vectors for a given scenario have been processed, counters which are still zero represent the vectors for which no spallings were observed. CUSP_CRA09_R1.TBL.vec, CUSP_CRA09_R2.TBL.vec, and CUSP_CRA09_R3.TBL.vec contain the list of vectors for each replicate for which no spallings were observed.

The results of the calculations performed using cusp_analysis.pl can be found in the files *CUSP_CRA_09*.TBL.scen* and *CUSP_CRA_09*.TBL.vec* in the ANALYSIS class of the SCMS library LIBCRA09_CUSP. The results were confirmed via visual inspection. To provide comparison data, the CUSP_CRA1BC_R*.TBL files were also processed using cusp_analysis.pl; the results are stored in the same library.

Table 8 and Table 9 were created using the results shown in Table 11. Maximum values for each scenario or location were found by visual inspection of the data, while the averages were found by importing the *.scen files created above into Microsoft Excel, and performing the averages as a function of scenario or intrusion location.

Appendix C.2 Source Code

The source code for *cusp_analysis.pl* is stored in the SCMS library LIBCRA09_CUSP in the ANALYSIS class and is reproduced below.

```
#!/usr/bin/perl

# Code:    cusp_analysis.pl
# Author:  Ahmed E. Ismail
# Date:    January 2008

# This code reads in the output files from CUTTINGS_S and uses this
# information to determine which vectors do not have spallings.

use strict;
use POSIX;
```

```
&analysis($_) for (@ARGV);

sub analysis{

  my $in = $_[0];
  open IN, "<$in" or die "Could not open $_[0].\n";

  # Remove header information.
  <IN> for (0 .. 2);

  # Convert data file entries to array indices.
  my %cav = (L => 0, M => 1, U => 2);
  my %time = (100 => 0, 3.50E2 => 1, 1000 => 2, 3000 => 3, 5000 => 4, 10000
=> 5,
            550 => 1, 750 => 2, 2000 => 3, 4000 => 4,
            1200 => 1, 1400 => 2, 3000 => 3, 5000 => 4);

  # Declare storage arrays.

  my (@cut, @spall, @spall_by_vec, @spall_by_scen, @max_spall, @tot_spall);

  # Read in data file.

  while (<IN>) {
    my @line = split;
    my $i = $line[0];
    my $j = $cav{$line[1]};
    my $k = $time{floor($line[2])};
    my $l = $line[3];

    # Store cuttings area and spallings volume.

    $cut[$i][$j][$k][$l] = $line[5];
    $spall[$i][$j][$k][$l] = $line[6];

    # If we have a positive spallings volume, check if it is the largest
    # spallings volume for the given scenario/location/time combination.

    # Also, augment the counters which check if the replica/vector
    # combination and scenario/location/time combinations experience
    # cavings.

    if ($line[6] > 0.0) {
      $spall_by_vec[$l]++;
      $spall_by_scen[$i][$j][$k]++;
      $tot_spall[$i][$j][$k] += $line[6];
      $max_spall[$i][$j][$k] = $line[6] if ($line[6] >
$max_spall[$i][$j][$k]);
    }
  }

  # Open output files.

  my $SCEN = $in . ".scen";
  my $VEC  = $in . ".vec";
```

```
  open SCEN, ">$SCEN" or die "Could not open $SCEN.\n";
  open VEC,  ">$VEC"  or die "Could not open $VEC.\n";

  # Write the vectors with no spalls to output file.

  print VEC "Vectors with no spalls:\n";

  for my $i (1 .. 100) {
    print VEC "$i, " if (!$spall_by_vec[$i]);
  }

  # For each scenario/location/time combination, write out the number of
  # vectors with spallings, the maximum spallings volume observed, and
  # the average nonzero volume.

  for my $i (1 .. 5) {
    for my $j (0 .. 2) {
      for my $k (0 .. 5) {
        next if ($k == 0 && $i != 1);
        my $avg = ($spall_by_scen[$i][$j][$k]) ?
          $tot_spall[$i][$j][$k] / $spall_by_scen[$i][$j][$k] : 0.0;
        printf(SCEN "%d %d %d  %3d  %7.4f  %7.4f\n", $i, $j, $k,
             $spall_by_scen[$i][$j][$k],  $max_spall[$i][$j][$k], $avg);
      }
    }
  }

  # Close files and exit.

  close IN;
  close SCEN;
  close VEC;
}
```

Herrick, Courtney Grant Courtney G Herrick 3/27/08

From: Clayton, Daniel James
Sent: Thursday, March 27, 2008 4:09 PM
To: Herrick, Courtney Grant
Cc: Ismail, Ahmed
Subject: Signature authority

I give signature authority to Courtney Herrick for documents related to:

Analysis Package for CUTTINGS_S: Compliance Recertification Application 2009

Dan Clayton