Appendix E

NUCLEAR WASTE MANAGEMENT PROGRAM Sandia National Laboratories	**Design Document Criteria Form**	**Form Number: NP 19-1-4** **Page 1 of 1**

1. **Software Name:** CUTTINGS_S
2. **Software Version:** 5.10
3. **Document Version:** 1.00
4. **ERMS #:** 532336

Prior to sign-off of the DD, all items shall be appropriately addressed by the code sponsor so that "**Yes**" may be checked. Include this form as part of the DD.

Are the following appropriately defined and documented in the DD?

5. Major Software Components — ☒ Yes
6. Technical description of the software with respect to: theoretical basis, embodied mathematical model, major control flow, control logic, and data structures — ☒ Yes
7. Allowable or Prescribed Ranges for Inputs and Outputs — ☒ Yes
8. Verifiability: Is the design verifiable through testing or other means? — ☒ Yes
9. Consistency and Traceability: Is the design consistent with and traceable to the software's requirements? — ☒ Yes
10. Technical Feasibility: Is the design technically feasible? — ☒ Yes
11. Implementation: Is the design presented in sufficient detail to allow for implementation as computer software? — ☒ Yes

	Signature	Date
Cliff Hansen 12. **Code Team/Sponsor** *(print)*	for Signature	10/22/03 Date
James Garner 13. **Technical Reviewer** *(print)*	J W Garner Signature	10/22/03 Date
for David Kessel 14. **Responsible Manager** *(print)*	Paul E. Shoemaker Signature	10/22/03 Date
Jennifer Long 15. **SCM Coordinator** *(print)*	Jennifer Long Signature	10/22/03 Date

Key for check boxes above:

Check **Yes** for each item reviewed and found acceptable

Dunagan, Sean

From: Hansen, Clifford W
Sent: Monday, October 20, 2003 10:26 AM
To: Dunagan, Sean; Chavez, Mario Joseph
Subject: Sig. authority for CUTTINGS documents

Sean,

In my absence, you have permission to sign CUTTINGS documents as the code sponsor. You may sign the RD, VVP, VD, the ID, the I&C, and the criteria forms for the RD, VVP, VD and the ID.

Cliff Hansen
Sandia National Labs Dept 6821
505-234-0103 (Carlsbad)
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10/21/2003

WIPP PA

DESIGN DOCUMENT

for

CUTTINGS_S (Version 5.10)

Document Version 1.00

ERMS# 532336

OCTOBER 2003

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List of Figures and Tables

INTRODUCTION

This document serves as a Design Document for the CUTTINGS_S program as used in the Waste Isolation Pilot Plant (WIPP) Performance Assessment (PA) calculation. As such, it provides an overview of CUTTINGS_S and describes its code architecture.

1.1 Software Identifier

Code Name:	CUTTINGS_S
WIPP Prefix:	CUSP
Version:	5.10

1.2 Points of Contact

Code Sponsor: Cliff Hansen (505-234-0103)
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1.3 Code Overview

The CUTTINGS_S code was written to calculate the quantity of material (in m^3) brought to the surface from a radioactive waste disposal repository as a consequence of an inadvertent human intrusion through drilling. The code determines the amount of material removed from the repository by several release mechanisms, including cuttings, cavings and spallings. The CUTTINGS_S code includes functionality to compute the radioactivity in the released material, including decay of the material to the time of intrusion.

2.0 REQUIREMENTS

The requirements for CUTTINGS_S are listed in the *WIPP PA Requirements Document And Verification Validation Plan for CUTTINGS_S Version 5.10* [WIPP PA 2003a]. The requirements are repeated here for the reader's convenience.

2.1 Functional Requirements

R.1 CUTTINGS_S calculates the amount of repository material brought to the surface due to erosion of the borehole resulting from laminar flow in the drilling fluid.

R.2 CUTTINGS_S calculates the amount of repository material brought to the surface due to erosion of the borehole resulting from turbulent flow in the drilling fluid.

R.3 CUTTINGS_S calculates the amount of repository material brought to the surface due to blowout of the borehole.

R.4 CUTTINGS_S calculates the amount of repository material brought to the surface due to gas erosion of the borehole.

R.5 CUTTINGS_S calculates the amount of repository material brought to the surface due to a stuckpipe.

R.6 CUTTINGS_S calculates model specific parameter values based on experimental data.

R.7 CUTTINGS_S calculates the volume of spalled material using a pressure threshold and a distribution of spallings volumes (spall model 3)

R.8 CUTTINGS_S determines the volume of spalled material using a set of distributions of spalled volumes, calculated for a set of reference repository pressures, by interpolating between distributions to account for current repository pressure (spall model 4).

2.2 Performance Requirements

There are no performance requirements for CUTTINGS_S.

2.3 Attribute Requirements

There are no attribute requirements for CUTTINGS_S.

2.4 External Interface Requirements

R.9 CUTTINGS_S utilizes routines from CAMDAT_LIB, CAMCON_LIB, SDBREAD_LIB, and CAMSUPES_LIB. Consequently it must be linked with these libraries.

R.10 CUTTINGS_S requires one CDB input file from the BRAGFLO code, CUSP_INP$BRAGCDB.

R.11 CUTTINGS_S requires one input file containing preliminary data base information, CUSP_INP$CDB.

R.12 CUTTINGS_S requires one input file containing model and site dependent parameters and radionuclide properties, inventories, drilling procedures, and characteristics of the drilling fluid, CUSP_INP$TXT0.

R.13 CUTTINGS_S requires one input file identifying input sample vector values that will be used in the analysis, CUSP_INP$TXT1.

R.14 CUTTINGS_S generates one output file CUSP_OUT$DBG, which contains information that is used for comparing with acceptance criteria, and is used only for testing purposes.

R.15 CUTTINGS_S generates one output file CUSP_OUT$NVERIFY, which contains information that is used in the functional testing for hand calculations, and is not used in production runs.

R.16 CUTTINGS_S generates one output CDB (binary) file, CUSP_OUT$CDB, containing output generated by the code. This output must comform to the format specified in the WIPP PA User's Manual for CAMDAT_LIB (4).

R.17 If spall model 4 is used, CUTTINGS_S reads spall volume data from a text input file, CUSP_SPL4$DAT.

2.5 Other Requirements

There are no other requirements for CUTTINGS_S.

3.0 DESIGN OVERVIEW

This section describes the structure and content of the input and output files for CCDFGF.

3.1 I/O Description

The files associated with running CUTTINGS_S are listed, along with their logicals in Table 3.1. For a detailed description of the input and output files see the *CUTTINGS_S User's Manual Version 5.10* (WIPP PA 2003b)

Table 3.1 Listing of Input and Output Files

File ID No.	Input/Output File Names	Associated Logical Symbol	Is the file Required or Not?
1.	Binary input CAMDAT file (from MATSET)	CUSP_INP$CDB	Yes
2.	Input control file (text) specifying repository/model parameters, initial inventories, generic radioisotope database.	CUSP_INP$TXT0	Yes
3.	Input control file (text) specifying drilling and intrusion parameters	CUSP_INP$TXT1	Yes
4.	BRAGFLO binary output .CDB file. Regulatory runs Test runs	CUSP_INP$BRAGCDB	 Yes No
5.	Input control file for Spall Model 4 specifing pressures and their volumes by vector	CUSP_SPL4$DAT	Yes (spall model 4 only)

6. CUTTINGS_S's binary output .CDB file	CUSP_OUT$CDB	Yes
7. CUTTINGS_S's output debug text file	CUSP_OUT$DBG	Yes
8. Text file for verification testing	CUSP_OUT$NVERIFY	No
9. Radioisotope inventory history (in CURIES) output text file	CUSP_OUT$IHISTO	No
10. Normalized-release-history output text file (EPA 40CFR191, Subpt B) file in ASCII format	CUSP_OUT$NHISTO	No
11. Time-history plotting text file for:		
Long half-life radioisotope decay	CUSP_OUT$PLT1	No
Medium half-life radioisotope decay	CUSP_OUT$PLT2	No
Short half-life radioisotope decay	CUSP_OUT$PLT3	No
12. Output text file for transfer to the WIPP code CCDFPERM	CUSP_OUT$ICTRN	No

3.2 Design Constraints

There are no constraints on the design of CUTTINGS_S Version 5.10

3.3 Other Design Considerations

There are no other design considerations for CUTTINGS_S Version 5.10.

4.0 THEORETICAL OVERVIEW

Three separate release modes, cuttings, cavings and spallings, are believed to determine the quantity of solid waste brought to the ground surface as the result of a drilling intrusion through a waste panel, where cuttings designates the waste contained in the cylindrical volume created by the cutting action of the drill bit passing through the waste, cavings designates the waste that erodes from the borehole in response to the upward-flowing drilling fluid within the borehole, and spallings designates the waste introduced into the borehole by the release of waste-generated gas escaping to the lower-pressure borehole. The releases associated with these processes are computed within the CUTTINGS_S code (WIPP PA 1996a). The mathematical representations are described in Section 5.0.

5.0 MATHEMATICAL MODEL

5.1 Cuttings

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

$$V_{cut} = AH_i = \pi D^2 H_i / 4, \tag{5.1}$$

where H_i is the initial (i.e., uncompacted) repository height (m), A is the drill bit area (m^2), and D is the drillbit diameter (m). In the 2003 WIPP PA, D = 12.25 in. = 0.31115m (BOREHOLE/DIAMMOD) and H_i = 3.96m (Berglund 1996a). For drilling intrusions through RH-TRU waste, H_i = 0.509m is used (Tierney 1996). The size of the cuttings release is independent of the conditions that exist in the repository at the time of a drilling intrusion, with the result that the cuttings volume V_{cut} is a lower bound on the quantity of material removed by a drilling intrusion.

5.2 Cavings (adapted from Sect. 3.5 of Helton et al. 1998a)

The cavings component of the direct surface release is caused by the shearing action of the drilling fluid (mud) on the waste as the mud flows up the borehole annulus. As is the case for the cuttings release, the cavings release is assumed to be independent of the conditions that exist in the repository at the time of a drilling intrusion.

The final diameter of the borehole will depend on the diameter of the drill-bit and on the extent to which the actual borehole diameter exceeds the drill-bit diameter. Although a number of factors affect erosion within a borehole (Broc 1982), the most important factor is believed to be the fluid shear stress on the borehole wall (i.e., the shearing force per unit area, (kg m/s^2/m^2)) resulting from circulating drilling fluids (Darley 1969, Walker and Holman 1971). As a result, the 2003 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 (i.e., the limiting shear stress below which the erosion of the waste ceases).

The final eroded diameter D_f(m) of the borehole through the waste determines the volume V (m^3) of uncompacted waste that will be removed to the surface by circulating drilling fluid. Specifically,

$$V = V_{cut} + V_{cav} = \pi D_f^2 H_i / 4, \tag{5.1.1}$$

where V_{cav} is the volume (m^3) of waste removed as cavings.

Most borehole erosion is believed to occur in the vicinity of the drill collar (Figure 5.2.1) (Rechard et al. 1990). An important determinant of the extent of this erosion is whether the flow of the drilling fluid in the vicinity of the collar is laminar or turbulent. The 2003 WIPP PA uses Reynolds numbers to distinguish between the occurrence of laminar flow and turbulent flow. The Reynolds number is the ratio between inertial and viscous (i.e., shear) forces in a fluid and can be expressed as

$$R_e = \frac{\rho_f \|\mathbf{v}\| D_e}{\eta}, \tag{5.1.2}$$

where R_e is the Reynolds number (dimensionless), ρ_f is the fluid density (kg m^{-3}), D_e is the equivalent diameter (m), $\mathbf{v}$ is the fluid velocity (m s^{-1}), and η is the fluid viscosity (kg m^{-1} s^{-1}).

Typically, ρ, $\mathbf{v}$ and η are averages over a control volume with an equivalent diameter of D_e. In the 2003 WIPP PA, $\rho_f = 1.21 \times 10^3$ kg m^{-3} (DRILLMUD/ DNSFLUID) (Berglund 1996a), $||\mathbf{v}|| =$ 0.7089 m s^{-1} (based on 40 gallons/min per inch of drill diameter, Sect. 2.3, Berglund 1992), and $D_e = 2\,(R - R_i)$ as shown in Figure 5.2.1. The diameter of the drill collar (i.e., $2R_i$ in Figure 5.2.1) is 8.0 in = 0.2032 m (Berglund 1996a). The fluid velocity, $||\mathbf{v}||$, is calculated by multiplying the 40 gallons/min by the diameter of the drill, 12.25 inches. Then converting this value to m^3 s^{-1}. The area calculated using R, minus the area calculated using R_i, divided by the value in m^3 s^{-1} results in 0.7089 m s^{-1}. The determination of η is discussed below. Reynolds numbers less than 2100 are assumed to be associated with laminar flow, while Reynolds numbers greater than 2100 are assumed to be associated with turbulent flow (Walker 1976).

Drilling fluids are non-Newtonian fluids, which means that the viscosity η is a function of the shear rate within the fluid (i.e., the rate at which the fluid velocity changes normal to the flow direction, ((m/s)/m). The 2003 WIPP PA uses a model proposed by Oldroyd (1958) to estimate the viscosity of drilling fluids. As discussed by Broc (1982), this model leads to the following expression for the Reynolds number associated with the helical flow of a drilling fluid within an annulus:

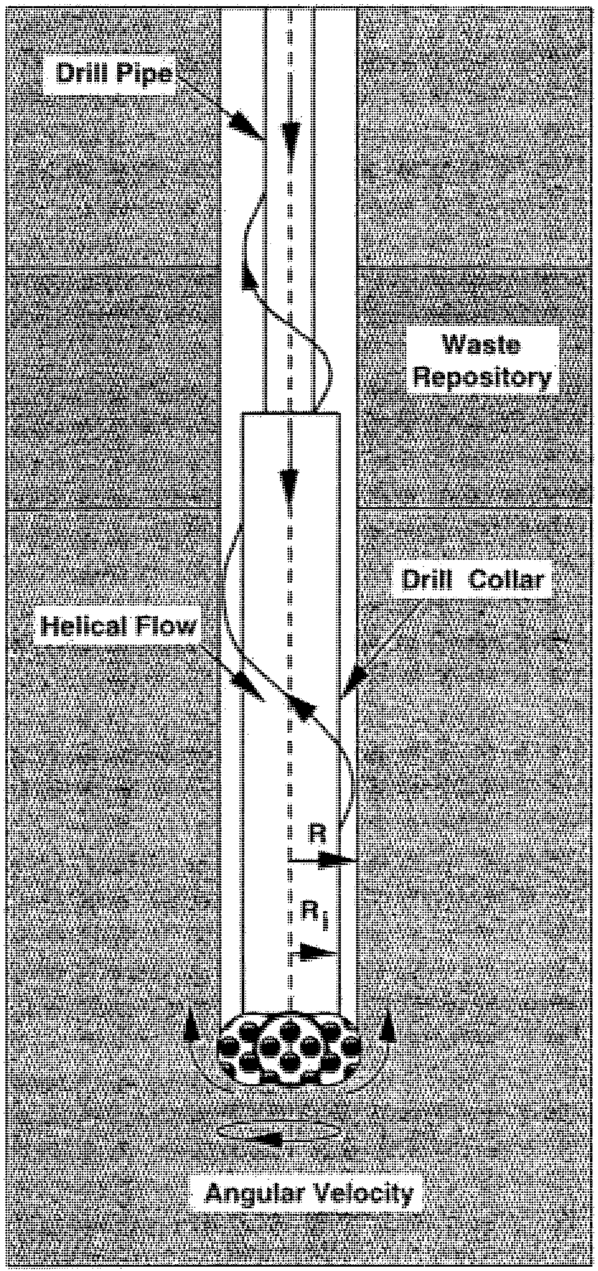

Figure 5.2.1 Detail of rotary drill string adjacent to drill-bit (Fig. 7.3, Vol. 2, WIPP PA 1991-1992; Fig. 13, Helton et al. 1995a)

$$R_e = \frac{0.8165\, D_e \|\mathbf{v}\| \rho_f}{\eta_\infty}, \tag{5.1.3}$$

where D_e, $||\mathbf{v}||$ and ρ_f are defined in conjunction with Eq. (5.1.2), and η_∞ is the asymptotic value for the derivative of the shear stress (τ, kg m^{-1} s^{-2}) with respect to the shear rate (Γ, s^{-1}) obtained as the shear rate increases (i.e., $\eta_\infty = d\tau/d\Gamma$ as $\Gamma \rightarrow \infty$). The 2003 WIPP PA uses Eq. (5.1.3) to obtain the Reynolds numbers that are used to determine whether drilling fluids in the area of the drill collar are undergoing laminar or turbulent flow.

The Oldroyd model assumes that the shear stress τ is related to the shear rate Γ by the relationship

$$\tau = \eta_0 \left(\frac{1 + \sigma_2 \Gamma^2}{1 + \sigma_1 \Gamma^2} \right) \Gamma, \tag{5.1.4}$$

where η_0 is the asymptotic value of the viscosity (kg m^{-1} s^{-1}) that results as the shear rate Γ approaches zero, and σ_1, σ_2 are constants (s^2). The expression leads to

$$\eta_\infty = \eta_0 \left(\frac{\sigma_2}{\sigma_1} \right). \tag{5.1.5}$$

The 2003 WIPP PA uses values of $\eta_0 = 1.834 \times 10^{-2}$ kg m^{-1} s^{-1}, $\sigma_1 = 1.082 \times 10^{-6}$ s^2 and $\sigma_2 = 5.410 \times 10^{-7}$ s^2 (Berglund 1996a; Berglund 1992), and a resultant value of $\eta_\infty = 9.17 \times 10^{-3}$ kg m^{-1} s^{-1} (DRILLMUD/VISCO). The quantity η_∞ is comparable to the plastic viscosity of the fluid (Broc 1982).

As previously indicated, different models are used to determine the eroded diameter of a borehole (i.e., $2R$ in Figure 5.2.1, with $R = D_f/2$ in Eq. (5.1.1)) depending on whether flow in the vicinity of the drill collar is laminar or turbulent. The model for borehole erosion in the presence of laminar flow is described next, and is then followed by a description of the model for borehole erosion in the presence of turbulent flow.

As shown by Savins and Wallick (1966), the shear stresses associated with the laminar helical flow of a non-Newtonian fluid can be expressed as

$$\tau(R,\rho) = \left\{ \left[\frac{C}{\rho^2} \right]^2 + \left[\frac{RJ}{2} \left(\frac{\rho^2 - \lambda^2}{\rho} \right) \right]^2 \right\}^{1/2} \tag{5.1.6}$$

for $R_i/R \le \rho \le 1$, where R_i and R are the inner and outer radii within which the flow occurs as indicated in Figure 5.2.1; $\tau(R, \rho)$ is the shear stress (kg m^{-1} s^{-2}) at a radial distance ΔR beyond the inner boundary (i.e., at $\rho = (R_i + \Delta R)/R$); and the quantities C, J and λ are functions of R that satisfy conditions indicated below. The shear stress at the outer boundary (i.e., R) is given by

$$\tau(R,1)=\left\{C^2+\left[\frac{RJ}{2}\left(1-\lambda^2\right)\right]^2\right\}^{1/2}. \tag{5.1.7}$$

As previously indicated, the borehole radius R is assumed to increase as a result of erosional processes until a value of R is reached at which $\tau(R, 1)$ is equal to the shear strength of the waste. In the 2003 WIPP PA, the shear strength of the waste is treated as an uncertain input variable (see *WTAUFAIL* (BOREHOLE/TAUFAIL) in Sect. 5.2 Helton et al. 1998). Computationally, determination of the eroded borehole diameter R associated with a particular waste shear strength requires repeated evaluation of $\tau(R, 1)$, as indicated in Eq. (5.1.7), until a value of R is determined for which $\tau(R, 1)$ equals that shear strength.

The quantities C, J and λ must satisfy the following three conditions (Savins and Wallick 1966) for the expression in Eq. (5.1.7) to be valid:

$$0=\int_{R_i/R}^{1}\left(\frac{\rho^2-\lambda^2}{\rho\eta}\right)d\rho, \tag{5.1.8}$$

$$0=C\int_{R_i/R}^{1}\left(\frac{1}{\rho^3\eta}\right)d\rho-\Delta\Omega, \tag{5.1.9}$$

and

$$0=\frac{4Q}{\pi R^3}+2RJ\int_{R_i/R}^{1}\left[\frac{(R_i/R)^2-\rho^2}{\eta}\right]\left[\frac{\rho^2-\lambda^2}{\rho}\right]d\rho, \tag{5.1.10}$$

where η is the drilling fluid viscosity (kg m^{-1} s^{-1}) and is a function of R and ρ, $\Delta\Omega$ is the drill string angular velocity (rad s^{-1}), and Q is the drilling fluid flow rate (m^3 s^{-1}).

The viscosity η in Eqs. (5.1.8) - (5.1.10) is introduced into the analysis through the assumption that the drilling fluid follows the Oldroyd model for shear stress in Eq. (5.1.4). In particular, because

$$\tau=\eta\Gamma \tag{5.1.11}$$

as a result of the definition of the viscosity η and

$$\Gamma^2=\frac{(\eta-\eta_0)}{(\eta_0\sigma_2-\eta\sigma_1)} \tag{5.1.12}$$

from Eq. (5.1.4), the expression in Eq. (5.1.6) can be reformulated as

$$\frac{\eta^2(\eta-\eta_0)}{(\eta_0\sigma_2-\eta\sigma_1)}=\left[\frac{C}{\rho^2}\right]^2+\left[\frac{RJ}{2}\left(\frac{\rho^2-\lambda^2}{\rho}\right)\right]^2. \tag{5.1.13}$$

As discussed by Savins and Wallick (1966) and also by Berglund (1992), the expressions in Eqs. (5.1.8) - (5.1.10) and (5.1.13) can be numerically evaluated to obtain C, J and λ for use in Eqs. (5.1.6) and (5.1.7). In the 2003 WIPP PA, $\Delta\Omega$(BORHOLE/DOMEGA) is sampled from a Cumulative Distribution with its mean = 8.63, median = 7.8, minimum = 4.2, and maximum = 230, all in rad s^{-1},

$$Q=\|\mathbf{v}\|\left(\pi R^2-\pi R_i^2\right) \tag{5.1.14}$$

where $\|\mathbf{v}\|$ = 0.7089 m s^{-1} as used in Eq. (5.1.2), and η_0, σ_1 and σ_2 are defined in conjunction with Eq. (5.1.5).

The model for borehole erosion in the presence of turbulent flow is now described. Unlike the theoretically derived relationship for erosion in the presence of laminar flow, the model for borehole erosion in the presence of turbulent flow is empirically based. In particular, pressure loss for axial flow in an annulus under turbulent flow conditions can be approximated by (Broc 1982)

$$\Delta P=\frac{2fL\rho_f\|\mathbf{v}\|^2}{0.8165D_e}, \tag{5.1.15}$$

where ΔP is the pressure change (Pa), L is distance (m) over which pressure change ΔP occurs, f is the Fanning friction factor (dimensionless), and ρ_f, $\|\mathbf{v}\|$ and D_e are defined in conjunction with Eq. (5.1.2).

For pipe flow, f is empirically related to the Reynolds number R_e and a roughness term ε by (Whittaker 1985)

$$\frac{1}{f^{1/2}}=-4\log_{10}\left(\frac{\varepsilon}{3.72D}+\frac{1.255}{R_e f^{1/2}}\right), \tag{5.1.16}$$

where D is the inside diameter (m) of the pipe and ε is the average depth (m) of pipe wall irregularities. In the absence of a similar equation for flow in an annulus, Eq. (5.1.16) is used in the 2003 WIPP PA to define f for use in Eq.(5.1.15), with D replaced by the effective diameter $D_e = 2(R - R_i)$ and ε equal to the average depth of irregularities in the waste-borehole interface. In the present analysis, ε = 0.025 m (WAS_AREA/ ABSROUGH) (Berglund 1996a), which exceeds the value often chosen for use in calculations involving very rough concrete or riveted steel piping (Streeter 1958). Further, the Reynolds number R_e is defined in Eq. (5.1.3).

The pressure change ΔP in Eq. (5.1.15) and the corresponding shear stress τ at the walls of the annulus are approximately related by

$$\Delta P\left[\pi\left(R^2 - R_i^2\right)\right] = \tau\left[2\pi L\left(R + R_i\right)\right], \tag{5.1.17}$$

where $\pi(R^2 - R_i^2)$ is the cross-sectional area of the annulus (see Figure 5.2.1) and $2\pi L\,(R + R_i)$ is the total (i.e., interior and exterior) surface area of the annulus. Rearrangement of Eq. (5.1.17) and use of the relationship in Eq. (5.1.15) yields

$$\tau = \frac{f\rho_f \|\mathbf{v}\|^2}{2(0.8165)}, \tag{5.1.18}$$

which was used in the 1991, 1992 and 1996 WIPP PAs to define the shear stress at the surface of a borehole of radius R. As a reminder, R enters into Eq. (5.1.8) through the use of $D = 2(R-R_i)$ in the definition of f in Eq. (5.1.16). As in the case for laminar flow, the borehole radius R is assumed to increase until a value of τ (actually, $\tau(R)$) is reached that equals the shear strength of the waste (i.e., the uncertain analysis input *WTAUFAIL*). Computationally, the eroded borehole diameter is determined by solving Eq. (5.1.18) for R under the assumption that τ equals the assumed shear strength of the waste.

A slight modification to the definition of τ in Eq. (5.1.18) is made to account for drillstring rotation when fluid flow in the vicinity of the drill collars is turbulent (Abdul Khader and Rao 1974, Bilgen et al. 1973). Specifically, an axial flow velocity correction factor (i.e., a rotation factor), F_r, was introduced into the definition of τ. The correction factor F_r is defined by

$$F_r = \|\mathbf{v}_{2100}\| / \|\mathbf{v}\|, \tag{5.1.19}$$

where $\|\mathbf{v}_{2100}\|$ is the norm of the flow velocity required for the eroded diameters to be the same for turbulent and laminar flow at a Reynolds number of 2100 and is obtained by solving

$$\tau_{fail} = \frac{f\rho_f \|\mathbf{v}_{2100}\|^2}{2(0.8165)} \tag{5.1.20}$$

for $\|\mathbf{v}_{2100}\|$ with D in the definition of f in Eq. (5.1.16) assigned the final diameter value that results for laminar flow at a Reynolds number of $R_e = 2100$ (i.e., the D in $D_e = 2(R-R_i) = D-2R_i$ obtained from Eq. (5.1.3) with $R_e = 2100$). The modified definition of τ is

$$\tau = \frac{f\rho_f (F_r\|\mathbf{v}\|)^2}{2(0.8165)} \tag{5.1.21}$$

and results in turbulent and laminar flow having the same eroded diameter at a Reynolds number of 2100, which is the Reynolds number at which a transition between turbulent and laminar flow is assumed to take place.

The following algorithm was used to determine the final eroded radius R_f of a borehole and incorporates the possible occurrence of a transition from turbulent to laminar fluid flow within a borehole:

Step 1. Use Eq. (5.1.3) to determine an initial Reynolds number R_e, with R set to the drill-bit radius (i.e., R_0). In the 2003 WIPP PA, $R_0 = 6.125$ in (Berglund 1996a).

Step 2. If $R_e < 2100$, then the flow is laminar and the procedures discussed in conjunction with Eqs. (5.1.6) and (5.1.7) are used to determine R_f. Because any increase in the borehole diameter will cause the Reynolds number to decrease, the flow will remain laminar and there is no need to consider the possibility of turbulent flow as the borehole diameter increases, with the result that R_f determined in this step is the final eroded radius of the borehole.

Step 3. If $R_e \geq 2100$, then the flow is turbulent and the procedures discussed in conjunction with Eqs. (5.1.18) and (5.1.21) are used to determine R_f. Once R_f is determined, the associated Reynolds number R_e is calculated with Eq. (5.1.3) and $R = R_f$. If $R_e > 2100$, then a transition from turbulent to laminar flow cannot take place, and the final eroded radius is R_f determined in this step.

Step 4. If the Reynolds number R_e determined in Step 3 satisfies the inequality $R_e \leq 2100$, then a transition from turbulent to laminar flow is assumed to have taken place. In this case, the calculation of R_f is redone for laminar flow, with the outer borehole radius R initially defined to be the radius at which the transition from turbulent to laminar flow occurs (i.e., the radius associated with $R_e = 2100$). In particular, the initial value for R is given by

$$R = R_i + \frac{2100\eta_\infty}{2(0.8165)\|\mathbf{v}\|\rho} \tag{5.1.22}$$

which is obtained from Eq. (5.1.3) by solving for R with $R_e = 2100$. A new value for R_f is then calculated with the procedures discussed in conjunction with Eqs. (5.1.6) and (5.1.7) for laminar flow, with this value of R_f replacing the value from step 3 as the final eroded diameter of the borehole.

Step 5. Once R_f is known, the amount of waste removed to the surface is determined by Eq. (5.1.1) with D_f=$2R_f$.

5.3 Spallings

Four spallings models are included in the CUTTINGS _S code. Spallings solid removal caused by blowout (models 1 and 2) are documented in CUTTINGS_S User Manual, Version 5.03 (WIPP PA 2003). The spallings model 3 is a simplified versions of models 1 and 2, used for the PAVT analysis. Model 3 is an IF statement that checks to see if the repository pressure is above or below the blowout threshold value specified in the CUSP_INP$TXT1 input file. If pressure is above the threshold the spall volume released is the value in the CUSP_INP$TXT1 input file. If pressure is below the threshold the spall volume released is zero.

The spallings model 4 computes the spall volume using the data in the input file CUSP_SPL4$DAT. This file (described in WIPP PA 2003b) contains a distribution of spall volumes for each of a set of reference values for repository pressure.

CUTTINGS obtains the repository pressure (P) at the time of intrusion from the output of BRAGFLO, and a random number (R) sampled from a uniform (0,1) distribution as specified in the CUSP_INP$TXT1 input file. To determine spall volume, CUTTINGS uses the random number R to select one of the distribution elements, then interpolates the spall volume from the DRSPALL results for that element. Algorithmically,

1. Select distribution element E by E = INT(R*NE)+1 where NE is the number of distribution elements
2. Find scenarios which bracket the repository pressure
    a. If P < MinPres then S = 1
    b. If P > MaxPres then S = NS where NS is the number of scenarios
    c. Else find I such that Pres(I) ≤ P < Pres(I+1)
3. Volume = Vol(E,I) + (P – Pres(I))/(Pres(I+1) – Pres(I)) × (Vol(E,I+1) – Vol(E,I))

6.0 REFERENCES

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534003

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Date: February 25, 2004

To: SNL WIPP Records Center
Carlsbad Programs Group

From: Jennifer Long Jennifer Long
SCM Coordinator

Subject: Record Correction to Design Document Criteria Form and Cover Sheet for CUTTINGS_S Version 5.10

Please disregard the Design Document Criteria Form and Cover Page for CUTTINGS_S Version 5.10 and replace with the attached Design Document Criteria Form and Cover Page. The originals incorrectly listed the Document Version as 1.00. The correct Document Version is 5.10.

Cc: C. Hansen

WIPP:1.5.1:SFT:QA-L:532334

Appendix E

NUCLEAR WASTE MANAGEMENT PROGRAM Sandia National Laboratories	Design Document Criteria Form	Form Number: NP 19-1-4 Page 1 of 1

1. **Software Name:** CUTTINGS_S
2. **Software Version:** 5.10
3. **Document Version:** ~~1.00~~ 5.10 GH 2/25/04
4. **ERMS #:** 532336

Prior to sign-off of the DD, all items shall be appropriately addressed by the code sponsor so that "**Yes**" may be checked. Include this form as part of the DD.

Are the following appropriately defined and documented in the DD?

5. Major Software Components ☒ Yes
6. Technical description of the software with respect to: theoretical basis, embodied mathematical model, major control flow, control logic, and data structures ☒ Yes
7. Allowable or Prescribed Ranges for Inputs and Outputs ☒ Yes
8. Verifiability: Is the design verifiable through testing or other means? ☒ Yes
9. Consistency and Traceability: Is the design consistent with and traceable to the software's requirements? ☒ Yes
10. Technical Feasibility: Is the design technically feasible? ☒ Yes
11. Implementation: Is the design presented in sufficient detail to allow for implementation as computer software? ☒ Yes

Cliff Hansen 12. **Code Team/Sponsor** (*print*)	[signature] for Signature	10/22/03 Date
James Garner 13. **Technical Reviewer** (*print*)	J W Garner Signature	10/22/03 Date
for David Kessel 14. **Responsible Manager** (*print*)	Paul E. Shoemaker Signature	10/22/03 Date
Jennifer Long 15. **SCM Coordinator** (*print*)	Jennifer Long Signature	10/22/03 Date

Key for check boxes above:

Check **Yes** for each item reviewed and found acceptable

WIPP PA

DESIGN DOCUMENT

for

CUTTINGS_S (Version 5.10)

Document Version 5.10

ERMS# 532336

OCTOBER 2003

535652

Sandia National Laboratories

Operated for the U.S. Department of Energy by
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Date: May 27, 2004

To: SNL WIPP Records Center
Carlsbad Programs Group

From: Janis Trone
Member of Technical Staff

Subject: Record Correction to Design Document for CUTTINGS_S Version 5.10

Please disregard the previous correction of the Design Document Cover Page for CUTTINGS_S Version 5.10 and replace the entire Design Document with the attached Design Document. The originals and the corrected cover page incorrectly listed the Document Version as 1.00. The correct Document Version is 5.10.

Cc: C. Hansen
J. Long

WIPP:1.5.1:SFT:QA-L:532334

WIPP PA

DESIGN DOCUMENT

for

CUTTINGS_S (Version 5.10)

Document Version 5.10

ERMS# 532336

OCTOBER 2003

Table of Contents

List of Figures and Tables

INTRODUCTION

This document serves as a Design Document for the CUTTINGS_S program as used in the Waste Isolation Pilot Plant (WIPP) Performance Assessment (PA) calculation. As such, it provides an overview of CUTTINGS_S and describes its code architecture.

1.1 Software Identifier

Code Name: CUTTINGS_S
WIPP Prefix: CUSP
Version: 5.10

1.2 Points of Contact

Code Sponsor: Cliff Hansen (505-234-0103)
4100 National Parks Highway
Carlsbad, NM 88220
E-mail: cwhanse@sandia.gov

1.3 Code Overview

The CUTTINGS_S code was written to calculate the quantity of material (in m^3) brought to the surface from a radioactive waste disposal repository as a consequence of an inadvertent human intrusion through drilling. The code determines the amount of material removed from the repository by several release mechanisms, including cuttings, cavings and spallings. The CUTTINGS_S code includes functionality to compute the radioactivity in the released material, including decay of the material to the time of intrusion.

2.0 REQUIREMENTS

The requirements for CUTTINGS_S are listed in the *WIPP PA Requirements Document And Verification Validation Plan for CUTTINGS_S Version 5.10* [WIPP PA 2003a]. The requirements are repeated here for the reader's convenience.

2.1 Functional Requirements

R.1 CUTTINGS_S calculates the amount of repository material brought to the surface due to erosion of the borehole resulting from laminar flow in the drilling fluid.

R.2 CUTTINGS_S calculates the amount of repository material brought to the surface due to erosion of the borehole resulting from turbulent flow in the drilling fluid.

R.3 CUTTINGS_S calculates the amount of repository material brought to the surface due to blowout of the borehole.

R.4 CUTTINGS_S calculates the amount of repository material brought to the surface due to gas erosion of the borehole.

R.5 CUTTINGS_S calculates the amount of repository material brought to the surface due to a stuckpipe.

R.6 CUTTINGS_S calculates model specific parameter values based on experimental data.

R.7 CUTTINGS_S calculates the volume of spalled material using a pressure threshold and a distribution of spallings volumes (spall model 3)

R.8 CUTTINGS_S determines the volume of spalled material using a set of distributions of spalled volumes, calculated for a set of reference repository pressures, by interpolating between distributions to account for current repository pressure (spall model 4).

2.2 Performance Requirements

There are no performance requirements for CUTTINGS_S.

2.3 Attribute Requirements

There are no attribute requirements for CUTTINGS_S.

2.4 External Interface Requirements

R.9 CUTTINGS_S utilizes routines from CAMDAT_LIB, CAMCON_LIB, SDBREAD_LIB, and CAMSUPES_LIB. Consequently it must be linked with these libraries.

R.10 CUTTINGS_S requires one CDB input file from the BRAGFLO code, CUSP_INP$BRAGCDB.

R.11 CUTTINGS_S requires one input file containing preliminary data base information, CUSP_INP$CDB.

R.12 CUTTINGS_S requires one input file containing model and site dependent parameters and radionuclide properties, inventories, drilling procedures, and characteristics of the drilling fluid, CUSP_INP$TXT0.

R.13 CUTTINGS_S requires one input file identifying input sample vector values that will be used in the analysis, CUSP_INP$TXT1.

R.14 CUTTINGS_S generates one output file CUSP_OUT$DBG, which contains information that is used for comparing with acceptance criteria, and is used only for testing purposes.

R.15 CUTTINGS_S generates one output file CUSP_OUT$NVERIFY, which contains information that is used in the functional testing for hand calculations, and is not used in production runs.

R.16 CUTTINGS_S generates one output CDB (binary) file, CUSP_OUT$CDB, containing output generated by the code. This output must comform to the format specified in the WIPP PA User's Manual for CAMDAT_LIB (4).

R.17 If spall model 4 is used, CUTTINGS_S reads spall volume data from a text input file, CUSP_SPL4$DAT.

2.5 Other Requirements

There are no other requirements for CUTTINGS_S.

3.0 DESIGN OVERVIEW

This section describes the structure and content of the input and output files for CCDFGF.

3.1 I/O Description

The files associated with running CUTTINGS_S are listed, along with their logicals in Table 3.1. For a detailed description of the input and output files see the *CUTTINGS_S User's Manual Version 5.10* (WIPP PA 2003b)

Table 3.1 Listing of Input and Output Files

File ID No. Input/Output File Names	Associated Logical Symbol	Is the file Required or Not?
1. Binary input CAMDAT file (from MATSET)	CUSP_INP$CDB	Yes
2. Input control file (text) specifying repository/model parameters, initial inventories, generic radioisotope database.	CUSP_INP$TXT0	Yes
3. Input control file (text) specifying drilling and intrusion parameters	CUSP_INP$TXT1	Yes
4. BRAGFLO binary output .CDB file.	CUSP_INP$BRAGCDB	
Regulatory runs		Yes
Test runs		No
5. Input control file for Spall Model 4 specifing	CUSP_SPL4$DAT	Yes

pressures and their volumes by vector		(spall model 4 only)
6. CUTTINGS_S's binary output .CDB file	CUSP_OUT$CDB	Yes
7. CUTTINGS_S's output debug text file	CUSP_OUT$DBG	Yes
8. Text file for verification testing	CUSP_OUT$NVERIFY	No
9. Radioisotope inventory history (in CURIES) output text file	CUSP_OUT$IHISTO	No
10. Normalized-release-history output text file (EPA 40CFR191, Subpt B) file in ASCII format	CUSP_OUT$NHISTO	No
11. Time-history plotting text file for:		
Long half-life radioisotope decay	CUSP_OUT$PLT1	No
Medium half-life radioisotope decay	CUSP_OUT$PLT2	No
Short half-life radioisotope decay	CUSP_OUT$PLT3	No
12. Output text file for transfer to the WIPP code CCDFPERM	CUSP_OUT$ICTRN	No

3.2 Design Constraints

There are no constraints on the design of CUTTINGS_S Version 5.10

3.3 Other Design Considerations

There are no other design considerations for CUTTINGS_S Version 5.10.

4.0 THEORETICAL OVERVIEW

Three separate release modes, cuttings, cavings and spallings, are believed to determine the quantity of solid waste brought to the ground surface as the result of a drilling intrusion through a waste panel, where cuttings designates the waste contained in the cylindrical volume created by the cutting action of the drill bit passing through the waste, cavings designates the waste that erodes from the borehole in response to the upward-flowing drilling fluid within the borehole, and spallings designates the waste introduced into the borehole by the release of waste-generated gas escaping to the lower-pressure borehole. The releases associated with these processes are computed within the CUTTINGS_S code (WIPP PA 1996a). The mathematical representations are described in Section 5.0.

5.0 MATHEMATICAL MODEL

5.1 Cuttings

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

$$V_{cut} = AH_i = \pi D^2 H_i / 4, \tag{5.1}$$

where H_i is the initial (i.e., uncompacted) repository height (m), A is the drill bit area (m^2), and D is the drillbit diameter (m). In the 2003 WIPP PA, D = 12.25 in. = 0.31115m (BOREHOLE/DIAMMOD) and H_i = 3.96m (Berglund 1996a). For drilling intrusions through RH-TRU waste, H_i = 0.509m is used (Tierney 1996). The size of the cuttings release is independent of the conditions that exist in the repository at the time of a drilling intrusion, with the result that the cuttings volume V_{cut} is a lower bound on the quantity of material removed by a drilling intrusion.

5.2 Cavings (adapted from Sect. 3.5 of Helton et al. 1998a)

The cavings component of the direct surface release is caused by the shearing action of the drilling fluid (mud) on the waste as the mud flows up the borehole annulus. As is the case for the cuttings release, the cavings release is assumed to be independent of the conditions that exist in the repository at the time of a drilling intrusion.

The final diameter of the borehole will depend on the diameter of the drill-bit and on the extent to which the actual borehole diameter exceeds the drill-bit diameter. Although a number of factors affect erosion within a borehole (Broc 1982), the most important factor is believed to be the fluid shear stress on the borehole wall (i.e., the shearing force per unit area, (kg m/s^2/m^2)) resulting from circulating drilling fluids (Darley 1969, Walker and Holman 1971). As a result, the 2003 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 (i.e., the limiting shear stress below which the erosion of the waste ceases).

The final eroded diameter D_f(m) of the borehole through the waste determines the volume V (m^3) of uncompacted waste that will be removed to the surface by circulating drilling fluid. Specifically,

$$V = V_{cut} + V_{cav} = \pi D_f^2 H_i / 4, \tag{5.1.1}$$

where V_{cav} is the volume (m^3) of waste removed as cavings.

Most borehole erosion is believed to occur in the vicinity of the drill collar (Figure 5.2.1) (Rechard et al. 1990). An important determinant of the extent of this erosion is whether the flow of the drilling fluid in the vicinity of the collar is laminar or turbulent. The 2003 WIPP PA uses Reynolds numbers to distinguish between the occurrence of laminar flow and turbulent flow. The Reynolds number is the ratio between inertial and viscous (i.e., shear) forces in a fluid and can be expressed as

$$R_e = \frac{\rho_f \|\mathbf{v}\| D_e}{\eta}, \tag{5.1.2}$$

where R_e is the Reynolds number (dimensionless), ρ_f is the fluid density (kg m^{-3}), D_e is the equivalent diameter (m), $\mathbf{v}$ is the fluid velocity (m s^{-1}), and η is the fluid viscosity (kg m^{-1} s^{-1}).

Typically, ρ, $\mathbf{v}$ and η are averages over a control volume with an equivalent diameter of D_e. In the 2003 WIPP PA, $\rho_f = 1.21 \times 10^3$ kg m^{-3} (DRILLMUD/ DNSFLUID) (Berglund 1996a), $\|\mathbf{v}\| =$ 0.7089 m s^{-1} (based on 40 gallons/min per inch of drill diameter, Sect. 2.3, Berglund 1992), and $D_e = 2\,(R - R_i)$ as shown in Figure 5.2.1. The diameter of the drill collar (i.e., $2R_i$ in Figure 5.2.1) is 8.0 in = 0.2032 m (Berglund 1996a). The fluid velocity, $\|\mathbf{v}\|$, is calculated by multiplying the 40 gallons/min by the diameter of the drill, 12.25 inches. Then converting this value to m^3 s^{-1}. The area calculated using R, minus the area calculated using R_i, divided by the value in m^3 s^{-1} results in 0.7089 m s^{-1}. The determination of η is discussed below. Reynolds numbers less than 2100 are assumed to be associated with laminar flow, while Reynolds numbers greater than 2100 are assumed to be associated with turbulent flow (Walker 1976).

Drilling fluids are non-Newtonian fluids, which means that the viscosity η is a function of the shear rate within the fluid (i.e., the rate at which the fluid velocity changes normal to the flow direction, ((m/s)/m). The 2003 WIPP PA uses a model proposed by Oldroyd (1958) to estimate the viscosity of drilling fluids. As discussed by Broc (1982), this model leads to the following expression for the Reynolds number associated with the helical flow of a drilling fluid within an annulus:

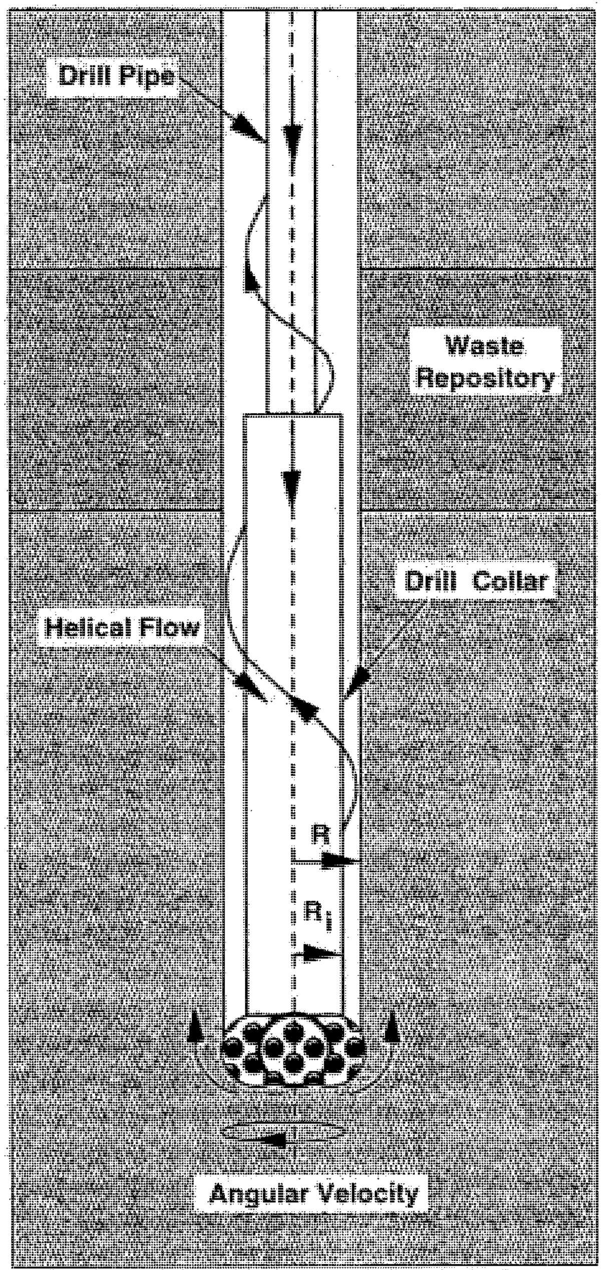

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Figure 5.2.1 **Detail of rotary drill string adjacent to drill-bit (Fig. 7.3, Vol. 2, WIPP PA 1991-1992; Fig. 13, Helton et al. 1995a)**

$$R_e = \frac{0.8165\, D_e \|\mathbf{v}\| \rho_f}{\eta_\infty}, \tag{5.1.3}$$

where D_e, $||\mathbf{v}||$ and ρ_f are defined in conjunction with Eq. (5.1.2), and η_∞ is the asymptotic value for the derivative of the shear stress (τ, kg m^{-1} s^{-2}) with respect to the shear rate (Γ, s^{-1}) obtained as the shear rate increases (i.e., $\eta_\infty = d\tau/d\Gamma$ as $\Gamma \rightarrow \infty$). The 2003 WIPP PA uses Eq. (5.1.3) to obtain the Reynolds numbers that are used to determine whether drilling fluids in the area of the drill collar are undergoing laminar or turbulent flow.

The Oldroyd model assumes that the shear stress τ is related to the shear rate Γ by the relationship

$$\tau = \eta_0 \left(\frac{1+\sigma_2 \Gamma^2}{1+\sigma_1 \Gamma^2} \right) \Gamma, \tag{5.1.4}$$

where η_0 is the asymptotic value of the viscosity (kg m^{-1} s^{-1}) that results as the shear rate Γ approaches zero, and σ_1, σ_2 are constants (s^2). The expression leads to

$$\eta_\infty = \eta_0 \left(\frac{\sigma_2}{\sigma_1} \right). \tag{5.1.5}$$

The 2003 WIPP PA uses values of $\eta_0 = 1.834 \times 10^{-2}$ kg m^{-1} s^{-1}, $\sigma_1 = 1.082 \times 10^{-6}$ s^2 and $\sigma_2 = 5.410 \times 10^{-7}$ s^2 (Berglund 1996a; Berglund 1992), and a resultant value of $\eta_\infty = 9.17 \times 10^{-3}$ kg m^{-1} s^{-1} (DRILLMUD/VISCO). The quantity η_∞ is comparable to the plastic viscosity of the fluid (Broc 1982).

As previously indicated, different models are used to determine the eroded diameter of a borehole (i.e., $2R$ in Figure 5.2.1, with $R = D_f/2$ in Eq. (5.1.1)) depending on whether flow in the vicinity of the drill collar is laminar or turbulent. The model for borehole erosion in the presence of laminar flow is described next, and is then followed by a description of the model for borehole erosion in the presence of turbulent flow.

As shown by Savins and Wallick (1966), the shear stresses associated with the laminar helical flow of a non-Newtonian fluid can be expressed as

$$\tau(R,\rho) = \left\{ \left[\frac{C}{\rho^2} \right]^2 + \left[\frac{RJ}{2} \left(\frac{\rho^2 - \lambda^2}{\rho} \right) \right]^2 \right\}^{1/2} \tag{5.1.6}$$

for $R_i/R \le \rho \le 1$, where R_i and R are the inner and outer radii within which the flow occurs as indicated in Figure 5.2.1; $\tau(R, \rho)$ is the shear stress (kg m^{-1} s^{-2}) at a radial distance ΔR beyond the inner boundary (i.e., at $\rho = (R_i + \Delta R)/R$); and the quantities C, J and λ are functions of R that satisfy conditions indicated below. The shear stress at the outer boundary (i.e., R) is given by

$$\tau(R,1) = \left\{ C^2 + \left[\frac{RJ}{2}\left(1-\lambda^2\right) \right]^2 \right\}^{1/2}. \tag{5.1.7}$$

As previously indicated, the borehole radius R is assumed to increase as a result of erosional processes until a value of R is reached at which $\tau(R, 1)$ is equal to the shear strength of the waste. In the 2003 WIPP PA, the shear strength of the waste is treated as an uncertain input variable (see *WTAUFAIL* (BOREHOLE/TAUFAIL) in Sect. 5.2 Helton et al. 1998). Computationally, determination of the eroded borehole diameter R associated with a particular waste shear strength requires repeated evaluation of $\tau(R, 1)$, as indicated in Eq. (5.1.7), until a value of R is determined for which $\tau(R, 1)$ equals that shear strength.

The quantities C, J and λ must satisfy the following three conditions (Savins and Wallick 1966) for the expression in Eq. (5.1.7) to be valid:

$$0 = \int_{R_i/R}^{1} \left(\frac{\rho^2 - \lambda^2}{\rho\eta} \right) d\rho, \tag{5.1.8}$$

$$0 = C\int_{R_i/R}^{1} \left(\frac{1}{\rho^3\eta} \right) d\rho - \Delta\Omega, \tag{5.1.9}$$

and

$$0 = \frac{4Q}{\pi R^3} + 2RJ\int_{R_i/R}^{1} \left[\frac{(R_i/R)^2 - \rho^2}{\eta} \right] \left[\frac{\rho^2 - \lambda^2}{\rho} \right] d\rho, \tag{5.1.10}$$

where η is the drilling fluid viscosity (kg m^{-1} s^{-1}) and is a function of R and ρ, $\Delta\Omega$ is the drill string angular velocity (rad s^{-1}), and Q is the drilling fluid flow rate (m^3 s^{-1}).

The viscosity η in Eqs. (5.1.8) - (5.1.10) is introduced into the analysis through the assumption that the drilling fluid follows the Oldroyd model for shear stress in Eq. (5.1.4). In particular, because

$$\tau = \eta\Gamma \tag{5.1.11}$$

as a result of the definition of the viscosity η and

$$\Gamma^2 = \frac{(\eta - \eta_0)}{(\eta_0\sigma_2 - \eta\sigma_1)} \tag{5.1.12}$$

from Eq. (5.1.4), the expression in Eq. (5.1.6) can be reformulated as

$$\frac{\eta^2(\eta-\eta_0)}{(\eta_0\sigma_2-\eta\sigma_1)}=\left[\frac{C}{\rho^2}\right]^2+\left[\frac{RJ}{2}\left(\frac{\rho^2-\lambda^2}{\rho}\right)\right]^2. \tag{5.1.13}$$

As discussed by Savins and Wallick (1966) and also by Berglund (1992), the expressions in Eqs. (5.1.8) - (5.1.10) and (5.1.13) can be numerically evaluated to obtain C, J and λ for use in Eqs. (5.1.6) and (5.1.7). In the 2003 WIPP PA, $\Delta\Omega$(BORHOLE/DOMEGA) is sampled from a Cumulative Distribution with its mean = 8.63, median = 7.8, minimum = 4.2, and maximum = 230, all in rad s^{-1},

$$Q=\|\mathbf{v}\|\left(\pi R^2-\pi R_i^2\right) \tag{5.1.14}$$

where $\|\mathbf{v}\|$ = 0.7089 m s^{-1} as used in Eq. (5.1.2), and η_0, σ_1 and σ_2 are defined in conjunction with Eq. (5.1.5).

The model for borehole erosion in the presence of turbulent flow is now described. Unlike the theoretically derived relationship for erosion in the presence of laminar flow, the model for borehole erosion in the presence of turbulent flow is empirically based. In particular, pressure loss for axial flow in an annulus under turbulent flow conditions can be approximated by (Broc 1982)

$$\Delta P=\frac{2fL\rho_f\|\mathbf{v}\|^2}{0.8165D_e}, \tag{5.1.15}$$

where ΔP is the pressure change (Pa), L is distance (m) over which pressure change ΔP occurs, f is the Fanning friction factor (dimensionless), and ρ_f, $\|\mathbf{v}\|$ and D_e are defined in conjunction with Eq. (5.1.2).

For pipe flow, f is empirically related to the Reynolds number R_e and a roughness term ε by (Whittaker 1985)

$$\frac{1}{f^{1/2}}=-4\log_{10}\left(\frac{\varepsilon}{3.72D}+\frac{1.255}{R_e f^{1/2}}\right), \tag{5.1.16}$$

where D is the inside diameter (m) of the pipe and ε is the average depth (m) of pipe wall irregularities. In the absence of a similar equation for flow in an annulus, Eq. (5.1.16) is used in the 2003 WIPP PA to define f for use in Eq.(5.1.15), with D replaced by the effective diameter $D_e = 2(R - R_i)$ and ε equal to the average depth of irregularities in the waste-borehole interface. In the present analysis, ε = 0.025 m (WAS_AREA/ ABSROUGH) (Berglund 1996a), which exceeds the value often chosen for use in calculations involving very rough concrete or riveted steel piping (Streeter 1958). Further, the Reynolds number R_e is defined in Eq. (5.1.3).

The pressure change ΔP in Eq. (5.1.15) and the corresponding shear stress τ at the walls of the annulus are approximately related by

$$\Delta P\left[\pi\left(R^2 - R_i^2\right)\right] = \tau\left[2\pi L\left(R + R_i\right)\right], \tag{5.1.17}$$

where $\pi(R^2 - R_i^2)$ is the cross-sectional area of the annulus (see Figure 5.2.1) and $2\pi L\ (R + R_i)$ is the total (i.e., interior and exterior) surface area of the annulus. Rearrangement of Eq. (5.1.17) and use of the relationship in Eq. (5.1.15) yields

$$\tau = \frac{f\rho_f \|\mathbf{v}\|^2}{2(0.8165)}, \tag{5.1.18}$$

which was used in the 1991, 1992 and 1996 WIPP PAs to define the shear stress at the surface of a borehole of radius R. As a reminder, R enters into Eq. (5.1.8) through the use of $D = 2(R-R_i)$ in the definition of f in Eq. (5.1.16). As in the case for laminar flow, the borehole radius R is assumed to increase until a value of τ (actually, $\tau(R)$) is reached that equals the shear strength of the waste (i.e., the uncertain analysis input *WTAUFAIL*). Computationally, the eroded borehole diameter is determined by solving Eq. (5.1.18) for R under the assumption that τ equals the assumed shear strength of the waste.

A slight modification to the definition of τ in Eq. (5.1.18) is made to account for drillstring rotation when fluid flow in the vicinity of the drill collars is turbulent (Abdul Khader and Rao 1974, Bilgen et al. 1973). Specifically, an axial flow velocity correction factor (i.e., a rotation factor), F_r, was introduced into the definition of τ. The correction factor F_r is defined by

$$F_r = \|\mathbf{v}_{2100}\| / \|\mathbf{v}\|, \tag{5.1.19}$$

where $\|\mathbf{v}_{2100}\|$ is the norm of the flow velocity required for the eroded diameters to be the same for turbulent and laminar flow at a Reynolds number of 2100 and is obtained by solving

$$\tau_{fail} = \frac{f\rho_f \|\mathbf{v}_{2100}\|^2}{2(0.8165)} \tag{5.1.20}$$

for $\|\mathbf{v}_{2100}\|$ with D in the definition of f in Eq. (5.1.16) assigned the final diameter value that results for laminar flow at a Reynolds number of $R_e = 2100$ (i.e., the D in $D_e = 2(R-R_i) = D-2R_i$ obtained from Eq. (5.1.3) with $R_e = 2100$). The modified definition of τ is

$$\tau = \frac{f\rho_f (F_r \|\mathbf{v}\|)^2}{2(0.8165)} \tag{5.1.21}$$

and results in turbulent and laminar flow having the same eroded diameter at a Reynolds number of 2100, which is the Reynolds number at which a transition between turbulent and laminar flow is assumed to take place.

The following algorithm was used to determine the final eroded radius R_f of a borehole and incorporates the possible occurrence of a transition from turbulent to laminar fluid flow within a borehole:

Step 1. Use Eq. (5.1.3) to determine an initial Reynolds number R_e, with R set to the drill-bit radius (i.e., R_0). In the 2003 WIPP PA, $R_0 = 6.125$ in (Berglund 1996a).

Step 2. If $R_e < 2100$, then the flow is laminar and the procedures discussed in conjunction with Eqs. (5.1.6) and (5.1.7) are used to determine R_f. Because any increase in the borehole diameter will cause the Reynolds number to decrease, the flow will remain laminar and there is no need to consider the possibility of turbulent flow as the borehole diameter increases, with the result that R_f determined in this step is the final eroded radius of the borehole.

Step 3. If $R_e \geq 2100$, then the flow is turbulent and the procedures discussed in conjunction with Eqs. (5.1.18) and (5.1.21) are used to determine R_f. Once R_f is determined, the associated Reynolds number R_e is calculated with Eq. (5.1.3) and $R = R_f$. If $R_e > 2100$, then a transition from turbulent to laminar flow cannot take place, and the final eroded radius is R_f determined in this step.

Step 4. If the Reynolds number R_e determined in Step 3 satisfies the inequality $R_e \leq 2100$, then a transition from turbulent to laminar flow is assumed to have taken place. In this case, the calculation of R_f is redone for laminar flow, with the outer borehole radius R initially defined to be the radius at which the transition from turbulent to laminar flow occurs (i.e., the radius associated with $R_e = 2100$). In particular, the initial value for R is given by

$$R = R_i + \frac{2100\eta_\infty}{2(0.8165)\|\mathbf{v}\|\rho} \qquad (5.1.22)$$

which is obtained from Eq. (5.1.3) by solving for R with $R_e = 2100$. A new value for R_f is then calculated with the procedures discussed in conjunction with Eqs. (5.1.6) and (5.1.7) for laminar flow, with this value of R_f replacing the value from step 3 as the final eroded diameter of the borehole.

Step 5. Once R_f is known, the amount of waste removed to the surface is determined by Eq. (5.1.1) with D_f=2R_f.

5.3 Spallings

Four spallings models are included in the CUTTINGS _S code. Spallings solid removal caused by blowout (models 1 and 2) are documented in CUTTINGS_S User Manual, Version 5.03 (WIPP PA 2003). The spallings model 3 is a simplified versions of models 1 and 2, used for the PAVT analysis. Model 3 is an IF statement that checks to see if the repository pressure is above or below the blowout threshold value specified in the CUSP_INP$TXT1 input file. If pressure is above the threshold the spall volume released is the value in the CUSP_INP$TXT1 input file. If pressure is below the threshold the spall volume released is zero.

The spallings model 4 computes the spall volume using the data in the input file CUSP_SPL4$DAT. This file (described in WIPP PA 2003b) contains a distribution of spall volumes for each of a set of reference values for repository pressure.

CUTTINGS obtains the repository pressure (P) at the time of intrusion from the output of BRAGFLO, and a random number (R) sampled from a uniform (0,1) distribution as specified in the CUSP_INP$TXT1 input file. To determine spall volume, CUTTINGS uses the random number R to select one of the distribution elements, then interpolates the spall volume from the DRSPALL results for that element. Algorithmically,

1. Select distribution element E by E = INT(R*NE)+1 where NE is the number of distribution elements
2. Find scenarios which bracket the repository pressure
   a. If P < MinPres then S = 1
   b. If P > MaxPres then S = NS where NS is the number of scenarios
   c. Else find I such that Pres(I) ≤ P < Pres(I+1)
3. Volume = Vol(E,I) + (P – Pres(I))/(Pres(I+1) – Pres(I)) × (Vol(E,I+1) – Vol(E,I))

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