Appendix C

NUCLEAR WASTE MANAGEMENT PROCEDURE Sandia National Laboratories	**Requirements Document Criteria**	**Form Number: NP 19-1-2** **Page 1 of 1**

1. **Software Name:** DRSPALL
2. **Software Version:** 1.24
3. **Document Version:** 1.24
4. **ERMS #:** 573905

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

5.	**Functionality:** Are the functions that the software is to perform adequately identified?	☒ Yes	
6.	**Performance:** Are time-related software operations issues, e.g., speed, recovery time, or response time identified, where applicable as based on the code functionality?	☐ Yes	☒ N/A
7.	**Design Constraints:** Are elements that will restrict design options identified?	☒ Yes	☐ N/A
8.	**Attributes (non-time-related):** Are the following identified, where applicable as based on the code functionality:		
	portability?	☐ Yes	☒ N/A
	acceptance criteria?	☒ Yes	
	maintainability?	☐ Yes	☒ N/A
9.	**External Interfaces:** Are the following interactions identified, where applicable as based on the code functionality:		
	People?	☐ Yes	☒ N/A
	Hardware?	☐ Yes	☒ N/A
	Software?	☒ Yes	☐ N/A
10.	**Completeness:** Are the requirements complete?	☒ Yes	
11.	**Verifiability:** Can meeting the requirements be verified?	☒ Yes	
12.	**Consistency:** Are requirements consistent with each other?	☒ Yes	
13.	**Technical Feasibility:** Are the requirements technically feasible and can they result in a useable code?	☒ Yes	

14.	Dwayne Kicker **Code Team/Sponsor's Name** (*print*)	*Signature on File* Signature	3/1/21 Date
15.	Cliff Hansen **Technical Reviewer's Name** (*print*)	*Signature on File* Signature	3/22/21 Date
16.	Shelly Nielsen **QA Reviewer's Name** (*print*)	Shelly R Nielsen Signature	3-5-2021 Date
17.	Steve Wagner **Responsible Manager's Name** (*print*)	*Signature on File* Signature	3/17/21 Date
18.	Jennifer Long **SCM Coordinator's Name** (*print*)	*Signature on File* Signature	3/5/2021 Date

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Appendix D

NUCLEAR WASTE MANAGEMENT PROCEDURE Sandia National Laboratories	**Verification and Validation Plan Criteria**	**Form Number: NP 19-1-3** **Page 1 of 1**

1. **Software Name:** DRSPALL
2. **Software Version:** 1.24
3. **Document Version:** 1.24
4. **ERMS #:** 573905

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

5.	**Sufficient Test Cases** Does the VVP identify sufficient test cases and acceptance criteria to ensure the final software and end product satisfies the requirements of the RD? (Check Yes if peer review is identified to fulfill the validation requirements)	☒ Yes	
6.	**Adequacy of Test Cases** Do the test cases demonstrate that the code adequately performs all intended functions and produces valid results for problems encompassing the range of permitted usage?	☒ Yes	
7.	**Operational Control** If the software is used for operational control, do tests demonstrate required performance over the range of operation of the controlled function or process?	☐ Yes	☒ N/A
8.	**Unintended Functions** Do the test cases show that the code does not perform any unintended function that either by itself or in combination with other functions can degrade the intended outcomes of the software?	☐ Yes	☒ N/A
9.	**Test Result Validation.** (check one or more, where applicable as based on code functionality)		
	The test results will be compared to the following:		
	- hand calculations,	☒ Yes	☐ N/A
	- manual inspection,	☒ Yes	☐ N/A
	- calculations using comparable proven problems,	☒ Yes	☐ N/A
	- empirical data and information from confirmed published data and correlation's and/or technical literature,	☒ Yes	☐ N/A
	- other validated software of similar purpose,	☐ Yes	☒ N/A
	- other independent software of similar purpose.	☒ Yes	☐ N/A
	A documented peer review will be performed.	☐ Yes	☒ N/A
	Do the test cases describe how the code results will be validated?	☒ Yes	
10.	**Does the VVP specify the following, where applicable as based on code functionality?**		
	(a) required tests and test sequence	☒ Yes	☐ N/A
	(b) required ranges of input parameters	☒ Yes	☐ N/A
	(c) identification of the stages at which testing is required	☒ Yes	☐ N/A
	(d) criteria for establishing test cases	☒ Yes	☐ N/A
	(e) requirements for testing logic branches	☒ Yes	☐ N/A
	(f) requirements for hardware integration	☐ Yes	☒ N/A
	(g) anticipated output values	☒ Yes	☐ N/A
	(h) acceptance criteria	☒ Yes	☐ N/A
11.	**Installation and Regression Testing** Are test cases which are suitable for installation testing and regression testing identified in the set of verification and validation test cases?	☒ Yes	

12.	Dwayne Kicker **Code Team/Sponsor's Name** (*print*)	Signature on File Signature	3/1/21 Date
13.	Cliff Hansen **Technical Reviewer's Name** (*print*)	Signature on File Signature	3/22/21 Date
14.	Shelly Nielsen **QA Reviewer's Name** (*print*)	Shelly R. Nielsen Signature	3-5-2021 Date
15.	Steve Wagner **Responsible Manager's Name** (*print*)	Signature on File Signature	3/17/21 Date
16.	Jennifer Long **SCM Coordinator's Name** (*print*)	Signature on File Signature	3/5/2021 Date

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Appendix H

NUCLEAR WASTE MANAGEMENT PROCEDURE Sandia National Laboratories	**Validation Document Criteria**	**Form Number: NP 19-1-7** **Page 1 of 1**

1. **Software Name:** DRSPALL
2. **Software Version:** 1.24
3. **Document Version:** 1.24
4. **ERMS #:** 573905

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

5. **Is the following information included, where applicable?**

(a) computer program and version tested	☒ Yes	
(b) computer hardware and operating system used	☒ Yes	
(c) test equipment and calibrations	☐ Yes	☒ N/A
(d) date of test	☒ Yes	
(e) tester or data recorder	☒ Yes	
(f) simulation models used,	☐ Yes	☒ N/A
(g) test problem input and output files	☒ Yes	
(h) results and acceptability	☒ Yes	
(I) action taken in connection with any deviations noted	☐ Yes	☒ N/A

6. **Test Result Validation**
The test results were compared to the following (check one or more, where applicable as based on code functionality):

- hand calculations,	☒ Yes	☐ N/A
- manual inspection,	☒ Yes	☐ N/A
- calculations using comparable proven problems,	☒ Yes	☐ N/A
- empirical data & information from confirmed published data and correlations and/or technical literature,	☒ Yes	☐ N/A
- other validated software of similar purpose,	☐ Yes	☒ N/A
- other independent software of similar purpose.	☒ Yes	☐ N/A

7. **Test Documentation Acceptability** ☒ Yes
Do the tests meet the acceptance criteria identified in the VVP?

8. **Test Documentation Repeatability** ☒ Yes
Are the tests documented in sufficient detail such that they can be repeated?

9. **Computer File Documentation** ☒ Yes
Are the test case input and output files included in the Validation Document or a reference to their location in a configuration management tool provided?

10. **Understandability of Documentation** ☒ Yes
Are the validation methods, test data, results, and conclusions documented in a form that can be understood by an independent, technically competent individual?

11.	Dwayne Kicker **Code Team/Sponsor** (*print*)	*Signature on File* Signature	3/1/21 Date
12.	Cliff Hansen **Technical Reviewer** (*print*)	*Signature on File* Signature	3/22/21 Date
13.	Shelly Nielsen **QA Reviewer** (*print*)	Shelly R. Nielsen Signature	3-5-2021 Date
14.	Steve Wagner **Responsible Manager** (*print*)	*Signature on File* Signature	3/17/21 Date
15.	Jennifer Long **SCM Coordinator** (*print*)	*Signature on File* Signature	3/5/2021 Date

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WIPP PA

Requirements Document,

Verification and Validation Plan,

And

Validation Document

for

DRSPALL Version 1.24

Document Version 1.24

ERMS # 573905

March 2021

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1.0 INTRODUCTION AND SCOPE

This Requirements Document, Verification and Validation Plan and Validation Document for DRSPALL Version 1.24, identifies the requirements, describes how the code was tested, and reports the results of the testing that ensure the requirements were satisfied, in accordance with the Nuclear Waste Management Procedure NP 19-1 Software Requirements (Long, 2020). This code is used by the Sandia National Laboratories' Performance Assessment (PA) Department in support of the performance assessment calculations for the Waste Isolation Pilot Plant (WIPP). It is controlled under the software configuration management system CVS (Concurrent Versions System) on the Linux cluster.

1.1 Software Identification

Code Name:	DRSPALL
Version:	1.24
CVS Repository:	/data/cvs/CVSLIB/WIPP_CODES/PA_CODES/DRSPALL
Platform:	CentOS 7/Dell PowerEdge C6420
Host:	fwm.sandia.gov
Compiler:	Gfortran/GCC 8.2.0

1.2 Points of Contact

Code Sponsor:	Dwayne Kicker	dckicke@sandia.gov	(575) 628-0117
Run Control Coordinator:	Jennifer Long	jjlong@sandia.gov	(575) 234-0106

1.3 Code Overview

DRSPALL is written to calculate the spallings release, defined as the mass of waste subject to tensile failure and transport during an inadvertent drilling intrusion into a high-pressure WIPP repository. Cuttings removed by the direct action of the drillbit, and cavings removed by shear forces of the drilling mud against the drilled cavity wall are handled separately in the CUTTINGS_S code. DRSPALL uses both text-formatted and CDB input and output files, and calculates coupled repository and wellbore transient compressible fluid flow before, during, and after the drilling intrusion process. Mathematical models are included of multi-phase flow in the well, fluid expulsion at the surface, coupling of the well and the repository, repository spalling (tensile) failure associated with fluidized bed transport, and repository internal gas flow. The wellbore model is one-dimensional linear, and the repository model is one-dimensional, either spherical or cylindrical.

DRSPALL is based on the theory of one-dimensional, time-dependent compressible isothermal fluid flow. Somewhat different forms of that theory are used, depending on whether the flow is in the wellbore or the repository, and whether the wellbore currently penetrates the repository.

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The wellbore and repository flows are coupled at a specified boundary. Flow in the well is treated as a compressible, viscous, multi-phase mixture of mud, gas, salt, and possibly waste solids. Flow in the repository is treated as viscous, compressible single-phase gas flow in a porous solid. At the cavity forming the repository-wellbore boundary (following penetration), waste solids freed by drilling, tensile failure, and associated fluidization may enter the wellbore flow stream. Between the well and the repository, flow is treated according to the state of penetration.

The wellbore calculations use time-marching finite differences. These are part of a single computational loop. The numerical method is Eulerian in that zone boundaries are fixed, and fluid moves through the interfaces by convection. Quantities are zone-centered and integration is explicit in time.

The repository calculations also use time-marching finite differences that are part of a single computational loop. The method is implicit with spatial derivatives determined after the time increment.

2.0 REQUIREMENTS

2.1 Functional Requirements

The functional requirements for DRSPALL Version 1.24 are listed below.

R.1 Compressible, viscous, isothermal, multiphase mixture flow (mud, salt, waste, repository gas) in the wellbore using one-dimensional linear geometry and assuming a Newtonian fluid. Either laminar or turbulent flow shall be modeled depending on wellbore and fluid properties.

Wellbore flow output variables will be evaluated against results from a commercial computational flow model configured to run the same test problem.

R.2 Repository gas flow as single-phase Darcy porous flow using either one dimensional cylindrical or spherical geometry

Repository pressure distributions will be compared to independent solutions (numerical, analytic, or semi-analytic) of the governing equations obtained from published scientific literature.

R.3 Coupling of the wellbore and the repository flow models prior to and after penetration

This requirement will be tested by reporting intermediate variables (pore velocity, gas density, cavity area) describing the mass flow between the repository and wellbore as a function of time in order to confirm mass balance.

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R.4 Spalling (tensile) failure of the homogeneous waste material using an effective stress law with seepage forces

The time-histories of the output variables pressure distribution, effective stress and tensile-failed volume will be examined for conceptually consistent behavior.

R.5 Fluidized bed transport of failed (disaggregated) waste material.

This requirement will be evaluated by comparing the DRSPALL fluidization velocity to that obtained from independent test evaluation script calculations.

R.6 Mixture expulsion at the surface

This requirement will be evaluated by reporting the time-history of waste expelled and computing a solids mass balance to assure that waste removed from the repository is accounted for at the surface.

2.2 Performance Requirements

There are no performance requirements for DRSPALL.

2.3 Design Constraints

DRSPALL describes one-dimension spherical or cylindrical flow in the repository and one-dimension linear flow in the wellbore and is therefore limited to predictions for which these approximations are adequate.

2.4 Attribute Requirements

There are no attribute requirements for DRSPALL.

2.5 External Interface Requirements

The external interface requirements are listed below:

R.7 DRSPALL shall read an input control file, which may be pre-generated using a text processor. It will contain numerical control parameters and, optionally, material properties and problem geometry.

R.8 Properties and non-numerical control parameters will, optionally, be read from a CDB.

R.9 Grid, properties, parameters and spatial and time dependent results will be written to an output CDB.

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DRSPALL will link to the standard WIPP code libraries, namely, CAMDAT_LIB, CAMCON_LIB, and CAMSUPES_LIB (Rechard et al., 1993). User interactions will consist of command line execution, batch files, and input files.

2.6 Other Requirements

There are no other requirements for DRSPALL.

2.7 Functionality Not Tested

All code functionality is covered in the requirements and test cases.

3.0 TESTING ENVIRONMENT

DRSPALL, Version 1.24, was tested in the following environment:

Platform:	CentOS 7/Dell PowerEdge C6420
Host:	fwm.sandia.gov
Test Date:	September 17, 2020

All DRSPALL test cases are run using the WIPP run control system on Linux. The core of this system is the software configuration management system CVS (Concurrent Versions System) and the Python module *rc.py*. A small Python program *drspall_Test.py* calls the appropriate *rc.py* routines to check out all test inputs from CVS, runs all the test cases and associated processes (such as comparing files), and stores all test outputs in CVS. The test process is run from a small script *RunTest.sh* that checks out the Python code from CVS and executes the code to perform all tests. The log file for the testing is *drspall_124_Test.rtf*. All files related to validation testing are stored in CVS Repository /data/cvs/CVSLIB/WIPP_CODES/PA_CODES/DRSPALL under the following test directories.

- Python code *drspall_Test.py* and *rc.py* and script RunTest.sh are in directory Test/RunControl/Linux.
- Log file *drspall _124_Test.rtf* is located in directory Test/RunControl/Linux.
- All test input files are in directory Test/Input.
- All test output files are in directories Test/Output/Linux_124.
- All auxiliary test files (i.e., Python scripts) are in directory Test/Auxiliary/.

Appendix A (Section 9) contains the summary of files used from the log file. Python test evaluation scripts used in post-processing are stored in CVS directory Test/Auxiliary/Test_Evaluation. The test evaluation output is shown in Appendix B (Section 10).

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4.0 TEST METHODOLOGY

The test set for DRSPALL consists of 4 test cases. These test cases are described in Section 5.0. In most cases, the test procedure describes how, following the execution of the test script and running of the DRSPALL code, a small test-specific script extracts pertinent data from the DRSPALL output file and compares the DRSPALL data to known results (e.g., confirmed published data, analytical calculation), with plots, against a defined acceptance criteria. The test-specific scripts may be run with a commercial-off-the-shelf Python interpreter. Optionally, validation of DRSPALL is performed utilizing regression testing against a previously validated version of DRSPALL.

4.1 Methodology for Evaluation of Regression Test

Test cases may be validated by comparing the ASCII output file from the DRSPALL results being considered for validation to the ASCII output file from validated DRSPALL results with a Unix diff command. The diff output will be examined for differences.

Nuclear Waste Management Procedure NP 19-1 Softare Requirements (Long, 2020) lists the following acceptable differences:

- Differences due to code executable names
- Differences due to code version numbers
- Differences due to code build dates and times
- Differences due to run dates and times
- Differences due to different file names
- Differences due to different directory and class names
- Differences due to different user names
- Differences due to platform and system version
- Differences due to different execution statistics

If all differences are found to be acceptable, it follows that the output of the DRSPALL version being considered for validation meets the acceptance criteria specified in Section 5.0 on the hardware platforms under which the tests were executed.

5.0 FUNCTIONAL TESTING

The test set for DRSPALL consists of four test cases, numbered #1, #2, #4, and #5 (i.e., there is no Test Case #3). Each test case requires multiple DRSPALL executions. Each execution is referred to as a "case" or "subcase" or "run", and the test files are labeled with the case number (e.g., tc52 for Case 5.2).

The following test cases have been designed to ensure that the software adequately performs all intended functions and produces valid results. Table 5-1 displays the list of requirements defined in Section 2.0 and the test cases defined in this section that verify those requirements. The

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results of the performance verification and validation tests, comparison of test case input and output, and evaluation of test results versus the acceptance criteria is given below.

Table 5-1– Requirement Coverage by Test Case.

Requirement Type	Requirement #	Test Case Number			
		1	2	4	5
Functional	R.1		X		X
	R.2	X	X		
	R.3		X	X	
	R.4		X	X	
	R.5		X	X	
	R.6		X	X	
External Interface	R.7		X	X	
	R.8			X	
	R.9		X	X	

Each DRSPALL execution reads an input control file and an optional input CAMDAT file. Each subcase has its own input control file. In addition to the DRSPALL run parameters, each input control file contains the test subcase number (as "Validation Test Case"). DRSPALL responds to the test case number by creating special output files that contain information used for validation, by initializing conditions (e.g., boundary conditions) specific to the test case, and by limiting the processing to that necessary for validation. The DRSPALL design document (Kicker, 2021) describes any non-standard processing that is dependent on the test case. Only one test case, Case 4.2, reads a CAMDAT file.

Each execution of DRSPALL generates an output CAMDAT file and a diagnostics file. In addition, a particular test case may generate additional text files to be used for validation only. These validation files are described under the relevant test case section. CAMDAT files are binary and cannot be examined directly. GROPECDB Version 2.14 (Feng, 2021a) or SUMMARIZE Version 3.03 (Feng, 2021b) is used to write relevant portions of the CAMDAT files as text for examination. The output text files are read into test evaluation python scripts for post-processing and plotting, as described under the relevant test case section. The DRSPALL, GROPECDB/SUMMARIZE and python test evaluation script executions are run as part of the official test script described in Section 3.0.

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5.1 Test Case #1 – Porous Flow Verification

5.1.1 Test Objective

The purpose of this test case is to determine whether DRSPALL can accurately calculate transient gas pressures in the repository during the first few seconds after a borehole intrusion. The porous flow test problem is implemented by comparing the one-dimensional cylindrical and spherical pressure profiles generated by DRSPALL to those calculated using the fortran utility code[1] developed by Djordjevic and Adams (2003) for an identical problem.

Correctly performing this test case validates the satisfactory implementation of Functional Requirement R.2.

5.1.2 Problem Description

This test case involves solving the equations of transient, radial, isothermal, compressible gas flow through a porous medium. In this test case, no failure of the medium or transport of solids is allowed. Furthermore, the coupling of mass flow between the wellbore and repository is simplified to a zero pressure boundary condition. As such, the wellbore calculations in DRSPALL are ignored. The problem is solved in both cylindrical and spherical geometry.

5.1.2.1 Cylindrical Geometry Equations

The cylindrical domain comprises a porous solid with a given porosity φ and permeability k, shown in Figure 5-1. There is a cylindrical cavity of radius r_o aligned with the axis that represents a borehole that depressurizes the simulated repository. The domain begins filled with an ideal gas at an initial pressure of P_1 with viscosity η. At $t > 0$, the gas pressure p inside the borehole is set to zero, thus creating a pressure step that diffuses radially outward through the domain.

Starting with the governing equation for flow of gas through a porous material in a radially symmetric system gives:

$$\frac{\partial p}{\partial t} = \frac{k}{2\varphi\eta}\nabla^2 p^2, \quad p = p(r,t), \quad r \geq r_0, \quad t \geq 0 \tag{5.1.1}$$

where p is the gas pressure in the porous medium at radius r and time t. The boundary and initial conditions are expressed as:

$$p(r_0,t) = f(t), \quad \lim_{r\to\infty} p(r,t) = p_{ff}, \quad p(r,0) = p_{ff} \text{ for } r > r_0 \tag{5.1.2}$$

[1] The fortran utility code (*da_cylindrical.f90* and *da_spherical.f90*) developed by Djordjevic and Adams (2003) is archived in CVS in the directory: /data/cvs/CVSLIB/WIPP_CODES/PA_CODES/DRSPALL/Test/Auxiliary/CMS_Files/.

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where p_{ff} is the far-field pressure at large r. For this problem, the pressure at the inner boundary r_0 representing the wellbore wall is held constant at zero. As such, $f(t) = 0$ for $t > 0$.

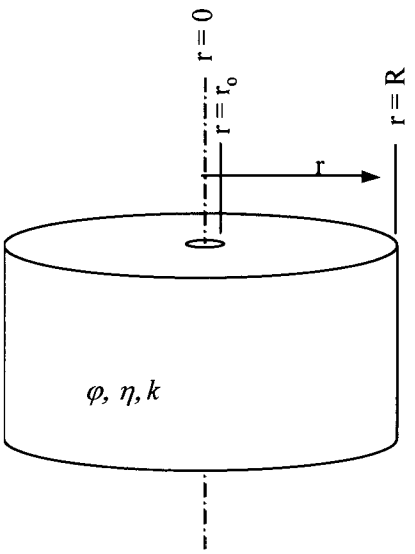

Figure 5-1 Schematic of cylindrical domain for porous flow test problem.

A pseudopressure approach is introduced after Chan et al. (1993) utilizing the following change of variables:

$$\psi(p) = \frac{p^2}{\eta} \tag{5.1.3}$$

which leads to

$$\frac{\partial \psi}{\partial t} = \frac{k}{\varphi\sqrt{\eta}}\sqrt{\psi}\nabla^2\psi, \quad \psi = \psi(r,t), \quad r \geq r_0, \quad t \geq 0 \tag{5.1.4}$$

and

$$\psi(r_0,t) = \frac{f^2}{\eta}, \quad \lim_{r\to\infty}\psi(r,t) = \frac{p_{ff}^2}{\eta}, \quad \psi(r,0) = \frac{p_{ff}^2}{\eta} \text{ for } r > r_0 \tag{5.1.5}$$

Nondimensional parameters may be defined as follows:

$$\psi = \frac{p_{ff}^2}{\eta}\Psi \quad t = t_0\tau, \quad t_0 = \frac{\varphi\eta r_0^2}{kp_{ff}} \tag{5.1.6}$$

and for cylindrical coordinates:

$$z = \ln(\frac{r}{r_0}) \tag{5.1.7}$$

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which upon substitution into Equation 5.1.4 yields the transformed equation:

$$\frac{\partial \Psi}{\partial \tau} = e^{-2z}\Psi^{1/2}\frac{\partial^2 \Psi}{\partial z^2} \tag{5.1.8}$$

Equation 5.1.8 is integrated numerically with the boundary and initial conditions

$$\Psi(0,\tau) = \frac{f^2}{p_{ff}^2}, \quad \lim_{z\to\infty}\Psi \to 1, \quad \Psi(z,0) = 1 \text{ for } z > 1 \tag{5.1.9}$$

5.1.2.2 Spherical Geometry Equations

For the spherical problem, the cavity is hemispherical in shape with radius ro as shown in Figure 5-2.

Equations 5.1.4 to 5.1.6 apply to the spherical geometry, but in order to proceed, z must be re-defined as:

$$z = \frac{r_o}{r} \tag{5.1.10}$$

The resulting transformed governing equation is then

$$\frac{\partial \Psi}{\partial \tau} = z^4\Psi^{1/2}\frac{\partial^2 \Psi}{\partial z^2} \tag{5.1.11}$$

Equation 5.1.11 is integrated numerically with the boundary conditions

$$\Psi(1,\tau) = \frac{f^2}{p_{ff}^2}, \quad \Psi(0,\tau) = 1, \quad \Psi(z,0) = 1 \text{ for } z > 1 \tag{5.1.12}$$

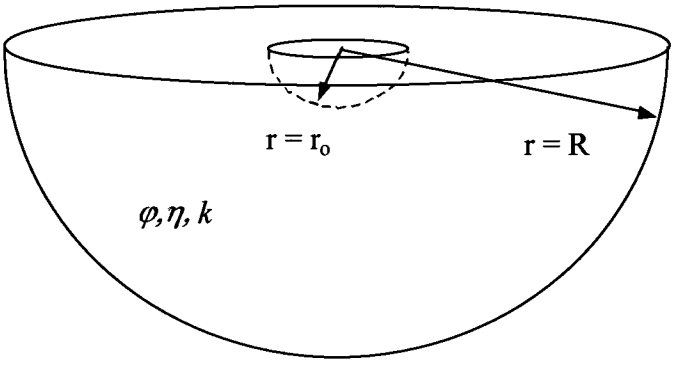

Figure 5-2 Schematic of spherical domain in porous flow test problem.

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5.1.2.3 Boundary Conditions

The Djordjevic and Adams (2003) solution, modeled after Chan et al. (1993), requires that (1) the gas pressure at $r = r_o$, the face of the borehole, is set to zero at all times, and (2) pressure in the far field, where $r >> r_o$, remains at the initial pressure, P_1. During normal execution of DRSPALL, the pressure at the inner boundary r_0 is calculated by coupling mass flows from the repository and wellbore. However, for purposes of this test case, the cavity pressure variable is assigned a value of zero during each computational loop. This will cause the cavity mass to artificially increase, but will not cause inaccuracy in the validation procedure, since the cavity mass is irrelevant in this test case.

At the outer boundary ($r = R$), DRSPALL uses a no-flow condition. Djordjevic and Adams (2003) and Chan et al. (1993), however, use a constant pressure in the far-field, p_{ff}. This difference will not be recognized by the models for the short execution times used in this test case because the pressure impulse travels at a finite speed away from the borehole, and will not reach the outer boundary in the time specified for this test. This can be confirmed by computing the approximate depth of penetration of a "dividing surface" defined as the point inside which $P(r) < P_1$, and outside which $P(r) = P_1$.

Chan et al. (1993) gives an approximate location of the dividing surface, $R(t)$, for small values of t in the cylindrical domain as follows:

$$\frac{R(t)}{a} = 1 + \sqrt{\frac{t}{t_o}} \tag{5.1.13}$$

The default outer radius in DRSPALL is 19.2 m. Recognizing that $t/t_o = \tau$, the expression above evaluates to $R = 0.649$ m when $\tau = 10$ and $a = 0.156$ m. $\tau = 10$ represents the longest scaled time evaluated in this test problem. The dividing surface is therefore clearly interior to the outer boundary for this and shorter times.

Chan gives another expression for the approximate location of the dividing surface at large t:

$$\frac{R(t)}{a} \cong \frac{(t/t_o)^{0.5}}{[\log(t/t_o)]^{0.5}} \tag{5.1.14}$$

If the DRSPALL outer boundary of 19.2 m is substituted into Equation 5.1.14 for R, and t_0 is evaluated with the input values given in Table 5-2, the resulting time t that satisfies the expression is $t \approx 2600$ seconds. Thus, for the short times ($t < 4$ sec) examined in this test case, the pressure impulse will not reach the boundary of the domain and the specific boundary conditions are irrelevant.

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Table 5-2– Input parameters for Test Case #1.

Symbol	Definition	Units	Value
P_1	Initial gas pressure	Pa	0.145E+08
φ	Porosity	–	0.575
η	Gas viscosity	Pa-s	0.8934E-05
k	Permeability	m^2	2.400E-13
T_s	Tensile strength	Pa	0.690E+06

5.1.2.4 Input Parameters

Relevant input parameters for this test case are given in Table 5-2. To avoid tensile failure of the repository material, tensile strength (T_s) is set to a high value of 0.690E+06 Pa (100 psi). The Forchheimer Beta input parameter was set to zero for Test Case #1, resulting in a constant permeability by removing the velocity-dependence. The DRSPALL input files *drs_v122_tc11.drs* and *drs_v122_tc12.drs* are stored in CVS directory Test/Input.

5.1.2.5 Repository Zoning

The zoning scheme in the repository domain in DRSPALL is set to a constant zone size of 0.002 m.

5.1.3 Analysis Methods

Chan et al. (1993) present numerical results as the dimensionless pseudopressure, Ψ, versus the dimensionless plotting parameter, ζ, for selected values of scaled time, τ. The dimensionless plotting parameter, comparable to a dimensionless radius, is defined as:

$$\zeta = \frac{\left(e^{z} - 1\right)}{\tau^{1/2}} \tag{5.1.15}$$

This analysis entails comparing DRSPALL and Djordjevic and Adams (2003) pseudopressure profiles at designated scaled times. DRSPALL output in the form $P(r, t)$ are thus converted to $\Psi(\zeta, \tau)$ at the four scaled times 0.01, 0.1, 1.0, 10. Output from DRSPALL and Djordjevic and Adams (2003) are displayed both graphically and in tabular form.

To provide a quantitative means for comparing DRSPALL and the independent solutions, the difference in $\Psi(\zeta)$ is computed for corresponding scaled times as follows:

$$DIFF(\zeta) = \left|\Psi(\zeta)_{DR\_SPALL} - \Psi(\zeta)_{Chan}\right| \tag{5.1.16}$$

For each array of *DIFF* values, a maximum value is calculated.

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5.1.3.1 Cylindrical Case Output from Djordjevic and Adams (2003)

The cylindrical case solutions were obtained using the independent utility code developed by Djordjevic and Adams (2003). Dimensionless pseudopressure profiles were produced at four dimensionless times, $\tau = 0.01, 0.1, 1.0, 10$. The solutions are illustrated graphically in Figure 5-3. Tabular results are given in Appendix C (Section 11).

Since the numerical grid used in DRSPALL may be different from that used in the comparison solutions shown in Figure 5-3, a curve was fit to the comparison data to facilitate computation of the difference defined in Equation 5.1.16. The general form of the function fit to the comparison data was:

$$\Psi(\zeta) = 1 - \exp\{-(C_1\zeta + C_2\zeta^2 + C_3\zeta^3)\} \quad \text{for } 0 \le \zeta \le 1 \tag{5.1.17}$$

where C_1, C_2, and C_3 are constants determined by minimizing the sum of squares:

$$SUM = \sum_i \left[\Psi_a(\zeta_i) - \Psi(\zeta_i)\right]^2 \tag{5.1.18}$$

where Ψ_a denotes the solution calculated by Djordjevic and Adams (2003), Ψ is the fitted function in Eq. 5.1. 17, and the sum is taken over all the reported grid indices i. The constants calculated for the four dimensionless times in the cylindrical geometry are given in Table 5-3. Details of the fitting procedure are provided in Appendix D (Section 12).

5.1.3.2 Spherical Case Output from Djordjevic and Adams (2003)

The spherical case solutions were obtained using an independent utility code developed by Djordjevic and Adams (2003). Dimensionless pseudopressure profiles were produced at the same four dimensionless times ($\tau = 0.01, 0.1, 1.0, 10$) as for the cylindrical case. The solutions are illustrated graphically in Figure 5-4. Tabular results are given in Appendix C (Section 11). Functions in the form of Equation 5.1.17 were fit to the data using a least squares method with associated constants reported in Table 5-4, and details of the fitting procedure shown in Appendix D (Section 12).

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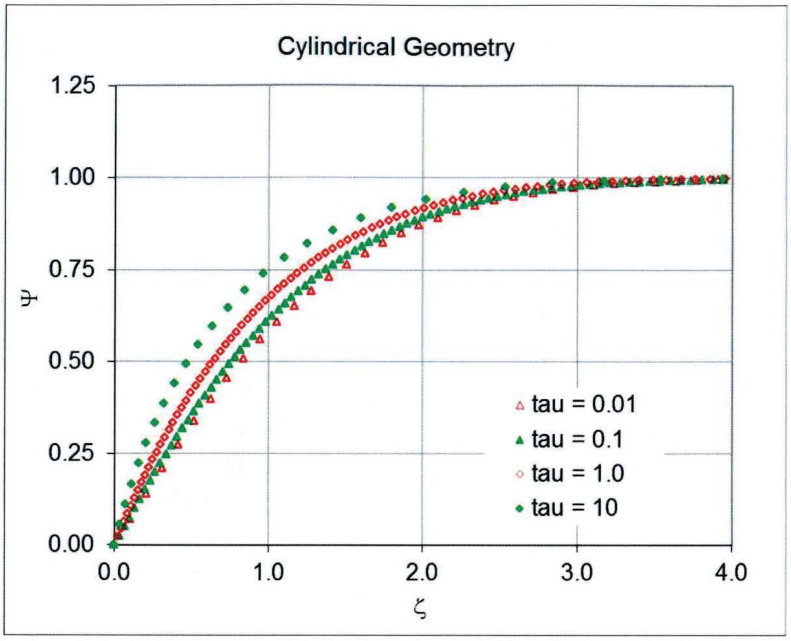

Figure 5-3 Numerical solutions to the dimensionless pseudopressure profiles for cylindrical geometry.

Table 5-3– Constants for functional fit to Djordjevic and Adams (2003) solution in cylindrical geometry.

τ	C_1	C_2	C_3
0.01	0.715	0.167	0.000
0.1	0.803	0.157	0.000
1	1.032	0.101	0.000
10	1.505	-0.071	0.000

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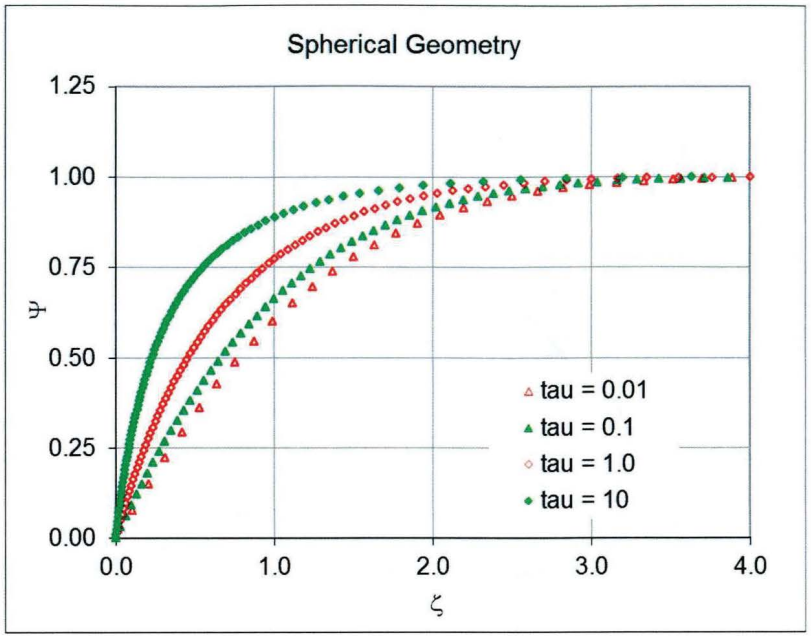

Figure 5-4 Numerical solutions to the dimensionless pseudopressure profiles for spherical geometry.

Table 5-4– Constants for functional fit to Djordjevic and Adams (2003) solution in spherical geometry.

τ	C_1	C_2	C_3
0.01	1.331	-0.073	0.000
0.1	1.000	0.126	0.000
1	1.537	-0.033	0.000
10	3.500	-2.229	0.858

5.1.4 Test Procedure

The DRSPALL validation Test Case #1 was ran as described in Section 3.0. DRSPALL is executed twice: once in cylindrical geometry and once in spherical geometry. Case 1.1 (tc11) refers to cylindrical geometry; Case 1.2 (tc12) refers to spherical geometry.

DRSPALL generates a "Chan" validation file (e.g., *drs_124_tc11_chan.dat*) for each case. The validation files are read in by the *drs_test_tc1.py* script for post-processing and plotting. The output CAMDAT files are not examined.

The following command lines run this test case:

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```
./drspall ./Input/drs_v122_tc11.drs DRSPALL/Test/Output/Linux_124/drs_124_tc11.dbg
        CANCEL DRSPALL/Test/Output/Linux_124/drs_124_tc11.cdb
        > DRSPALL/Test/Output/Linux_124/drs_124_tc11.crt
./drspall ./Input/drs_v122_tc12.drs DRSPALL/Test/Output/Linux_124/drs_124_tc12.dbg
        CANCEL DRSPALL/Test/Output/Linux_124/drs_124_tc12.cdb
        > DRSPALL/Test/Output/Linux_124/drs_124_tc12.crt
```

5.1.5 Input/Output Files

The DRSPALL input and output files for Test Case #1 are listed in Appendix A (Section 9).

5.1.6 Acceptance Criteria

Test Case #1 will pass if the following statements are true for both the cylindrical case and the spherical case:

- **Acceptance Criterion 1-1** — Pressure profiles generated by DRSPALL closely approximate the solutions by Djordjevic and Adams (2003) for corresponding dimensionless times. A linear interpolation of the Djordjevic and Adams solution to the DRSPALL ζ (dimensionless radius) values produces a maximum absolute difference in Ψ (dimensionless pressure) values that does not exceed 0.1.

- **Acceptance Criterion 1-2** — Maximum difference for Ψ (dimensionless) between DRSPALL and Djordjevic and Adams (2003) functional fit for corresponding times does not exceed 0.1.

This will verify Functional Requirement R.2.

5.1.7 Test Results

The dimensionless pseudopressure (Ψ) is plotted versus the dimensionless plotting parameter (ζ) at four selected values of dimensionless time (τ). The comparison curves on each plot were generated from the parameters in Table 5-3 for the cylindrical geometry and Table 5-4 for the spherical geometry. Conceptually, the curves represent the evolution of the pore pressure profile. The initial condition is set to $\Psi = 1$ throughout the domain. For $\tau > 0$, Ψ at the inner boundary of the domain, $\zeta = 0$, is set to zero representing zero pressure in the wellbore. The outer boundary Ψ is held at unity representing a constant far-field pressure. The tendency of the curves at different τ to nearly overlay one another is related, in part, to the presence of the $t^{-0.5}$ in the plotting parameter function (Equation 5.1.15).

Figure 5-5 shows the results of Case 1.1 in the cylindrical geometry, and Figure 5-6 shows the results of Case 1.2 in the spherical geometry. Visual inspection indicates that in both cases the DRSPALL results overlay the Djordjevic and Adams (2003) solutions quite closely. In the cylindrical case the maximum difference values between the DRSPALL results and the

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Djordjevic and Adams results range from 0.007 to 0.045. In the Spherical case the difference values range from 0.006 to 0.016, so **Acceptance Criterion 1-1** (Section 5.1.6) is met.

The simple statistical analysis that reports the maximum value of DIFF also indicates close overlay, with values below 0.05 for all τ examined. The DIFF values for all times examined for both cylindrical and spherical geometry are summarized in Table 5-5. DIFF values for the cylindrical case ranged from 0.007 to 0.045, representing a favorable match between DRSPALL and the comparison solution. For the spherical case, the maximum differences fall at 0.016 or below, indicating close agreement between solutions. All maximum differences are less than 0.1, so **Acceptance Criterion 1-2** (Section 5.1.6) is met.

5.1.8 Conclusions

The discussion in Section 5.1.7 verifies that all acceptance criteria (Section 5.1.6) for this test case are met for both the cylindrical and spherical geometry. Thus, this test case passes and satisfies Functional Requirement R.2.

The successful completion of this test case demonstrates that the DRSPALL solutions to transient, compressible, ideal gas flow compare favorably to those generated by an independent utility code developed by Djordjevic and Adams (2003). Both codes utilize an implicit solution algorithm to solve an initial boundary value problem that represents the evolution of pore pressure and resulting blowdown in a simplified gas repository following intrusion by an underbalanced (low-pressure) borehole.

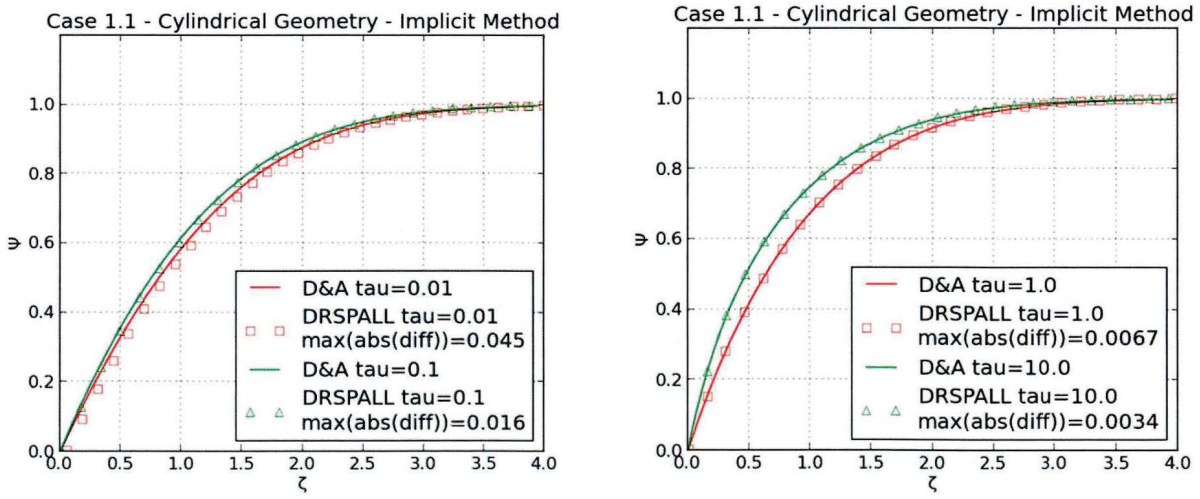

Figure 5-5 Overlay of DRSPALL with Djordjevic and Adams solutions for the cylindrical geometry with τ = 0.01, 0.1, 1, 10.

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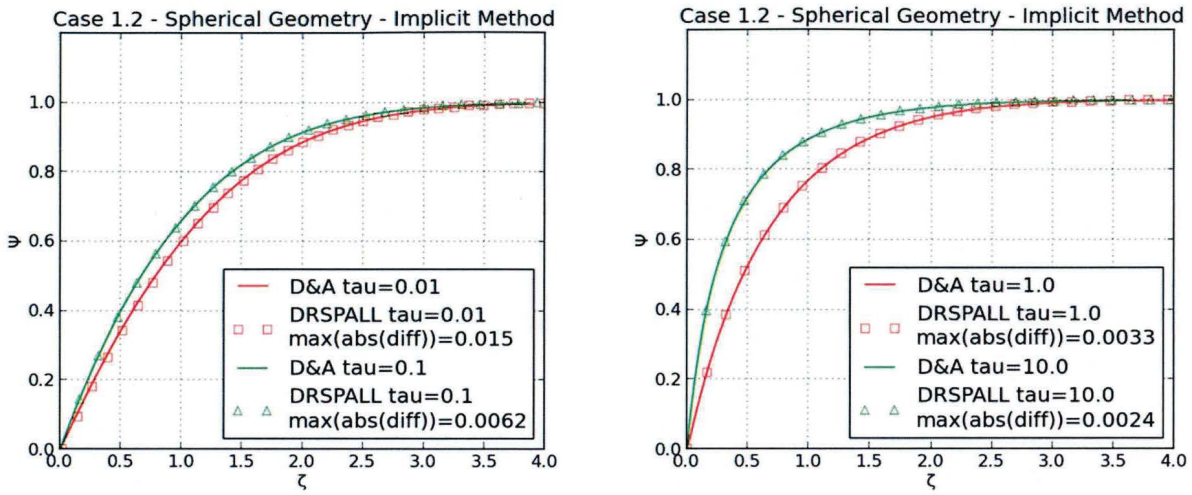

Figure 5-6 Overlay of DRSPALL with Djordjevic and Adams solutions for the spherical geometry with $\tau = 0.01, 0.1, 1, 10$.

Table 5-5– Maximum difference values for implicit solution in cylindrical and spherical geometry (*drs_test_evaluation.out*).

τ	Case 1.1 Cylindrical MAX DIFF	Case 1.2 Spherical MAX DIFF
0.01	0.045	0.016
0.1	0.016	0.006
1	0.007	0.007
10	0.014	0.013

5.2 Test Case #2 – Coalbed Methane Validation

5.2.1 Test Objective

The purpose of this test case is to demonstrate that DRSPALL can simulate the results of a field-scale coalbed cavitation completion experiment. Since this process of completing a coalbed methane well involves injecting high-pressure air and allowing a controlled blowout to occur which induces tensile failure of the coal and transports coal particles to the surface, it would appear to be an acceptable analog of the repository drilling intrusion spall phenomenon. The coalbed data chosen for comparison are reported by Khodaverdian et al. (1996).

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Test Case #2 demonstrates the applicability of DRSPALL to simulating a drilling intrusion into the WIPP repository by modeling a field scale experiment that has similar characteristics. Test Case #2 exercises all requirements except R.8 (input from CAMDAT file): with the following limitation:

- Functionality for requirement R.1 is only partially exercised since Test Case #2 does not simulate mud in the wellbore flow component. Wellbore flow is verified in Test Case #5.

5.2.2 Problem Description

5.2.2.1 Coalbed Cavitation

Coal is a naturally fractured organic material. The fractures, usually orthogonal and closely-spaced, are called "cleats." In-situ, the cleats are normally saturated with water and methane. Cleat porosity is usually a few percent. Coal, however, is different than most other geologic materials in that its matrix can hold abundant methane in an adsorbed state. When a coal reservoir is de-watered, this adsorbed methane can flow to the cleats and then to a well. As a result, the amount of methane producible from some coal reservoirs is as if porosity was several tens of percent, rather than just a few percent. Because of this, these coal reservoirs are often drilled and produced as a methane source.

Wells in parts of certain coal reservoirs are most successfully completed using the "cavitation" process. To do this, the well is first drilled and cased to the top of the coal seam. Drilling then continues through the coal seam, which is left as an open hole. The completion process then takes several days to more than a week. The well is cyclically opened to atmosphere and allowed to blow down, and then shut in and allowed to build up. When this is done (rarely) without any surface pumping, it is called "natural" cavitation. More often, air is introduced by high-pressure pumping at the surface to downhole pressures somewhere between reservoir pressure and lithostatic. This is "induced" cavitation. Anywhere from a few to many tens of cycles may be used, with possible bit runs between cycles to clean out the hole. When a cavitated well is blowing, a strongly flowing mixture of air, coal fines, methane, and some water comes to the surface. This is, in effect, an induced but controlled blowout. If successful, the cavitation process produces a cavity of a few meters in diameter in the coal and leads to greatly enhanced water and ultimately, methane production.

5.2.2.2 An Acceptable Analog

Coalbed cavity completions would appear to be analogs to the WIPP drilling intrusion. This is because cavitated coal seams may be:

- in the same depth regime
- in the same thickness regime
- in the same mechanical property regime
- gas-pressurized during cavitation to the same pressure regime
- blown down in the same time regime as possible drilling intrusion occurrences.

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Possible shortcomings of coalbed cavitation as an analog are that peak coal cavitation pressures are somewhat lower than peak possible WIPP pressures and the strength of coal may be outside the WIPP tensile strength range, with particulate properties that may be different than degraded WIPP waste.

5.2.3 Analysis Method

5.2.3.1 Selected Field Test for Comparison

The cavitation experiments on the GRI COAL Site Well I#2 (Khodaverdian et al. 1996) have been selected for numerical simulation using DRSPALL. This selection was made based on the availability and quality of data. The well is in the Fruitland coals located in the San Juan Basin of New Mexico, and shown in Figure 5-7. The well was cavitated in July of 1991.

The key parameters, as reported by Khodaverdian et al. (1996), of the selected coal well are given in Table 5-6. After all cavitation procedures were finished, the final cavity diameter was determined by sonar logging, and is shown in Figure 5-8.

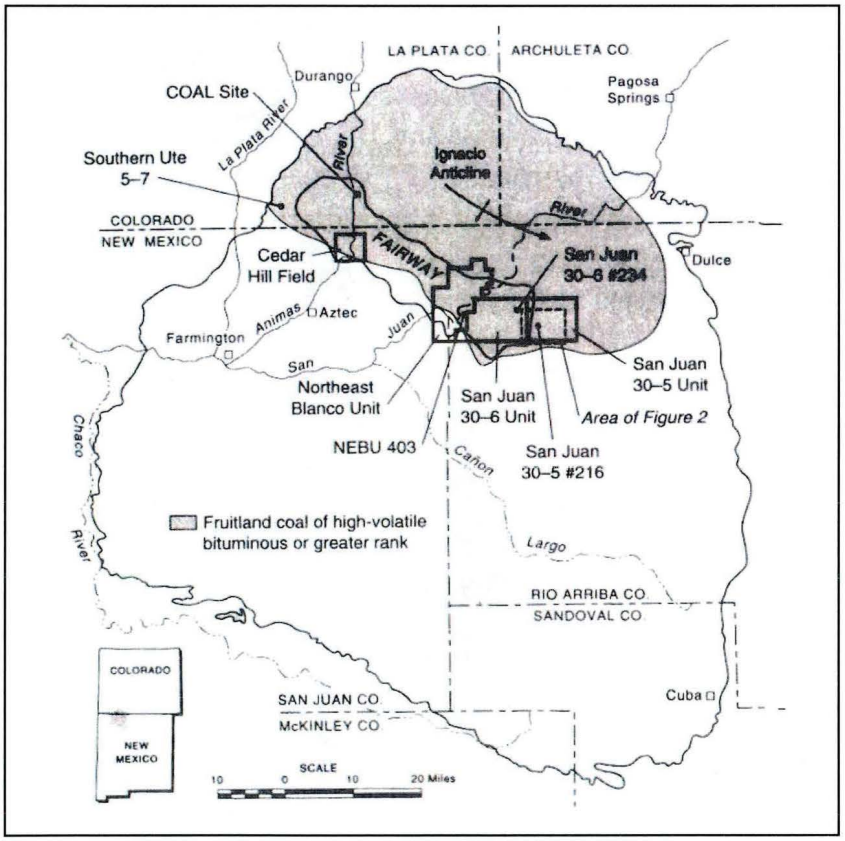

Figure 5-7 Location of cavitated coalbed well (Khodaverdian et al. 1996).

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Table 5-6– Key coal well parameters.

Parameter	Value (US)	Value (SI)
Depth	3150 ft	960 m
Thickness	45 ft	13.7 m
Bit Radius	0.5 ft	0.15 m
Post-Drilling (washout) Radius	1.0 ft	0.3 m
Horizontal Stress	2220 psi	15.3 MPa
Pore Pressure	1020 psi	7.0 MPa
Permeability	25 md	2.5×10^{-14} m^2

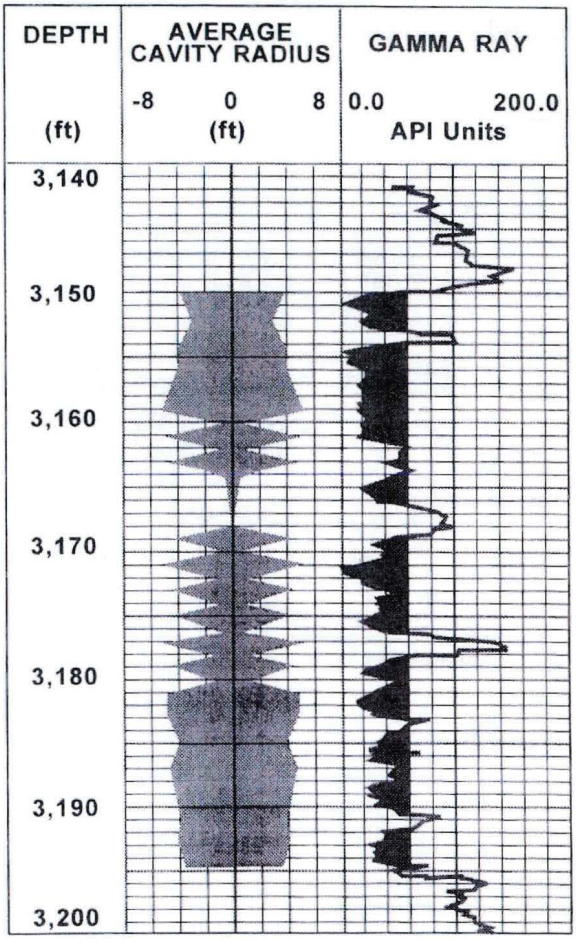

Figure 5-8 Cavity radius (Khodaverdian et al. 1996).

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5.2.3.2 Approach

The authors (Khodaverdian et al. 1996) used observed surface injection pressures to estimate bottomhole pressures over time for the various cavitation cycles, as shown for the first day of cavitation activities, in Figure 5-9.

The first day saw 6 cavitation cycles. Khodaverdian et al. felt most cavity growth was completed in that time, and have assumed so for their analysis. As can be seen from Figure 5-9, they assumed an instantaneous drawdown to 80 psi downhole upon the start of each cavitation blowdown. In actuality, the drawdown rate would depend on pipe flow to surface and take some time (a minute or so) to develop. DRSPALL simulates the drawdown time and rates, since it includes viscous pipe flow. The relevant values in the figure are thus the peak injection pressures and the cavitation time intervals. These pressures and times are simulated in DRSPALL. The duration of the last blowdown interval is not reported, but is assumed by us to be the same as #5.

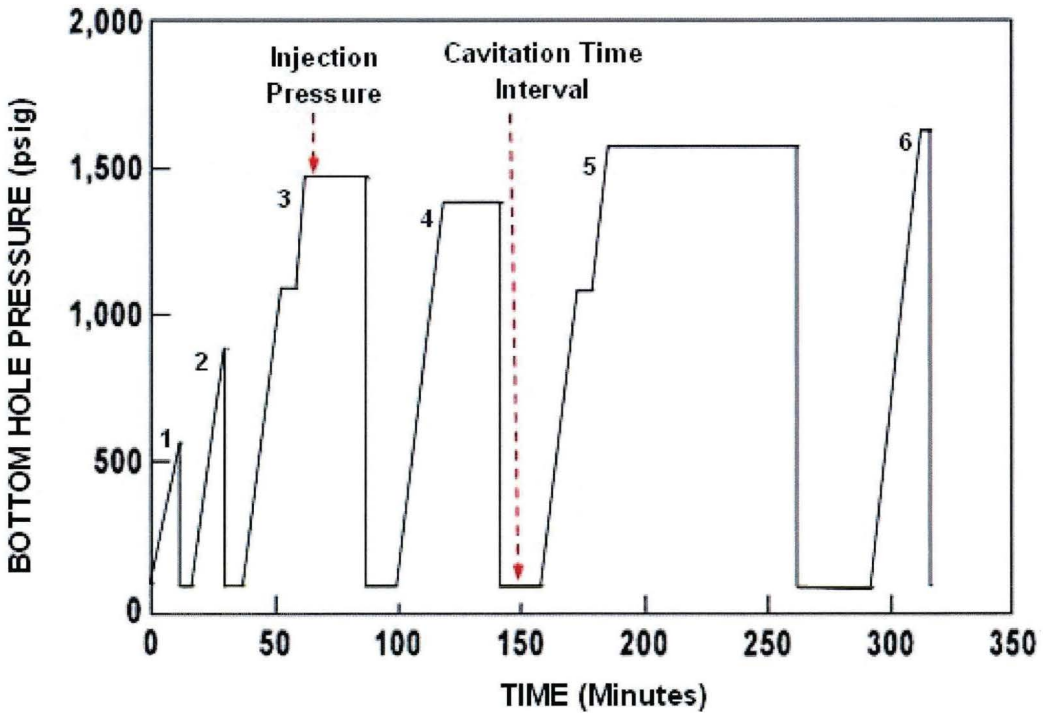

Figure 5-9 Figure 9. Cavitation times and inferred bottomhole pressures (Khodaverdian et al. 1996). Red arrows added for this report.

Khodaverdian et al. used a numerical model (without accounting for wellbore flow) to reproduce their interpretation of the final cavity diameter (after 6 cycles) from Figure 5-8. Their model used the tensile failure radius as the cavity radius. Their calculations for earlier cycles thus were used to infer the cavity diameters vs. time. They used a number of permeability values (2.5, 25

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and 250 md) in an attempt to match the measured results, and found that a 25 md permeability gave the best match. This was accepted for their primary interpretation, supported also by rough laboratory measurements and other observations. Considerable uncertainty is added by having to interpret an average cavity size from the irregular data shown in Figure 5-8. Their final matching interpretations are shown in Figure 5-10. The input pressures and times, and results to compare with DRSPALL, as we obtain from the author's figures, are shown in Table 5-7.

5.2.3.3 Input Parameters

DRSPALL is set up for these runs to only model the wellbore from the cavity to the surface, with flow allowed in the annulus. Also, only gas (air) and coal particles are allowed to flow. The code is run in cylindrical symmetry to best match the observed cavity geometry. For each of the six runs required, an initial formation (repository) gas pressure is set to match the value in Table 5-7 and an initial cavity size is set to match the previous run results. The first cavity size is 0.31 m. Each run continues for the reported time. Recall that the duration of the last cavitation cycle is unknown, which adds additional uncertainty to the results for the last cavitation cycle.

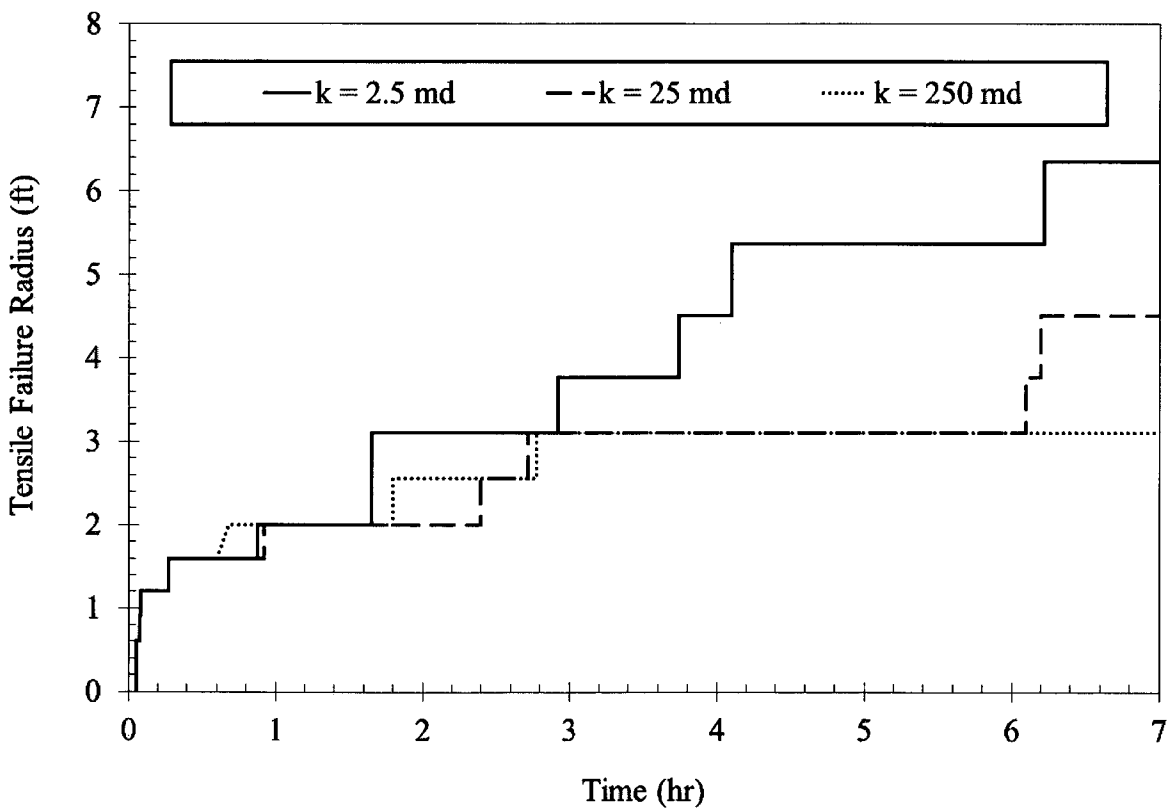

Figure 5-10 Interpreted cavity radii (based on tensile failure radii) from Khodaverdian et al. (1996).

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Table 5-7– Input values and experimental results to be used and compared with DRSPALL results.

Cycle	Pressure, MPa	Duration, s	Cavity Radius, m Best Estimate	Cavity Radius, m Range
1	3.8	300	0.31	.31 – .31
2	6.2	360	0.49	.49 – .61
3	10.1	660	0.61	.61 – .91
4	9.6	900	0.73	.61 – .91
5	11.0	1680	0.91	.91 – 1.65
6	11.4	1680	1.37	.91 – 1.8

DRSPALL results will depend on the tensile strength and permeability assumed in DRSPALL. It is unclear as to the exact tensile strength Khodaverdian et al. assumed. They discuss cohesion in detail as it pertains to shear failure, but not tensile strength explicitly. The DRSPALL input files *drs_v122_tc21.drs* through *drs_v122_tc26.drs* are stored in CVS directory Test/Input. All runs are the same, except for initial pressure, initial cavity size, and run time. The following parameters that were assumed for the DRSPALL 1.22 validation have remained unchanged in the DRSPALL 1.24 validation: tensile strength is 0.25 MPa, permeability is 3.0 md (3.0E-15 m^2), and the minimum characteristic velocity is 0.5 m/s.

5.2.4 Test Procedure

DRSPALL is executed six times, once for each run. Each of the six DRSPALL runs is a subcase (Cases 2.1 through 2.6, labeled as tc21 through tc26).

For this validation, the cavity radius is extracted from the output CAMDAT files with a single SUMMARIZE (Feng, 2021b) execution; for the DRSPALL 1.00 validation the same data was manually extracted from each diagnostics file. The SUMMARIZE input file is shown in Figure 5-11. The SUMMARIZE output is read in by *drs_test_tc2.py* for plotting and evaluation.

The following command lines show the DRSPALL execution for Case 2.1 (Cases 2.2 through 2.6 are similar), and the single SUMMARIZE execution:

```
./drspall ./Input/drs_v122_tc21.drs DRSPALL/Test/Output/Linux_124/drs_124_tc21.dbg
        CANCEL DRSPALL/Test/Output/ Linux_124/drs_124_tc21.cdb
        > DRSPALL/Test/Output/ Linux_124/drs_124_tc21.crt
... similarly for tc22, tc23, tc24, tc25, tc26
./summarize ./Input/drs_tc2_summarize.inp
        DRSPALL/Test/Output/Linux_124/drs_124_tc2^.cdb
        DRSPALL/Test/Output/Linux_124/drs_124_tc2_summarize.tbl
        drs_124_tc2_summarize.log NO  > x.x
```

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```
! For DRSPALL Test Case 2, all 6 subcases
! Derived from GROPECDB file of HVAR CAVRAD at TIME 10000
!
! Note that final cdb times range from 300 to 1680.  Requesting a large time
! will read the item from the last time step.  The time on the output file
! will always be 9999 and should be ignored.
*times
   read=   years
   input=  years
   output= years
   time=   9999

*vectors
   vector= 1 to 6
   id=     ^
*items
   type=   history
   name=   CAVRAD

*output
   driver= text
   write=  vector vs item

*end
```

Figure 5-11 SUMMARIZE input control file *drs_tc2_summarize.inp*.

5.2.5 Input/Output Files

The DRSPALL input and output files for Test Case #2 are listed in Appendix A (Section 9).

5.2.6 Acceptance Criteria

This test case is used as validation to show that DRSPALL can adequately simulate a drilling intrusion into the WIPP repository. This test case will pass if the following is observed:

- **Acceptance Criterion 2-1** — The validation will be acceptable if DRSPALL reasonably predicts cavity growth over six cavitation cycles. A majority of the DRSPALL predictions (≥ 50% of timesteps) will be between the minimum and maximum values of the field results, and all DRSPALL values will be within 0.2 m of the reported best value.

This test case supports the verification of Functional Requirements R.1 through R.6 and External Interface Requirements R.7 and R.9.

5.2.7 Test Results

Table 5-8 and Figure 5-12 show the results of the DRSPALL runs and the comparison with field results. The DRSPALL results are for tensile failed and fluidized radii.

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Table 5-8– Field inferred and DRSPALL results comparison (*drs_test_evaluation.out*).

Cycle	Field Inferred Cavity Radius, m	DRSPALL V1.24 CAVRAD
1	0.31	0.30000
2	0.49	0.30000
3	0.61	0.64104
4	0.73	0.88227
5	0.91	1.10815
6	1.37	1.30824

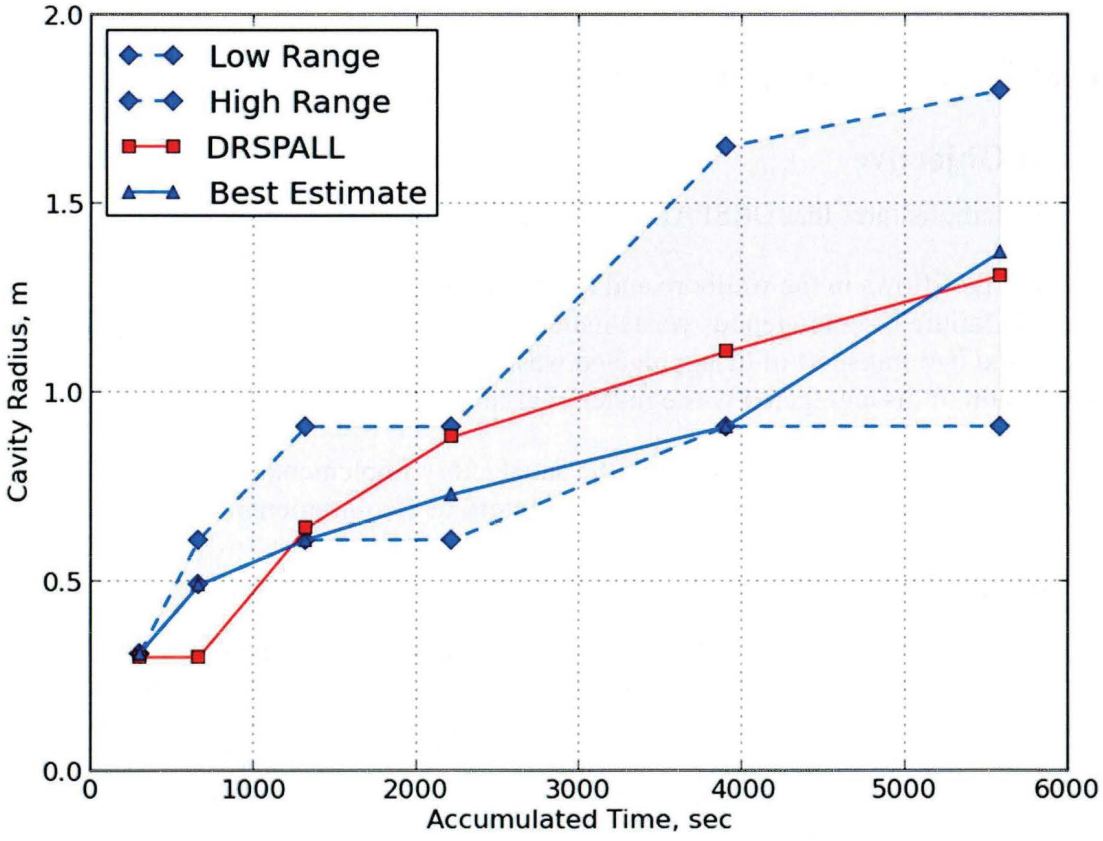

Figure 5-12 Reported field results and DRSPALL results compared.

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5.2.8 Conclusions

The shape and scale of the cavity radius as a function of cavitation time show reasonable agreement as demonstrated in Figure 5-12. The DRSPALL results are within the range of the field measurements for 4 out of the 6 cavitation times and have a maximum difference of 0.19 m from the best estimate when outside of the measurement range and, therefore, meets the acceptance criteria established in Section 5.2.6 for this test case. Thus, this test case passes and successfully exercises Functional Requirements R.1 (partial), R.3 through R.6, and External Interface Requirements R.7 and R.9.

As discussed in Section 5.2.2.2, the coalbed methane cavitation process is an acceptable analog to the WIPP drilling intrusion-created spall process. The analog is good because of the similarities between the DRSPALL conceptual model and the coalbed cavitation process, both in behavior and scale.

5.3 Test Case #3 (Obsolete)

No Test Case #3 is defined.

5.4 Test Case #4 – Internal Logic Checks

5.4.1 Test Objective

This test case demonstrates that DRSPALL accurately calculates:

1. Coupling of flows in the wellbore and the repository
2. Tensile failure of homogenous waste material using effective stress and seepage laws
3. Fluidized bed transport of disaggregated waste material
4. Expulsion of disaggregated waste material at the land surface.

Correctly performing this test case validates the satisfactory implementation of Functional Requirements R.3, R.4, R.5, and R.6 and External Interface Requirements R.7, R.8, and R.9.

5.4.2 Problem Description

The evolution of the WIPP underground over the 10,000-year regulatory period could result in a gas-filled repository at near-lithostatic pressure. DRSPALL is designed to estimate the mass of WIPP waste subject to tensile failure (spalling) and transport to the surface, if a drilling intrusion penetrates such a high-pressure repository. The problem domain here is a WIPP repository at a high, initial repository pressure in which a drilling intrusion results in a significant well blowout at the land surface. The repository domain is cast in hemispherical geometry.

This test case differs from the other DRSPALL test cases in that DRSPALL outputs are not compared against an independent model or experimental data. Rather, the selected intermediate and standard output variables are reported in tabular and graphical format to facilitate tests of (1)

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the program logic, and (2) verification or proper implementation of the mathematics outlined in the DRSPALL design document (Kicker, 2021).

5.4.2.1 Boundary Conditions

The boundary conditions are set by the default conditions in DRSPALL. This includes a constant mud pump rate into the drill pipe at the inlet to the wellbore, a constant pressure (1 atm) boundary condition at the outlet from the wellbore, and a no-flow gas boundary at the outer edge of the repository domain.

5.4.2.2 Input Parameters

The DRSPALL input file *drs_v122_tc41.drs* is stored in CVS directory Test/Input. In order to assure a spalling event, the repository initial pressure will be near lithostatic pressure at 14.8 MPa, and the tensile strength will be set to a low value in its range, 1.2E+05 Pa (17.4 psi).

5.4.3 Analysis Methods

5.4.3.1 Coupling of the Wellbore and the Repository Flow Models

The coupling of the wellbore and repository flow models in DRSPALL is handled differently before and after bit penetration into the repository. Before penetration, a cylinder of altered-permeability salt material (called the drilling-damaged zone, or DDZ) with diameter equal to the drillbit moves ahead of the drillbit and is assumed to carry limited porous gas flow from the repository to the wellbore. Gas flow is driven by the difference between the gas pressure at the face of the waste and the gas pressure in the bottom of the approaching wellbore. Once the repository is penetrated, these two pressures equalize and gas flow from the repository is added directly to the wellbore. In order to avoid forcing gas to flow to a point in the 1-D, radially symmetric repository domain prior to bit penetration, a preliminary cavity, referred to throughout the DRSPALL documentation as the "pseudocavity," is formed where the repository meets the DDZ. The volume of this cavity is small, with a surface area equal to that of a circle with a diameter equal to the bit diameter. The purpose of this pseudocavity is to avoid forcing gas flow to converge to a single point (spherical geometry) or line (cylindrical geometry) at the origin of the radial coordinate system.

Coupling of the wellbore and repository flow models will be tested by reporting intermediate variables near the time of bit penetration. The variables include:

- Run time (sec)
- Bit above repository (m) – Distance between bit and top of repository
- Repository penetrated (true/false)

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- Cavity pressure (Pa) – Gas pressure in the preliminary cavity created at the point where the repository domain meets the DDZ
- Wellbore bottomhole pressure (Pa)
- Total gas in well (kg) – Spatial integral of gas mass over entire wellbore domain
- Total gas injected (kg) – Time integral of gas mass injected at bottom of well
- Gas mass in repository (kg) – Spatial integral over entire pore space in repository
- Gas mass from repository (kg) – Difference between starting gas mass in repository and current gas mass in repository
- Gas in storage[2] (kg) – Gas removed from repository by removal of repository zones is added to "storage" before it is released to the cavity
- Mass balance error (-) – Error in the mass of gas in the entire repository and wellbore system relative to time 0.

While distance of the bit above the repository is greater than zero, the logical variable, repository penetrated, should be false. In addition, the cavity pressure at the face of the repository and wellbore bottomhole pressure should converge as gas bleeds from the repository to the wellbore through the drilling-damaged zone. Once the height of the bit above the repository reaches zero, repository penetrated should be true. The cavity pressure and well bottomhole pressure should then be the same. Also, the spatial integral of total gas in well should be equivalent to the time integral of gas injected into the bottom of the well until gas is ejected at the annulus outlet at the land surface. The 'gas mass from repository' should be similar to but not necessarily the same as the 'total gas injected.' Recall that pressure is the dependent variable in the repository model and gas density and flux are found by post processing using the equation-of-state and Darcy's law, respectively. 'Gas mass from repository' includes all mass sources and sinks in the repository model including the wellbore boundary, far-field boundary and local mass balance errors due to errors in the pressure solution. The wellbore boundary should dominate the term and therefore be similar in value to total gas injected. The 'total gas injected' is calculated using Darcy's law applied at the interior boundary of repository domain and requires an approximation of the pressure gradient at the boundary which is discontinuous.

[2] Both gas and solids removed from the repository by drilling are moved into "storage" before being released to the wellbore domain. Mass in storage is then released to the wellbore over a mixing time = (radius/superficial gas velocity) where the radius is the center of the cell that forms the cavity wall, the first intact repository zone. This is done because instantaneously adding the entire contents of one computational zone to the cavity causes numerical noise, and the controlled release from store dampens the numerical shock.

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5.4.3.2 Tensile Failure of Waste Material

In DRSPALL, the radial effective stress at any radius r > r_c is calculated as the sum of the radial seepage and elastic stress, minus the pore pressure:

$$\sigma_r'(r) = \sigma_{sr}(r) + \sigma_{er}(r) - \beta p(r) \tag{5.4.1}$$

where the radial seepage stress is evaluated with the following integral:

$$\sigma_{sr}(r) = (m-1)\beta\left(\frac{1-2\upsilon}{1-\upsilon}\right)\frac{1}{r^m}\int_{r_c}^{r}(p(r)-p_{ff})r^{m-1}dr \tag{5.4.2}$$

and the radial elastic stress is evaluated as:

$$\sigma_{er}(r) = \left\{\sigma_{ff}\left[1-\left(\frac{r_c}{r}\right)^m\right] + p_c\left(\frac{r_c}{r}\right)^m\right\} \tag{5.4.3}$$

and the pore pressure, $p(r)$, is obtained from the transient solution to porous flow. The terms for Equations 5.4.1 to 5.4.3 are defined in Table 5-9.

Table 5-9– Nomenclature for stress calculations.

Symbol	Definition	Units
m	Geometry exponent (m=3 for spherical, m=2 for cylindrical)	–
$p(r)$	Gas pressure at a distance r from wellbore axis	Pa
p_c	Pressure at cavity face	Pa
p_{ff}	Pressure in far-field (constant)	Pa
r	Radius	m
r_c	Radius at cavity face	m
T_s	Tensile strength	Pa
β	Biot's constant	–
σ_{ff}	Stress in far-field (constant)	Pa
$\sigma_{sr}(r)$	Radial seepage stress	Pa
$\sigma_{er}(r)$	Radial elastic stress	Pa
$\sigma_r'(r)$	Radial effective stresses	Pa
Υ	Poisson s ratio	–
L_t	Characteristic length for testing tensile failure	m
I	Zone index in discretized repository domain	–

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Tensile failure of the solid waste material is determined by comparing the radial effective stress ($\sigma_r'(r)$) at every point in the repository domain to the tensile strength T_s of the solid, shown graphically in Figure 5-13. DRSPALL uses the convention that a positive stress denotes compression, while a negative stress denotes tension. The maximum effective radial stress in tension (where $\sigma_r'(r) < 0$) will typically appear near the cavity wall and transition to compression ($\sigma_r'(r) > 0$) as r increases to the far-field. As such, tensile failure in the solid starts near the cavity wall and moves outward.

In the DRSPALL discretized repository domain, the failure criterion is tested according to the following expression:

$$\text{if } \frac{1}{n}\sum_{i=1}^{n}\sigma'_{r,i} < T_s, \text{ then failure is initiated over } L_t \qquad (5.4.4)$$

where the sum is evaluated over n repository zones in a characteristic length L_t. Note that since T_s is represented by negative constant in the current calculations, a tensile stress exceeding T_s would actually evaluate to less than T_s, hence the "less than" symbol in Equation 5.4.4. Failure in DRSPALL thus occurs only when the mean radial effective stress (in tension) over a characteristic length, L_t, exceeds the tensile strength. L_t in this analysis was 2 cm. The characteristic length concept is introduced because without it, the stress formulations in Equations 5.4.1 to 5.4.3 preclude tensile failure in zones near the wall at small zone size. Close examination of Equations 5.4.1 to 5.4.3 will reveal that the radial effective stress is exactly zero at the cavity wall. This is also illustrated in Figure 5-13. A zone size can always be found in which the very first zone representing the cavity wall has an effective stress insufficient to fail the solids. Also, numerical noise at the cavity boundary can cause spurious failure of the first zone, independent of the physical conditions in the simulation. For these reasons, a characteristic length is introduced that averages the stress over the first several repository zones to capture the expected physical behavior rather than allow failure, or lack thereof, from numerical artifacts.

Tensile failure of waste material will be tested by reporting the following output variables for selected times:

- Run time (sec)
- Cavity pressure (Pa)
- Cavity radius (m)
- Drilled radius (m)
- Cavity volume (m^3)

For computational cells in the repository in the vicinity of the wellbore, the following will be reported as a function of selected times:

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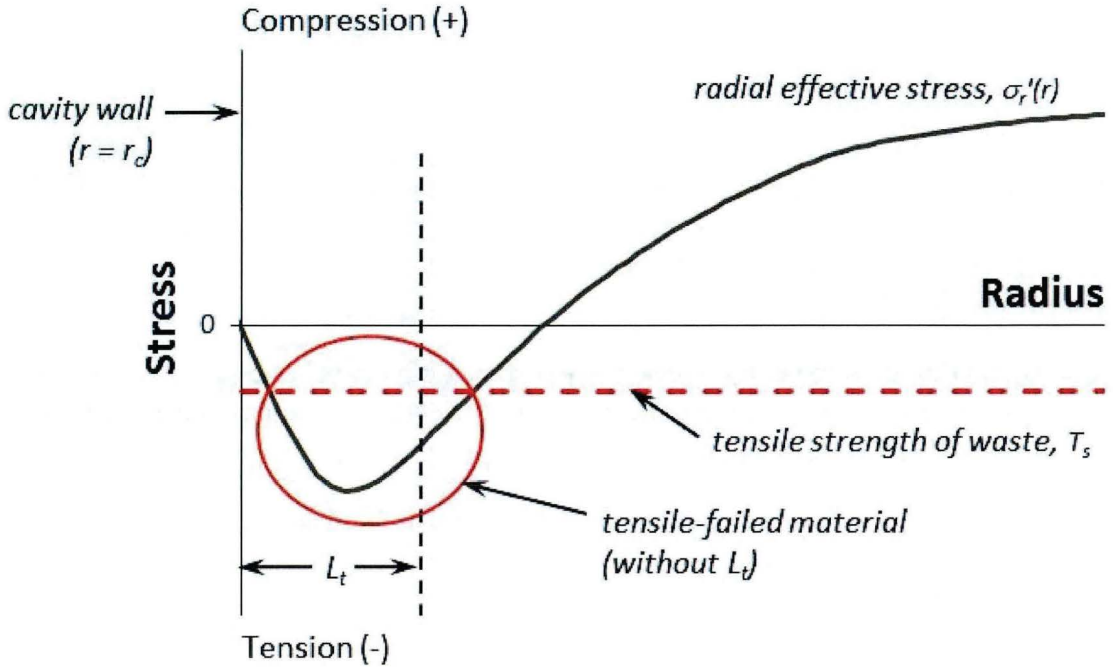

Figure 5-13 Drawing of a theoretical radial effective stress curve. Material is subject to tensile failure where $\sigma_r'(r)<T_s$.

- Repository cell index (-)
- Radius of cell center (m)
- Pore pressure in cell (Pa)
- Radial elastic stress in cell (Pa)
- Radial seepage stress in cell (Pa)
- Radial effective stress in cell (Pa)
- Tensile failure started (true/false)
- Fraction of cell fluidized (-)

In addition, elastic stress, seepage stress and effective stress will be calculated from Equations 5.4.1 to 5.4.3 in an independent test evaluation script analysis using a pore pressure profile, $p(r)$, generated by DRSPALL at one selected time. The test evaluation script values will be compared to those output from DRSPALL to verify that the stress calculations in DRSPALL are implemented correctly.

5.4.3.3 Fluidized Bed Transport of Disaggregated Waste Material

Once tensile failure occurs, material is moved from the repository to the wellbore by fluidized bed transport. In DRSPALL, the Ergun (1952) equation:

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$$\frac{1.75}{a\phi^3}\left(\frac{d_p U_f \rho}{\eta}\right)^2 + 150\left(\frac{1-\phi}{a^2\phi^3}\right)\left(\frac{d_p U_f \rho}{\eta}\right) = \frac{d_p{}^3 \rho(\rho_w - \rho)g}{\eta^2} \tag{5.4.5}$$

is solved for fluidization velocity, and compared with the superficial gas velocity perpendicular to the cavity wall. The superficial gas velocity is defined as the volume flow rate divided by the area perpendicular to flow direction. If the superficial gas velocity exceeds the fluidization velocity, the failed solids are assumed fluidized and added to the wellbore. The terms for Equation 5.4.5 are defined in Table 5-10.

In DRSPALL, the fluidization velocity is nearly constant for a given set of input parameters, though it does change slightly as pressure near the cavity decreases and gas density decreases as a result.

Fluidization of a given zone requires a finite period of time, defined by the fluidization time t_f:

$$t_f = \frac{r_{c1}}{U_s} \tag{5.4.6}$$

Fluidized bed transport will be tested by reporting the following output variables as a function of time:

- Runtime (sec)
- Cavity pressure (Pa)
- Cavity radius (m)
- Fluidization velocity (m/s)
- Superficial gas velocity at the cell center (m/s)
- Total waste in well (kg)

Table 5-10– Nomenclature for fluidization calculations.

Symbol	Definition	Units
a	Particle shape factor	–
d_p	Diameter of particles (mean)	m
g	Acceleration of gravity	m/s^2
U_f	Fluidization velocity	m/s
η	Viscosity of gas	kg /m s
ρ	Density of gas	kg/m^3
ρ_w	Density of waste solids	kg/m^3
ϕ	Porosity	–
U_s	Superficial fluid velocity	m/s
r_{c1}	Radius to center of first intact cell	m
t_f	Fluidization time	s

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For computational cells in the repository in the vicinity of the wellbore, the following will be reported as a function of time:

- Cell index (-)
- Radius of cell center (m)
- Tensile failure completed (true/false)
- Fluidization started (true/false)
- Fluidization completed (true/false)
- Fraction fluidized (-)

Also, the fluidization velocity and fluidization time will be calculated given specific input variables using Equation 5.4.5, independent of DRSPALL. These values will be compared to output from DRSPALL to verify that DRSPALL computed the values correctly.

Finally, the volume and mass of material removed from the repository due to drilling (cuttings) and/or failure and fluidization will be verified by test evaluation script calculations based on the repository computational grid and zone removal tracking variables stored on the CAMDAT output file. The CAMDAT variables to be verified are:

- CUTMASS – mass of material removed by drilling (kg)
- TOTMASS – total mass of material removed due to either drilling or spall (kg)
- SPLMASS – difference between TOTMASS and CUTMASS (kg)
- SPLMAS2 – incrementally summed mass of material removed due to failure and fluidization (spall) (kg)
- CUTVOLEQ – equivalent uncompacted volume of material removed by drilling (m^3)
- TOTVOLEQ – equivalent uncompacted total volume of material removed due to either drilling or spall (m^3)
- SPLVOLEQ – difference between TOTVOLEQ and CUTVOLEQ (m^3)
- SPLVOL2 – incrementally summed equivalent uncompacted volume of material removed due to spall (m^3).

5.4.3.4 Expulsion of Disaggregated Waste Material

Upon transport of the waste material from the cavity at the bottom of the wellbore to the land surface, DRSPALL expels the waste from the problem domain and calculates the total mass of waste expelled as a function of time.

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Expulsion of disaggregated waste material at the land surface will be tested by displaying the following output variables at selected times:

- Run time (sec)
- Repository penetrated (true/false)
- Zones removed from repository domain (-) – Actual number of computational cells removed from the inner wall of the repository domain due to cutting action of the drillbit or spalling
- Mass of waste removed (kg) – Mass of waste solids removed from repository domain
- Waste in store (kg) – Mass of waste in "store" after fluidization of a zone has completed but before it is released to the cavity
- Total waste in well (kg) – Spatial integral of waste mass in wellbore domain
- Waste mass ejected (kg) – Time integral of waste mass ejected at annulus outlet to land surface
- Waste position in well (m) – Position of waste front in well, where ~ 655 m is the well bottom, and 0 m is the land surface
- Mass balance error (-) – Relative difference between mass removed from repository domain and mass ejected to the surface.

Once the bit penetrates the repository, waste cuttings and potentially spallings will be transported up the wellbore to the surface. Monitoring the position of the waste front in the well will indicate how close it is to the land surface. Once the front reaches the surface, the quantity ejected will increase from zero. The mass of waste removed from the repository should balance with the sum of the waste in the well and the waste ejected.

5.4.4 Test Procedure

DRSPALL is executed once to 450 seconds (Case 4.1) to verify DRSPALL processing (Functional Requirements R.3 through R.6). DRSPALL is executed again (Case 4.2) for a short period of time to verify the External Interface Requirements R.7 through R.9 only.

DRSPALL generates four validation files for Case 4.1 (tc41), as follows.

- *drs_124_tc41_coupling.dat* coupling data at selected times.
- *drs_124_tc41_stress.dat* pore pressure and stress profiles.
- *drs_124_tc41_fluidization.dat* fluidization data at selected times.
- *drs_124_tc41_expulsion.dat* solids transport data.

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For Case 4.1, the output CAMDAT file is post-processed with GROPECDB (Feng, 2021a), using the input control file shown in Figure 5-14. The diagnostics file is also examined. The validation files, GROPECDB output, and diagnostics file for Case 4.1 are read in by *drs_test_tc4.py* for post-processing and plotting.

The following command lines run DRSPALL and GROPECDB for Case 4.1:

```
./drspall ./Input/drs_v122_tc41.drs DRSPALL/Test/Output/Linux_124/drs_124_tc41.dbg
        CANCEL DRSPALL/Test/Output/Linux_124/drs_124_tc41.cdb
        > DRSPALL/Test/Output/Linux_124/drs_124_tc41.crt

./gropecdb DRSPALL/Test/Output/Linux_124/drs_124_tc41.cdb
        ./Input/drs_tc41_grope.inp
        DRSPALL/Test/Output/Linux_124/drs_124_tc41.gr  > x.x
```

Case 4.2 is the only test case that inputs a CAMDAT file. For Case 4.2, the diagnostics file is examined to verify that DRSPALL is setting the input parameters as instructed by the DRSPALL input file using the properties in the input CAMDAT file. The output CAMDAT file is not examined. The four validation files mentioned above are generated, but are not examined.

The following command line runs DRSPALL for Case 4.2:

```
./drspall ./Input/drs_v122_tc42.drs DRSPALL/Test/Output/Linux_124/drs_124_tc42.dbg
        ./Input/drs_tc42_ms.cdb DRSPALL/Test/Output/Linux_124/drs_124_tc42.cdb
        > DRSPALL/Test/Output/Linux_124/drs_124_tc42.crt
```

5.4.5 Input/Output Files

The DRSPALL input and output files for Test Case #4 are listed in Appendix A (Section 9).

5.4.6 Acceptance Criteria

Note that **Acceptance Criterion 4-1** through **Acceptance Criterion 4-15** (Sections 5.4.6.1 through 5.4.6.4) and **Acceptance Criterion 4-17** (Section 5.4.6.5) are addressed by Case 4.1. **Acceptance Criterion 4-16** (Section 5.4.6.5) is verified for Case 4.2 only.

5.4.6.1 Coupling of the Wellbore and the Repository Flow Models

As the bit approaches the repository [Bit Above Repository > 0], the following should be observed:

- **Acceptance Criterion 4-1** — Cavity pressure decreases and well bottomhole pressure increases with time (after they stabilize).

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```
DIGITS 8  !apg V1.22 use 8 digits for all
!
!apg For history plots in VD (were done by BLOTCDB)
SELECT ALLTIMES
SELECT HVAR CAVPRS BOTPRS
PRINT HVAR
SELECT HVAR DRILLRAD TENSRAD CAVRAD  !apg may not be used
PRINT HVAR
!
!v1.22 fluidization time comes from separate file
!!!SELECT HVAR FLUIDTIM
!
!apg For drilling and spall volume and masses table in VD
!apg DIGITS 8
SELECT PROP CAVRAD0
PRINT PROP
SELECT TIME 450
SELECT HVAR CUTMASS TOTMASS SPLMASS SPLMAS2 &
            CUTVOLEQ TOTVOLEQ SPLVOLEQ SPLVOL2
PRINT HVAR
!
!For Excel SPLVOL CHECK
SELECT TIME 450
SELECT BLOCK 2  !FLUDSTOP defined in REPOS only
SELECT EVARS COORD FLUDSTOP
PRINT EVARS
!
EXIT
```

Figure 5-14 GROPECDB input command file *drs_tc41_grope.inp*.

- **Acceptance Criterion 4-2** — Repository has not yet been penetrated, indicated by the logical variable Repository Penetrated = "F" (false).

- **Acceptance Criterion 4-3** — The total mass of gas in the bottom of the well is updated by adding gas from the waste. The total fractional mass balance error (dimensionless) should be less than 0.10.

When the bit intersects the repository [Bit Above Repository <= 0], the following should be observed:

- **Acceptance Criterion 4-4** — Cavity pressure and well bottomhole pressure are equal.

- **Acceptance Criterion 4-5** — Repository has been penetrated, indicated by the logical variable Repository Penetrated = "T" (true).

- **Acceptance Criterion 4-6** — The total mass of gas in the well is updated by adding gas from the waste. The total fractional mass balance error (dimensionless) should be less than 0.10.

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5.4.6.2 Tensile Failure of Waste Material

This test will pass if, for a selected output time, the following is observed:

- **Acceptance Criterion 4-7** — The radial effective stress is equal to the sum of the component stresses per Equation 5.4.1.

- **Acceptance Criterion 4-8** — If a zone has not started tensile failure at an earlier timestep, then start tensile failure in the zones within the characteristic length L_t if the average radial effective stress over the characteristic length L_t = 2 cm exceeds the material tensile strength.

- **Acceptance Criterion 4-9** — Independent test evaluation script calculations of the radial effective stress, radial seepage stress, and radial elastic stress based on Equations 5.4.1 to 5.4.3 and the given DRSPALL pore pressure profile demonstrate agreement within a relative difference of 1E-4.

5.4.6.3 Fluidized Bed Transport of Disaggregated Waste Material

This test will pass if, for a selected output time, the following is observed:

- **Acceptance Criterion 4-10** — If the superficial gas velocity for any cell within the characteristic length exceeds the critical fluidization velocity, the fluidization of the disaggregated waste should be started.

- **Acceptance Criterion 4-11** — The fluidization velocity calculated independently using the Ergun equation (Equation 5.4.5) is consistent with the value reported by DRSPALL to within a relative difference of 1E-4.

- **Acceptance Criterion 4-12** — The volume and mass of waste material removed by drilling and spall agree with independent calculations to within a relative difference of 1E-4.

5.4.6.4 Expulsion of Disaggregated Waste Material

Once waste has been transported up the borehole, it must be ejected at the land surface. This test will pass if the following is observed:

- **Acceptance Criterion 4-13** — The position of the waste front in the well must move from the bottom (653 m) to the top (0 m) as time progresses after repository penetration.

- **Acceptance Criterion 4-14** — The cumulative mass of waste ejected must be small (< 1.0 kg) before the waste position in the well reaches z = 0, after which the cumulative mass of waste ejected will be a monotonically increasing positive number.

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- **Acceptance Criterion 4-15** — The mass of waste removed from the repository must correspond with the mass of waste present in the cavity, wellbore, and ejected to the land surface. The relative mass balance error must not exceed 0.01.

5.4.6.5 External Interfaces

The proper use of external interfaces will be verified if:

- **Acceptance Criterion 4-16** — The program successfully reads the DRSPALL parameters from the input control file and the input CAMDAT file, as confirmed by the parameter values listed on the diagnostics file.

- **Acceptance Criterion 4-17** — An output CAMDAT file is generated by DRSPALL. The file must be readable by the BLOTCDB utility or the GROPECDB utility to confirm that it is a valid CAMDAT file.

Test Case #4 will pass if all criteria listed in Sections 5.4.6.1 through 5.4.6.5 are satisfied. This test case will verify Functional Requirements R.3, R.4, R.5, and R.6 and External Interface Requirements R.7, R.8, and R.9.

5.4.7 Test Results

The presentation of results starts with a general description of the run behavior, and then breaks out into discussions of specific functionality.

Key history variables for this run are shown in Figure 5-15 and Figure 5-16. Note that the code was executed for 450 seconds DRSPALL time. This was sufficient time to allow for the cavity pressure to stabilize (Figure 5-15), drilling to complete and failure of repository material to stop and cavity radius to stabilize (Figure 5-16). Output variable names shown in the figures represent the CAMDAT variable names, described in the DRSPALL user's manual (Kicker, 2021). The plot data was extracted from the output CAMDAT file with GROPECDB, and plotted with python.

Understanding DRSPALL output typically begins with studying the pressure and cavity radius history plots. The pressure history plot in Figure 5-15 shows the fluid pressure at the bottom of the well (BOTPRS) and the repository pressure at the point of impending intrusion (CAVPRS). At the start of the simulation, BOTPRS is near hydrostatic (~8 MPa), and CAVPRS is at the initial repository pressure, 14.8 MPa. The well pressure is a little noisy at startup because the initial pressure distribution is chosen arbitrarily, and stable, dynamic flowing solution must be found, which takes a few seconds of DRSPALL time. The important issue here is for the wellbore pressure to settle down before bit penetration of the repository, which it does in all DRSPALL runs. As the bit nears the repository, gas bleed between the repository and wellbore causes BOTPRS and CAVPRS to converge and reach a common value near 9.5 MPa at the time of intrusion. After intrusion, direct coupling between the high-pressure repository and wellbore causes the drilling mud column to blow out, resulting in a drop in BOTPRS to near 3.0 MPa

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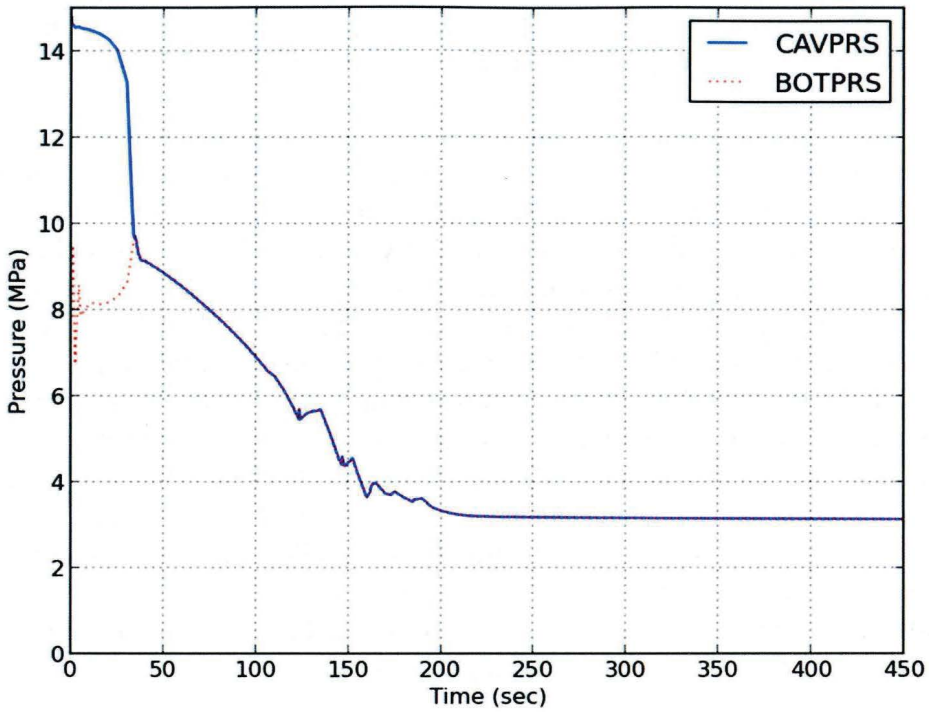

Figure 5-15 Pressure history plot.

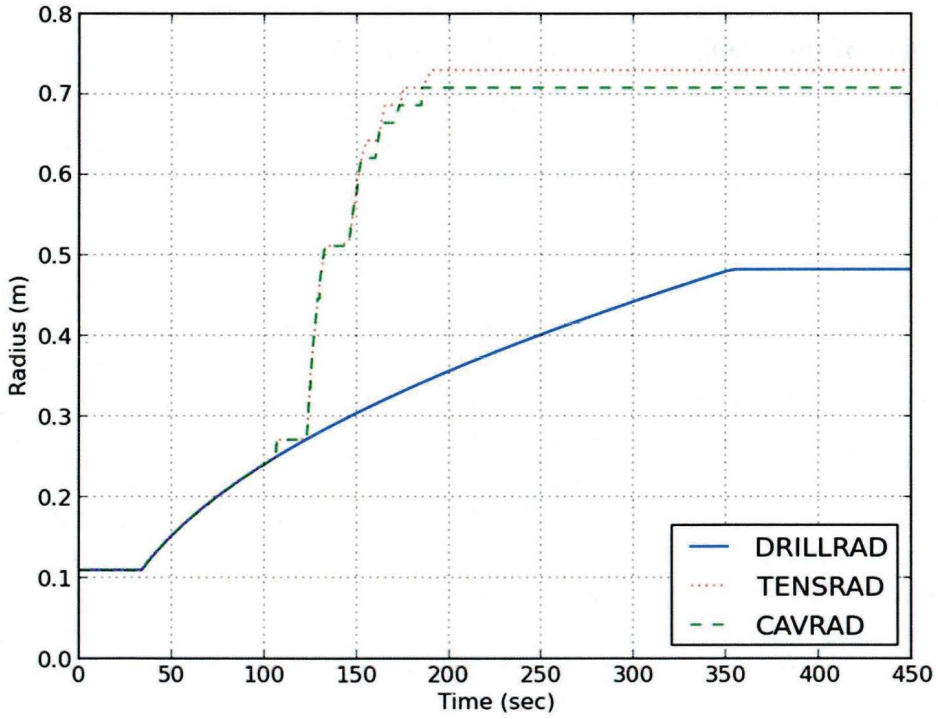

Figure 5-16 Radius history plot.

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where it stays for the remainder of the run. The pressure spikes observed between 130 and 200 seconds are caused by tensile failure of repository solids and subsequent entrainment into the wellbore flow stream.

Also instructive is the radius history plot, shown here in Figure 5-16. Recall that the repository geometry is hemispherical in this study. Note that the initial cavity radius (CAVRAD) is small but not zero, representing the radius of the pseudocavity (Section 5.4.3.1) created prior to bit penetration. The cavity then grows upon penetration of the repository, starting at 34 seconds. Until about 107 seconds, all radial variables grow due to drilling. After 107 seconds, tensile failure occurs, and tensile radius (TENSRAD) and cavity radius (CAVRAD) grow accordingly. Drilled radius (DRILLRAD) continues along its path independent of the growing cavity in front of it, and stops only when the drill bit would have hit the bottom of the repository in the real system. In this case, the effective (spherical) drilled radius is 0.48 m. The cavity radius and tensile-failed radius settle to constant values of 0.71 m and 0.73 m, respectively. The tensile-failed radius (TENSRAD) identifies solid material that has failed due to the stress state, but has not mobilized into the flow stream. The tensile-failed radius is equal to or greater than the cavity radius. The difference between the tensile-failed radius and the drilled radius represents the material considered to be "spalled" in this conceptual model.

Relative difference is used several times in this section. It is calculated as:

$$\text{ABS}\,(DRSPALL\_value - Calculated\_value) \,/\, DRSPALL\_value \qquad (5.4.7)$$

5.4.7.1 Coupling of the Wellbore and Repository Flow Models

An excerpt from the coupling file (as formatted by Excel) is shown in Table 5-11. The information shown in this table relates to gas transport from the repository domain to the wellbore domain. The table columns are defined in Section 5.4.3.1. Figure 5-17 shows a pressure versus time plot.

Reporting in Table 5-11 starts at a run time of approximately 28.28 seconds. The bit is 0.02428 m above the top of the repository at this point, and the Repository Penetrated logical is "F" (false). Gas pressure in the repository (Cavity Pressure = 13.67 MPa) is greater than Well Bottom Pressure at 8.48 MPa. This causes some gas to bleed from the repository to the well bottom through the drilling-damaged zone (DDZ), resulting in a nonzero and growing Total Gas in Well = 1.90 kg. As the bit proceeds downward with time, Cavity Pressure and Well Bottom Pressure converge to a common value of 9.69 MPa at approximately 33.77 seconds when the repository is penetrated. A horizontal line is drawn in the table at the time of penetration. The pressure behavior is also illustrated graphically in Figure 5-17, where data from Figure 5-15 is plotted on a time scale from 0 to 50 seconds to zoom in on events around the time of intrusion. The plot data was extracted from the output CAMDAT file with GROPECDB, and plotted with python.

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Table 5-11– Excerpt from *drs_124_tc41_coupling.dat.*

Initial Repository Pressure (Pa): 1.480000000000000E+07
Initial Gas in Repository (kg): 1.021635964442419E+05

Runtime (sec)	Bit Above Repository (m)	Repository Penetrated (T/F)	Cavity Pressure (Pa)	Well Bottom Pressure (Pa)	Total Gas In Well (kg)	Total Gas Injected (kg)	Gas Mass In Repository (kg)	Gas Mass From Repository (kg)	Gas Storage (kg)	Mass Balance Error (-)
28.28294	0.02428	F	13667368	8478921	1.9019528	1.9019528	102161.71	1.8895154	0	1.22E-07
28.44442	0.02356	F	13639878	8491562.3	1.9285714	1.9285714	102161.68	1.915227	0	1.31E-07
28.60589	0.02285	F	13611055	8504894.2	1.9557763	1.9557763	102161.65	1.94148	0	1.40E-07
28.76736	0.02213	F	13580770	8518713.5	1.9835934	1.9835934	102161.63	1.9682975	0	1.50E-07
28.92883	0.02141	F	13548898	8533020.4	2.0120507	2.0120507	102161.6	1.9957048	0	1.60E-07
29.0903	0.02069	F	13515349	8548117.9	2.0411779	2.0411779	102161.57	2.0237282	0	1.71E-07
29.25178	0.01998	F	13480002	8564096.5	2.0710058	2.0710058	102161.54	2.0523955	0	1.82E-07
29.41325	0.01926	F	13442678	8580762.6	2.101568	2.101568	102161.51	2.0817364	0	1.94E-07
29.57472	0.01854	F	13403192	8598119.3	2.1329012	2.1329012	102161.48	2.1117838	0	2.07E-07
29.73619	0.01782	F	13361379	8616376.3	2.1650444	2.1650444	102161.45	2.1425723	0	2.20E-07
29.89766	0.0171	F	13317045	8635655	2.1980392	2.1980392	102161.42	2.1741389	0	2.34E-07
30.05914	0.01639	F	13269950	8655960.8	2.2319303	2.2319303	102161.39	2.2065234	0	2.49E-07
30.22061	0.01567	F	13219818	8677297.3	2.2667664	2.2667664	102161.36	2.2397687	0	2.64E-07
30.38208	0.01495	F	13166346	8699712.5	2.3026003	2.3026003	102161.32	2.2739218	0	2.81E-07
30.54355	0.01423	F	13109204	8723347.5	2.3394892	2.3394892	102161.29	2.3090331	0	2.98E-07
30.70503	0.01352	F	13048031	8748386.1	2.3774947	2.3774947	102161.25	2.3451572	0	3.17E-07
30.8665	0.0128	F	12982392	8774892.1	2.4166837	2.4166837	102161.21	2.3823528	0	3.36E-07
31.02797	0.01208	F	12911765	8802873.6	2.4571295	2.4571295	102161.18	2.4206848	0	3.57E-07
31.18944	0.01136	F	12835573	8832461	2.4989126	2.4989126	102161.14	2.4602236	0	3.79E-07
31.35091	0.01065	F	12753179	8863898.2	2.5421206	2.5421206	102161.1	2.5010464	0	4.02E-07
31.51239	0.00993	F	12663831	8897362.8	2.586849	2.586849	102161.05	2.5432369	0	4.27E-07
31.67386	0.00921	F	12566616	8932944.6	2.6332034	2.6332034	102161.01	2.5868876	0	4.53E-07
31.83533	0.00849	F	12460468	8970779.5	2.6813005	2.6813005	102160.96	2.6321005	0	4.82E-07
31.9968	0.00777	F	12344155	9011118	2.7312691	2.7312691	102160.92	2.6789883	0	5.12E-07
32.15827	0.00706	F	12216228	9054246.2	2.7832516	2.7832516	102160.87	2.7276752	0	5.44E-07
32.31975	0.00634	F	12074931	9100410.7	2.8374061	2.8374061	102160.82	2.778299	0	5.79E-07
32.48122	0.00562	F	11918129	9149848.2	2.8939088	2.8939088	102160.77	2.8310132	0	6.16E-07
32.64269	0.0049	F	11743230	9202850.2	2.9529568	2.9529568	102160.71	2.8859892	0	6.55E-07
32.80416	0.00419	F	11547084	9259795.3	3.0147704	3.0147704	102160.65	2.9434189	0	6.98E-07
32.96563	0.00347	F	11325789	9321103.8	3.0795966	3.0795966	102160.59	3.003517	0	7.45E-07
33.12711	0.00275	F	11074430	9387190.9	3.1477129	3.1477129	102160.53	3.0665249	0	7.95E-07
33.28858	0.00203	F	10786726	9458480.1	3.2194318	3.2194318	102160.46	3.1327151	0	8.49E-07
33.45005	0.00131	F	10454565	9535460.6	3.2951061	3.2951061	102160.39	3.2023954	0	9.07E-07

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Table 5 11– Excerpt from *drs_124_tc41_coupling.dat*. (Continued)

Runtime (sec)	Bit Above Repository (m)	Repository Penetrated (T/F)	Cavity Pressure (Pa)	Well Bottom Pressure (Pa)	Total Gas In Well (kg)	Total Gas Injected (kg)	Gas Mass In Repository (kg)	Gas Mass From Repository (kg)	Gas Storage (kg)	Mass Balance Error (-)
33.61152	0.0006	F	10067276	9618690.5	3.3751325	3.3751325	102160.32	3.275914	0	9.71E-07
33.77299	-0.00012	T	9694116	9694116	3.4595385	3.4595385	102160.24	3.3534591	0	1.04E-06
33.93447	-0.00084	T	9712604.1	9712604.1	3.5440731	3.5440731	102160.16	3.4314584	0	1.10E-06
34.09594	-0.00156	T	9724542.4	9724542.4	3.6280251	3.6280251	102160.09	3.5089378	0	1.17E-06
34.25741	-0.00227	T	9728442.2	9728442.2	3.7116835	3.7116835	102160.01	3.5861557	0	1.23E-06
34.41888	-0.00299	T	9743275.1	9743275.1	3.7960036	3.7960036	102159.93	3.6646049	0.0006104	1.29E-06
34.58035	-0.00371	T	9718182.4	9718182.4	3.8818675	3.8818675	102159.85	3.7435841	0.0003318	1.36E-06
34.74183	-0.00443	T	9680289.4	9680289.4	3.9677983	3.9677983	102159.77	3.8227403	0.0001797	1.42E-06
34.9033	-0.00515	T	9643108.7	9643108.7	4.0539415	4.0539415	102159.69	3.9021512	9.69E-05	1.49E-06
35.06477	-0.00586	T	9623817.5	9623817.5	4.1411067	4.1411067	102159.61	3.9831748	0.000687	1.55E-06
35.22624	-0.00658	T	9588268.3	9588268.3	4.2301414	4.2301414	102159.53	4.065006	0.0003743	1.62E-06
35.38771	-0.0073	T	9536884.7	9536884.7	4.319319	4.319319	102159.45	4.1470966	0.0002029	1.69E-06
35.54919	-0.00802	T	9481983.3	9481983.3	4.4089149	4.4089149	102159.37	4.2296351	0.0001093	1.76E-06
35.71066	-0.00873	T	9446470.8	9446470.8	4.4994413	4.4994413	102159.28	4.3137527	0.0007418	1.82E-06
... lines deleted ...										
104.98405	-0.31665	T	6664683.4	6664683.4	86.76156	86.76156	102083.6	79.99611	0.0013752	6.62E-05
105.14554	-0.31737	T	6655700.3	6655700.3	87.050832	87.050832	102083.33	80.262175	0.0010383	6.65E-05
105.30703	-0.31809	T	6646574.4	6646574.4	87.340034	87.340034	102083.07	80.528258	0.0007836	6.67E-05
105.46852	-0.31881	T	6637310.2	6637310.2	87.629233	87.629233	102082.8	80.794399	0.0005912	6.69E-05
105.63001	-0.31953	T	6627893.7	6627893.7	87.918471	87.918471	102082.54	81.060623	0.0004458	6.71E-05
105.7915	-0.32024	T	6618368.7	6618368.7	88.207776	88.207776	102082.27	81.326945	0.0003359	6.74E-05
105.95299	-0.32096	T	6608767.9	6608767.9	88.497166	88.497166	102082	81.593373	0.000253	6.76E-05
106.11448	-0.32168	T	6602758.8	6602758.8	88.790011	88.790011	102081.73	81.86931	0.0023096	6.78E-05
106.27597	-0.3224	T	6566780.2	6566780.2	89.069868	89.069868	102081.44	82.156439	0.0017662	6.77E-05
106.42141	-0.32304	T	6557105.1	6557105.1	89.310796	89.310797	102081.18	82.415169	0.0014005	6.75E-05
106.54897	-0.32361	T	6603011.8	6603011.8	89.54398	89.54398	102080.94	82.65962	0.0154312	6.75E-05
106.71046	-0.32433	T	6579669.3	6579669.3	89.859901	89.859902	102080.63	82.963034	0.0118929	6.76E-05
106.85322	-0.32496	T	6565360.7	6565360.7	90.125315	90.125316	102080.37	83.231026	0.0095433	6.76E-05
106.99329	-0.32559	T	6602981.3	6602981.3	90.408806	90.408807	102080.09	83.509959	0.0196032	6.77E-05
107.15478	-0.3263	T	6598328.6	6598328.6	90.743039	90.743042	102079.78	83.813961	0.0153326	6.80E-05
107.31627	-0.32702	T	6596614.3	6596614.3	91.074863	91.074868	102079.48	84.116663	0.0120043	6.82E-05
107.47776	-0.32774	T	6594290.5	6594290.5	91.405127	91.405135	102079.18	84.41863	0.0094037	6.85E-05
107.63925	-0.32846	T	6589478.7	6589478.7	91.734349	91.734363	102078.88	84.72018	0.007368	6.87E-05
107.80075	-0.32917	T	6585177.6	6585177.6	92.06277	92.062794	102078.58	85.021418	0.0057736	6.90E-05
107.96224	-0.32989	T	6578675.9	6578675.9	92.390614	92.390656	102078.27	85.322462	0.0045241	6.92E-05
108.12373	-0.33061	T	6572609.4	6572609.4	92.718022	92.718095	102077.97	85.623375	0.0035445	6.95E-05
108.28523	-0.33133	T	6566469.9	6566469.9	93.045062	93.045189	102077.67	85.924175	0.0027767	6.97E-05

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Table 5 11– Excerpt from *drs_124_tc41_coupling.dat.* (Continued)

Runtime (sec)	Bit Above Repository (m)	Repository Penetrated (T/F)	Cavity Pressure (Pa)	Well Bottom Pressure (Pa)	Total Gas In Well (kg)	Total Gas Injected (kg)	Gas Mass In Repository (kg)	Gas Mass From Repository (kg)	Gas Storage (kg)	Mass Balance Error (-)
108.44672	-0.33205	T	6559186	6559186	93.371831	93.372053	102077.37	86.224922	0.0021748	7.00E-05
108.60821	-0.33276	T	6551787.1	6551787.1	93.698371	93.698758	102077.07	86.52565	0.0017029	7.02E-05
108.76971	-0.33348	T	6544161.2	6544161.2	94.024672	94.025344	102076.77	86.826369	0.0013331	7.05E-05
108.9312	-0.3342	T	6535793.8	6535793.8	94.350716	94.351876	102076.47	87.127117	0.0010432	7.07E-05
109.09269	-0.33492	T	6527395.3	6527395.3	94.6764	94.678382	102076.17	87.427904	0.0008161	7.10E-05
109.25419	-0.33563	T	6518842.4	6518842.4	95.001559	95.004888	102075.87	87.728741	0.0006382	7.12E-05
109.41568	-0.33635	T	6510124.5	6510124.5	95.325962	95.331416	102075.57	88.029639	0.0004989	7.15E-05
109.57718	-0.33707	T	6501256.2	6501256.2	95.649315	95.657986	102075.27	88.330608	0.0003899	7.17E-05
109.73867	-0.33779	T	6492244.7	6492244.7	95.971278	95.984615	102074.96	88.631656	0.0003045	7.20E-05
109.90016	-0.33851	T	6483110	6483110	96.291492	96.311316	102074.66	88.932793	0.0002378	7.22E-05
110.06166	-0.33922	T	6473851.3	6473851.3	96.609592	96.6381	102074.36	89.234023	0.0001856	7.25E-05
110.22315	-0.33994	T	6464480.3	6464480.3	96.925224	96.964977	102074.06	89.535353	0.0001448	7.27E-05
110.38465	-0.34066	T	6455003.7	6455003.7	97.238054	97.291957	102073.76	89.83679	0.0001129	7.30E-05
110.54614	-0.34138	T	6445408.8	6445408.8	97.547771	97.619046	102073.46	90.138337	8.80E-05	7.32E-05
110.70764	-0.3421	T	6435697.3	6435697.3	97.854089	97.946252	102073.16	90.440001	6.85E-05	7.35E-05
110.86913	-0.34281	T	6425898.4	6425898.4	98.156746	98.27358	102072.85	90.741786	5.34E-05	7.37E-05
111.03063	-0.34353	T	6416044.6	6416044.6	98.455502	98.601036	102072.55	91.043694	4.15E-05	7.40E-05
111.19212	-0.34425	T	6406130.9	6406130.9	98.750139	98.928622	102072.25	91.345728	3.23E-05	7.42E-05
111.35362	-0.34497	T	6396144.3	6396144.3	99.040459	99.256342	102071.95	91.647891	2.51E-05	7.45E-05
111.51512	-0.34568	T	6386098	6386098	99.326284	99.584201	102071.65	91.950187	1.95E-05	7.47E-05
111.67661	-0.3464	T	6375998.2	6375998.2	99.607455	99.9122	102071.34	92.252617	1.52E-05	7.50E-05
111.83811	-0.34712	T	6365831.6	6365831.6	99.883833	100.24034	102071.04	92.555183	1.18E-05	7.52E-05
... lines deleted ...										
258.43264	-0.99873	T	3185456.8	3185456.8	50.727039	801.328	101220.54	943.0556	1.35E-15	0.001387
258.59483	-0.99945	T	3185400.3	3185400.3	50.726121	802.16028	101219.46	944.1393	1.26E-15	0.00139

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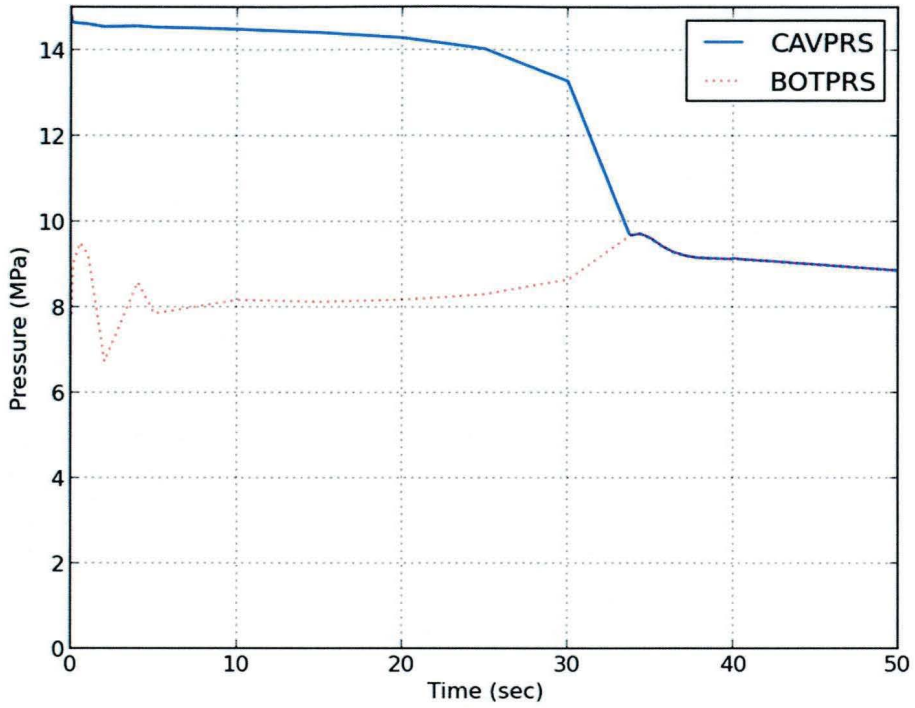

Figure 5-17 Pressure history plot for time = 0 to 50 sec.

An examination of Table 5-11 and *drs_124_tc41_coupling.dat* confirms that **Acceptance Criterion 4-2** and **Acceptance Criterion 4-5** (Section 5.4.6.1) are met: the Repository Penetrated is always "F" (false) when Bit Above Repository is greater than zero, and always "T" (true) when Bit Above Repository is less than or equal to zero. An examination of Table 5-11 and Figure 5-17 confirms that **Acceptance Criterion 4-1** (Section 5.4.6.1) is met: Cavity Pressure (CAVPRS) decreases and Well Bottom Pressure (BOTPRS) increases (after CAVPRS stabilizes) as the bit approaches the repository. Further examination confirms that **Acceptance Criterion 4-4** (Section 5.4.6.1) is met: Cavity Pressure (CAVPRS) and Well Bottom Pressure (BOTPRS) are equal when the bit intersects the repository.

In Table 5-11, the spatial integral Total Gas In Well agrees closely with the time integral Total Gas Injected until gas transports all the way to the top of the wellbore at the land surface (run time approximately 107 seconds) at which point gas is ejected to the atmosphere and out of the problem domain. Mass of gas injected and gas mass from repository are similar as expected and explained in Section 5.4.3.1. The total fractional mass balance error remains on the order of 1E-3 to 1E-7 for all reported times in Table 5-11 and in *drs_124_tc41_coupling.dat*, so **Acceptance Criterion 4-3** and **Acceptance Criterion 4-6** (Section 5.4.6.1) are met. The total fractional mass balance error is defined as the absolute value of [Initial Gas in Repository – (Gas Mass In Repository + Gas Storage + Total Gas Injected)] / Initial Gas in Repository.

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5.4.7.2 Tensile Failure of Waste Material

An excerpt from the stress output file (as formatted by Excel) is shown in Table 5-12. The header to this table gives information such as run time, cavity pressure, cavity radius, drilled radius, cavity volume, far-field pressure at the no-flow outer boundary (R = 19.2 m), and first intact zone. The first intact zone is defined as the repository computational cell corresponding to the intact cavity wall. Zones that are failed and fluidizing are considered intact until the fluidization process is complete. Below the header is a listing of repository cells in the vicinity of the cavity wall showing selected properties related to stress and material failure. Shown are the cell index, radius of the cell center relative to the origin of the repository domain, pore (gas) pressure, radial elastic stress, radial seepage stress, radial effective stress, logical flag for tensile failure, and fraction of the zone fluidized. Tensile strength for this test case is 0.12 MPa.

Acceptance Criterion 4-7 (Section 5.4.5.2) states that the radial effective stress must equal the sum of the component stresses. This criterion is checked by the evaluation script calculations of the radial effective stress for every zone, shown as "*Calculated Effective Stress*" (in italics) in Table 5-12. In each case, the DRSPALL-calculated radial effective stress EffStre is equal to the evaluation script-calculated stress (*Calculated Effective Stress* = SeepStr + ElastStr – PorePres) for all digits shown. Thus, **Acceptance Criterion 4-7** (Section 5.4.6.2) is met.

Table 5-12– Excerpt from *drs_124_tc41_stress.dat*, run time = 124.080 sec.

Runtime(sec) = 124.080282845
CavPres(Pa) = 5470703.75933
DrilledRad(m) = 0.273076705118
CavityVol(m^3) = 0.101603354112
Pff(Pa) = 14796536.9316
FirstIntactZone = 104.0

Zone Index	Radius (m)	PorePres (Pa)	SeepStr (Pa)	EffStre (Pa)	*Calculated Effective Stress* (Pa)	Failed (T/F)	Fluidized (-)
94	0.295937	5502550	4.132571	156961.8	156961.8	T	1
95	0.297925	5537532	8.812012	305783.3	305783.3	T	1
96	0.299914	5572007	13.35046	450268.9	450268.9	T	1
97	0.301902	5605649	17.75287	590902.9	590902.9	T	1
98	0.303891	5638458	22.02408	727838.5	727838.5	T	1
99	0.305879	5670463	26.16874	861193	861193	T	1
100	0.307868	5701695	30.1913	991075.2	991075.2	T	1
101	0.309856	5732206	34.09602	1117570	1117570	T	1
102	0.311845	5762257	37.88692	1240544	1240544	T	1
103	0.313834	5794455	41.56718	1357519	1357519	T	1
104	0.315822	5470704	-45174.6	-45174.6	-45174.6	T	0
105	0.317811	5921163	-88134 7	362702	362702	T	0
106	0.319799	6130433	128458	-440751	-440751	T	0
107	0.321788	6283002	166932	-464463	-464463	T	0

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Table 5 12– Excerpt from *drs_124_tc41_stress.dat*, run time = 124.080 sec. (Continued)

Zone Index	Radius (m)	PorePres (Pa)	SeepStr (Pa)	EffStre (Pa)	*Calculated Effective Stress* (Pa)	Failed (T/F)	Fluidized (-)
108	0.323776	6419252	-203784	-474321	-474321	T	0
109	0.325765	6548125	-239119	-479246	-479246	T	0
110	0.327753	6671827	-273013	-481400	-481400	T	0
111	0.329742	6791076	-305530	-481453	-481453	T	0
112	0.33173	6906243	-336731	-479723	-479723	T	0
113	0.333719	7017596	-366674	-476430	-476430	T	0
114	0.335708	7125366	-395412	-471754	-471754	T	0
115	0.337696	7229758	-422997	-465853	-465853	F	0
116	0.339685	7330960	-449476	-458867	-458867	F	0
117	0.341673	7429143	-474896	-450919	-450919	F	0
118	0.343662	7524465	-499300	-442120	-442120	F	0
119	0.34565	7617068	-522729	-432571	-432571	F	0
120	0.347639	7707089	-545224	-422359	-422359	F	0
121	0.349627	7794649	-566821	-411567	-411567	F	0
122	0.351616	7879865	-587556	-400265	-400265	F	0
123	0.353604	7962842	-607463	-388521	-388521	F	0
124	0.355593	8043680	-626575	-376392	-376392	F	0

5.4.7.2.1 Stress and failure logic

Reviewing Table 5-12 allows for an examination of the logic that controls waste material failure due to stresses in the solid. Starting with the first intact zone 104, if radial effective stress exceeds the tensile strength (T_s = 0.12 MPa), the material is subject to failure. Section 5.4.3.2 explains that negative stress denotes tension. Recall that failure is allowed only if the mean radial effective stress in the cells that cover the specified characteristic length, L_t, exceeds the tensile strength. For this problem, L_t = 2 cm or 11 zones for the region where zone size is constant at slightly less than 0.2 cm. Further examination of the output *drs_124_tc41_stress.dat* file shows that at the previous output time t=106.05179162907 zones 71 through 81 are in the critical length and in tensile failure, with a mean radial effective stress exceeding the tensile strength. Zones 82 through 92 enter tensile failure at time t=106.90511, zones 93 through 103 enter tensile failure at time t=123.48853, and zones 104 through 114 enter tensile failure at time t=124.08028, leading to the example output shown in Table 5-12. Examination of the radial effective stress EffStre for zones 104 through 114 reveals that the mean stress = -4.2340E+05 Pa, which exceeds the tensile strength (T_s = 0.12 MPa), and the logical variable Failed is thus True for zones within the characteristic length. Zones beyond the characteristic length are not allowed to fail until all the zones within the characteristic length have fluidized. The Failed variable value of "T" (true) for zones 104 through 114 (within the characteristic length), and "F" (false)

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for zones 115 through 124 (outside the characteristic length) confirms that **Acceptance Criterion 4-8** (Section 5.4.6.2) is met. The evaluation script runs this test for all time steps after material failure starts, only data from one time step is reproduced here.

5.4.7.2.2 Verification of stress calculations

The data from Table 5-12 was used to verify the stress calculations with the test evaluation scripts (Table 5-13). The DRSPALL pore pressure profile shown in Table 5-12 was used to calculate a stress profile, which is compared back to the stress profile calculated by DRSPALL. Table 5-13 displays the new stress profile calculations.

The header in Table 5-13 contains global properties such as Far-Field Stress, Tensile Strength, Poisson's Ratio, Geometry Index (2 = cylindrical, 3 = spherical), Far-Field Pressure, Biot's Beta, and the prefactor which is a convenient coupling of terms to create an intermediate variable as follows (see Table 5-9 for definitions of terms):

$$prefactor = (m-1)\beta\left(\frac{1-2\upsilon}{1-\upsilon}\right) \tag{5.4.8}$$

The calculations start at the first intact zone 104 and are carried through to zone 124. The following notes apply:

- r_c/r denotes the ratio cavity radius to zone center radius
- The Radial Elastic Stress is calculated per Equation 5.4.3
- The Integral Over dr represents the integral in Equation 5.4.2 over one zone
- The sum is the integral over all zones from First Intact Zone to the given zone
- The Radial Seepage Stress is calculated by Equation 5.4.2
- The Radial Effective Stress is calculated by Equation 5.4.1.

The evaluation calculated stress values are compared to DRSPALL values and the results appear in Table 5-14. The script calculates stresses and differences at all time steps not just the one shown here. The maximum relative difference was 1.02E-13 for Radial Elastic Stress, 3.98E-12 for Radial Seepage Stress, and 7.15E-12 for Radial Effective Stress. The small differences for the three stresses confirm that **Acceptance Criterion 4-9** (Section 5.4.6.2) is met.

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Table 5-13– Independent calculations of stress profiles from pore pressure data.

Far-field stress = 1.4900E+07
Tensile strength = 1.2000E+05
Poisson's ratio = 3.8000E-01
Geometry index = 3
Far-field pressure = 1.4797E+07
Biot Beta = 1.0000E+00
Prefactor = 7.7419E-01

Zone Index	r_c/r	Radial Elastic Stress	Integral over dr	Sum	Radial Seepage Stress	Radial Effective Stress
104	1	5470704	-1838.12	-1838.12	-45174.6	-45174.6
105	0.993743	5646596	-1816.17	-3654.29	-88134.7	-362702
106	0.987564	5818140	-1772.53	-5426.81	-128458	-440751
107	0.981461	5985471	-1757.72	-7184.53	-166932	-464463
108	0.975433	6148715	-1749.67	-8934.2	-203784	-474321
109	0.969479	6307998	-1743.5	-10677.7	-239119	-479246
110	0.963597	6463439	-1738.1	-12415.8	-273013	-481400
111	0.957786	6615153	-1733.22	-14149	-305530	-481453
112	0.952044	6763251	-1728.76	-15877.8	-336731	-479723
113	0.946371	6907840	-1724.68	-17602.5	-366674	-476430
114	0.940766	7049024	-1720.95	-19323.4	-395412	-471754
115	0.935226	7186901	-1717.55	-21040.9	-422997	-465853
116	0.929751	7321569	-1714.45	-22755.4	-449476	-458867
117	0.92434	7453120	-1711.63	-24467	-474896	-450919
118	0.918991	7581644	-1709.08	-26176.1	-499300	-442120
119	0.913704	7707227	-1706.78	-27882.9	-522729	-432571
120	0.908478	7829953	-1704.72	-29587.6	-545224	-422359
121	0.903311	7949903	-1702.87	-31290.5	-566821	-411567
122	0.898202	8067155	-1701.24	-32991.7	-587556	-400265
123	0.893151	8181784	-1699.8	-34691.5	-607463	-388521
124	0.888156	8293864	-1698.54	-36390.1	-626575	-376392

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Table 5-14– Summary of differences between DRSPALL and Independent calculations for stress verification.

Zone Index	Radial Elastic Stress		Radial Seepage Stress		Radial Effective Stress	
	Absolute Diff	Relative Diff	Absolute Diff	Relative Diff	Absolute Diff	Relative Diff
104	0	0	5.02E-08	1.11E-12	5.15E-08	1.14E-12
105	1.83E-07	3.25E-14	9.75E-08	1.11E-12	2.07E-08	5.71E-14
106	3.10E-07	5.33E-14	1.44E-07	1.12E-12	2.27E-07	5.14E-13
107	4.79E-07	8.00E-14	1.78E-07	1.07E-12	3.31E-07	7.12E-13
108	1.60E-07	2.61E-14	3.55E-08	1.74E-13	2.15E-07	4.54E-13
109	4.75E-08	7.53E-15	7.13E-08	2.98E-13	1.37E-08	2.87E-14
110	2.39E-07	3.70E-14	1.12E-07	4.09E-13	1.28E-07	2.66E-13
111	3.16E-07	4.77E-14	1.42E-07	4.66E-13	2.04E-07	4.24E-13
112	4.76E-07	7.04E-14	1.72E-07	5.12E-13	3.63E-07	7.58E-13
113	9.59E-08	1.39E-14	5.39E-08	1.47E-13	1.50E-07	3.14E-13
114	6.33E-08	8.98E-15	9.06E-08	2.29E-13	3.14E-09	6.66E-15
115	2.93E-07	4.08E-14	1.17E-07	2.76E-13	1.67E-07	3.59E-13
116	3.78E-07	5.16E-14	1.44E-07	3.21E-13	2.53E-07	5.52E-13
117	9.78E-08	1.31E-14	4.47E-08	9.41E-14	1.23E-07	2.73E-13
118	2.24E-08	2.95E-15	7.44E-08	1.49E-13	8.60E-08	1.94E-13
119	1.31E-07	1.70E-14	9.91E-08	1.90E-13	2.25E-08	5.19E-14
120	3.29E-07	4.20E-14	1.20E-07	2.20E-13	1.29E-07	3.05E-13
121	4.32E-07	5.44E-14	1.41E-07	2.48E-13	2.12E-07	5.15E-13
122	9.78E-08	1.21E-14	5.93E-08	1.01E-13	1.77E-07	4.43E-13
123	1.13E-07	1.38E-14	8.20E-08	1.35E-13	4.97E-08	1.28E-13
124	2.10E-07	2.53E-14	9.53E-08	1.52E-13	9.35E-08	2.48E-13
Maximum	4.79E-07	8.00E-14	1.78E-07	1.12E-12	3.63E-07	1.14E-12
Maximum over all time	6.02E-07	1.02E-13	1.78E-07	3.98E-12	5.63E-07	7.15E-12

5.4.7.3 Fluidized Bed Transport of Disaggregated Waste Material

An excerpt from the fluidization output file (formatted in Excel) is shown in Table 5-15. The header to this table gives information such as run time, cavity pressure, cavity radius, gas density in the cavity, minimum fluidization velocity, superficial gas velocity at the cavity wall, mass of waste in well, and the first intact zone. The first intact zone is defined as the repository computational cell corresponding to the intact cavity wall. Zones that are failed and fluidizing are considered intact until the fluidization process is complete. Below the header is a listing of repository cells in the vicinity of the cavity wall showing selected properties related to fluidization: cell index, radius of the cell center relative to the origin of the repository domain, logical flags for failure of the cell completed, fluidization started, and fluidization completed, and the fraction of the cell fluidized. A value of -1.0 in the Fraction Fluidized column indicates that the cell was removed by drilling, while a 1.0 indicates that the zone was removed by tensile failure and fluidized bed transport.

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Table 5-15– Excerpt from *drs_124_tc41_fluidization.dat*, run time = 124.67270 sec.

Runtime (sec) = 124.672703156
Cavity Pressure (Pa) = 5516419.71261
Gas Density (kg/m^3) = 4.46737680589
Fluidization Velocity (m) = 0.277323721963
Superficial Gas Velocity (m)
(First Intact Zone) = 0.506618830932
Waste In Well (kg) = 55.0436220991
First Intact Zone = 115.0

Cell Index	Radius (m)	Failure Completed (T/F)	Fluidization Start (T/F)	Fluidization Complete (T/F)	Fraction Fluidized
105	0.317811	T	T	T	1
106	0.319799	T	T	T	1
107	0.321788	T	T	T	1
108	0.323776	T	T	T	1
109	0.325765	T	T	T	1
110	0.327753	T	T	T	1
111	0.329742	T	T	T	1
112	0.33173	T	T	T	1
113	0.333719	T	T	T	1
114	0.335708	T	T	T	1
115	0.337696	T	T	F	0.0001
116	0.339685	T	T	F	0.0002
117	0.341673	T	T	F	0.0001
118	0.343662	T	T	F	0.0001
119	0.34565	T	T	F	0
120	0.347639	T	T	F	0
121	0.349627	F	F	F	0
122	0.351616	F	F	F	0
123	0.353604	F	F	F	0
124	0.355593	F	F	F	0
125	0.357581	F	F	F	0
126	0.35957	F	F	F	0
127	0.361559	F	F	F	0
128	0.363547	F	F	F	0
129	0.365536	F	F	F	0
130	0.367524	F	F	F	0
131	0.369513	F	F	F	0
132	0.371501	F	F	F	0
133	0.37349	F	F	F	0
134	0.375478	F	F	F	0
135	0.377467	F	F	F	0

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5.4.7.3.1 Fluidization logic

At the point in the code execution shown in Table 5-15, 114 computational cells in the repository have been removed and transported into the cavity and wellbore by a combination of drilling and tensile failure/fluidization. The first intact zone that forms the cavity wall is cell 115. Zones 105 through 114 were completely removed by tensile failure and fluidization (Fraction Fluidized = 1.0). Zones 115 through 120 have failed in tension (Failure Completed = T), and zones 115 through 118 are currently fluidizing (Fraction Fluidized > 0). In order for zones to fluidize, the superficial gas velocity at the cavity wall must exceed the minimum fluidization velocity. The header in Table 5-15 confirms that the Superficial Gas Velocity at the first intact zone (115) = 0.5066 m/s, while the Fluidization Velocity = 0.2773 m/s. As such, the failed zone 115 is subject to fluidization, and fluidization is currently in process. **Acceptance Criterion 4-10** (Section 5.4.6.3) is met because the Fluidization Start = "T" (true) in zone 115 confirms that fluidization has started in the first intact zone. Zones must complete fluidization in sequence such that zone 116 cannot completely fluidize until after zone 115 has completely fluidized. Also, zones require a finite time to fluidize. The progress of a particular zone through the fluidization process is given by the fraction fluidized, which varies from 0.0 (not fluidized) to 1.0 (fully fluidized). Notice that zones 115 through 118 are just starting to fluidize in Table 5-15 (run time 124.67270, line 4915 in *drs_124_tc41_fluidization.dat*). Fluidization does not occur before failure has occurred, and all time steps are tested against this fluidization logic. In this case earlier time steps show zone 115 was intact and had not started fluidization at time 124.08239989512. These zones are fully fluidized at run time 125.34018 sec (line 5135 in *drs_124_tc41_fluidization.dat*).

5.4.7.3.2 Verification of fluidization velocity

Data from Table 5-15 were imported into the test evaluation scripts (Table 5-16) in order to verify proper calculation of Ergun's minimum fluidization velocity (Equation 4.4.5). The dependent variable in Ergun's formula is U_f, which can be solved for by the quadratic formula:

$$AU_f^2 + BU_f + C = 0 \tag{5.4.9}$$

$$U_f = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{5.4.10}$$

Equation 5.4.5 was rearranged to form the constants A, B, and C, defined in Equation 5.4.9, which are evaluated in Table 5-16. The final lines in Table 5-16 compare the fluidization velocity calculated by Ergun's equation to that calculated by DRSPALL for the given input conditions. The relative difference evaluated to 1.56E-14. This small relative difference is less than 1E-4, so **Acceptance Criterion 4-11** (Section 5.4.6.3) is met.

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Table 5-16– Ergun solution for minimum fluidization velocity U_f.

Parameter	Value	Units
run time	1.25E+02	sec
gas density	4.47E+00	kg/m^3
porosity	5.75E-01	
waste density	2.65E+03	kg/m^3
gas viscosity	8.93E-06	Pa sec
particle diameter	1.00E-03	m
shape factor	2.50E-01	
gravity	9.81E+00	m/sec^2
a	9.21E+06	
b	2.68E+06	
c	-1.45E+06	
b^2-4ac	6.07E+13	
Ergun fluidization velocity	**0.27732372**	**m/s**
DRSPALL fluidization velocity	**0.27732372**	**m/s**
Relative difference	**1.56E-14**	

5.4.7.3.3 Verification of fluidization time

The evaluation script calculation of the fluidization time is shown in Table 5-17. For the given conditions, the fluidization time using parameters from run time = 124.6727 sec was t_f = 0.667 seconds. For comparison, the fluidization time, t_f provided in output file *drs_124_tc41_fluidization_time.dat* for zone 115 is 0.665 sec (Figure 5-18).

Confirmation of proper implementation of t_f in DRSPALL is possible by examining the amount of time required to completely fluidize zone 115 that started to fluidize near run time = 124.6727 sec. The reporting frequency in *drs_124_tc41_fluidization.dat* is not sufficient to capture both the beginning and ending of fluidization for zone 115, but the report of fraction fluidized at two times may be used to extrapolate an approximate fluidization time. This strategy is shown in the lower half of Table 5-17, with runtime #1 and runtime #2 representing the two selected run time reports from which the fluidization time is extrapolated. The projected fluidization time from this coarse method is 0.646 sec. This compares favorably with the values calculated by an independent solution (t_f = 0.667 sec) and from output file *drs_124_tc41_fluidization_time.dat* (Figure 5-18, zone 115, t_f = 0.665).

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Table 5-17– Independent solution for fluidization time, t_f.

Parameter	Value	Units
run time	124.6727	sec
radius to center of first intact cell	0.33769606	m
superficial gas velocity	0.50661883	m/sec
fluidization time	**0.66656832**	**sec**
From drs_124_tc41_fluidization.dat		
runtime #1	124.67264	sec
fraction fluidized #1	0	
runtime #2	124.67277	sec
fraction fluidized #2	0.0002	
projected fluidization time	**0.64604225**	**sec**

```
DRSPALL/Test/Output/Linux_124/drs_124_tc41_fluidization_time.dat
Program DR_SPALL - WIPP PA 2003
ASCII Output file for Test Case #4

 Zone     Fluidization Time
  71      4.6455952686076E-01
  72      2.9282307302072E-01
     …lines deleted…
 114      5.2535536408641E-01
 115      6.6528440246980E-01
 116      4.0037583698628E-01
     …lines deleted…
 311      1.2602353319808E+00
 312      1.3002073612996E+00
```

Figure 5-18 Fluidization time values from *drs_124_tc41_fluidization_time.dat*.

5.4.7.3.4 Verification of drilling and spall volumes and masses

The evaluation script calculations of waste volumes and masses removed from the repository due to drilling and spall (failure and fluidization) are shown in Table 5-18. The table also gives the values that were extracted from the diagnostics file and the output CAMDAT file. The difference in CAVRAD0 between the diagnostics and CAMDAT files is due the precision in the displayed number not the actual value. The maximum relative difference evaluated to 4.59E-06 for SPLMASS. This small relative difference is less than 1E-4, so **Acceptance Criterion 4-12** (Section 5.4.6.3) is met.

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Table 5-18– Drilling and spall volumes and masses from output CAMDAT file.

CAMDAT Variable	Description	Diagnostics File	Output CAMDAT File	Evaluation Script Calculation	Relative Difference
CAVRAD0	Initial pseudo-cavity radius	0.1378	0.11000814	0.110008137483	2.29E-08
CUTMASS	Cuttings mass	260.78	260.77912	260.778344755	2.97E-06
TOTMASS	Total mass	835.98	835.97639	835.978255779	2.23E-06
SPLMASS	Spall mass	575.2	575.19727	575.199911024	4.59E-06
SPL2MASS	Incremental spall mass	802.61	802.6102	802.608306238	2.36E-06
CUTVOLEQ	Equivalent uncompacted cuttings volume	0.65605	0.65604809	0.656046150326	2.96E-06
TOTVOLEQ	Equivalent uncompacted total volume	2.1031	2.1030853	2.10308995165	2.21E-06
SPLVOLEQ	Equivalent uncompacted spall volume	1.447	1.4470372	1.44704380132	4.56E-06
SPLVOL2EQ	Equivalent uncompacted incremental spall volume	2.0191	2.0191452	2.01914039305	2.38E-06

5.4.7.4 Expulsion of Disaggregated Waste Material

Excerpts from the expulsion output file (as formatted by Excel) show data at various run times as follows:

a) Table 5-19 shows data near the time of penetration (run time = 33.2 to 34.8 sec).

b) Table 5-20 shows data exhibiting early waste expulsion (run time = 113.5 to 115.3 sec).

c) Table 5-21 shows late time waste expulsion data approaching steady conditions (run time = 405.2 to 406.6 sec).

5.4.7.4.1 Near bit penetration

Table 5-19 shows the expulsion data at several times near bit penetration at 33.9 sec. Prior to bit penetration, the logical variable Repository Penetrated = "F" (false), and no zones have been removed from the repository. Also, all of the waste mass accounting variables (i.e., total waste in well) are zero, and the waste position in the well is -653 m, representing the well bottom. After bit penetration, the number of zones removed increases monotonically due to drilling. The drill bit must completely penetrate a zone before that zone is removed from the repository, so there is a time lag between bit penetration (33.9 sec) and the removal of the first zone (34.5 sec). Mass Waste Removed is the sum of Waste in Store + Total Waste In Well + Waste Mass Ejected. Waste Mass Ejected is still zero since it has not had time to transport 653 m to the land

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surface, and Waste Position In Well shows that the location of the waste front moves upward with time.

5.4.7.4.2 Early waste expulsion at surface

Table 5-20 shows the expulsion data near the time of the first arrival of waste solids at the land surface. Note that the position of the waste front in the well approaches z = 0 with time, and waste is first expelled at the surface at about 114.7 seconds. The Waste Mass Ejected variable reflects a time integral at the wellbore outlet, and the leading "tail" of the waste causes this variable to compute small but nonzero releases prior to the arrival of the "front" defined by Waste Position in Well. The mass balance error in this table is defined as the absolute value of [Mass Waste Removed – (Waste In Store + Total Waste In Well + Waste Mass Ejected)] / Mass Waste Removed.

Table 5-19– Excerpt from *drs_124_tc41_expulsion.dat* near the time of penetration.

Runtime (sec)	Repository Penetrated (T/F)	Zones Removed ( )	Mass Waste Removed (kg)	Waste In Store (kg)	Total Waste In Well (kg)	Waste Mass Ejected (kg)	Waste Position In Well (m)	Mass Balance Error ( )
33.20878	F	0	0.0000000E+00	0 0000000E+00	0.0000000E+00	0 0000000E+00	-653 0	0.0000E+00
33.37025	F	0	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	-653.0	0.0000E+00
33.53172	F	0	0.0000000E+00	0.0000000E+00	0.0000000E+00	0 0000000E+00	-653 0	0 0000E+00
33.69319	F	0	0 0000000E+00	0.0000000E+00	0 0000000E+00	0 0000000E+00	-653.0	0.0000E+00
33.85467	T	0	0.0000000E+00	0.0000000E+00	0 0000000E+00	0.0000000E+00	-653.0	0.0000E+00
34.01614	T	0	0.0000000E+00	0.0000000E+00	0 0000000E+00	0.0000000E+00	-653.0	0.0000E+00
34 17761	T	0	0 0000000E+00	0.0000000E+00	0 0000000E+00	0.0000000E+00	-653.0	0.0000E+00
34.33908	T	0	0.0000000E+00	0.0000000E+00	0 0000000E+00	0.0000000E+00	-653 0	0.0000E+00
34.50055	T	1	1 7339102E-01	1 1157058E-01	6.1820442E-02	0.0000000E+00	-65ı 0	ı.2806E-ı5
34.66203	T	1	1 7339102E-01	6.0555936E-02	1.1283509E-01	0 0000000E+00	-649 0	8.0038E-16
34.82350	T	1	1.7339102E-01	3.2726283E-02	1.4066474E-01	0.0000000E+00	-648.0	4.3220E-15

Table 5-20– Excerpt from *drs_124_tc41_expulsion.dat* near the time of early waste expulsion at land surface.

Runtime (sec)	Repository Penetrated (T/F)	Zones Removed (-)	Mass Waste Removed (kg)	Waste In Store (kg)	Total Waste In Well (kg)	Waste Mass Ejected (kg)	Waste Position In Well (m)	Mass Balance Error (-)
113.53477	T	81	4.3847677E+01	2.9076403E-04	4.3831036E+01	1.6349750E-02	-29.1	6.4430E-13
113.69626	T	81	4.3847677E+01	2.2431259E-04	4.3826315E+01	2.1137832E-02	-25.1	6.4511E-13
113.85776	T	81	4.3847677E+01	1.7294702E-04	4.3820416E+01	2.7087633E-02	-21.0	6.4657E-13
114.01926	T	81	4.3847677E+01	1.3326515E-04	4.3813131E+01	3.4412466E-02	-17.0	6.5338E-13
114.18076	T	81	4.3847677E+01	1.0262702E-04	4.3804226E+01	4.3347826E-02	-12.0	6.5224E-13
114.34226	T	81	4.3847677E+01	7.8985240E-05	4.3793448E+01	5.4150008E-02	-6.0	6.5516E-13
114.50376	T	81	4.3847677E+01	6.0752859E-05	4.3780522E+01	6.7093859E-02	-2.0	6.6116E-13
114.66526	T	81	4.3847677E+01	4.6700489E-05	4.3765160E+01	8.2469659E-02	0.0	6.6845E-13
114.82676	T	81	4.3847677E+01	3.5876280E-05	4.3747062E+01	1.0057913E-01	0.0	6.7055E-13
114.98825	T	81	4.3847677E+01	2.7543675E-05	4.3725919E+01	1.2173065E-01	0.0	6.6780E-13
115.14975	T	81	4.3847677E+01	2.1133045E-05	4.3701422E+01	1.4623382E-01	0.0	6.6391E-13
115.31125	T	81	4.3847677E+01	1.6204108E-05	4.3673267E+01	1.7439348E-01	0.0	6.5403E-13

Information Only

5.4.7.4.3 Late time waste expulsion

Table 5-21 shows expulsion data at late time (run time > 405 sec) showing steady state behavior with a total of 301 zones removed, corresponding to 836.0 kg of waste removed from the repository and an identical 836.0 kg of waste expelled to the surface. The mass balance error is reported as 6.73E-12.

5.4.7.4.4 Summary

The acceptance criteria for the expulsion of disaggregated waste material is confirmed by examining *drs_124_tc41_expulsion.dat* (excerpts of which are shown in Table 5-19, Table 5-20, and Table 5-21). Waste Position In Well decreases from -653 to 0, so **Acceptance Criterion 4-13** (Section 5.4.6.4) is met. Waste Mass Ejected is very small (< 0.08 kg) before z = 0 (when Waste Position in Well reaches 0), then it monotonically increases, confirming the **Acceptance Criterion 4-14** (Section 5.4.6.4) is met. The Mass Balance Error is small (≤ 6.73E-12) for all times, so **Acceptance Criterion 4-15** (Section 5.4.6.4) is met.

Table 5-21– Excerpt from *drs_124_tc41_expulsion.dat* at late time nearing steady conditions.

Runtime (sec)	Repository Penetrated (T/F)	Zones Removed (-)	Mass Waste Removed (kg)	Waste In Store (kg)	Total Waste In Well (kg)	Waste Mass Ejected (kg)	Waste Position In Well (m)	Mass Balance Error (-)
405.15887	T	301	8.3597639E+02	5.9184467E-41	-6.6503774E-11	8.3597639E+02	-653.0	6.7276E-12
405.32258	T	301	8.3597639E+02	5.5069310E-41	-6.6503774E-11	8.3597639E+02	-653.0	6.7276E-12
405.48630	T	301	8.3597639E+02	5.1240279E-41	-6.6503774E-11	8.3597639E+02	-653.0	6.7276E-12
405.65001	T	301	8.3597639E+02	4.7677480E-41	-6.6503774E-11	8.3597639E+02	-653.0	6.7276E-12
405.81373	T	301	8.3597639E+02	4.4362403E-41	-6.6503774E-11	8.3597639E+02	-653.0	6.7276E-12
405.97745	T	301	8.3597639E+02	4.1277824E-41	-6.6503774E-11	8.3597639E+02	-653.0	6.7276E-12
406.14117	T	301	8.3597639E+02	3.8407716E-41	-6.6503774E-11	8.3597639E+02	-653.0	6.7276E-12
406.30490	T	301	8.3597639E+02	3.5737168E-41	-6.6503774E-11	8.3597639E+02	-653.0	6.7276E-12
406.46862	T	301	8.3597639E+02	3.3252304E-41	-6.6503774E-11	8.3597639E+02	-653.0	6.7276E-12
406.63235	T	301	8.3597639E+02	3.0940214E-41	-6.6503774E-11	8.3597639E+02	-653.0	6.7276E-12

5.4.7.5 External Interfaces

The output CAMDAT file from Case 4.1 was successfully examined with GROPECDB in the analysis presented above (Section 5.4.7.1), confirming that the output file is in the proper CAMDAT file format, so **Acceptance Criterion 4-17** (Section 5.4.6.5) is met.

Case 4.2 is the only test case that reads data from an input CAMDAT file. The GROPECDB excerpt of all properties of the input CAMDAT file for Case 4.2 is shown in Figure 5-19. The input control file for Case 4.2 is shown in Figure 5-20. Many of the inputs are from properties on the input CAMDAT file; some values are explicitly specified; and some are set to DEFAULT. The excerpt of the diagnostics file for Case 4.2 is shown in Figure 5-21. An examination of this file confirms that the DRSPALL parameters are being read correctly from the input control file and the input CAMDAT file.

Information Only

```
CAMDAT File:  /home/run_mast/Test_Run/DRSPALL/DRSPALL/Input/drs_tc42_ms.cdb

  PROPERTIES

  Element Block 1)     "GLOBAL  "      1=ID      1 elements (1..1)

  Element Block 2)     "DRSPALL "      2=ID      0 elements
    SURFELEV     REPOSTOP     REPOSTCK     DRZTCK       DRZPERM      REPOTRAD
   1.0373E+03   3.8531E+02   1.4200E+00   8.5000E-01   1.0000E-15   1.9200E+01
    REPIPRES     FFPORPRS     FFSTRESS     REPIPOR      REPIPERM     BIOTBETA
   1.4800E+07   1.4800E+07   1.4900E+07   5.7500E-01   1.7000E-13   1.0000E+00
    POISRAT      COHESION     FRICTANG     TENSLSTR     PARTDIAM     GASBSDEN
   3.8000E-01   1.3000E+05   4.5800E+01   1.2000E+05   1.0000E-03   8.2000E-02
    GASVISCO     INITMDEN     MUDVISCO     ANNUROUG     MUDSOLMX     MUDSOLVE
   8.9339E-06   1.2100E+03   1.1000E-02   3.9400E-04   6.1500E-01  -1.5000E+00
    BITDIAM      PIPEDIAM     COLRDIAM     PIPEID       COLRLNGT     DRILRATE
   3.1115E-01   1.1430E-01   2.0320E-01   9.7180E-02   1.8290E+02   4.4450E-03
    INITBAR      MUDPRATE     DDZTHICK     DDZPERM      STPDVOLR     STPPVOLR
   1.5000E-01   2.0181E-02   1.6000E-01   1.0000E-14   1.0000E+03   1.0000E+03
    STPDTIME     SHAPEFAC     FRCHBETA     CHARLEN      PIPEROUG     EXITPLEN
   1.0000E+03   5.5000E-01   1.1500E-06   2.0000E-02   5.0000E-05   0.0000E+00
    EXITPDIA     MAXPPRES
   2.0320E-01   2.7500E+07

  Element Block 3)     "REFCON  "      3=ID      0 elements
    PI           GRAVACC
   3.1416E+00   9.8067E+00

  Element Block 4)     "BLOWOUT "      4=ID      0 elements
    RGAS         TREPO        RHOS
   4.1160E+03   3.0000E+02   2.6500E+03

  Element Block 5)     "BRINESAL"      5=ID      0 elements
    COMPRES
   3.1000E-10
```

Figure 5-19 Properties from input CAMDAT file *drs_tc42_ms.cdb* for Case 4.2.

The diagnostics file echoes the input file (not shown in Figure 5-21), then echoes the input file with numeric values replacing all CAMDAT properties and DEFAULT values, then lists the parameters used in the run. Note that under "Parameters used in this run", the parameters are listed in order within category in the input control file, as explained in the DRSPALL user's manual (Kicker, 2021). The parameter identifier in the input control file is just a comment and may not match the identifier in the diagnostics file.

Information Only

```
REPOSITORY
Land Elevation                    (m):  DRSPALL SURFELEV
Repository top                    (m):  DRSPALL REPOSTOP
Total Thickness                   (m):  0.0
DRZ Thickness                     (m):  DRSPALL DRZTCK
DRZ Permeability                (m^2):  DRSPALL DRZPERM
Outer Radius                      (m):  1.9200E+01
Initial Gas Pressure              (m):  DRSPALL REPIPRES
Far-Field In-Situ Stress          (m):  DRSPALL FFSTRESS

WASTE
Porosity                          (-):  DRSPALL REPIPOR
Permeability                    (m^2):  DRSPALL REPIPERM
Forchheimer Beta                  (-):  DRSPALL FRCHBETA
Biot Beta                         (-):  DRSPALL BIOTBETA
Poisson's Ratio                   (-):  DRSPALL POISRAT
Cohesion                         (Pa):  DRSPALL COHESION
Friction Angle                  (deg):  DRSPALL FRICTANG
Tensile Strength                 (Pa):  DRSPALL TENSLSTR
Lt                                (m):  0.02
Particle Diameter                 (m):  DRSPALL PARTDIAM
Gas Viscosity                  (Pa-s):  DRSPALL GASVISCO

MUD
Density                      (kg/m^3):  DRSPALL INITMDEN
Viscosity                      (Pa-s):  DRSPALL MUDVISCO
Wall Roughness Pipe               (m):  DRSPALL PIPEROUG
Wall Roughness Annulus            (m):  DRSPALL ANNUROUG
Max Solids Vol. Frac.          (Pa-s):  DRSPALL MUDSOLMX
Solids Viscosity Exp.          (Pa-s):  DRSPALL MUDSOLVE

WELLBORE/DRILLING
Bit Diameter                      (m):  DRSPALL BITDIAM
Pipe Diameter                     (m):  DRSPALL PIPEDIAM
Collar Diameter                   (m):  DRSPALL COLRDIAM
Pipe Inside Diameter              (m):  DRSPALL PIPEID
Collar Length                     (m):  DRSPALL COLRLNGT
Exit pipe Length                  (m):  DRSPALL EXITPLEN
Exit Pipe Diameter                (m):  DRSPALL EXITPDIA
Drilling Rate                   (m/s):  DRSPALL DRILRATE
Bit Above Respository(init.)      (m):  DRSPALL INITBAR
Mud Pump Rate                 (m^3/s):  DRSPALL MUDPRATE
Max Pump Pressure                (Pa):  27.5d6
DDZ Thickness                     (m):  DRSPALL DDZTHICK
DDZ Permeability                (m^2):  DRSPALL DDZPERM
Stop Drill Exit Vol Rate      (m^3/s):  DRSPALL STPDVOLR
Stop Pump Exit Vol Rate       (m^3/s):  DRSPALL STPPVOLR
Stop Drilling Time                (s):  DRSPALL STPDTIME
```

Figure 5-20 Input control file *drs_v122_tc42.drs* for Case 4.2.

Information Only

```
COMPUTATIONAL
Spherical/Cylindrical          (S/C): S
Allow Fluidization             (Y/N): Y
Max Run Time                     (s): 1.0
Respository Cell Length          (m): 0.002
radius, Growth rate            (m,-): 0.5, 1.0 !V1.22 growth always 1, was 1.01
Wellbore Cell Length             (m): 1.0
wellbore Zone Growth Rate        (-): 1.0  !V1.22 growth always 1, was 1.01
First wellbore Zone              (-): 10
Well Stability factor            (-): 0.02
Repository Stability factor      (-): 5.0
Mass Diffusion factor            (-): 0.002
Momentum Diffusion factor        (-): 0.002

VALIDATION
Validation Test Case             (-): 4.2

PARAMETERS
Pi                               (-): REFCON   PI
Atmospheric Pressure            (Pa): 1.0170E+05
gravity                      (m/s^2): REFCON   GRAVACC
Gas Constant                (J/kg K): BLOWOUT  RGAS
Repository Temperature           (K): BLOWOUT  TREPO
Water Compressibility         (1/Pa): 12.4e-10
Waste Density               (kg/m^3): BLOWOUT  RHOS
Salt Density                (kg/m^3): 2.1800E+3
Shape Factor                     (-): DRSPALL SHAPEFAC
Tensile Velocity               (m/s): DEFAULT
Bit Nozzle Number                (-): DEFAULT
Bit Nozzle Diameter              (m): DEFAULT
Choke Efficiency                 (-): DEFAULT
```

Figure 5-20 Input control file *drs_v122_tc42.drs* for Case 4.2. (Continued)

When a CAMDAT property is referenced in the input control file, its value matches the value listed in the diagnostics file with one exception: Exit Pipe Diameter under "Parameters used in this run". When a value is explicitly specified in the input control file, the value matches the value listed in the diagnostics file with two exceptions: Total Thickness and First Wellbore Zone under "Parameters used in this run". Note that the "Input Echo (with numeric values)" always lists the input values. The calculations below apply to "Parameters used in this run" only.

Exit Pipe Diameter is read from CAMDAT property DRSPALL:EXITPDIA (0.2032), but there is no exit pipe, i.e., the Exit Pipe Length (DRSPALL:EXITPLEN) is zero. The Exit Pipe Diameter is overwritten with the annulus diameter. The annulus diameter is calculated with the Bit Diameter (DRSPALL:BITDIAM) = 0.31115 and Pipe Diameter (DRSPALL:PIPEDIAM) = 0.11430. Thus, the Exit Pipe Diameter is calculated as follows:

$$ExitPipeDiameter = 2\sqrt{\frac{\pi(BitDiameter/2)^2 - \pi(PipeDiameter/2)^2}{\pi}} = 0.2894 \quad (5.4.11)$$

Information Only

```
Input Echo (with numeric values)
 -------------------------------
REPOSITORY
  surfaceElevation              :  1.037300E+03   !!DRSPALL SURFELEV
  repositoryTop                 :  3.853100E+02   !!DRSPALL REPOSTOP
  repositoryThickness           : 0.0
  dRZThickness                  :  8.500000E-01   !!DRSPALL DRZTCK
  dRZPerm                       :  1.000000E-15   !!DRSPALL DRZPERM
  repositoryOuterRadius         : 1.9200E+01
  repositoryInitialPressure     :  1.480000E+07   !!DRSPALL REPIPRES
  farFieldStress                :  1.490000E+07   !!DRSPALL FFSTRESS
WASTE
  repositoryInitialPorosity     :  5.750000E-01   !!DRSPALL REPIPOR
  repositoryInitialPerm         :  1.700000E-13   !!DRSPALL REPIPERM
  forchBeta                     :  1.150000E-06   !!DRSPALL FRCHBETA
  biotBeta                      :  1.000000E+00   !!DRSPALL BIOTBETA
  poissonsRatio                 :  3.800000E-01   !!DRSPALL POISRAT
  cohesion                      :  1.300000E+05   !!DRSPALL COHESION
  frictionAngle                 :  4.580000E+01   !!DRSPALL FRICTANG
  tensileStrength               :  1.200000E+05   !!DRSPALL TENSLSTR
  Lt                            : 0.02
  particleDiameter              :  1.000000E-03   !!DRSPALL PARTDIAM
  gasViscosity                  :  8.933900E-06   !!DRSPALL GASVISCO
MUD
  initialMudDensity             :  1.210000E+03   !!DRSPALL INITMDEN
  mudViscosity                  :  1.100000E-02   !!DRSPALL MUDVISCO
  wallRoughness(1)              :  5.000000E-05   !!DRSPALL PIPEROUG
  wallRoughness(2)              :  3.940000E-04   !!DRSPALL ANNUROUG
  mudSolidsMax                  :  6.150000E-01   !!DRSPALL MUDSOLMX
  mudSolidsViscosityExponent    : -1.500000E+00   !!DRSPALL MUDSOLVE
WELL
  bitDiameter                   :  3.111500E-01   !!DRSPALL BITDIAM
  pipeDiameter                  :  1.143000E-01   !!DRSPALL PIPEDIAM
  collarDiameter                :  2.032000E-01   !!DRSPALL COLRDIAM
  pipeInsideDiameter            :  9.718000E-02   !!DRSPALL PIPEID
  collarLength                  :  1.829000E+02   !!DRSPALL COLRLNGT
  exitPipeLength                :  0.000000E+00   !!DRSPALL EXITPLEN
  exitPipeDiameter              :  2.032000E-01   !!DRSPALL EXITPDIA
  drillingRate                  :  4.445000E-03   !!DRSPALL DRILRATE
  initialBitAboveRepository     :  1.500000E-01   !!DRSPALL INITBAR
  mudPumpRate                   :  2.018100E-02   !!DRSPALL MUDPRATE
  maxPumpPressure               : 27.5D6
  dDZThickness                  :  1.600000E-01   !!DRSPALL DDZTHICK
  dDZPerm                       :  1.000000E-14   !!DRSPALL DDZPERM
  stopDrillingExitVolRate       :  1.000000E+03   !!DRSPALL STPDVOLR
  stopPumpingExitVolRate        :  1.000000E+03   !!DRSPALL STPPVOLR
  stopDrillingTime              :  1.000000E+03   !!DRSPALL STPDTIME
COMPUTATIONAL
  geometry                        S
  allowFluidization               Y
  maxTime                       : 1.0
  initialReposZoneSize          : 0.002
  radius,growthRate             : 0.5, 1.0 !V1.22 GROW
  initialWellZoneSize           : 1.0
  wellGRowthRate                : 1.0
  firstWellZone                 : 10
  wellStabilityFactor           : 0.02
```

Figure 5-21 Excerpts from *drs_124_tc42.dbg*, diagnostics file for Case 4.2.

Information Only

```
  reposStabilityFactor          : 5.0
  massDiffusionFactor           : 0.002
  momentumDiffusionFactor       : 0.002
VALIDATION
  ValidationTestCase            : 4.2
PARAMETER
  Pi                            :  3.141593E+00   !!REFCON PI
  AtmosphericPressure           : 1.0170E+05
  gravity                       :  9.806650E+00   !!REFCON GRAVACC
  GasConstant                   :  4.116000E+03   !!BLOWOUT RGAS
  ReposTemp                     :  3.000000E+02   !!BLOWOUT TREPO
  WaterCompressibility          : 12.4E-10
  WasteDensity                  :  2.650000E+03   !!BLOWOUT RHOS
  SaltDensity                   : 2.1800E+3
  ShapeFactor                   :  5.500000E-01   !!DRSPALL SHAPEFAC
  TensileVelocity               :  1.000000E+03   !!DEFAULT
  BitNozzleNumber               :  3.000000E+00   !!DEFAULT
  BitNozzleDiameter             :  1.111250E-02   !!DEFAULT
  ChokeEfficiency               :  9.000000E-01   !!DEFAULT
  VALIDATION TEST CASE:  4  SUBCASE:  2
*******************************************************************************
PARAMETERS USED IN THIS RUN
*******************************************************************************

REPOSITORY
Land Elevation                    (m):  1.0373E+03
Repository top                    (m):  3.8531E+02
Total Thickness                   (m):  1.3976E+00
DRZ Thickness                     (m):  8.5000E-01
DRZ Permeability                (m^2):  1.0000E-15
Outer Radius                      (m):  1.9200E+01
Initial Gas Pressure              (m):  1.4800E+07
Far-Field In-Situ Stress          (m):  1.4900E+07

WASTE
Porosity                          (-):  5.7500E-01
Permeability                    (m^2):  1.7000E-13
Forchheimer Beta                  (-):  1.1500E-06
Biot Beta                         (-):  1.0000E+00
Poissons   Ratio                  (-):  3.8000E-01
Cohesion                         (Pa):  1.3000E+05
Friction Angle                  (deg):  4.5800E+01
Tensile Strength                 (Pa):  1.2000E+05
Failure Characteristic Length     (m):  2.0000E-02
Particle Diameter                 (m):  1.0000E-03
Gas Viscosity                  (Pa-s):  8.9339E-06

MUD
Density                      (kg/m^3):  1.2100E+03
Viscosity                      (Pa-s):  1.1000E-02
Wall Roughness Pipe               (m):  5.0000E-05
Wall Roughness Annulus            (m):  3.9400E-04
Máx Solids Vol. Frac.          (Pa-s):  6.1500E-01
Solids Viscosity Exp.          (Pa-s): -1.5000E+00
```

Figure 5-21 Excerpts from *drs_124_tc42.dbg*, diagnostics file for Case 4.2. (Continued)

Information Only

```
WELLBORE/DRILLING
Bit Diameter                    (m):  3.1115E-01
Pipe Diameter                   (m):  1.1430E-01
Collar Diameter                 (m):  2.0320E-01
Pipe Inside Diameter            (m):  9.7180E-02
Collar Length                   (m):  1.8290E+02
Exit Pipe Length                (m):  0.0000E+00
Exit Pipe Diameter              (m):  2.8940E-01
Drilling Rate                 (m/s):  4.4450E-03
Bit Above Respository           (m):  1.5000E-01
Mud Pump Rate               (m^3/s):  2.0181E-02
Max Pump Pressure              (Pa):  2.7500E+07
DDZ Thickness                   (m):  1.6000E-01
DDZ Permeability              (m^2):  1.0000E-14
Stop Drill Exit Vol Rate    (m^3/s):  1.0000E+03
Stop Pump Exit Vol Rate     (m^3/s):  1.0000E+03
Stop Drilling Time              (s):  1.0000E+03

COMPUTATIONAL
Spherical/Cylindrical         (S/C): S
Allow Fluidization          (Y/N/A): Y
Max Run Time                    (s):  1.0000E+00
Respository Cell Length         (m):  2.0000E-03
Radius, Growth Rate           (m,-):  0.500  1.000
Wellbore Cell Length            (m):  1.0000E+00
Wellbore Cell Growth Rate       (-):  1.0000E+00
First Wellbore Zone             (-): 651
Well Stability factor           (-):  2.0000E-02
Repository Stability factor     (-):  5.0000E+00
Mass Diffusion factor           (-):  2.0000E-03
Momentum Diffusion factor       (-):  2.0000E-03

VALIDATION
Validation Test Case            (-): 4.2
Initial Cavity Radius           (-):  0.0000E+00
Minimum Characteristic Vel      (-):  1.0000E-06
Minimum Number Zones/Lt         (-):   5

PARAMETERS
Pi                              (-):  3.1416E+00
Atmospheric Pressure           (Pa):  1.0170E+05
gravity                     (m/s^2):  9.8067E+00
Gas Constant                (J/kg K):  4.1160E+03
Repository Temperature          (K):  3.0000E+02
Reference gas Density       (kg/m^3):  8.2362E-02
Water Compressibility        (1/Pa):  1.2400E-09
Waste Density               (kg/m^3):  2.6500E+03
Salt Density                (kg/m^3):  2.1800E+03
Shape Factor                    (-):  5.5000E-01
Tensile Velocity              (m/s):  1.0000E+03
Bit Nozzle Number               (-):  3.0000E+00
Bit Nozzle Diameter             (m):  1.1112E-02
Choke Efficiency                (-):  9.0000E-01
```

Figure 5-21 Excerpts from *drs_124_tc42.dbg*, diagnostics file for Case 4.2. (Continued)

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Total Thickness is specified as 0.0 by the user, so it is calculated internally from the initial repository height (H = constant 3.96), the uncompacted waste porosity (φ_u = constant 0.85) and the input initial waste porosity (φ_i = 0.575 = DRSPALL:REPIPOR) as follows:

$$T_{rep} = H\left(\frac{1-\varphi_u}{1-\varphi_i}\right) = 3.96\left(\frac{1-0.85}{1-0.575}\right) = 1.3976 \qquad (5.4.12)$$

First Wellbore Zone is a flag indicating whether downward flow inside of the pipe is modeled. If the input value is greater than zero (only the flow up the annulus is modeled), First Wellbore Zone is set to the index of the computational cell at the bottom of wellbore, or 651 for this problem.

Tensile Velocity, Bit Nozzle Number, Bit Nozzle Diameter, and Choke Efficiency request DEFAULT values in the input control file. The default values as specified in the DRSPALL user's manual (Kicker, 2021) are: 1000.0, 3.0, 0.011112, and 0.9, respectively.

Initial Cavity Radius, Min Characteristic Velocity and Min Number Zones/Lt are listed in the diagnostics file under "Parameters used in this run", but not in the input control file. These are optional input parameters that were not specified in the input control file and were set to default values.

Comparisons of the input CAMDAT file, and input control file with the excerpt from the diagnostics file indicated that all parameters were properly set to CAMDAT property values, set explicitly, or set to default values as directed by the input control file. This confirms that **Acceptance Criterion 4-16** (Section 5.4.6.5) is met.

5.4.8 Conclusions

The discussion in Section 5.4.7 verifies that all acceptance criteria (Section 5.4.6) for this test case are met. Thus, this test case passes and validates the satisfactory implementation of Functional Requirements R.3, R.4, R.5, and R.6 and External Interface Requirements R.7, R.8, and R.9.

The successful completion of this test case verifies that DRSPALL demonstrates the correct, expected behavior for the functionality examined. Coupling data shows that the gas transported from the repository is successfully accounted for in the wellbore and ejected at the land surface. An analysis of the stress data indicates proper implementation of the stress equations and failure logic. A similar analysis of the fluidization data reveals proper calculation of the fluidization velocity and mobilization of solids by fluidized bed theory. The waste expulsion analysis demonstrates proper accounting for waste solids drilled or spalled from the repository, transported up the wellbore, and ejected at the land surface. Finally, (1) examination of the diagnostic file indicating correct specification of input parameters and (2) proper execution of the GROPECDB utility verifies the external interfaces to CAMDAT files.

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5.5 Test Case #5 – Wellbore Flow Verification

5.5.1 Test Objective

The objective of this test case is to verify the wellbore flow model against an independent computational fluid dynamics model FLUENT (2003). Details of the FLUENT runs are provided in Section 5.5.7.

Correctly performing this test case validates the satisfactory implementation of Functional Requirement R.1.

5.5.2 Problem Description

This test case will focus on the wellbore model, and thus decouple its behavior from the repository. Known boundary conditions will be imposed to observe the model's response to steady flow of:

1. mud
2. mud and gas
3. mud, gas, and solids

Independent calculations will be run in parallel with the commercial computational fluid dynamics code FLUENT (2003).

The problem domain is the wellbore annulus in a typical WIPP intrusion. The geometric description of the wellbore is given in the *Parameter Justification Report for DRSPALL* (Hansen et al. 2003), and default values are used for most DRSPALL parameters. A schematic of the domain is shown in Figure 5-22.

5.5.2.1 Boundary Conditions

Boundary conditions are set to simulate a WIPP intrusion scenario, however the bottom of the wellbore is decoupled from the repository and controlled directly to facilitate comparison between DRSPALL and the FLUENT code. The inlet boundary to the wellbore annulus is a constant volumetric flow rate. The outlet boundary from the wellbore annulus is constant at atmospheric pressure, 0.1 MPa. Gas and solids are added at pre-determined mass flow rates at the lower boundary to the annulus.

5.5.2.2 Input Parameters

Input parameters for the wellbore domain represent a typical WIPP intrusion. Repository flow parameters are irrelevant since the domains are decoupled in this test case. There are several run-specific parameters such as mud density, mud pump rate, and gas/solids loading rate that vary among runs and are discussed below. The DRSPALL input files *drs_v122_tc51.drs* through *drs_v122_tc57.drs* are stored in CVS directory Test/Input.

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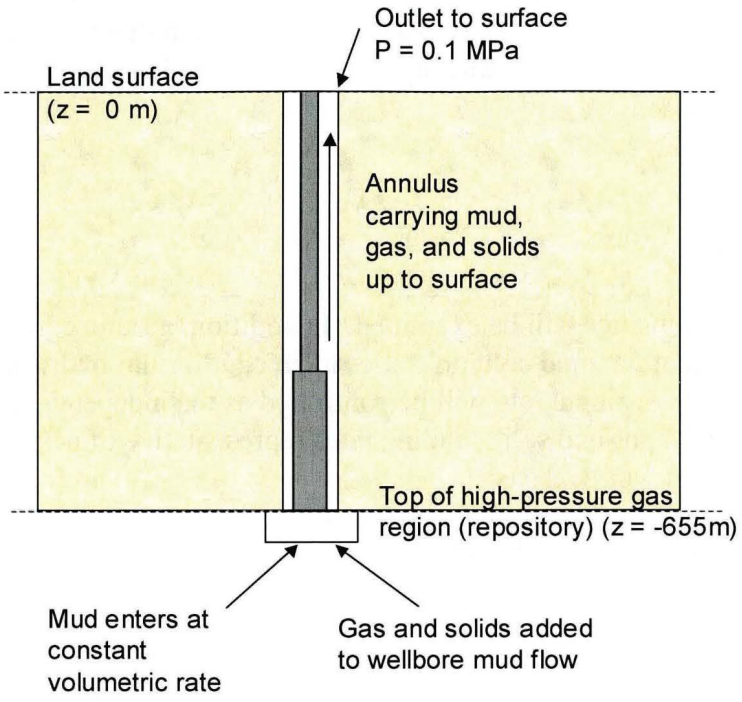

Figure 5-22 Schematic of wellbore flow test problem domain.

5.5.3 Analysis Method

Six runs will be executed under this test case. The run matrix is shown in

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Table 5-22. More detailed descriptions are given in the text that follows.

Steady-state runs. Steady state runs will be examined to establish that the steady pressure profiles in the wellbore are matched reasonably between DRSPALL and FLUENT. Three basic types of runs will be required:

1. Mud only
2. Mud and gas
3. Mud, gas, and solids

For mud only, two mud densities will be examined. In addition, a static case will be run with no mud pumping to assure that the mud column settles to an equilibrium hydrostatic distribution. For the mud and gas case, gas input rate will be controlled as the independent variable. For the three-phase run (Case 5.7), gas and solid loading rates representative of near-steady conditions in a WIPP spallings intrusion will be tested.

Specific test run information is given below.

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Table 5-22– Run conditions for FLUENT comparison.

Case	Mud Density, kg/m^3	Mud Flow Rate, m^3/s	Gas Flow Rate, kg/s	Solid Flow Rate, kg/s	Description
5.1	1210	0.02081	0	0	Static mud in wellbore
5.2	1210	0.02081	0	0	Mud-only, steady flow, nominal mud density
5.3	1380	0.02081	0	0	Mud-only, steady flow, high-end mud density
5.4	–	–	–	–	*Not used*
5.5	1210	0.02081	0.25	0	Steady mud flow, gas added to flow at low, constant rate
5.6	1210	0.02081	2.5	0	Steady mud flow, gas added to flow at medium, constant rate
5.7	1210	0.02081	2.5	2.5	Steady mud flow, gas added to flow at medium, constant rate; solids added at low constant rate

5.5.3.1 Case 5.1 – Static Mud in Wellbore

The mud pump will be turned off and the pressure distribution will be monitored to assure that it settles to a hydrostatic distribution. The boundaries at the pump inlet and annulus outlet will both be set to atmospheric pressure. No gas or solids will be added to the wellbore domain. Mud density will be set to the DRSPALL default value 1210 kg/m^3. DRSPALL is a transient code, and the initial pressure distribution in the wellbore is arbitrary. The objective of this seemingly simple test is to see whether DRSPALL will eventually arrive at a stable solution demonstrating the hydrostatic pressure distribution.

5.5.3.2 Case 5.2 – Mud-only, Steady Flow, Nominal Mud Density

Volumetric mud flow rate at the pump inlet and mud density will be set to the DRSPALL default values of 0.02081 m^3/sec and 1210 kg/m^3, respectively. No gas or solids will be added.

5.5.3.3 Case 5.3 – Mud-only, Steady Flow, High-end Mud Density

This test run is the same as Case 5.2, Section 5.5.3.2 above, except that the mud density is increased to ρ = 1380 kg/m^3, the highest value in its sampling range recommended in the *Parameter Justification Report for DRSPALL* (Hansen et al. 2003). The slightly higher density should lead to a proportionally higher pressure at the bottom of the well due to the weight of the mud column.

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5.5.3.4 Case 5.5 – Gas Added to Flow at Low, Constant Rate

This test run will add hydrogen gas to the flow stream at the bottom of the well. Mudflow rate and physical properties are set to defaults as in Case 5.2. The hydrogen mass flow rate is fixed at 0.25 kg/sec, a value representative of the gas flow rate into the wellbore through the DDZ just prior to bit penetration of the repository.

5.5.3.5 Case 5.6 – Gas Added to Flow at Medium, Constant Rate

This test run will add hydrogen gas to the flow stream at the bottom of the well. Mud flow and physical properties are set to defaults as in Case 5.2. The hydrogen mass flow rate = 2.5 kg/sec, a value representative of the gas flow rate into the wellbore during a blowout while the mud column is accelerating.

5.5.3.6 Case 5.7 – Gas Added to Flow at Medium, Constant Rate; Solids Added at Low, Constant Rate

This test run is the same as Case 5.6, Section 5.5.3.5, with gas flowing into the well bottom, except solids are also added. A solids loading rate of 2.5 kg/sec is selected to represent a slow, steady material failure case. In normal model executions where a spalling event occurs, this mass loading rate tends to spike early and diminish to zero. The constant rate was selected here for simplicity in implementation and comparison between models.

5.5.4 Test Procedure

DRSPALL is executed once for each of the six cases: Cases 5.1, 5.2, 5.3, 5.5, 5.6, and 5.7 (there is no Case 5.4).

DRSPALL generates a "wellbore" validation file for each case, but these files are not examined. Each output CAMDAT file is post-processed with GROPECDB (Feng, 2021a) to extract the pressure, fluid velocities and volume fraction profiles in the wellbore. The GROPECDB data are read in by the evaluation scripts for comparison with the corresponding data generated from FLUENT. The GROPECDB input command file is shown in Figure 5-23.

The following command lines run DRSPALL and GROPECDB for Case 5.1 (tc51). The other cases are similar:

```
./drspall ./Input/drs_v122_tc51.drs DRSPALL/Test/Output/Linux_124/drs_124_tc51.dbg
        CANCEL DRSPALL/Test/Output/Linux_124/drs_124_tc51.cdb
        > DRSPALL/Test/Output/Linux_124/drs_124_tc51.crt
./gropecdb DRSPALL/Test/Output/Linux_124/drs_124_tc51.cdb
        ./Input/drs_tc5_grope.inp
        DRSPALL/Test/Output/Linux_124/drs_124_tc51.gr  > x.x
```

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```
select block 1
select property INITMDEN GASBSDEN WASTDENS MUDPRATE
print property

!apg WELLGSVF is only needed for TC55-TC57
!apg WELLWSVF is only needed for TC57
select time 450.  !apg select final time step, may be <450
select block  4
select evar COORD WELLPRS WELLVEL WELLGSVF WELLWSVF
print evar

exit
```

Figure 5-23 GROPECDB input command file *drs_tc5_grope.inp*.

5.5.5 Input/Output Files

The DRSPALL input and output files for Test Case #5 are listed in Appendix A (Section 9).

5.5.6 Acceptance Criteria

This test will pass if the following are observed when comparing DRSPALL and FLUENT output:

- **Acceptance Criterion 5-1** — The fluid pressure agrees within 20% at wellbore positions 0.1 m and greater. Boundary effects in the bottom of the wellbore from positions < 0.1 m are excluded from this acceptance criterion.

- **Acceptance Criterion 5-2** — The volume fraction of gas in two- and three-phase runs (Cases 5.5, 5.6, 5.7) agrees within 0.02.

- **Acceptance Criterion 5-3** — The DRSPALL and FLUENT values for volume fraction of waste in the three-phase run (Case 5.7) agree within 25% at each well position.

- **Acceptance Criterion 5-4** — The DRSPALL and FLUENT values for velocity of the mixture agree within 35% at each well position. Analytical velocities will be used as the basis of comparison for Case 5.2 and 5.3. Case 5.1 is static, therefore, velocities should be near zero (< 1E-4).

Test Case #5 will pass if all criteria are satisfied. This test case will verify Functional Requirement R.1.

5.5.7 Test Results

Results for each case are presented individually in the following subsections. Results consist of graphical comparisons of pressure, fluid velocity and volume fractions as a function of wellbore position. The DRSPALL values are extracted from output CAMDAT file element variables WELLPRS (pressure), WELLVEL (fluid velocity), WELLGSVF (gas volume fraction),

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WELLWSVF (waste volume fraction), and COORD (wellbore position) for all elements in element block UP_WB (the wellbore annulus). The bottom of the wellbore is located at 0.0 and the land surface is located at 653 m. FLUENT actually solves the steady state problem. DRSPALL solves the transient problem for constant boundary conditions. DRSPALL cases were run until pressure and velocity maintained a relatively constant value, therefore run time varied for each subcase.

FLUENT runs were executed independently (Webb, 2003). FLUENT is a commercial computational fluid dynamics code. FLUENT solves conservation equations for the fluids and solids phases in the pipe using the Navier-Stokes equations assuming no-slip wall boundary conditions. The pressure drop is evaluated from the momentum equation using the calculated velocity profiles and the effective fluid viscosity including turbulence and wall roughness. Friction factors are not employed by FLUENT. It was run in 2-D cylindrical geometry for this test problem. Details of the FLUENT calculations are documented by Webb (2003).

5.5.7.1 Case 5.1 – Static with Nominal Mud Density

Results for Case 5.1 are summarized by the pressure and velocity profile comparisons shown in Figure 5-24. DRSPALL results are at 90 s because it takes some time for the code to settle to a steady pressure profile after the arbitrary starting profile. The results visually overlay, and are within the 20% error bounds, so **Acceptance Criterion 5-1** (Section 5.5.6) is met for this case. A simple hydrostatic model gives the expected bottomhole pressure as ρgh = 7.75 MPa, where ρ = 1210 kg/m^3 is the mud density, g = 9.81 m/s^2, and h = 653 m is the wellbore height. In the code results, the pressure decreases linearly to 0.1 MPa at the land surface. FLUENT calculated a bottomhole pressure value of 7.74 MPa. DRSPALL calculated a value of 7.77 MPa. The velocities for this test case should be zero. But, because DRSPALL uses a transient algorithm, a small residual velocity can be expected. The velocities shown in Figure 5-24 are well below 1E-4, so **Acceptance Criterion 5-4** (Section 5.5.6) is met for this case. (**Acceptance Criteria 5-2** and **Acceptance Criteria 5-3** do not apply to this case.) While this test problem may seem trivial, stable behavior of a transient code under steady-state conditions is not guaranteed. Correct and stable solution of this problem lends confidence that the differencing scheme and mass balance are working as designed.

5.5.7.2 Case 5.2 – Steady Flow, Nominal Mud Density

The results for Case 5.2 (mud pumping rate = 0.02018 m^3/s and nominal mud density = 1210 kg/m^3) are summarized by the pressure and fluid velocity profiles at 90 s shown in Figure 5-25 are similar to Case 5.1 with only very minor differences due to dynamic effects. Pressures are within the 20% error bars, so **Acceptance Criterion 5-1** (Section 5.5.6) is met for this case. The velocity profiles show the effects of the two annulus areas – one for the collar region just above the well bottom and another for the drill pipe extending to the land surface. Velocities are within the 35% error bars, so **Acceptance Criterion 5-4** (Section 5.5.6) is met for this case. Fluid velocities, u_i, can be determined analytically from the pumping rates, R = 0.02018, and the annulus cross sectional areas, A_1 = 0.044, A_2 = 0.066, as follows: $u_i = R/A_i$, where, i=1 is the collar region and 2 is the drill pipe region. This gives analytic values for the fluid velocities of

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0.46 m/s and 0.31 m/s for the collar and drill pipe regions, respectively. (**Acceptance Criteria 5-2** and **Acceptance Criteria 5-3** do not apply to this case.)

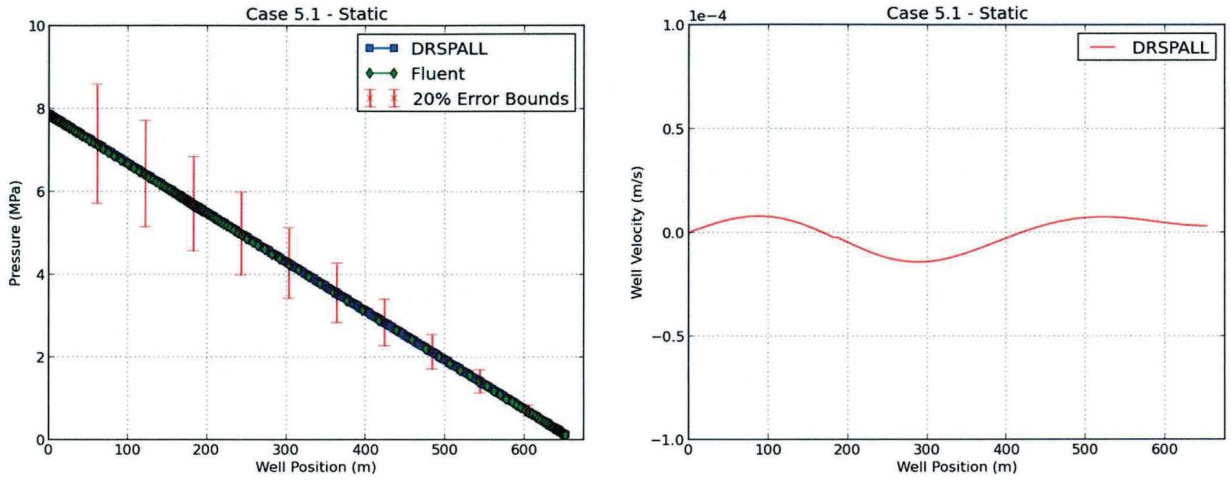

Figure 5-24 Pressure and velocity profiles for static wellbore, Case 5.1.

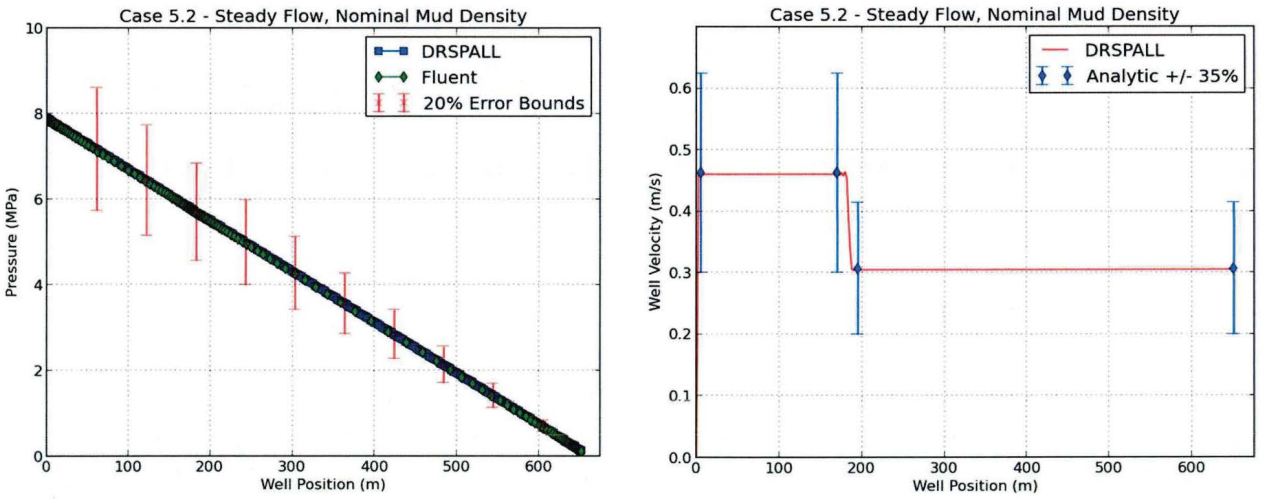

Figure 5-25 Pressure and velocity profiles for steady state and nominal mud density, Case 5.2.

5.5.7.3 Case 5.3 – Steady Flow, High Mud Density

The results for Case 5.3 (constant mud pumping rate = 0.02018 m^3/s and a high mud density = 1380 kg/m^3) are summarized by the pressure and fluid velocity profiles at 90 s shown in Figure 5-26. The results from FLUENT and DRSPALL visually overlay. The pressure profiles are similar to Case 5.2 except for an increase in bottomhole pressure due the increase in mud density. Pressures are within the 20% error bars, so **Acceptance Criterion 5-1** (Section 5.5.6) is

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met for this case. The estimated value of bottomhole pressure is ρgh = 8.84 MPa, where ρ = 1380 kg/m^3 is the mud density, g = 9.81 m/s^2, and h = 653 m is the wellbore height. The calculated values for bottomhole pressure were 8.85 MPa and 8.89 MPa for FLUENT and DRSPALL, respectively. The velocity profiles show the effects of the two annulus areas – one for the collar region just above the well bottom and another for the drill pipe extending to the land surface. Velocities are within the 35% error bars, so **Acceptance Criterion 5-4** (Section 5.5.6) is met for this case. The expected values of fluid velocities are the same as in Case 5.2. (**Acceptance Criteria 5-2** and **Acceptance Criteria 5-3** do not apply to this case.)

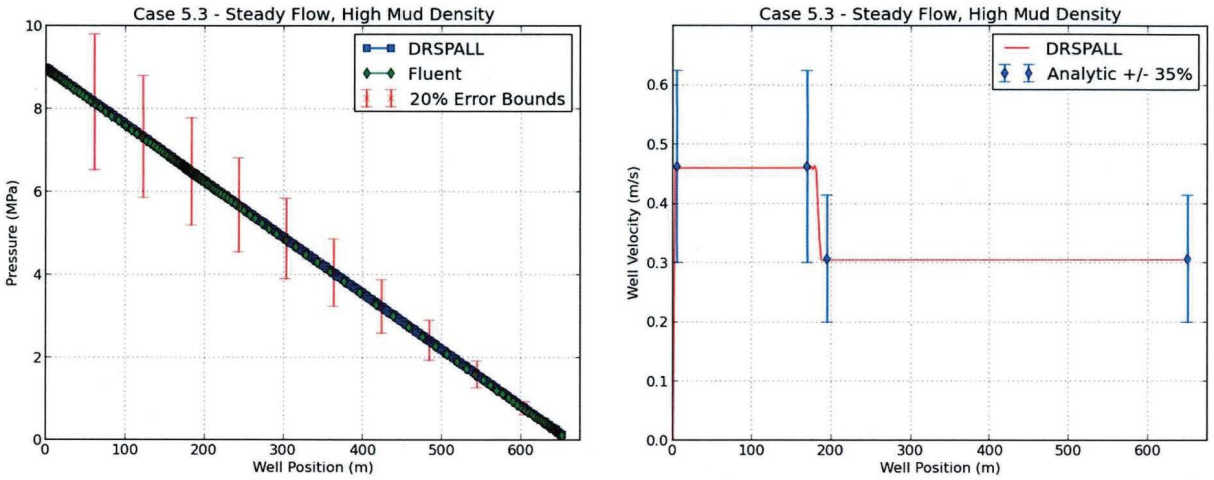

Figure 5-26 Pressure and velocity profiles for steady state and high mud density, Case 5.3.

5.5.7.4 Case 5.5 – Low Gas Injection Rate

The results for Case 5.5 (constant mud pumping rate = 0.02018 m^3/s, nominal mud density = 1210 kg/m^3, and a low gas injection rate = 0.25 kg/s) are summarized by the pressure, fluid velocity, and gas volume fraction profiles at 450 s shown in Figure 5-27. The pressure profile results from FLUENT and DRSPALL visually overlay. Pressures are within the 20% error bars, so **Acceptance Criterion 5-1** (Section 5.5.6) is met for this case. Note that the bottomhole pressures have dropped from 9 MPa to 0.5 MPa because of the large amount of gas in the wellbore. Gas volume fractions are around 98% with differences between FLUENT and DRSPALL less than 0.2. Gas volume fractions are within the 0.01 error bars and the acceptance criterion of 0.02, so **Acceptance Criterion 5-2** (Section 5.5.6) is met for this case. The fluid velocity profiles show increasing fluid acceleration with height because of the decrease in gas density and pressure. The drop in velocity at about 180 m is at the collar drill pipe interface and indicates the increase in annulus area. Velocities are within the 35% error bounds, so **Acceptance Criterion 5-4** (Section 5.5.6) is met for this case. (**Acceptance Criterion 5-3** does not apply to this case.)

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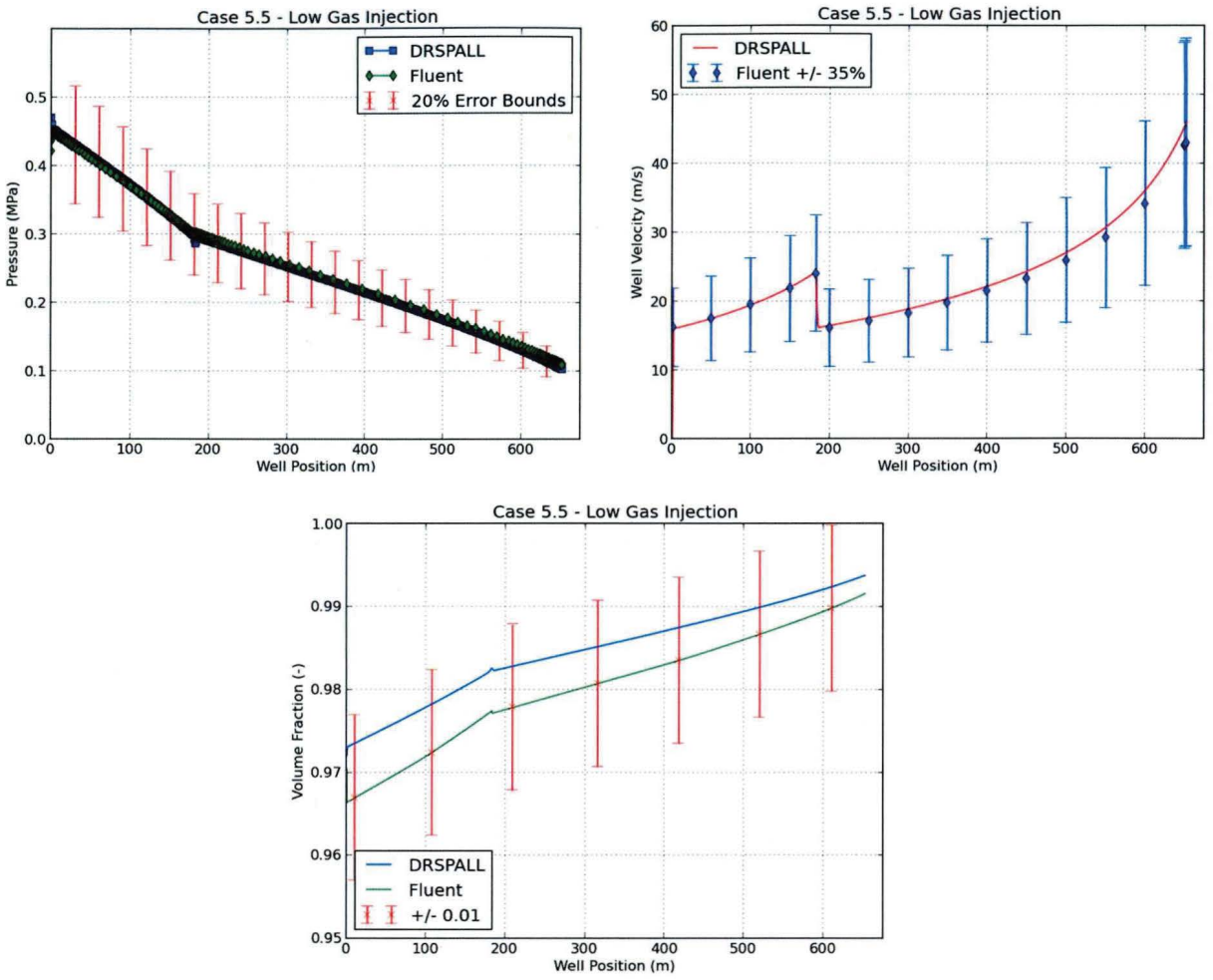

Figure 5-27 Pressure, velocity, and gas volume fraction profiles for steady state, nominal mud density, and low gas injection rate, Case 5.5.

5.5.7.5 Case 5.6 – Medium Gas Injection

The results for Case 5.6 (constant mud pumping rate = 0.02018 m^3/s; nominal mud density = 1210 kg/m^3; and a medium gas injection rate = 2.5 kg/s) are summarized by the pressure, fluid velocity, and gas volume fraction profiles at 120 s shown in Figure 5-28. The gas injection rate was ten times larger than in Case 5.5. The bottomhole pressure, gas volume fraction, and fluid velocity have increased relative to Case 5.5 because of the increased gas injection rate. Pressure profiles compare very well. Pressures are within the 20% error bars, so **Acceptance Criterion 5-1** (Section 5.5.6) is met for this case. Gas volume fractions are above 99% for both DRSPALL and FLUENT. Gas volume fractions are within the 0.01 error bars and the acceptance criterion of 0.02, so **Acceptance Criterion 5-2** (Section 5.5.6) is met for this case. DRSPALL fluid velocities are slightly low relative to FLUENT because of the slightly lower gas volume fraction. Velocities are within the 35% error bars, so **Acceptance Criterion 5-4** (Section 5.5.6) is met for this case. (**Acceptance Criterion 5-3** does not apply to this case.)

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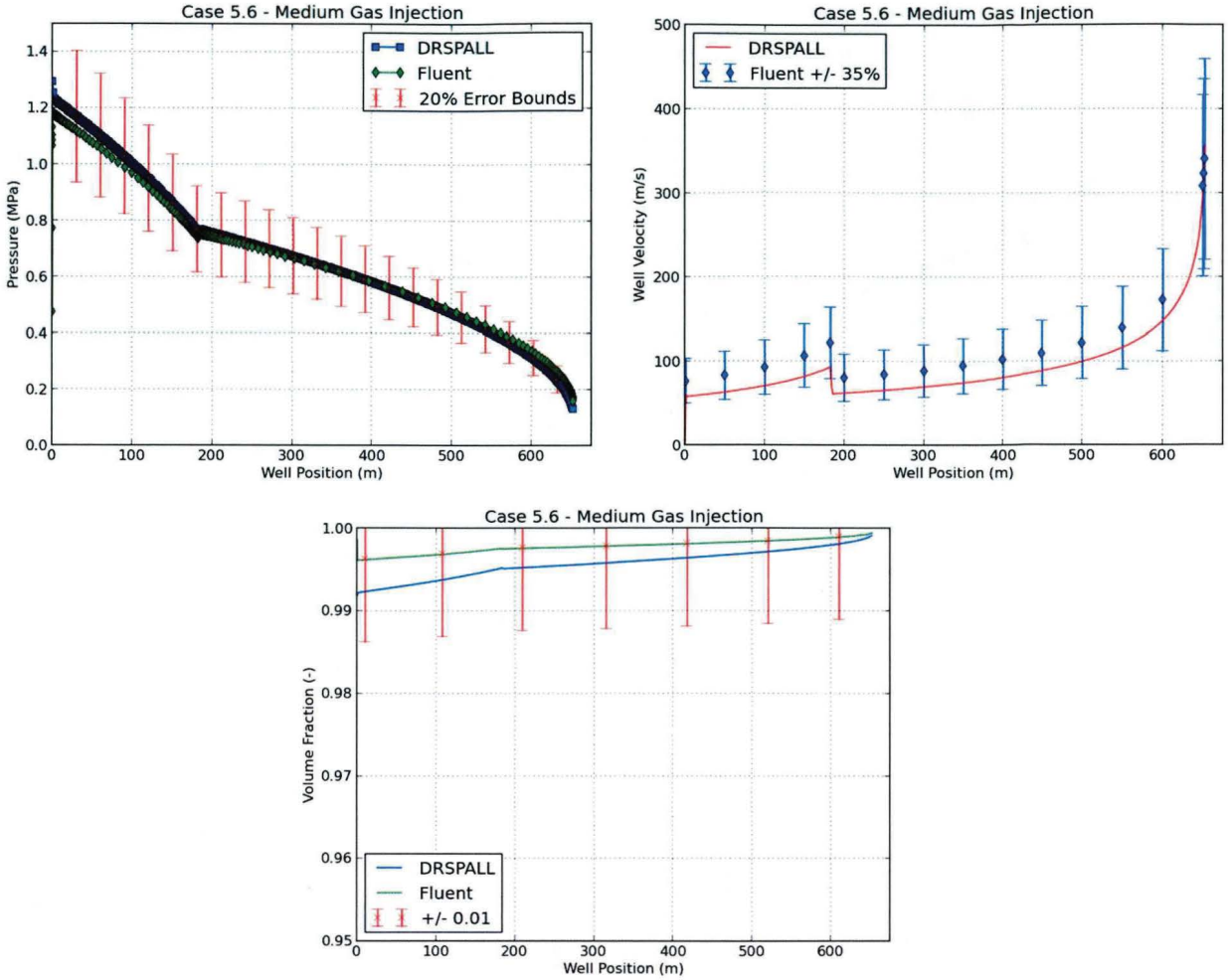

Figure 5-28 Pressure, velocity, and gas volume fraction profiles for steady state, nominal mud density, and medium gas injection rate, Case 5.6.

5.5.7.6 Case 5.7 – Medium Gas and Low Solid Injection

The results for Case 5.7 (constant mud pumping rate = 0.02018 m^3/s; nominal mud density = 1210 kg/m^3; medium gas injection rate = 2.5 kg/s; and low solid injection rate = 2.5 kg/s) are summarized by the pressure, fluid velocity and gas and solid volume fraction profiles at 100 s shown in Figure 5-29. The gas injection rate was the same as in Case 5.6. The pressure profiles essentially overlay with an increase in bottomhole pressure relative to Case 5.6 due to the presence of solids in the wellbore. Pressures are within the 20% error bars, so **Acceptance Criterion 5-1** (Section 5.5.6) is met for this case. Gas volume fractions are near 99% but are lower than Case 5.6 because of the solids. Gas volume fractions are within the 0.01 error bars and the acceptance criterion of 0.02, so **Acceptance Criterion 5-2** (Section 5.5.6) is met for this case. Solid volume fractions are very small, near 5E-4. Solid volume fractions are within the 25% error bars, so **Acceptance Criterion 5-3** (Section 5.5.6) is met for this case. The fluid velocity profiles are very similar to Case 5.6 because of the dominance of the gas. Velocities are within the 35% error bars, so **Acceptance Criterion 5-4** (Section 5.5.6) is met for this case.

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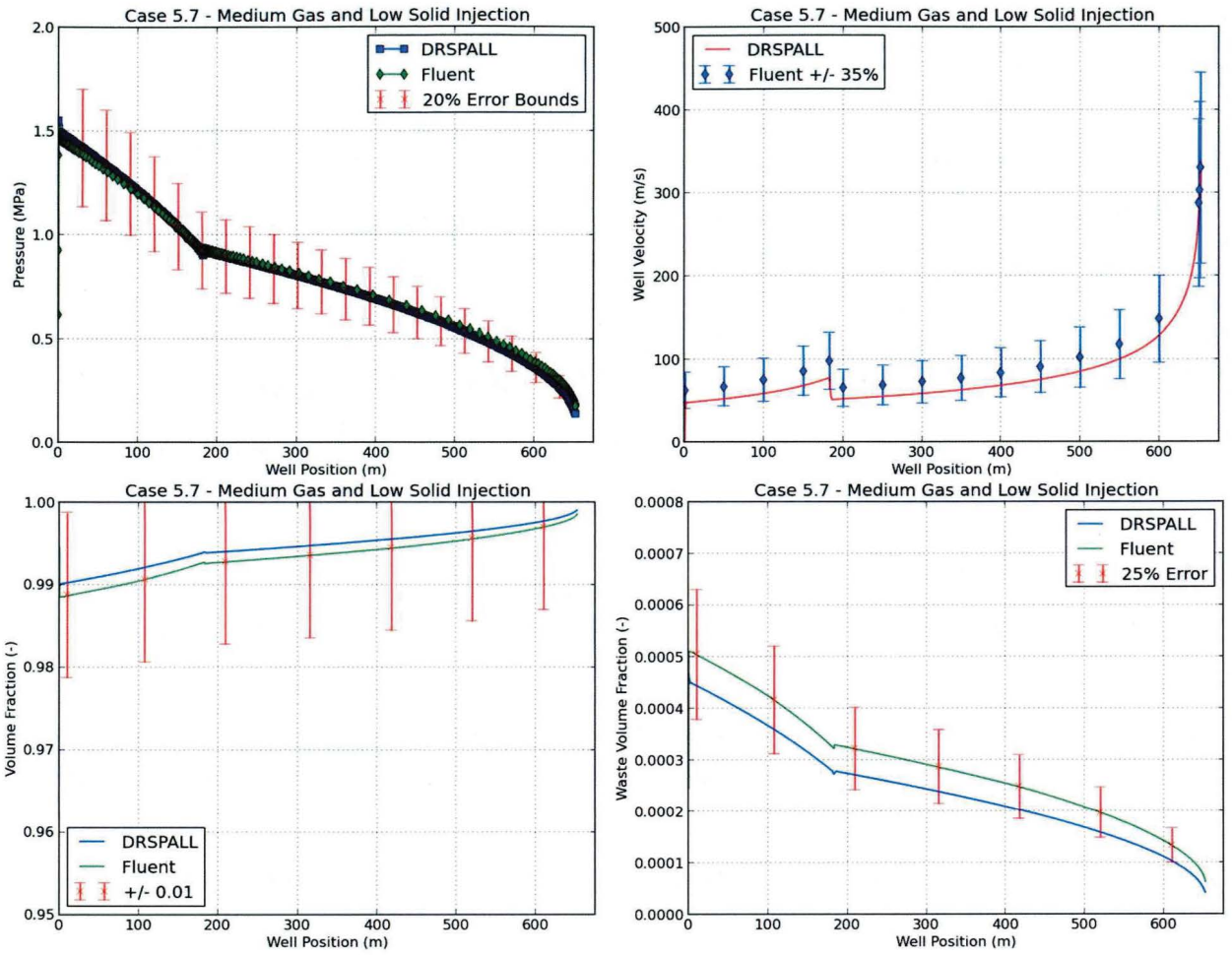

Figure 5-29 Pressure, velocity, and volume fraction profiles for steady state, nominal mud density, medium gas and low solid injection rate, Case 5.7.

5.5.8 Conclusions

The discussion in Section 5.5.7 verifies that all acceptance criteria (Section 5.5.6) for this test case are met. Thus, this test case passes and validates the satisfactory implementation of Functional Requirement R.1.

Comparisons of the FLUENT and DRSPALL results for both the static (Case 5.1) and steady state, mud-only (Cases 5.2, 5.3) calculations show very close agreement. All steady state cases with mud and gas injection (Cases 5.5, 5.6) or mud, gas and solid injection (Case 5.7) are also in good agreement. Much of the differences are probably due to the way friction loss is handled in the two models. DRSPALL uses an empirical friction factor that is a function of wall roughness and Reynolds number. FLUENT calculates shear forces in its two-dimensional cylindrical flow domain and assumed smooth walls for this analysis.

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The successful completion of this test case confirms that DRSPALL is properly calculating the multi-component mixture flow in the wellbore.

6.0 CONCLUSION

Testing for DRSPALL, Version 1.24 has been completed and the acceptance criteria for all test cases has been successfully met. The testing verifies that DRSPALL satisfies all the requirements listed in Section 2.0.

7.0 INSTALLATION AND REGRESSION TESTING

Test Cases #1, #2, #4, and #5 described in Section 5.0 are suitable for installation testing and regression testing.

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9.0 APPENDIX A: SUMMARY OF FILES USED

This appendix contains an extract of test log file *drspall_124_Test.rtf* showing the summary of files used. All test files are available in CVS, as described in Section 3.0. A summary of files used is provided in Table 9-1 through Table 9-6.

Note that all output CAMDAT test files (that is, all files in Table 9-5 with extension .cdb) are automatically compressed by the rc.py code before they are stored in CVS with the Unix gzip –c –f command. The compressed file has extension .cdb.gz in CVS. It may be converted to a normal CAMDAT file with the Unix gunzip –f command.

Table 9-1– The run script files used were:

File	Repository	Comment
Test/RunControl/Linux/drspall_Test.py	$REP1/PA_CODES/DRSPALL	Python run control script
Test/RunControl/Linux/rc.py	$REP1/PA_CODES/DRSPALL	Run control module
Test/RunControl/Linux/RunTest.sh	$REP1/PA_CODES/DRSPALL	User shell script

Where:

$REP1 = /data/cvs/CVSLIB/WIPP_CODES

Table 9-2– The input files used were:

File	Repository	Comment
Test/Auxiliary/Test_Evaluation/drs_test_evaluation.py	$REP1/PA_CODES/DRSPALL	test script
Test/Auxiliary/Test_Evaluation/drs_test_tc1.py	$REP1/PA_CODES/DRSPALL	test script
Test/Auxiliary/Test_Evaluation/drs_test_tc2.py	$REP1/PA_CODES/DRSPALL	test script
Test/Auxiliary/Test_Evaluation/drs_test_tc4.py	$REP1/PA_CODES/DRSPALL	test script
Test/Auxiliary/Test_Evaluation/drs_test_tc5.py	$REP1/PA_CODES/DRSPALL	test script
Test/Auxiliary/Test_Evaluation/results.py	$REP1/PA_CODES/DRSPALL	test script
Test/Input/drs_tc11.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_tc12.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_tc21.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_tc22.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_tc23.drs	$REP1/PA_CODES/DRSPALL	test input

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Test/Input/drs_tc24.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_tc25.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_tc26.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_tc2_summarize.inp	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_tc41.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_tc41_grope.inp	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_tc42.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_tc42_ms.cdb	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_tc42_ms.ctxt	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_tc51.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_tc52.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_tc53.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_tc55.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_tc56.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_tc57.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_tc5_grope.inp	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_v122_tc11.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_v122_tc12.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_v122_tc21.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_v122_tc22.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_v122_tc23.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_v122_tc24.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_v122_tc25.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_v122_tc26.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_v122_tc41.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_v122_tc42.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_v122_tc51.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_v122_tc52.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_v122_tc53.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_v122_tc55.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_v122_tc56.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/drs_v122_tc57.drs	$REP1/PA_CODES/DRSPALL	test input
Test/Input/ReadMe	$REP1/PA_CODES/DRSPALL	test input
Test/Input/TableB22_DA_CylTau0_01.txt	$REP1/PA_CODES/DRSPALL	test input
Test/Input/TableB23_DA_CylTau0_1.txt	$REP1/PA_CODES/DRSPALL	test input
Test/Input/TableB24_DA_CylTau1_0.txt	$REP1/PA_CODES/DRSPALL	test input
Test/Input/TableB25_DA_CylTau10_0.txt	$REP1/PA_CODES/DRSPALL	test input
Test/Input/TableB26_DA_SphTau0_01.txt	$REP1/PA_CODES/DRSPALL	test input
Test/Input/TableB27_DA_SphTau0_1.txt	$REP1/PA_CODES/DRSPALL	test input
Test/Input/TableB28_DA_SphTau1_0.txt	$REP1/PA_CODES/DRSPALL	test input
Test/Input/TableB29_DA_SphTau10_0.txt	$REP1/PA_CODES/DRSPALL	test input
Test/Input/tc51_fluent_results.dat	$REP1/PA_CODES/DRSPALL	test input
Test/Input/tc52_fluent_results.dat	$REP1/PA_CODES/DRSPALL	test input
Test/Input/tc53_fluent_results.dat	$REP1/PA_CODES/DRSPALL	test input
Test/Input/tc55_fluent_results.dat	$REP1/PA_CODES/DRSPALL	test input
Test/Input/tc55_fluent_velocities.dat	$REP1/PA_CODES/DRSPALL	test input
Test/Input/tc56_fluent_results.dat	$REP1/PA_CODES/DRSPALL	test input
Test/Input/tc56_fluent_velocities.dat	$REP1/PA_CODES/DRSPALL	test input
Test/Input/tc57_fluent_results.dat	$REP1/PA_CODES/DRSPALL	test input
Test/Input/tc57_fluent_velocities.dat	$REP1/PA_CODES/DRSPALL	test input
Test/Output/Solaris_123/drs_123_tc11.cdb.gz	$REP1/PA_CODES/DRSPALL	regression output

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Test/Output/Solaris_123/drs_123_tc11.crt	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc11.dbg	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc11_chan.dat	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc11_chan.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc12.cdb.gz	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc12.crt	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc12.dbg	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc12_chan.dat	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc12_chan.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc21.cdb.gz	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc21.crt	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc21.dbg	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc22.cdb.gz	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc22.crt	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc22.dbg	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc23.cdb.gz	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc23.crt	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc23.dbg	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc24.cdb.gz	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc24.crt	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc24.dbg	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc25.cdb.gz	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc25.crt	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc25.dbg	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc26.cdb.gz	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc26.crt	$REP1/PA_CODES/DRSPALL	regression output

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Test/Output/Solaris_123/drs_123_tc26.dbg	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc2_summarize.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc2_summarize.tbl	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc41.cdb.gz	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc41.crt	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc41.dbg	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc41.gr	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc41_coupling.dat	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc41_coupling.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc41_dbg.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc41_expulsion.dat	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc41_expulsion.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc41_fluidization.dat	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc41_fluidization.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc41_fluidization_time.dat	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc41_fluidization_time.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc41_grope.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc41_stress.dat	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc41_stress.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc42.cdb.gz	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc42.crt	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc42.dbg	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc42_coupling.dat	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc42_coupling.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc42_dbg.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc42_expulsion.dat	$REP1/PA_CODES/DRSPALL	regression output

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Test/Output/Solaris_123/drs_123_tc42_expulsion.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc42_fluidization.dat	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc42_fluidization.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc42_fluidization_time.dat	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc42_fluidization_time.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc42_stress.dat	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc42_stress.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc51.cdb.gz	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc51.crt	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc51.dbg	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc51.gr	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc51_grope.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc51_wellbore.dat	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc51_wellbore.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc52.cdb.gz	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc52.crt	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc52.dbg	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc52.gr	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc52_grope.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc52_wellbore.dat	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc52_wellbore.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc53.cdb.gz	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc53.crt	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc53.dbg	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc53.gr	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc53_grope.dif	$REP1/PA_CODES/DRSPALL	regression output

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Test/Output/Solaris_123/drs_123_tc53_wellbore.dat	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc53_wellbore.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc55.cdb.gz	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc55.crt	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc55.dbg	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc55.gr	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc55_grope.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc55_wellbore.dat	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc55_wellbore.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc56.cdb.gz	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc56.crt	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc56.dbg	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc56.gr	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc56_grope.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc56_wellbore.dat	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc56_wellbore.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc57.cdb.gz	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc57.crt	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc57.dbg	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc57.gr	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc57_grope.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc57_wellbore.dat	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_123_tc57_wellbore.dif	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/drs_test_evaluation.out	$REP1/PA_CODES/DRSPALL	regression output
Test/Output/Solaris_123/ReadMe	$REP1/PA_CODES/DRSPALL	regression output

Where:

$REP1 = /data/cvs/CVSLIB/WIPP_CODES

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Table 9-3– The CVS repositories used were:

CVS Repositories
$REP1/PA_CODES/DRSPALL
/data/cvs/CVSLIB/WIPP_CODES/PA_CODES/DRSPALL
/data/cvs/CVSLIB/WIPP_CODES/PA_CODES/GROPECDB
/data/cvs/CVSLIB/WIPP_CODES/PA_CODES/SUMMARIZE

Where:

$REP1 = /data/cvs/CVSLIB/WIPP_CODES

Table 9-4– The log files used were:

File	Repository	Comment
Test/RunControl/Linux/drspall_124_Test.log	$REP1/PA_CODES/DRSPALL	Log file
Test/RunControl/Linux/drspall_124_Test.rtf	$REP1/PA_CODES/DRSPALL	Formatted log file (Word file)

Where:

$REP1 = /data/cvs/CVSLIB/WIPP_CODES

Table 9-5– The output files produced were:

File	Repository	Comment
Test/Output/Linux_124/drs_124_tc11.cdb	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc11.crt	$REP1/PA_CODES/DRSPALL	DRSPALL screen output
Test/Output/Linux_124/drs_124_tc11.dbg	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc11_chan.dat	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc11_chan.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc12.cdb	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc12.crt	$REP1/PA_CODES/DRSPALL	DRSPALL screen output
Test/Output/Linux_124/drs_124_tc12.dbg	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc12_chan.dat	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc12_chan.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc21.cdb	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc21.crt	$REP1/PA_CODES/DRSPALL	DRSPALL screen output
Test/Output/Linux_124/drs_124_tc21.dbg	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc22.cdb	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc22.crt	$REP1/PA_CODES/DRSPALL	DRSPALL screen output
Test/Output/Linux_124/drs_124_tc22.dbg	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc23.cdb	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc23.crt	$REP1/PA_CODES/DRSPALL	DRSPALL screen output
Test/Output/Linux_124/drs_124_tc23.dbg	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc24.cdb	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc24.crt	$REP1/PA_CODES/DRSPALL	DRSPALL screen output

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Test/Output/Linux_124/drs_124_tc24.dbg	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc25.cdb	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc25.crt	$REP1/PA_CODES/DRSPALL	DRSPALL screen output
Test/Output/Linux_124/drs_124_tc25.dbg	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc26.cdb	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc26.crt	$REP1/PA_CODES/DRSPALL	DRSPALL screen output
Test/Output/Linux_124/drs_124_tc26.dbg	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc2_summarize.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc2_summarize.tbl	$REP1/PA_CODES/DRSPALL	SUMMARIZE output
Test/Output/Linux_124/drs_124_tc41.cdb	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc41.crt	$REP1/PA_CODES/DRSPALL	DRSPALL screen output
Test/Output/Linux_124/drs_124_tc41.dbg	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc41.gr	$REP1/PA_CODES/DRSPALL	GROPECDB output
Test/Output/Linux_124/drs_124_tc41_coupling.dat	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc41_coupling.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc41_dbg.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc41_expulsion.dat	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc41_expulsion.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc41_fluidization.dat	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc41_fluidization.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc41_fluidization_time.dat	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc41_fluidization_time.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc41_grope.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc41_stress.dat	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc41_stress.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc42.cdb	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc42.crt	$REP1/PA_CODES/DRSPALL	DRSPALL screen output
Test/Output/Linux_124/drs_124_tc42.dbg	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc42_coupling.dat	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc42_coupling.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc42_dbg.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc42_expulsion.dat	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc42_expulsion.dif	$REP1/PA_CODES/DRSPALL	diff output

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Test/Output/Linux_124/drs_124_tc42_fluidization.dat	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc42_fluidization.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc42_fluidization_time.dat	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc42_fluidization_time.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc42_stress.dat	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc42_stress.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc51.cdb	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc51.crt	$REP1/PA_CODES/DRSPALL	DRSPALL screen output
Test/Output/Linux_124/drs_124_tc51.dbg	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc51.gr	$REP1/PA_CODES/DRSPALL	GROPECDB output
Test/Output/Linux_124/drs_124_tc51_grope.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc51_wellbore.dat	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc51_wellbore.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc52.cdb	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc52.crt	$REP1/PA_CODES/DRSPALL	DRSPALL screen output
Test/Output/Linux_124/drs_124_tc52.dbg	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc52.gr	$REP1/PA_CODES/DRSPALL	GROPECDB output
Test/Output/Linux_124/drs_124_tc52_grope.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc52_wellbore.dat	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc52_wellbore.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc53.cdb	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc53.crt	$REP1/PA_CODES/DRSPALL	DRSPALL screen output
Test/Output/Linux_124/drs_124_tc53.dbg	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc53.gr	$REP1/PA_CODES/DRSPALL	GROPECDB output
Test/Output/Linux_124/drs_124_tc53_grope.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc53_wellbore.dat	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc53_wellbore.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc55.cdb	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc55.crt	$REP1/PA_CODES/DRSPALL	DRSPALL screen output
Test/Output/Linux_124/drs_124_tc55.dbg	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc55.gr	$REP1/PA_CODES/DRSPALL	GROPECDB output
Test/Output/Linux_124/drs_124_tc55_grope.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc55_wellbore.dat	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc55_wellbore.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc56.cdb	$REP1/PA_CODES/DRSPALL	DRSPALL output

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Test/Output/Linux_124/drs_124_tc56.crt	$REP1/PA_CODES/DRSPALL	DRSPALL screen output
Test/Output/Linux_124/drs_124_tc56.dbg	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc56.gr	$REP1/PA_CODES/DRSPALL	GROPECDB output
Test/Output/Linux_124/drs_124_tc56_grope.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc56_wellbore.dat	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc56_wellbore.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc57.cdb	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc57.crt	$REP1/PA_CODES/DRSPALL	DRSPALL screen output
Test/Output/Linux_124/drs_124_tc57.dbg	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc57.gr	$REP1/PA_CODES/DRSPALL	GROPECDB output
Test/Output/Linux_124/drs_124_tc57_grope.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_124_tc57_wellbore.dat	$REP1/PA_CODES/DRSPALL	DRSPALL output
Test/Output/Linux_124/drs_124_tc57_wellbore.dif	$REP1/PA_CODES/DRSPALL	diff output
Test/Output/Linux_124/drs_test_evaluation.out	$REP1/PA_CODES/DRSPALL	Validation chk

Where:

$REP1 = /data/cvs/CVSLIB/WIPP_CODES

Table 9-6– The executable files used were:

File	Repository	Comment
Build/Linux/drspall (Ver:1.24)	/data/cvs/CVSLIB/WIPP_CODES/PA_CODES/DRSPALL	Computes volume of waste from drilling
Build/Linux/gropecdb (Ver:2.14)	/data/cvs/CVSLIB/WIPP_CODES/PA_CODES/GROPECDB	Displays CAMDAT data in text form
Build/Linux/summarize (Ver:3.03)	/data/cvs/CVSLIB/WIPP_CODES/PA_CODES/SUMMARIZE	Writes tables of data from many CAMDAT files

10.0 APPENDIX B: OUTPUT FROM TEST EVALUATION

In addition to the figures and tables included in the document the test evaluation script has a text output (*drs_test_evaluation.out*) for each test run.

```
# ***********************************************
# Test Case 1.1 Cylindrical Geometry
# ***********************************************

Figures Created
```

Information Only

```
Pressure profiles closely match D&A solution for cylindrical case.

Case 1.1 - Cylindrical
     Tau  MAX_DIFF  MEAN_DIFF
0   0.01  0.045041   0.016462
1   0.10  0.016088   0.005895
2   1.00  0.006944   0.003287
3  10.00  0.013719   0.007927

Maximum difference less than 0.1 for all tau in cylindrical case.

# ***********************************************
# Test Case 1.2 Spherical Geometry
# ***********************************************

Figures Created

[0.015497266815851615, 0.006221359167366762, 0.0033283703807215122,
0.0024400983100071852]
Pressure profiles closely match D&A solution for spherical case.

Case 1.2 - Spherical
     Tau  MAX_DIFF  MEAN_DIFF
0   0.01  0.015696   0.005714
1   0.10  0.006222   0.002187
2   1.00  0.006992   0.004255
3  10.00  0.013406   0.004996

Maximum difference less than 0.1 for all tau in spherical case.

# ***********************************************
# Test Case 2
# ***********************************************

('\n',        DRSPALL CAVRAD  Field Inferred Cavity Radius, m
Cycle
1             0.300000                                 0.31
2             0.300000                                 0.49
3             0.641040                                 0.61
4             0.882270                                 0.73
5             1.108154                                 0.91
6             1.308242                                 1.37)

Figures Created

# ***********************************************
# Test Case 4.1
# ***********************************************

# ***********************************************
# Coupling of Wellbore and Repository Flow Models
# ***********************************************
First Value of Repository Penetration is F: True

Repository Penetrated is always F when Bit above repository is >0 and T when bit above
repository is <= 0:True

Cavity pressure decreases and well bottomhole pressure increases with time: True
```

Information Only

```
Cavity pressure and well bottomhole pressure are equal when and after bit intersects
the repository: True

Total mass balance error less than 0.1: True

First time Total gas in well and Total gas injected significantly deviate is 108.9312
seconds

# ************************************************
# Tensile Failure of Waste Material
# ************************************************
The radial effective stress is within 1.0E-06 of the sum of the component stresses:
True

Beyond the characteristic length failure value is always F: True

Within the characteristic length failure always occurs if the mean effective stress is
less than 0.12 MPa: True

RadElasticStress_abs_diff    6.016344e-07
RadElasticStress_rel_diff    1.019319e-13
SeepStress_abs_diff          1.784938e-07
SeepStress_rel_diff          3.982601e-12
EffectStress_abs_diff        5.625770e-07
EffectStress_rel_diff        7.146415e-12
dtype: float64
Calculated stress values agree with DRSPALL values with absolute and relative
differences less than 1e-04: True

# ******************************************************
# Fluidized Bed Transport of Disaggregated Waste Material
# ******************************************************
Fluidization of disaggregated waste has started for any cell within the characteristic
length where the superficial gas velocity exceeds the critical fluidization velocity:
True

Minimum fluidization velocity calculation:
Parameter                Value           Units
run time                 1.2467270e+02   sec
gas density              4.4673768e+00   kg/m^3
porosity                 5.7500000e-01   -
waste density            2.6500000e+03   kg/m^3
gas viscosity            8.9339000e-06   Pa*sec
particle diameter        1.0000000e-03   m
shape factor             2.5000000e-01   -
gravity                  9.8067000e+00   m/sec^2
a                        9.2069864e+06
b                        2.6829226e+06
c                        -1.4521331e+06
b^2-4ac                  6.0677152e+13
Ergun Equation velocity  0.27732372       m/s
DRSPALL velocity         0.27732372       m/s
Relative difference      1.561e-14

The fluidization velocity calculated independently using the Ergun equation is
consistent with the value reported by DRSPALL to within a relative difference of 1E-4:
True

-----------------------------------------------------------------------------
|Parameter                              |Value                   |Units   |
|run time                               |124.6727                |sec     |
```

Information Only

```
|Radius to center of first intact cell   |0.33769606              |m       |
|superficial gas velocity                |0.50661883              |m/sec   |
|Fluidization Time                       |0.66656832              |sec     |
|----------------------------------------------------------------------------|
|From fluidization.dat file              |                        |        |
|runtime #1                              |124.67264               |sec     |
|fraction fluidized #1                   |0.0                     |-       |
|runtime #2                              |124.67277               |sec     |
|fraction fluidized #2                   |0.0002                  |-       |
|Projected Fluidization Time             |0.64604225              |sec     |
|----------------------------------------------------------------------------|
|From fluidization time file             |                        |        |
|Zone                                    |115.0                   |-       |
|Fluidization Time                       |0.6652844               |sec     |
------------------------------------------------------------------------------

Salt Exit Frac. value of   3.8731-208 set to 0

Initial Cavity Radius
*****************
DBG File: 0.1378
CDB File: 0.11000814
Calculated: 0.110008137483
Relative Difference in Initial Cavity Radius: 2.28792422139e-08

Cuttings Mass
*****************
DBG File: 260.78
CDB File: 260.77912
Calculated: 260.778344755
Relative Difference in Cuttings Mass: 2.97280406171e-06

Total Mass
*****************
DBG File: 835.98
CDB File: 835.97639
Calculated: 835.978255779
Relative Difference in Total Mass: 2.23185602751e-06

Spall Mass
*****************
DBG File: 575.2
CDB File: 575.19727
Calculated: 575.199911024
Relative Difference in Spall Mass: 4.5915102692e-06

Spall2 Mass
*****************
DBG File: 802.61
CDB File: 802.6102
Calculated: 802.608306238
Relative Difference in Spall2 Mass: 2.35950458491e-06

Equivalent uncompacted cuttings volume
*****************
DBG File: 0.65605
CDB File: 0.65604809
Calculated: 0.656046150326
Relative Difference in Equivalent uncompacted cuttings volume: 2.95660265921e-06

Equivalent uncompacted total volume
```

Information Only

```
*****************
DBG File: 2.1031
CDB File: 2.1030853
Calculated: 2.10308995165
Relative Difference in Equivalent uncompacted total volume: 2.21181953209e-06

Equivalent uncompacted spall volume
*****************
DBG File: 1.447
CDB File: 1.4470372
Calculated: 1.44704380132
Relative Difference in Equivalent uncompacted spall volume: 4.56195505665e-06

Equivalent uncompacted spall volume 2
*****************
DBG File: 2.0191
CDB File: 2.0191452
Calculated: 2.01914039305
Relative Difference in Equivalent uncompacted spall volume 2: 2.38068542678e-06

Waste position in well going from -653 to 0: True

Waste mass small prior to z=0, then monotonically increasing: True

Mass balance error small for all times: True

# ***********************************************
# Test Case 4.2
# ***********************************************

# ***********************************************
# External Interfaces:
# ***********************************************
Groped CDB files exists: True

Exit pipe diameter given as 0.2894 with calculated value 0.289395633174

Total thickness given as 1.3976 with calculated value 1.39764705882

Select Values from dbg file:
-------------------------------------------------
| Exit Pipe Diameter              (m): 0.2894     |
| First Wellbore Zone             (-): 651.0      |
| Initial Cavity Radius           (-): 0.0        |
| Minimum Characteristic Vel      (-): 1e-06      |
| Minimum Number Zones/Lt         (-): 5.0        |
| Tensile Velocity             (m/s): 1000.0     |
| Bit Nozzle Number               (-): 3.0        |
| Bit Nozzle Diameter             (m): 0.011112   |
| Choke Efficiency                (-): 0.9        |
-------------------------------------------------

# ***********************************************
# Test Case 5.1 Static
# ***********************************************

Figures Created

Test Case 5.1 plot files created
# ***********************************************
# Test Case 5.2 Steady Flow, Nominal Mud Density
```

Information Only

```
# ********************************************

Figures Created

Test Case 5.2 plot files created
# ********************************************
# Test Case 5.3 Steady Flow, High Mud Density
# ********************************************

Figures Created

Test Case 5.3 plot files created
# ********************************************
# Test Case 5.5 Low Gas Injection
# ********************************************

Figures Created

Test Case 5.5 plot files created
# ********************************************
# Test Case 5.6 Medium Gas Injection
# ********************************************

Figures Created

Test Case 5.6 plot files created
# ********************************************
# Test Case 5.7 Medium Gas and Low Solid Injection
# ********************************************

Figures Created

Test Case 5.7 plot files created


**********************************************************************************************
**********
**********************************************************************************************
**********
Test suite successfully evaluated, all acceptance criterion passed
```

11.0 APPENDIX C: DJORDJEVIC AND ADAMS (2003) RESULTS

The utility code developed by Djordjevic and Adams (2003)[3] was used to generate independent solutions to the cylindrical and spherical geometry in a manner analogous to the Chan (1993) solutions. The code output for the four cases of τ examined are shown in

[3] The fortran utility code (*da_cylindrical.f90* and *da_spherical.f90*) developed by Djordjevic and Adams (2003) together with the input and output files are archived in CVS in the directory: /data/cvs/CVSLIB/WIPP_CODES/PA_CODES/DRSPALL/Test/Auxiliary/CMS_Files/.

Information Only

Table 11-1 through Table 11-8.

Information Only

Table 11-1– Cylindrical solution for Tau = 0.01 (*da_cyltau0_01.out*)

```
Simulation of Cylindrical Gas Flow with Dimensionless Pseudopressure
Comparison of Numerical Chan et. al. and DR_SPALL - WIPP PA
delz
     0.010000
delt
     0.000100
Taumax
     0.010000
zetamax
     4.000000
phi
     0.050000
eta
     0.000020
r0
0.4760E-04
kperm
0.6400E-13
pff
 10135000.00
NPCavsTpts
         1
Time (s)  Cavity Pressure (Pa)
0.00         0.00
```

Z	zeta	Y(z)
0.0000000000	0.0000000000	0.0000000000
0.0100000000	0.1005016708	0.0709623043
0.0200000000	0.2020134003	0.1406349730
0.0300000000	0.3045453395	0.2084847320
0.0400000000	0.4081077419	0.2741168299
0.0500000000	0.5127109638	0.3372192652
0.0600000000	0.6183654655	0.3975420958
0.0700000000	0.7250818125	0.4548872252
0.0800000000	0.8328706767	0.5091024448
0.0900000000	0.9417428371	0.5600774690
0.1000000000	1.0517091808	0.6077409497
0.1100000000	1.1627807046	0.6520579571
0.1200000000	1.2749685158	0.6930276366
0.1300000000	1.3882838332	0.7306808747
0.1400000000	1.5027379886	0.7650778704
0.1500000000	1.6183424273	0.7963055556
0.1600000000	1.7351087099	0.8244748354
0.1700000000	1.8530485132	0.8497176446
0.1800000000	1.9721736312	0.8721838375
0.1900000000	2.0924959766	0.8920379400
0.2000000000	2.2140275816	0.9094558117
0.2100000000	2.3367805996	0.9246212752
0.2200000000	2.4607673059	0.9377227768
0.2300000000	2.5860000993	0.9489501521
0.2400000000	2.7124915032	0.9584915664
0.2500000000	2.8402541669	0.9665307037
0.2600000000	2.9693008667	0.9732442642
0.2700000000	3.0996445073	0.9787998276
0.2800000000	3.2312981234	0.9833541191
0.2900000000	3.3642748803	0.9870517033
0.3000000000	3.4985880758	0.9900241120
0.3100000000	3.6342511413	0.9923893923
0.3200000000	3.7712776434	0.9942520496
0.3300000000	3.9096812846	0.9957033400

Information Only

Table 11-2– Cylindrical solution for Tau = 0.1 (*da_cyltau0_1.out*)

```
Simulation of Cylindrical Gas Flow with Dimensionless Pseudopressure
Comparison of Numerical Chan et. al. and DR_SPALL - WIPP PA
delz
     0.010000
delt
     0.001000
Taumax
     0.100000
zetamax
     4.000000
phi
     0.050000
eta
     0.000020
r0
0.4760E-04
kperm
0.6400E-13
pff
 10135000.00
NPCavsTpts
         1
Time (s)  Cavity Pressure (Pa)
0.00         0.00
```

Z	zeta	Y(z)
0.0000000000	0.0000000000	0.0000000000
0.0100000000	0.0317814189	0.0254244066
0.0200000000	0.0638822463	0.0507794474
0.0300000000	0.0963056924	0.0760347627
0.0400000000	0.1290549995	0.1011660435
0.0500000000	0.1621334427	0.1261520102
0.0600000000	0.1955443297	0.1509732742
0.0700000000	0.2292910018	0.1756117737
0.0800000000	0.2633768335	0.2000504508
0.0900000000	0.2978052335	0.2242730519
0.1000000000	0.3325796447	0.2482639974
0.1100000000	0.3677035446	0.2720082934
0.1200000000	0.4031804455	0.2954914727
0.1300000000	0.4390138952	0.3186995536
0.1400000000	0.4752074770	0.3416190129
0.1500000000	0.5117648104	0.3642367697
0.1600000000	0.5486895511	0.3865401751
0.1700000000	0.5859853917	0.4085170095
0.1800000000	0.6236560616	0.4301554837
0.1900000000	0.6617053281	0.4514442433
0.2000000000	0.7001369960	0.4723723770
0.2100000000	0.7389549087	0.4929294266
0.2200000000	0.7781629478	0.5131053990
0.2300000000	0.8177650343	0.5328907799
0.2400000000	0.8577651284	0.5522765488
0.2500000000	0.8981672301	0.5712541946
0.2600000000	0.9389753797	0.5898157321
0.2700000000	0.9801936580	0.6079537189
0.2800000000	1.0218261869	0.6256612726
0.2900000000	1.0638771296	0.6429320878
0.3000000000	1.1063506914	0.6597604534
0.3100000000	1.1492511196	0.6761412688
0.3200000000	1.1925827042	0.6920700602
0.3300000000	1.2363497785	0.7075429963

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0.3400000000	1.2805567192	0.7225569019
0.3500000000	1.3252079470	0.7371092719
0.3600000000	1.3703079272	0.7511982834
0.3700000000	1.4158611696	0.7648228057
0.3800000000	1.4618722298	0.7779824099
0.3900000000	1.5083457088	0.7906773758
0.4000000000	1.5552862541	0.8029086971
0.4100000000	1.6026985596	0.8146780846
0.4200000000	1.6505873668	0.8259879669
0.4300000000	1.6989574645	0.8368414888
0.4400000000	1.7478136897	0.8472425071
0.4500000000	1.7971609282	0.8571955838
0.4600000000	1.8470041146	0.8667059762
0.4700000000	1.8973482334	0.8757796246
0.4800000000	1.9481983191	0.8844231364
0.4900000000	1.9995594565	0.8926437680
0.5000000000	2.0514367820	0.9004494030
0.5100000000	2.1038354833	0.9078485272
0.5200000000	2.1567608003	0.9148502017
0.5300000000	2.2102180255	0.9214640315
0.5400000000	2.2642125048	0.9277001326
0.5500000000	2.3187496377	0.9335690952
0.5600000000	2.3738348778	0.9390819453
0.5700000000	2.4294737338	0.9442501030
0.5800000000	2.4856717696	0.9490853390
0.5900000000	2.5424346050	0.9535997293
0.6000000000	2.5997679165	0.9578056076
0.6100000000	2.6576774373	0.9617155171
0.6200000000	2.7161689584	0.9653421605
0.6300000000	2.7752483291	0.9686983498
0.6400000000	2.8349214574	0.9717969557
0.6500000000	2.8951943106	0.9746508568
0.6600000000	2.9560729160	0.9772728897
0.6700000000	3.0175633615	0.9796757998
0.6800000000	3.0796717964	0.9818721934
0.6900000000	3.1424044313	0.9838744914
0.7000000000	3.2057675398	0.9856948855
0.7100000000	3.2697674580	0.9873452965
0.7200000000	3.3344105862	0.9888373355
0.7300000000	3.3997033885	0.9901822687
0.7400000000	3.4656523945	0.9913909845
0.7500000000	3.5322641989	0.9924739659
0.7600000000	3.5995454632	0.9934412652
0.7700000000	3.6675029154	0.9943024834
0.7800000000	3.7361433513	0.9950667541
0.7900000000	3.8054736351	0.9957427302
0.8000000000	3.8755006998	0.9963385764
0.8100000000	3.9462315482	0.9968619638

Table 11-3– Cylindrical solution for Tau = 1.0 (*da_cyltau1_0.out*)

```
Simulation of Cylindrical Gas Flow with Dimensionless Pseudopressure
Comparison of Numerical Chan et. al. and DR_SPALL - WIPP PA
delz
     0.020000
delt
     0.010000
Taumax
     1.000000
zetamax
     4.000000
```

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```
phi
     0.050000
eta
     0.000020
r0
0.4760E-04
kperm
0.6400E-13
pff
 10135000.00
NPCavsTpts
         1
Time (s)  Cavity Pressure (Pa)
0.00        0.00
```

Z	zeta	Y(z)
0.0000000000	0.0000000000	0.0000000000
0.0200000000	0.0202013400	0.0213322404
0.0400000000	0.0408107742	0.0426440165
0.0600000000	0.0618365465	0.0639257209
0.0800000000	0.0832870677	0.0851691755
0.1000000000	0.1051709181	0.1063667825
0.1200000000	0.1274968516	0.1275112032
0.1400000000	0.1502737989	0.1485951966
0.1600000000	0.1735108710	0.1696115243
0.1800000000	0.1972173631	0.1905528899
0.2000000000	0.2214027582	0.2114118959
0.2200000000	0.2460767306	0.2321810137
0.2400000000	0.2712491503	0.2528525605
0.2600000000	0.2969300867	0.2734186826
0.2800000000	0.3231298123	0.2938713417
0.3000000000	0.3498588076	0.3142023056
0.3200000000	0.3771277643	0.3344031409
0.3400000000	0.4049475906	0.3544652085
0.3600000000	0.4333294146	0.3743796607
0.3800000000	0.4622845894	0.3941374414
0.4000000000	0.4918246976	0.4137292869
0.4200000000	0.5219615556	0.4331457295
0.4400000000	0.5527072185	0.4523771031
0.4600000000	0.5840739850	0.4714135507
0.4800000000	0.6160744022	0.4902450334
0.5000000000	0.6487212707	0.5088613424
0.5200000000	0.6820276497	0.5272521131
0.5400000000	0.7160068622	0.5454068408
0.5600000000	0.7506725003	0.5633148997
0.5800000000	0.7860384308	0.5809655641
0.6000000000	0.8221188004	0.5983480320
0.6200000000	0.8589280418	0.6154514517
0.6400000000	0.8964808793	0.6322649513
0.6600000000	0.9347923344	0.6487776706
0.6800000000	0.9738777322	0.6649787966
0.7000000000	1.0137527075	0.6808576011
0.7200000000	1.0544332106	0.6964034822
0.7400000000	1.0959355145	0.7116060082
0.7600000000	1.1382762205	0.7264549644
0.7800000000	1.1814722655	0.7409404033
0.8000000000	1.2255409285	0.7550526968
0.8200000000	1.2704998375	0.7687825916
0.8400000000	1.3163669768	0.7821212665
0.8600000000	1.3631606937	0.7950603921
0.8800000000	1.4108997064	0.8075921923
0.9000000000	1.4596031112	0.8197095065

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0.9200000000	1.5092903899	0.8314058536
0.9400000000	1.5599814183	0.8426754958
0.9600000000	1.6116964734	0.8535135023
0.9800000000	1.6644562419	0.8639158118
1.0000000000	1.7182818285	0.8738792937
1.0200000000	1.7731947640	0.8834018064
1.0400000000	1.8292170144	0.8924822522
1.0600000000	1.8863709893	0.9011206277
1.0800000000	1.9446795511	0.9093180692
1.1000000000	2.0041660239	0.9170768904
1.1200000000	2.0648542033	0.9244006139
1.1400000000	2.1267683652	0.9312939932
1.1600000000	2.1899332761	0.9377630248
1.1800000000	2.2543742029	0.9438149502
1.2000000000	2.3201169227	0.9494582456
1.2200000000	2.3871877336	0.9547025992
1.2400000000	2.4556134648	0.9595588760
1.2600000000	2.5254214874	0.9640390679
1.2800000000	2.5966397256	0.9681562306
1.3000000000	2.6692966676	0.9719244068
1.3200000000	2.7434213773	0.9753585356
1.3400000000	2.8190435054	0.9784743489
1.3600000000	2.8961933018	0.9812882560
1.3800000000	2.9749016275	0.9838172183
1.4000000000	3.0551999668	0.9860786138
1.4200000000	3.1371204403	0.9880900961
1.4400000000	3.2206958170	0.9898694478
1.4600000000	3.3059595283	0.9914344325
1.4800000000	3.3929456809	0.9928026472
1.5000000000	3.4816890703	0.9939913790
1.5200000000	3.5722251951	0.9950174667
1.5400000000	3.6645902710	0.9958971738
1.5600000000	3.7588212451	0.9966460719
1.5800000000	3.8549558112	0.9972789387
1.6000000000	3.9530324244	0.9978096729

Table 11-4– Cylindrical solution for Tau = 10.0 (*da_cyltau10_0.out*)

```
Simulation of Cylindrical Gas Flow with Dimensionless Pseudopressure
Comparison of Numerical Chan et. al. and DR_SPALL - WIPP PA
delz
     0.100000
delt
     0.100000
Taumax
    10.000000
zetamax
     4.000000
phi
     0.050000
eta
     0.000020
r0
0.4760E-04
kperm
0.6400E-13
pff
 10135000.00
NPCavsTpts
         1
Time (s)  Cavity Pressure (Pa)
```

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```
0.00        0.00
      Z                       zeta                    Y(z)
  0.0000000000          0.0000000000          0.0000000000
  0.1000000000          0.0332579645          0.0557565560
  0.2000000000          0.0700136996          0.1114442379
  0.3000000000          0.1106350691          0.1670133177
  0.4000000000          0.1555286254          0.2224057896
  0.5000000000          0.2051436782          0.2775507387
  0.6000000000          0.2599767916          0.3323604592
  0.7000000000          0.3205767540          0.3867263948
  0.8000000000          0.3875500700          0.4405147022
  0.9000000000          0.4615670311          0.4935614400
  1.0000000000          0.5433684240          0.5456675348
  1.1000000000          0.6337729445          0.5965938466
  1.2000000000          0.7336853914          0.6460568930
  1.3000000000          0.8441057220          0.6937260978
  1.4000000000          0.9661390603          0.7392238271
  1.5000000000          1.1010067567          0.7821299241
  1.6000000000          1.2500586126          0.8219928871
  1.7000000000          1.4147863890          0.8583500873
  1.8000000000          1.5968387368          0.8907591988
  1.9000000000          1.7980376973          0.9188418666
  2.0000000000          2.0203969371          0.9423380255
  2.1000000000          2.2661419023          0.9611647877
  2.2000000000          2.5377320912          0.9754677205
  2.3000000000          2.8378856695          0.9856464694
  2.4000000000          3.1696066752          0.9923351578
  2.5000000000          3.5362150837          0.9963263818
  2.6000000000          3.9413800350          0.9984486661
```

Table 11-5– Spherical solution for Tau = 0.01 (*da_sphtau0_01.out*)

```
Simulation of Spherical Gas Flow with Dimensionless Pseudopressure
Comparison of Numerical Chan et. al. and DR_SPALL - WIPP PA
delz
     0.010000
delt
     0.000100
Taumax
     0.010000
phi
     0.575000
eta
     0.000090
r0
0.1500E+00
kperm
0.2400E-12
pff
 14550000.00
NPCavsTpts
         1
Time (s)  Cavity Pressure (Pa)
0.00        0.00
      Z                       zeta                    Y(z)
  0.7200000000          3.8888888889          0.9961538437
  0.7300000000          3.6986301370          0.9942479158
  0.7400000000          3.5135135135          0.9916031875
  0.7500000000          3.3333333333          0.9880184465
  0.7600000000          3.1578947368          0.9832655731
  0.7700000000          2.9870129870          0.9770929602
```

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0.7800000000	2.8205128205	0.9692304397
0.7900000000	2.6582278481	0.9593954665
0.8000000000	2.5000000000	0.9473002176
0.8100000000	2.3456790123	0.9326592093
0.8200000000	2.1951219512	0.9151970252
0.8300000000	2.0481927711	0.8946557754
0.8400000000	1.9047619048	0.8708019680
0.8500000000	1.7647058824	0.8434325491
0.8600000000	1.6279069767	0.8123799513
0.8700000000	1.4942528736	0.7775160769
0.8800000000	1.3636363636	0.7387552124
0.8900000000	1.2359550562	0.6960559369
0.9000000000	1.1111111111	0.6494221378
0.9100000000	0.9890109890	0.5989032887
0.9200000000	0.8695652174	0.5445941779
0.9300000000	0.7526881720	0.4866343169
0.9400000000	0.6382978723	0.4252073104
0.9500000000	0.5263157895	0.3605405619
0.9600000000	0.4166666667	0.2929058896
0.9700000000	0.3092783505	0.2226220640
0.9800000000	0.2040816327	0.1500614405
0.9900000000	0.1010101010	0.0756665602
1.0000000000	0.0000000000	0.0000000000

Table 11-6– Spherical solution for Tau = 0.1 (*da_sphtau0_1.out*)

```
Simulation of Spherical Gas Flow with Dimensionless Pseudopressure
Comparison of Numerical Chan et. al. and DR_SPALL - WIPP PA
delz
     0.010000
delt
     0.010000
Taumax
     0.100000
phi
     0.050000
eta
     0.000020
r0
0.4760E-04
kperm
0.6400E-13
pff
 10135000.00
NPCavsTpts
         1
Time (s)  Cavity Pressure (Pa)
0.00        0.00
```

Z	zeta	Y(z)
0.4500000000	3.8650060291	0.9966094035
0.4600000000	3.7122389924	0.9954847220
0.4700000000	3.5659726806	0.9940827730
0.4800000000	3.4258007985	0.9923605251
0.4900000000	3.2913502177	0.9902732702
0.5000000000	3.1622776602	0.9877752811
0.5100000000	3.0382667715	0.9848204917
0.5200000000	2.9190255325	0.9813631760
0.5300000000	2.8042839628	0.9773586036
0.5400000000	2.6937920809	0.9727636530
0.5500000000	2.5873180856	0.9675373667
0.5600000000	2.4846467330	0.9616414375

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0.5700000000	2.3855778840	0.9550406186
0.5800000000	2.2899252022	0.9477030546
0.5900000000	2.1975149842	0.9396005317
0.6000000000	2.1081851068	0.9307086511
0.6100000000	2.0217840778	0.9210069293
0.6200000000	1.9381701788	0.9104788307
0.6300000000	1.8572106893	0.8991117414
0.6400000000	1.7787811838	0.8868968907
0.6500000000	1.7027648939	0.8738292283
0.6600000000	1.6290521280	0.8599072654
0.6700000000	1.5575397431	0.8451328878
0.6800000000	1.4881306636	0.8295111464
0.6900000000	1.4207334415	0.8130500336
0.7000000000	1.3552618544	0.7957602495
0.7100000000	1.2916345373	0.7776549639
0.7200000000	1.2297746456	0.7587495781
0.7300000000	1.1696095455	0.7390614901
0.7400000000	1.1110705292	0.7186098663
0.7500000000	1.0540925534	0.6974154215
0.7600000000	0.9986139979	0.6755002099
0.7700000000	0.9445764439	0.6528874280
0.7800000000	0.8919244683	0.6296012298
0.7900000000	0.8406054540	0.6056665568
0.8000000000	0.7905694150	0.5811089807
0.8100000000	0.7417688339	0.5559545610
0.8200000000	0.6941585108	0.5302297165
0.8300000000	0.6476954244	0.5039611112
0.8400000000	0.6023386019	0.4771755533
0.8500000000	0.5580489989	0.4498999092
0.8600000000	0.5147893865	0.4221610298
0.8700000000	0.4725242481	0.3939856913
0.8800000000	0.4312196809	0.3654005501
0.8900000000	0.3908433063	0.3364321109
0.9000000000	0.3513641845	0.3071067116
0.9100000000	0.3127527356	0.2774505248
0.9200000000	0.2749806661	0.2474895796
0.9300000000	0.2380208992	0.2172498086
0.9400000000	0.2018475102	0.1867571287
0.9500000000	0.1664356663	0.1560375709
0.9600000000	0.1317615692	0.1251174847
0.9700000000	0.0978024019	0.0940238757
0.9800000000	0.0645362788	0.0627850004
0.9900000000	0.0319421986	0.0314315730
1.0000000000	0.0000000000	0.0000000000

Table 11-7– Spherical solution for Tau = 1.0 (*da_sphtau1_0.out*)

```
Simulation of Spherical Gas Flow with Dimensionless Pseudopressure
Comparison of Numerical Chan et. al. and DR_SPALL - WIPP PA
delz
     0.010000
delt
     0.010000
Taumax
     1.000000
phi
     0.050000
eta
     0.000020
r0
0.4760E-04
```

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```
kperm
0.6400E-13
pff
 10135000.00
NPCavsTpts
         1
Time (s)  Cavity Pressure (Pa)
0.00        0.00
```

Z	zeta	Y(z)
0.2000000000	4.0000000000	0.9991165648
0.2100000000	3.7619047619	0.9984728373
0.2200000000	3.5454545455	0.9975305591
0.2300000000	3.3478260870	0.9962245850
0.2400000000	3.1666666667	0.9944948962
0.2500000000	3.0000000000	0.9922893424
0.2600000000	2.8461538462	0.9895652764
0.2700000000	2.7037037037	0.9862902022
0.2800000000	2.5714285714	0.9824416459
0.2900000000	2.4482758621	0.9780064833
0.3000000000	2.3333333333	0.9729799328
0.3100000000	2.2258064516	0.9673643825
0.3200000000	2.1250000000	0.9611681781
0.3300000000	2.0303030303	0.9544044542
0.3400000000	1.9411764706	0.9470900618
0.3500000000	1.8571428571	0.9392446185
0.3600000000	1.7777777778	0.9308896910
0.3700000000	1.7027027027	0.9220481085
0.3800000000	1.6315789474	0.9127433972
0.3900000000	1.5641025641	0.9029993250
0.4000000000	1.5000000000	0.8928395416
0.4100000000	1.4390243902	0.8822873001
0.4200000000	1.3809523810	0.8713652478
0.4300000000	1.3255813953	0.8600952730
0.4400000000	1.2727272727	0.8484983989
0.4500000000	1.2222222222	0.8365947139
0.4600000000	1.1739130435	0.8244033322
0.4700000000	1.1276595745	0.8119423769
0.4800000000	1.0833333333	0.7992289812
0.4900000000	1.0408163265	0.7862793036
0.5000000000	1.0000000000	0.7731085523
0.5100000000	0.9607843137	0.7597310176
0.5200000000	0.9230769231	0.7461601087
0.5300000000	0.8867924528	0.7324083939
0.5400000000	0.8518518519	0.7184876426
0.5500000000	0.8181818182	0.7044088685
0.5600000000	0.7857142857	0.6901823716
0.5700000000	0.7543859649	0.6758177808
0.5800000000	0.7241379310	0.6613240946
0.5900000000	0.6949152542	0.6467097205
0.6000000000	0.6666666667	0.6319825132
0.6100000000	0.6393442623	0.6171498101
0.6200000000	0.6129032258	0.6022184659
0.6300000000	0.5873015873	0.5871948848
0.6400000000	0.5625000000	0.5720850508
0.6500000000	0.5384615385	0.5568945566
0.6600000000	0.5151515152	0.5416286299
0.6700000000	0.4925373134	0.5262921589
0.6800000000	0.4705882353	0.5108897156
0.6900000000	0.4492753623	0.4954255774
0.7000000000	0.4285714286	0.4799037479
0.7100000000	0.4084507042	0.4643279758

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0.7200000000	0.3888888889	0.4487017724
0.7300000000	0.3698630137	0.4330284280
0.7400000000	0.3513513514	0.4173110278
0.7500000000	0.3333333333	0.4015524653
0.7600000000	0.3157894737	0.3857554564
0.7700000000	0.2987012987	0.3699225513
0.7800000000	0.2820512821	0.3540561461
0.7900000000	0.2658227848	0.3381584935
0.8000000000	0.2500000000	0.3222317129
0.8100000000	0.2345679012	0.3062777997
0.8200000000	0.2195121951	0.2902986341
0.8300000000	0.2048192771	0.2742959893
0.8400000000	0.1904761905	0.2582715391
0.8500000000	0.1764705882	0.2422268651
0.8600000000	0.1627906977	0.2261634639
0.8700000000	0.1494252874	0.2100827534
0.8800000000	0.1363636364	0.1939860789
0.8900000000	0.1235955056	0.1778747197
0.9000000000	0.1111111111	0.1617498945
0.9100000000	0.0989010989	0.1456127679
0.9200000000	0.0869565217	0.1294644561
0.9300000000	0.0752688172	0.1133060337
0.9400000000	0.0638297872	0.0971385407
0.9500000000	0.0526315789	0.0809629909
0.9600000000	0.0416666667	0.0647803829
0.9700000000	0.0309278351	0.0485917146
0.9800000000	0.0204081633	0.0323980064
0.9900000000	0.0101010101	0.0162003457
1.0000000000	0.0000000000	0.0000000000

Table 11-8– Spherical solution for Tau = 10.0 (*da_sphtau10_0.out*)

```
Simulation of Spherical Gas Flow with Dimensionless Pseudopressure
Comparison of Numerical Chan et. al. and DR_SPALL - WIPP PA
delz
     0.010000
delt
     0.100000
Taumax
    10.000000
phi
     0.050000
eta
     0.000020
r0
0.4760E-04
kperm
0.6400E-13
pff
 10135000.00
NPCavsTpts
         1
Time (s)  Cavity Pressure (Pa)
0.00        0.00
```

Z	zeta	Y(z)
0.0800000000	3.6366193092	0.9992171386
0.0900000000	3.1974140786	0.9979660812
0.1000000000	2.8460498942	0.9958159566
0.1100000000	2.5585701069	0.9926616018
0.1200000000	2.3190036175	0.9884948708
0.1300000000	2.1162935110	0.9833705721

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0.1400000000	1.9425419912	0.9773760850
0.1500000000	1.7919573408	0.9706104689
0.1600000000	1.6601957716	0.9631721056
0.1700000000	1.5439355635	0.9551523112
0.1800000000	1.4405931563	0.9466326337
0.1900000000	1.3481288972	0.9376842355
0.2000000000	1.2649110641	0.9283683546
0.2100000000	1.1896187388	0.9187372551
0.2200000000	1.1211711704	0.9088353386
0.2300000000	1.0586755645	0.8987002490
0.2400000000	1.0013879257	0.8883638874
0.2500000000	0.9486832981	0.8778533083
0.2600000000	0.9000328725	0.8671914913
0.2700000000	0.8549861822	0.8563979952
0.2800000000	0.8131571126	0.8454895076
0.2900000000	0.7742128065	0.8344803046
0.3000000000	0.7378647874	0.8233826339
0.3100000000	0.7038618018	0.8122070330
0.3200000000	0.6719840028	0.8009625952
0.3300000000	0.6420381916	0.7896571899
0.3400000000	0.6138538987	0.7782976476
0.3500000000	0.5872801369	0.7668899137
0.3600000000	0.5621826951	0.7554391778
0.3700000000	0.5384418719	0.7439499824
0.3800000000	0.5159505656	0.7324263136
0.3900000000	0.4946126597	0.7208716788
0.4000000000	0.4743416490	0.7092891719
0.4100000000	0.4550594682	0.6976815286
0.4200000000	0.4366954864	0.6860511733
0.4300000000	0.4191856433	0.6744002601
0.4400000000	0.4024717022	0.6627307063
0.4500000000	0.3865006029	0.6510442229
0.4600000000	0.3712238992	0.6393423394
0.4700000000	0.3565972681	0.6276264259
0.4800000000	0.3425800799	0.6158977123
0.4900000000	0.3291350218	0.6041573044
0.5000000000	0.3162277660	0.5924061982
0.5100000000	0.3038266772	0.5806452929
0.5200000000	0.2919025532	0.5688754009
0.5300000000	0.2804283963	0.5570972580
0.5400000000	0.2693792081	0.5453115313
0.5500000000	0.2587318086	0.5335188268
0.5600000000	0.2484646733	0.5217196955
0.5700000000	0.2385577884	0.5099146394
0.5800000000	0.2289925202	0.4981041166
0.5900000000	0.2197514984	0.4862885451
0.6000000000	0.2108185107	0.4744683074
0.6100000000	0.2021784078	0.4626437539
0.6200000000	0.1938170179	0.4508152057
0.6300000000	0.1857210689	0.4389829575
0.6400000000	0.1778781184	0.4271472804
0.6500000000	0.1702764894	0.4153084236
0.6600000000	0.1629052128	0.4034666167
0.6700000000	0.1557539743	0.3916220715
0.6800000000	0.1488130664	0.3797749835
0.6900000000	0.1420733442	0.3679255332
0.7000000000	0.1355261854	0.3560738879
0.7100000000	0.1291634537	0.3442202022
0.7200000000	0.1229774646	0.3323646195
0.7300000000	0.1169609546	0.3205072730
0.7400000000	0.1111070529	0.3086482861

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0.7500000000	0.1054092553	0.2967877738
0.7600000000	0.0998613998	0.2849258431
0.7700000000	0.0944576444	0.2730625934
0.7800000000	0.0891924468	0.2611981176
0.7900000000	0.0840605454	0.2493325024
0.8000000000	0.0790569415	0.2374658288
0.8100000000	0.0741768834	0.2255981725
0.8200000000	0.0694158511	0.2137296043
0.8300000000	0.0647695424	0.2018601909
0.8400000000	0.0602338602	0.1899899944
0.8500000000	0.0558048999	0.1781190737
0.8600000000	0.0514789387	0.1662474839
0.8700000000	0.0472524248	0.1543752769
0.8800000000	0.0431219681	0.1425025021
0.8900000000	0.0390843306	0.1306292058
0.9000000000	0.0351364184	0.1187554322
0.9100000000	0.0312752736	0.1068812233
0.9200000000	0.0274980666	0.0950066193
0.9300000000	0.0238020899	0.0831316585
0.9400000000	0.0201847510	0.0712563782
0.9500000000	0.0166435666	0.0593808142
0.9600000000	0.0131761569	0.0475050021
0.9700000000	0.0097802402	0.0356289771
0.9800000000	0.0064536279	0.0237527752
0.9900000000	0.0031942199	0.0118764347
1.0000000000	0.0000000000	0.0000000000

12.0 APPENDIX D: DJORDJEVIC AND ADAMS (2003) CURVE FIT

The curve fits to the Djordjevic and Adams (2003) solutions are shown graphically in Figure 12-1 and Figure 12-2. These fits were obtained by a least-squares routine documented in the Excel file *AppendixD_CurveFit.xlsx* (archived in CVS in the directory: /data/cvs/CVSLIB/WIPP_CODES/PA_CODES/DRSPALL/Test/Auxiliary/CMS_Files/). The data used to generate these fits are shown in

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Table 12-1 through Table 12-4.

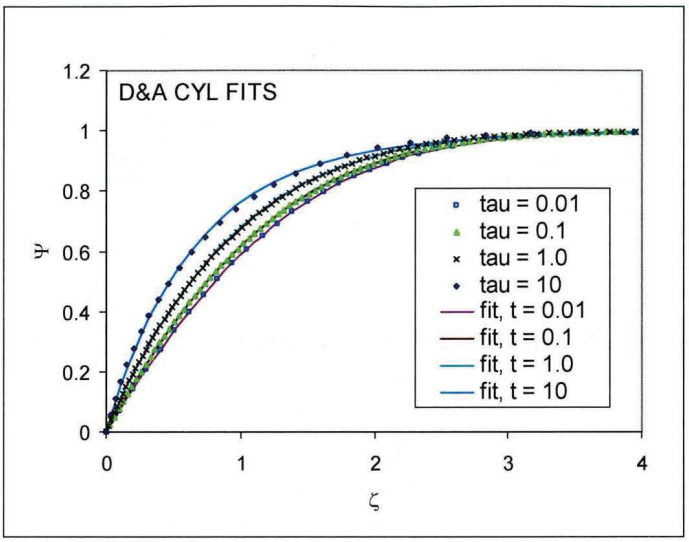

Figure 12-1 Graphical representation of curve fits to Djordjevic and Adams (2003) cylindrical geometry solutions.

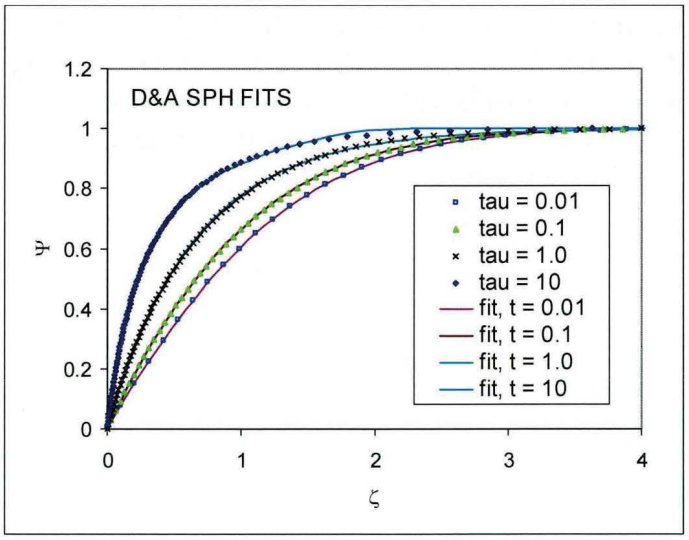

Figure 12-2 Graphical representation of curve fits to Djordjevic and Adams (2003) spherical geometry solutions.

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Table 12-1– Constants for functional fit to Djordjevic and Adams (2003) solution in cylindrical geometry

τ	C_1	C_2	C_3
0.01	0.715	0.167	0.000
0.1	0.803	0.157	0.000
1	1.032	0.101	0.000
10	1.505	-0.071	0.000

Table 12-2– Constants for functional fit to Djordjevic and Adams (2003) solution in spherical geometry

τ	C_1	C_2	C_3
0.01	1.331	-0.073	0.000
0.10	1.000	0.126	0.000
1.0	1.537	-0.033	0.000
10.0	3.500	-2.229	0.858

The EXCEL spreadsheet (file *AppendixD_CurveFit.xlsx* archived in CVS in the directory: /data/cvs/CVSLIB/WIPP_CODES/PA_CODES/DRSPALL/Test/Auxiliary/CMS_Files/) used to generate the least square fits is shown in Table 12-3 and Table 12-4. The "Solver" worksheet function was used to minimize the SUM for each Tau. Resulting a, b, and c-values correspond to C_1, C_2, and C_3, which are defined in Eq. 5.1.17 and listed in

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Table 12-1 and Table 12-2.

Table 12-3– Spreadsheet excerpts showing least squares fits for cylindrical geometry

	a	0.715022	C_1	
	b	0.166806	C_2	
	c	0	C_3	
Tau = 0.01				
Z	ζ	Ψ	proposed f(ζ)	(Ψ-f)^2
0	0	0	0	0
0.01	0.100502	0.070962	0.070907	3.07E-09
0.02	0.202013	0.140635	0.140368	7.13E-08
0.03	0.304545	0.208485	0.208026	2.1E-07
0.04	0.408108	0.274117	0.273552	3.2E-07
0.05	0.512711	0.337219	0.336647	3.27E-07
0.06	0.618365	0.397542	0.397054	2.39E-07
0.07	0.725082	0.454887	0.454551	1.13E-07
0.08	0.832871	0.509102	0.50896	2.02E-08
0.09	0.941743	0.560077	0.560142	4.23E-09
0.1	1.051709	0.607741	0.608002	6.79E-08
0.11	1.162781	0.652058	0.652484	1.82E-07
0.12	1.274969	0.693028	0.693575	2.99E-07
0.13	1.388284	0.730681	0.731296	3.78E-07
0.14	1.502738	0.765078	0.765705	3.93E-07
0.15	1.618342	0.796306	0.796892	3.44E-07
0.16	1.735109	0.824475	0.824975	2.5E-07
0.17	1.853049	0.849718	0.850094	1.41E-07
0.18	1.972174	0.872184	0.87241	5.11E-08
0.19	2.092496	0.892038	0.892099	3.78E-09
0.2	2.214028	0.909456	0.90935	1.13E-08
0.21	2.336781	0.924621	0.924355	7.09E-08
0.22	2.460767	0.937723	0.937311	1.7E-07
0.23	2.586	0.94895	0.948416	2.85E-07
0.24	2.712492	0.958492	0.957861	3.98E-07
0.25	2.840254	0.966531	0.965832	4.88E-07
0.26	2.969301	0.973244	0.972506	5.44E-07
0.27	3.099645	0.9788	0.978049	5.64E-07
0.28	3.231298	0.983354	0.982614	5.47E-07
0.29	3.364275	0.987052	0.986343	5.03E-07
0.3	3.498588	0.990024	0.989362	4.39E-07
0.31	3.634251	0.992389	0.991784	3.66E-07
0.32	3.771278	0.994252	0.993711	2.93E-07
0.33	3.909681	0.995703	0.995229	2.25E-07
			Sum	8.32E-06

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	a	0.802919	C_1	
	b	0.156585	C_2	
	c	0	C_3	
Tau = 0.1				
Z	ζ	Ψ	proposed f(ζ)	(Ψ-f)^2
0	0	0	0	0
0.01	0.031781	0.025424	0.025349	5.64E-09
0.02	0.063882	0.050779	0.050606	3E-08
0.03	0.096306	0.076035	0.075755	7.83E-08
0.04	0.129055	0.101166	0.100781	1.48E-07
0.05	0.162133	0.126152	0.125669	2.34E-07
0.06	0.195544	0.150973	0.150403	3.25E-07
0.07	0.229291	0.175612	0.174969	4.13E-07
0.08	0.263377	0.20005	0.199351	4.89E-07
0.09	0.297805	0.224273	0.223533	5.48E-07
0.1	0.33258	0.248264	0.2475	5.83E-07
0.11	0.367704	0.272008	0.271238	5.93E-07
0.12	0.40318	0.295491	0.29473	5.79E-07
0.13	0.439014	0.3187	0.317963	5.43E-07
0.14	0.475207	0.341619	0.340922	4.86E-07
0.15	0.511765	0.364237	0.363593	4.15E-07
0.16	0.54869	0.38654	0.38596	3.36E-07
0.17	0.585985	0.408517	0.408011	2.56E-07
0.18	0.623656	0.430155	0.429732	1.79E-07
0.19	0.661705	0.451444	0.45111	1.12E-07
0.2	0.700137	0.472372	0.472133	5.73E-08
0.21	0.738955	0.492929	0.492788	2E-08
0.22	0.778163	0.513105	0.513063	1.77E-09
0.23	0.817765	0.532891	0.532948	3.22E-09
0.24	0.857765	0.552277	0.552431	2.38E-08
0.25	0.898167	0.571254	0.571504	6.24E-08
0.26	0.938975	0.589816	0.590156	1.15E-07
0.27	0.980194	0.607954	0.608379	1.81E-07
0.28	1.021826	0.625661	0.626164	2.53E-07
0.29	1.063877	0.642932	0.643505	3.29E-07
0.3	1.106351	0.65976	0.660395	4.04E-07
0.31	1.149251	0.676141	0.676828	4.72E-07
0.32	1.192583	0.69207	0.692799	5.31E-07
0.33	1.23635	0.707543	0.708303	5.78E-07
0.34	1.280557	0.722557	0.723337	6.09E-07
0.35	1.325208	0.737109	0.737899	6.25E-07
0.36	1.370308	0.751198	0.751987	6.22E-07
0.37	1.415861	0.764823	0.765599	6.02E-07
0.38	1.461872	0.777982	0.778736	5.69E-07
0.39	1.508346	0.790677	0.791398	5.2E-07
0.4	1.555286	0.802909	0.803587	4.6E-07

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0.41	1.602699	0.814678	0.815305	3.93E-07
0.42	1.650587	0.825988	0.826555	3.22E-07
0.43	1.698957	0.836841	0.837341	2.5E-07
0.44	1.747814	0.847243	0.847669	1.81E-07
0.45	1.797161	0.857196	0.857543	1.2E-07
0.46	1.847004	0.866706	0.866969	6.92E-08
0.47	1.897348	0.87578	0.875955	3.07E-08
0.48	1.948198	0.884423	0.884509	7.37E-09
0.49	1.999559	0.892644	0.892638	3.54E-11
0.5	2.051437	0.900449	0.900352	9.42E-09
0.51	2.103835	0.907849	0.90766	3.58E-08
0.52	2.156761	0.91485	0.914572	7.73E-08
0.53	2.210218	0.921464	0.921099	1.34E-07
0.54	2.264213	0.9277	0.927251	2.02E-07
0.55	2.31875	0.933569	0.93304	2.79E-07
0.56	2.373835	0.939082	0.938479	3.64E-07
0.57	2.429474	0.94425	0.943578	4.52E-07
0.58	2.485672	0.949085	0.94835	5.4E-07
0.59	2.542435	0.9536	0.952808	6.27E-07
0.6	2.599768	0.957806	0.956965	7.08E-07
0.61	2.657677	0.961716	0.960832	7.81E-07
0.62	2.716169	0.965342	0.964424	8.43E-07
0.63	2.775248	0.968698	0.967753	8.94E-07
0.64	2.834921	0.971797	0.970831	9.33E-07
0.65	2.895194	0.974651	0.973672	9.58E-07
0.66	2.956073	0.977273	0.976288	9.7E-07
0.67	3.017563	0.979676	0.978692	9.68E-07
0.68	3.079672	0.981872	0.980896	9.53E-07
0.69	3.142404	0.983874	0.982911	9.27E-07
0.7	3.205768	0.985695	0.98475	8.93E-07
0.71	3.269767	0.987345	0.986424	8.48E-07
0.72	3.334411	0.988837	0.987944	7.97E-07
0.73	3.399703	0.990182	0.989321	7.41E-07
0.74	3.465652	0.991391	0.990565	6.82E-07
0.75	3.532264	0.992474	0.991686	6.21E-07
0.76	3.599545	0.993441	0.992693	5.59E-07
0.77	3.667503	0.994302	0.993596	4.98E-07
0.78	3.736143	0.995067	0.994403	4.41E-07
0.79	3.805474	0.995743	0.995122	3.85E-07
0.8	3.875501	0.996339	0.995762	3.33E-07
0.81	3.946232	0.996862	0.996328	2.85E-07
			Sum	3.35E-05

a	1.031862	C_1
b	0.101223	C_2
c	0	C_3

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Tau = 1.0

Z	ζ	Ψ	proposed f(ζ)	(Ψ-f)^2
0	0	0	0	0
0.02	0.020201	0.021332	0.020669	4.39E-07
0.04	0.040811	0.042644	0.041399	1.55E-06
0.06	0.061837	0.063926	0.062177	3.06E-06
0.08	0.083287	0.085169	0.082995	4.72E-06
0.1	0.105171	0.106367	0.103845	6.36E-06
0.12	0.127497	0.127511	0.124714	7.82E-06
0.14	0.150274	0.148595	0.145593	9.01E-06
0.16	0.173511	0.169612	0.166471	9.87E-06
0.18	0.197217	0.190553	0.187336	1.03E-05
0.2	0.221403	0.211412	0.208178	1.05E-05
0.22	0.246077	0.232181	0.228985	1.02E-05
0.24	0.271249	0.252853	0.249743	9.67E-06
0.26	0.29693	0.273419	0.270441	8.87E-06
0.28	0.32313	0.293871	0.291067	7.86E-06
0.3	0.349859	0.314202	0.311607	6.73E-06
0.32	0.377128	0.334403	0.332049	5.54E-06
0.34	0.404948	0.354465	0.352379	4.35E-06
0.36	0.433329	0.37438	0.372582	3.23E-06
0.38	0.462285	0.394137	0.392648	2.22E-06
0.4	0.491825	0.413729	0.41256	1.37E-06
0.42	0.521962	0.433146	0.432305	7.08E-07
0.44	0.552707	0.452377	0.451868	2.59E-07
0.46	0.584074	0.471414	0.471237	3.13E-08
0.48	0.616074	0.490245	0.490396	2.3E-08
0.5	0.648721	0.508861	0.509333	2.23E-07
0.52	0.682028	0.527252	0.528032	6.08E-07
0.54	0.716007	0.545407	0.546479	1.15E-06
0.56	0.750673	0.563315	0.564661	1.81E-06
0.58	0.786038	0.580966	0.582564	2.55E-06
0.6	0.822119	0.598348	0.600175	3.34E-06
0.62	0.858928	0.615451	0.61748	4.12E-06
0.64	0.896481	0.632265	0.634466	4.84E-06
0.66	0.934792	0.648778	0.65112	5.49E-06
0.68	0.973878	0.664979	0.667432	6.02E-06
0.7	1.013753	0.680858	0.683388	6.4E-06
0.72	1.054433	0.696403	0.698978	6.63E-06
0.74	1.095936	0.711606	0.714191	6.68E-06
0.76	1.138276	0.726455	0.729016	6.56E-06
0.78	1.181472	0.74094	0.743445	6.27E-06
0.8	1.225541	0.755053	0.757468	5.83E-06
0.82	1.2705	0.768783	0.771078	5.26E-06
0.84	1.316367	0.782121	0.784266	4.6E-06
0.86	1.363161	0.79506	0.797028	3.87E-06
0.88	1.4109	0.807592	0.809357	3.12E-06

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0.9	1.459603	0.81971	0.821248	2.37E-06
0.92	1.50929	0.831406	0.832699	1.67E-06
0.94	1.559981	0.842675	0.843706	1.06E-06
0.96	1.611696	0.853514	0.854267	5.67E-07
0.98	1.664456	0.863916	0.864383	2.18E-07
1	1.718282	0.873879	0.874052	3.01E-08
1.02	1.773195	0.883402	0.883278	1.54E-08
1.04	1.829217	0.892482	0.892062	1.77E-07
1.06	1.886371	0.901121	0.900407	5.09E-07
1.08	1.94468	0.909318	0.908319	9.97E-07
1.1	2.004166	0.917077	0.915804	1.62E-06
1.12	2.064854	0.924401	0.922867	2.35E-06
1.14	2.126768	0.931294	0.929517	3.16E-06
1.16	2.189933	0.937763	0.935762	4.01E-06
1.18	2.254374	0.943815	0.941612	4.85E-06
1.2	2.320117	0.949458	0.947077	5.67E-06
1.22	2.387188	0.954703	0.952169	6.42E-06
1.24	2.455613	0.959559	0.9569	7.07E-06
1.26	2.525421	0.964039	0.961282	7.6E-06
1.28	2.59664	0.968156	0.96533	7.99E-06
1.3	2.669297	0.971924	0.969056	8.23E-06
1.32	2.743421	0.975359	0.972475	8.32E-06
1.34	2.819044	0.978474	0.975603	8.24E-06
1.36	2.896193	0.981288	0.978453	8.04E-06
1.38	2.974902	0.983817	0.981042	7.7E-06
1.4	3.0552	0.986079	0.983384	7.26E-06
1.42	3.13712	0.98809	0.985495	6.73E-06
1.44	3.220696	0.989869	0.98739	6.14E-06
1.46	3.30596	0.991434	0.989085	5.52E-06
1.48	3.392946	0.992803	0.990593	4.88E-06
1.5	3.481689	0.993991	0.99193	4.25E-06
1.52	3.572225	0.995017	0.99311	3.64E-06
1.54	3.66459	0.995897	0.994146	3.06E-06
1.56	3.758821	0.996646	0.995052	2.54E-06
1.58	3.854956	0.997279	0.995839	2.07E-06
1.6	3.953032	0.99781	0.99652	1.66E-06
			Sum	0.000357

	a	1.505438	C_1
	b	-0.07061	C_2
	c	0	C_3

Tau = 10

Z	ζ	Ψ	proposed f(ζ)	(Ψ-f)^2
0	0	0	0	0

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0.1	0.033258	0.055757	0.048761	4.89E-05
0.2	0.070014	0.111444	0.099726	0.000137
0.3	0.110635	0.167013	0.152691	0.000205
0.4	0.155529	0.222406	0.207396	0.000225
0.5	0.205144	0.277551	0.26351	0.000197
0.6	0.259977	0.33236	0.320642	0.000137
0.7	0.320577	0.386726	0.378334	7.04E-05
0.8	0.38755	0.440515	0.436071	1.97E-05
0.9	0.461567	0.493561	0.49329	7.32E-08
1	0.543368	0.545668	0.549393	1.39E-05
1.1	0.633773	0.596594	0.603763	5.14E-05
1.2	0.733685	0.646057	0.655792	9.48E-05
1.3	0.844106	0.693726	0.704899	0.000125
1.4	0.966139	0.739224	0.750564	0.000129
1.5	1.101007	0.78213	0.79235	0.000104
1.6	1.250059	0.821993	0.82993	6.3E-05
1.7	1.414786	0.85835	0.863104	2.26E-05
1.8	1.596839	0.890759	0.891813	1.11E-06
1.9	1.798038	0.918842	0.916136	7.32E-06
2	2.020397	0.942338	0.936286	3.66E-05
2.1	2.266142	0.961165	0.95259	7.35E-05
2.2	2.537732	0.975468	0.965461	0.0001
2.3	2.837886	0.985646	0.975365	0.000106
2.4	3.169607	0.992335	0.98279	9.11E-05
2.5	3.536215	0.996326	0.988211	6.59E-05
2.6	3.94138	0.998449	0.992066	4.07E-05
			Sum	0.002167

Table 12-4– Spreadsheet excerpts showing least squares fits for spherical geometry

	a	0.761332	C_1
	b	0.164771	C_2
	c	0	C_3

Tau = 0.01

Z	ζ	Ψ	proposed f(ζ)	(Ψ-f)^2
0.72	3.888889	0.996154	0.995715	1.93E-07
0.73	3.69863	0.994248	0.993717	2.82E-07
0.74	3.513514	0.991603	0.990986	3.8E-07
0.75	3.333333	0.988018	0.987331	4.73E-07
0.76	3.157895	0.983266	0.982531	5.4E-07
0.77	2.987013	0.977093	0.976346	5.58E-07
0.78	2.820513	0.96923	0.968512	5.16E-07
0.79	2.658228	0.959395	0.95875	4.17E-07
0.8	2.5	0.9473	0.946771	2.8E-07

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0.81	2.345679	0.932659	0.932285	1.4E-07
0.82	2.195122	0.915197	0.915006	3.64E-08
0.83	2.048193	0.894656	0.894662	4.11E-11
0.84	1.904762	0.870802	0.871003	4.03E-08
0.85	1.764706	0.843433	0.843806	1.39E-07
0.86	1.627907	0.81238	0.812885	2.56E-07
0.87	1.494253	0.777516	0.778099	3.39E-07
0.88	1.363636	0.738755	0.739349	3.53E-07
0.89	1.235955	0.696056	0.696591	2.86E-07
0.9	1.111111	0.649422	0.649833	1.69E-07
0.91	0.989011	0.598903	0.599137	5.47E-08
0.92	0.869565	0.544594	0.544618	5.69E-10
0.93	0.752688	0.486634	0.486443	3.64E-08
0.94	0.638298	0.425207	0.424829	1.43E-07
0.95	0.526316	0.360541	0.360037	2.54E-07
0.96	0.416667	0.292906	0.292366	2.92E-07
0.97	0.309278	0.222622	0.222152	2.21E-07
0.98	0.204082	0.150061	0.14976	9.05E-08
0.99	0.10101	0.075667	0.075575	8.47E-09
1	0	0	0	0
			Sum	6.50E-06

	a	0.950457	C_1
	b	0.13871	C_2
	c	0	C_3

Tau = 0.1

Z	ζ	Ψ	proposed f(ζ)	(Ψ-f)^2
0.45	3.865006	0.997546	0.996803	5.52E-07
0.46	3.712239	0.99654	0.99566	7.75E-07
0.47	3.565973	0.995235	0.994219	1.03E-06
0.48	3.425801	0.99358	0.992433	1.31E-06
0.49	3.29135	0.991519	0.990254	1.6E-06
0.5	3.162278	0.988997	0.987633	1.86E-06
0.51	3.038267	0.98596	0.98452	2.07E-06
0.52	2.919026	0.982356	0.980867	2.22E-06
0.53	2.804284	0.978135	0.976627	2.27E-06
0.54	2.693792	0.973251	0.971756	2.23E-06
0.55	2.587318	0.967661	0.966213	2.1E-06
0.56	2.484647	0.961328	0.95996	1.87E-06
0.57	2.385578	0.954219	0.952961	1.58E-06
0.58	2.289925	0.946308	0.945188	1.26E-06
0.59	2.197515	0.93757	0.936612	9.17E-07
0.6	2.108185	0.92799	0.927214	6.02E-07
0.61	2.021784	0.917555	0.916975	3.36E-07

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0.62	1.93817	0.906258	0.905883	1.41E-07
0.63	1.857211	0.894095	0.893929	2.77E-08
0.64	1.778781	0.881068	0.881108	1.63E-09
0.65	1.702765	0.867182	0.867422	5.75E-08
0.66	1.629052	0.852445	0.852872	1.83E-07
0.67	1.55754	0.836869	0.837467	3.58E-07
0.68	1.488131	0.820469	0.821217	5.6E-07
0.69	1.420733	0.80326	0.804135	7.66E-07
0.7	1.355262	0.785263	0.786238	9.51E-07
0.71	1.291635	0.766497	0.767545	1.1E-06
0.72	1.229775	0.746986	0.748076	1.19E-06
0.73	1.16961	0.726751	0.727854	1.22E-06
0.74	1.111071	0.705819	0.706906	1.18E-06
0.75	1.054093	0.684214	0.685255	1.08E-06
0.76	0.998614	0.661962	0.66293	9.38E-07
0.77	0.944576	0.639089	0.63996	7.58E-07
0.78	0.891924	0.615622	0.616373	5.63E-07
0.79	0.840605	0.591587	0.592198	3.74E-07
0.8	0.790569	0.56701	0.567467	2.08E-07
0.81	0.741769	0.541919	0.542208	8.37E-08
0.82	0.694159	0.516339	0.516453	1.3E-08
0.83	0.647695	0.490296	0.49023	4.3E-09
0.84	0.602339	0.463816	0.463572	5.95E-08
0.85	0.558049	0.436923	0.436506	1.74E-07
0.86	0.514789	0.409644	0.409062	3.39E-07
0.87	0.472524	0.382001	0.381269	5.36E-07
0.88	0.43122	0.354019	0.353156	7.46E-07
0.89	0.390843	0.325722	0.324748	9.5E-07
0.9	0.351364	0.297131	0.296073	1.12E-06
0.91	0.312753	0.268271	0.267159	1.24E-06
0.92	0.274981	0.239162	0.238029	1.28E-06
0.93	0.238021	0.209828	0.208707	1.26E-06
0.94	0.201848	0.180289	0.179219	1.14E-06
0.95	0.166436	0.150567	0.149587	9.61E-07
0.96	0.131762	0.120684	0.119832	7.26E-07
0.97	0.097802	0.090661	0.089975	4.7E-07
0.98	0.064536	0.060523	0.060039	2.35E-07
0.99	0.031942	0.030293	0.030041	6.37E-08
1	0	0	0	0
			Sum	4.76E-05

a	1.537306	C_1
b	-0.0335	C_2
c	0	C_3

Tau = 1.0

proposed

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Z	ζ	Ψ	f(ζ)	(Ψ-f)^2
0.2	4	0.999117	0.996351	7.65E-06
0.21	3.761905	0.998473	0.995054	1.17E-05
0.22	3.545455	0.997531	0.993457	1.66E-05
0.23	3.347826	0.996225	0.99153	2.2E-05
0.24	3.166667	0.994495	0.989243	2.76E-05
0.25	3	0.992289	0.986572	3.27E-05
0.26	2.846154	0.989565	0.983494	3.69E-05
0.27	2.703704	0.98629	0.979991	3.97E-05
0.28	2.571429	0.982442	0.976045	4.09E-05
0.29	2.448276	0.978006	0.971645	4.05E-05
0.3	2.333333	0.97298	0.966782	3.84E-05
0.31	2.225806	0.967364	0.96145	3.5E-05
0.32	2.125	0.961168	0.955644	3.05E-05
0.33	2.030303	0.954404	0.949365	2.54E-05
0.34	1.941176	0.94709	0.942614	2E-05
0.35	1.857143	0.939245	0.935395	1.48E-05
0.36	1.777778	0.93089	0.927714	1.01E-05
0.37	1.702703	0.922048	0.919577	6.1E-06
0.38	1.631579	0.912743	0.910995	3.06E-06
0.39	1.564103	0.902999	0.901977	1.04E-06
0.4	1.5	0.89284	0.892535	9.31E-08
0.41	1.439024	0.882287	0.88268	1.55E-07
0.42	1.380952	0.871365	0.872427	1.13E-06
0.43	1.325581	0.860095	0.861787	2.86E-06
0.44	1.272727	0.848498	0.850776	5.19E-06
0.45	1.222222	0.836595	0.839408	7.91E-06
0.46	1.173913	0.824403	0.827697	1.09E-05
0.47	1.12766	0.811942	0.815658	1.38E-05
0.48	1.083333	0.799229	0.803305	1.66E-05
0.49	1.040816	0.786279	0.790654	1.91E-05
0.5	1	0.773109	0.777718	2.12E-05
0.51	0.960784	0.759731	0.764512	2.29E-05
0.52	0.923077	0.74616	0.751052	2.39E-05
0.53	0.886792	0.732408	0.737349	2.44E-05
0.54	0.851852	0.718488	0.723418	2.43E-05
0.55	0.818182	0.704409	0.709273	2.37E-05
0.56	0.785714	0.690182	0.694927	2.25E-05
0.57	0.754386	0.675818	0.680392	2.09E-05
0.58	0.724138	0.661324	0.66568	1.9E-05
0.59	0.694915	0.64671	0.650804	1.68E-05
0.6	0.666667	0.631983	0.635775	1.44E-05
0.61	0.639344	0.61715	0.620604	1.19E-05
0.62	0.612903	0.602218	0.605303	9.51E-06
0.63	0.587302	0.587195	0.589881	7.22E-06
0.64	0.5625	0.572085	0.574349	5.13E-06
0.65	0.538462	0.556895	0.558717	3.32E-06
0.66	0.515152	0.541629	0.542993	1.86E-06

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0.67	0.492537	0.526292	0.527186	8E-07
0.68	0.470588	0.51089	0.511306	1.73E-07
0.69	0.449275	0.495426	0.495361	4.24E-09
0.7	0.428571	0.479904	0.479358	2.98E-07
0.71	0.408451	0.464328	0.463305	1.05E-06
0.72	0.388889	0.448702	0.447209	2.23E-06
0.73	0.369863	0.433028	0.431077	3.81E-06
0.74	0.351351	0.417311	0.414915	5.74E-06
0.75	0.333333	0.401552	0.398731	7.96E-06
0.76	0.315789	0.385755	0.382529	1.04E-05
0.77	0.298701	0.369923	0.366317	1.3E-05
0.78	0.282051	0.354056	0.350098	1.57E-05
0.79	0.265823	0.338158	0.333879	1.83E-05
0.8	0.25	0.322232	0.317664	2.09E-05
0.81	0.234568	0.306278	0.301458	2.32E-05
0.82	0.219512	0.290299	0.285265	2.53E-05
0.83	0.204819	0.274296	0.269089	2.71E-05
0.84	0.190476	0.258272	0.252936	2.85E-05
0.85	0.176471	0.242227	0.236809	2.94E-05
0.86	0.162791	0.226163	0.22071	2.97E-05
0.87	0.149425	0.210083	0.204643	2.96E-05
0.88	0.136364	0.193986	0.188613	2.89E-05
0.89	0.123596	0.177875	0.172622	2.76E-05
0.9	0.111111	0.16175	0.156671	2.58E-05
0.91	0.098901	0.145613	0.140766	2.35E-05
0.92	0.086957	0.129464	0.124908	2.08E-05
0.93	0.075269	0.113306	0.109099	1.77E-05
0.94	0.06383	0.097139	0.093342	1.44E-05
0.95	0.052632	0.080963	0.077639	1.1E-05
0.96	0.041667	0.06478	0.061992	7.77E-06
0.97	0.030928	0.048592	0.046403	4.79E-06
0.98	0.020408	0.032398	0.030873	2.33E-06
0.99	0.010101	0.0162	0.015405	6.32E-07
1	0	0	0	0
			Sum	0.00129

	a	3.499583	C_1
	b	-2.22862	C_2
	c	0.858172	C_3

Tau = 10

Z	ζ	Ψ	proposed f(ζ)	(Ψ-f)^2
0.07	4.201312	0.999787	1	4.54E-08
0.08	3.636619	0.999217	1	6.13E-07
0.09	3.197414	0.997966	1	4.14E-06
0.1	2.84605	0.995816	0.999992	1.74E-05

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0.11	2.55857	0.992662	0.99984	5.15E-05
0.12	2.319004	0.988495	0.998922	0.000109
0.13	2.116294	0.983371	0.996147	0.000163
0.14	1.942542	0.977376	0.990711	0.000178
0.15	1.791957	0.97061	0.982627	0.000144
0.16	1.660196	0.963172	0.972519	8.74E-05
0.17	1.543936	0.955152	0.961189	3.64E-05
0.18	1.440593	0.946633	0.949311	7.17E-06
0.19	1.348129	0.937684	0.937346	1.14E-07
0.2	1.264911	0.928368	0.925554	7.92E-06
0.21	1.189619	0.918737	0.914051	2.2E-05
0.22	1.121171	0.908835	0.902865	3.56E-05
0.23	1.058676	0.8987	0.891972	4.53E-05
0.24	1.001388	0.888364	0.881326	4.95E-05
0.25	0.948683	0.877853	0.870872	4.87E-05
0.26	0.900033	0.867191	0.860557	4.4E-05
0.27	0.854986	0.856398	0.85033	3.68E-05
0.28	0.813157	0.84549	0.840149	2.85E-05
0.29	0.774213	0.83448	0.829977	2.03E-05
0.3	0.737865	0.823383	0.819786	1.29E-05
0.31	0.703862	0.812207	0.80955	7.06E-06
0.32	0.671984	0.800963	0.799252	2.93E-06
0.33	0.642038	0.789657	0.788878	6.07E-07
0.34	0.613854	0.778298	0.778416	1.4E-08
0.35	0.58728	0.76689	0.767859	9.4E-07
0.36	0.562183	0.755439	0.757203	3.11E-06
0.37	0.538442	0.74395	0.746443	6.21E-06
0.38	0.515951	0.732426	0.735578	9.94E-06
0.39	0.494613	0.720872	0.72461	1.4E-05
0.4	0.474342	0.709289	0.713538	1.81E-05
0.41	0.455059	0.697682	0.702364	2.19E-05
0.42	0.436695	0.686051	0.691093	2.54E-05
0.43	0.419186	0.6744	0.679727	2.84E-05
0.44	0.402472	0.662731	0.668269	3.07E-05
0.45	0.386501	0.651044	0.656724	3.23E-05
0.46	0.371224	0.639342	0.645097	3.31E-05
0.47	0.356597	0.627626	0.633391	3.32E-05
0.48	0.34258	0.615898	0.621613	3.27E-05
0.49	0.329135	0.604157	0.609765	3.15E-05
0.5	0.316228	0.592406	0.597855	2.97E-05
0.51	0.303827	0.580645	0.585885	2.75E-05
0.52	0.291903	0.568875	0.57386	2.49E-05
0.53	0.280428	0.557097	0.561786	2.2E-05
0.54	0.269379	0.545312	0.549668	1.9E-05
0.55	0.258732	0.533519	0.537509	1.59E-05
0.56	0.248465	0.52172	0.525315	1.29E-05
0.57	0.238558	0.509915	0.513089	1.01E-05
0.58	0.228993	0.498104	0.500836	7.46E-06
0.59	0.219751	0.486289	0.488559	5.15E-06

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0.6	0.210819	0.474468	0.476265	3.23E-06
0.61	0.202178	0.462644	0.463953	1.71E-06
0.62	0.193817	0.450815	0.451632	6.67E-07
0.63	0.185721	0.438983	0.439302	1.02E-07
0.64	0.177878	0.427147	0.426968	3.2E-08
0.65	0.170276	0.415308	0.414632	4.56E-07
0.66	0.162905	0.403467	0.4023	1.36E-06
0.67	0.155754	0.391622	0.389973	2.72E-06
0.68	0.148813	0.379775	0.377653	4.5E-06
0.69	0.142073	0.367926	0.365345	6.66E-06
0.7	0.135526	0.356074	0.35305	9.14E-06
0.71	0.129163	0.34422	0.340772	1.19E-05
0.72	0.122977	0.332365	0.328513	1.48E-05
0.73	0.116961	0.320507	0.316276	1.79E-05
0.74	0.111107	0.308648	0.304061	2.1E-05
0.75	0.105409	0.296788	0.291872	2.42E-05
0.76	0.099861	0.284926	0.279711	2.72E-05
0.77	0.094458	0.273063	0.267581	3.01E-05
0.78	0.089192	0.261198	0.255479	3.27E-05
0.79	0.084061	0.249333	0.243415	3.5E-05
0.8	0.079057	0.237466	0.231382	3.7E-05
0.81	0.074177	0.225598	0.219388	3.86E-05
0.82	0.069416	0.21373	0.207431	3.97E-05
0.83	0.06477	0.20186	0.195514	4.03E-05
0.84	0.060234	0.18999	0.183637	4.04E-05
0.85	0.055805	0.178119	0.171802	3.99E-05
0.86	0.051479	0.166247	0.160011	3.89E-05
0.87	0.047252	0.154375	0.148262	3.74E-05
0.88	0.043122	0.142503	0.136562	3.53E-05
0.89	0.039084	0.130629	0.124907	3.27E-05
0.9	0.035136	0.118755	0.113299	2.98E-05
0.91	0.031275	0.106881	0.10174	2.64E-05
0.92	0.027498	0.095007	0.090231	2.28E-05
0.93	0.023802	0.083132	0.07877	1.9E-05
0.94	0.020185	0.071256	0.067362	1.52E-05
0.95	0.016644	0.059381	0.056004	1.14E-05
0.96	0.013176	0.047505	0.044696	7.89E-06
0.97	0.00978	0.035629	0.033442	4.78E-06
0.98	0.006454	0.023753	0.022243	2.28E-06
0.99	0.003194	0.011876	0.011093	6.13E-07
1	0	0	0	0
			Sum	0.002423

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