Appendix D

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

1. **Software Name:** DRSPALL
2. **Software Version:** 1.00
3. **Document Version:** 1.00
4. **ERMS #:** 524782

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** — ☒ Yes
   Does the VVP identify sufficient test cases and acceptance criteria to ensure the final software and end product satisfies the requirements of the approved RD? (Check Yes if peer review is identified to fulfill the validation requirements)
6. **Adequacy of Test Cases** — ☒ Yes
   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?
7. **Operational Control** — ☒ Yes
   If the software is used for operational control, do tests demonstrate required performance over the range of operation of the controlled function or process?
8. **Unintended Functions** — ☒ Yes
   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?
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** — ☒ Yes
    Are test cases which are suitable for installation testing and regression testing identified in the set of verification and validation test cases?

	Name (print)	Signature	Date
12.	Dave Lord **Code Team/Sponsor's** Name (*print*)	David L. Lord	10/6/2003
13.	Cliff Hansen **Technical Reviewer's** Name (*print*)	Clifford Hansen	10/6/2003
14.	Dave Kessel **Responsible Manager's** Name (*print*)	David Kessel	10/6/03
15.	Jennifer Long **SCM Coordinator's** Name (*print*)	Jennifer Long	10/6/03

Key for check boxes above:
Check **Yes** for each item reviewed and found acceptable
Check **N/A** for items not applicable, where applicable as based on code functionality

Appendix H

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

1. **Software Name:** DRSPALL
2. **Software Version:** 1.00
3. **Document Version:** 1.00
4. **ERMS #:** 524782

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	☐ N/A
(b) computer hardware and operating system used	☒ Yes	☐ N/A
(c) test equipment and calibrations	☐ Yes	☒ N/A
(d) date of test	☒ Yes	☐ N/A
(e) tester or data recorder	☒ Yes	☐ N/A
(f) simulation models used,	☒ Yes	☐ N/A
(g) test problem input and output files	☒ Yes	☐ N/A
(h) results and acceptability	☒ Yes	☐ N/A
(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 approved 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?

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.	Dave Lord **Code Team/Sponsor** *(print)*	David L. Lord Signature	10/6/2003 Date
12.	Cliff Hansen **Technical Reviewer** *(print)*	Clifford Hansen Signature	10/6/2003 Date
13.	Dave Kessel **Responsible Manager** *(print)*	David Kessel Signature	10/6/03 Date
14.	Jennifer Long **SCM Coordinator** *(print)*	Jennifer Long Signature	10/6/03 Date

Key for check boxes above:

Check **Yes** for each item reviewed and found acceptable
Check **N/A** for items not applicable

WIPP PA

Verification and Validation Plan

and

Validation Document

for

DRSPALL Version 1.00

Document Version 1.00

ERMS # 524782

September 2003

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1 INTRODUCTION

This document serves as a Verification and Validation Plan / Validation Document (VVP/VD) for DRSPALL, as used by the Sandia National Laboratories (SNL) Performance Assessment and Decision Analysis Department for application to the Waste Isolation Pilot Plant (WIPP) and related performance assessments (PA). The purpose of this document is to (i) describe how DRSPALL will be tested to ensure that the code functional requirements are satisfied, and (ii) present the results of these tests.

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. The code uses both text-formatted and CAMDAT database (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.

1.1 Software Identifier

Code Name: DRSPALL
Version Number: 1.00
WIPP Prefix: DRS
CMS Library: DRS (WP$CMSROOT:[DRS])
CMS Class: QE0100

Executable: DRSPALL_QE0100.EXE
Executable Date/time: 17-SEP-2003 09:25:01.64

Executable Platform: OpenVMS V7.3-1 ES40

1.2 Points of Contact

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Jennifer Long
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1.3 Description

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 code (WIPP PA, 1996c). 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. 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.

DRSPALL was originally developed in Digital Visual FORTRAN Version 6 and was designed to run under Microsoft Windows™. However, for implementation in WIPP and other similar performance assessments (PA) the code has been ported to the WIPP Alpha Cluster running OpenVMS.

Additional details are available in the DRSPALL Design Document (WIPP PA, 2003b).

2 REQUIREMENTS

The requirements for DRSPALL are listed in the DRSPALL Requirements Document (WIPP PA, 2003a). Those requirements are repeated below for convenience.

2.1 Functional Requirements

In general DRSPALL shall calculate the volume of WIPP waste subject to material failure and transport to the surface as a result of an inadvertent drilling intrusion into the repository. More specifically DRSPALL will calculate the following:

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.

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 spreadsheet 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 External Interface Requirements

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.

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.

3 ADDITIONAL FUNCTIONALITY TO BE TESTED

No additional functionality will be tested.

4 FUNCTIONALITY NOT TESTED

All functionality represented by the requirements (see Section 2) will be tested.

5 TESTING ENVIRONMENT

Hardware Platform:	Compaq Alpha ES40
Operating System:	OpenVMS Version 7.3-1
Test Dates:	September 1924, 2003

6 STATIC TESTING

6.1 Tools

Static testing identifies unreachable portions of the code, although it does not require execution of the code. Static testing is performed using the DECset Source Code Analyzer, which is an interactive, multi-language, source code cross-reference, and static analysis tool.

6.2 Procedure

Static testing is automatically performed when the production executable is built as described in the DRSPALL Implementation Document (WIPP PA, 2003c).

This analysis produces a file containing a list of all program routines within the code that are not referenced. These routines are often referred to as "dead code" since they have no means of being executed.

6.3 Acceptance Criteria

All uncalled program routines must be justified (i.e., their purpose in the code must be explained). This test will pass if the uncalled program routines are not necessary to perform the functionality described by the tested requirements.

6.4 Results

This analysis produces two output files: DRS_CALLTREE_QE0100.TXT and DRS_SCA_MOD_NOT_REF_QE0100.TXT. The two SCA output files are available in the QE0100 class of the DRS library in the SCMS. DRS_CALLTREE_QE0100.TXT contains a tree diagram indicating the call structure within the code. It is included in the DRSPALL Implementation Document (WIPP PA, 2003c).

DRS_SCA_MOD_NOT_REF_QE0100.TXT, shown in Table 6.4-1, contains a list of all program routines within the code that are not referenced. Only the main program DRSPALL (which can never be referenced) is listed as not referenced.

Table 6.4-1. SCA output DRS_SCA_MOD_NOT_REF_QE0100.TXT.

```
DRSPALL procedure
    DRSPALL\1            SUBROUTINE or PROGRAM declaration
```

6.5 Conclusions

Since there are no routines identified by SCA as not referenced, the test criteria for static testing are satisfied.

7 COVERAGE TESTING

7.1 Tools

Coverage testing identifies routine-level portions of the code that are not exercised by the test cases for functionality (the test cases used for testing functionality will be used for coverage testing). Coverage testing will be performed using the DECset Performance Coverage Analyzer, which is a tool that locates performance problems and identifies parts of a code that are not exercised.

7.2 Procedure

A unique executable is created for the purpose of coverage analysis. The generation of this executable is described in the DRSPALL Implementation Document (WIPP PA, 2003c).

Maximum coverage testing would be achieved by running PCA on all DRSPALL test cases. However, since the execution time for some test cases is very large, the tester tried to determine whether a subset of the test cases would provide adequate PCA coverage. It was found that Test Case #4.2 provided adequate coverage.

The command file DRS_PCA.COM runs Test Case #4.2 with the PCA executable. The PCA generates a file that gives a complete listing of the routines associated with the code (not including routines linked through libraries), along with the "data count" of the number of test cases that call each routine.

7.3 Acceptance Criteria

Each unexercised routine (i.e., a routine with a data count of zero in the PCA output) must be identified and the reason it is not called must be explained. This test will pass if the unexercised routines are not necessary to perform the functionality described by the tested requirements.

7.4 Results

This analysis produces an output file DRS_PCA.OUT that gives a complete listing of the routines associated with the code (not including routines linked through libraries), along with the data count of the number of test cases that call each routine. The PCA command file (DRS_PCA.COM) and the output PCA file (DRS_PCA.OUT) are available in the QE0100 class of the DRS library in the SCMS. Table 7.4-1 shows an excerpt of the output file listing all unexercised routines identified by PCA.

Table 7.4-1. Excerpt of PCA output DRS_PCA.OUT.

```
Data
  Bucket Name                   Count  Percent
  CALCULATEWELLBOREFLOW\
   TESTCASEFIVEMASSLOA
    DING . . . . . . . . . .        0     0.0%
  CLOSERUNFILES\
   WRITETOCHANVALIDATI
    ONFILE  . . . . . . . .         0     0.0%
   WRITETOCOUPLINGVALI
    DATIONFILE  . . . . . .         0     0.0%
   WRITETOEXPULSIONVAL
    IDATIONFILE . . . . . .         0     0.0%
   WRITETOFLUIDIZATION
    VALIDATIONFILE  . . . .         0     0.0%
   WRITETOWELLBOREVALI
    DATIONFILE  . . . . . .         0     0.0%
  LOADDEFAULTPARAMETERS\
   BOUNDCHECK . . . . . . .         0     0.0%
  SYSTEM$SERVICE\
   SYSTEM$SERVICE . . . . .         0      -
  SYSTEM$SPACE\
   SYSTEM$SPACE . . . . . .         0      -
```

The justification for each unexercised routine follows.

- TESTCASEFIVEMASSLOADING and WRITETOWELLBOREVALIDATIONFILE are only used in verification Test Case 5.
- WRITETOCHANVALIDATIONFILE is only used in verification Test Case 1.
- WRITETOCOUPLINGVALIDATIONFILE, WRITETOEXPULSIONVALIDATIONFILE and WRITETOFLUIDIZATIONVALIDATIONFILE routines are only used in verification Test Case 4.1. Test Case 4.2 is not run long enough to write data to the referenced file.
- SYSTEM$SERVICE and SYSTEM$SPACE are system routines that are always listed by PCA. They are unimportant for the coverage test.

These above routines are not necessary for performing the functionality described by the tested requirements nor are they used in normal PA calculations.

- BOUNDCHECK checks that certain input parameters are within acceptable WIPP property ranges. It is not called by any of the verification test cases, because some verification inputs maybe outside the specified range for WIPP materials and geometry. It would normally be called for PA analyses, but it is not required for proper execution of the code.

7.5 Conclusions

All unexercised routines identified by the PCA analysis are associated with features that are not necessary to perform the functionality described by the tested requirements. Most are associated with testing the functionality, but not with the functionality itself. Therefore, the test criteria for coverage testing are satisfied.

8 FUNCTIONAL TESTING

The test set for DRSPALL consists of four test cases that are designed to address the requirements established in Section 2. The test cases are numbered #1, #2, #4, and #5 (i.e., there is no Test Case #3). Functional testing will be performed by running the test cases with the production executable for DRSPALL. (The production executable will be used to perform the PA calculations.) The production executable is generated as described in the DRSPALL Implementation Document (WIPP PA, 2003c).

All files used in functional testing will be stored in class QE0100 of the DRS library of the Software Configuration Management System (SCMS) accessible from the WIPP Alpha Cluster. The files include the DRSPALL input and output files, all procedure files to execute DRSPALL, and output files from other numerical solutions used for comparisons.

A single test case requires that DRSPALL be executed one or more times. Each execution is referred to as a "case" or "subcase" or "run". For example, Test Case #5 has six subcases, labeled case 5.1 through 5.7 (5.4 is not defined), and the files for the test case are distinguished by "TC51" through "TC57" in their names.

DRSPALL reads its run parameters from an input control file (file extension ".DRS"). The DRSPALL User's Manual (WIPP PA, 2003d) provides instructions on constructing and interpreting the input control file. Each subcase of the four test cases has its own input control file. The 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 Design Document for DRSPALL (WIPP PA, 2003b) describes any non-standard processing that is dependent on the test case.

Each execution of DRSPALL generates an output CAMDAT file (".CDB") and an output diagnostics file (".DBG"). The DRSPALL User's Manual (WIPP PA, 2003d) describes the variables output on the CAMDAT file. Variables on a CAMDAT file may be extracted in tabular form with the GROPECDB utility (WIPP PA, 1996a) or plotted with the BLOTCDB utility (WIPP PA, 1996b). In addition to the standard output files, a particular test case may generate additional files to be used for validation only. These validation files are described under the relevant test case section.

Most test cases compare the results of the DRSPALL execution with those generated by analytical and other numerical solutions. These solutions are described in detail under the relevant test case section. However, the procedure for generating the solution may not be described in detail as it is not relevant to the validation of DRSPALL and it does not need to be reproduced in subsequent validations of DRSPALL.

The DRSPALL test cases are run with a set of procedure files. Each test case has its own procedure file, and each subcase has a procedure file. The procedure file for the test case (e.g., DRS_TC5.COM shown in Table A.1-1) executes all subcases. It creates a subdirectory for the subcase, fetches the subcase procedure file from the SCMS, and executes the subcase procedure file, usually by submitting a job to a batch queue. The procedure file for the subcase (e.g., DRS_TC51.COM shown in Table A.1-2) fetches the DRSPALL input file(s), and executes DRSPALL with the appropriate input and output file designations. The subcase procedure file may also do some simple post-processing on the CAMDAT file, but most post-processing will be done manually by the tester.

The requirements coverage is shown in Table 8.0-1. Test cases 1,2, 4 and 5 are used to verify that the DRSPALL correctly implements all requirements. All requirement testing is covered by these test cases.

Table 8.0-1. Requirements coverage by test case.

Requirement		**Test Case**			
Type	**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	

8.1 Test Case #1 – Porous Flow Verification

8.1.1 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 utility code developed by Djordjevic and Adams (2003) for an identical problem.

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

8.1.2 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.

8.1.2.1 Cylindrical Geometry Equations

The cylindrical domain comprises a porous solid with a given porosity φ and permeability k, shown in Figure 8.1-1. 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.

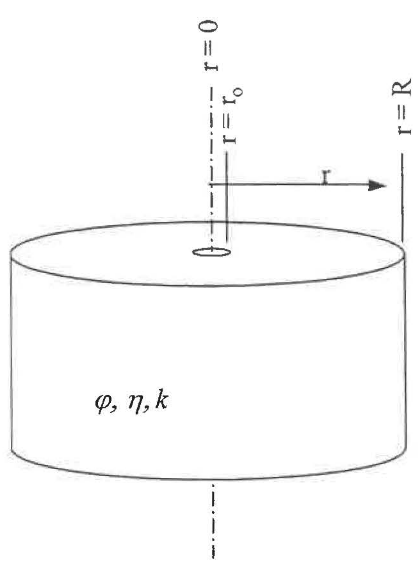


Figure 8.1-1. Schematic of cylindrical domain for porous flow test problem.

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

$$\frac{\partial p}{\partial t} = \frac{k}{2\varphi\eta}\nabla^2 p^2, \quad p = p(r,t), \quad r \geq r_{0,} \quad t \geq 0 \tag{8.1.1}$$

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

$$p(r_0, t) = f(t), \quad \lim_{r\to\infty} p(r,t) = p_{ff}, \quad p(r,0) = p_{ff} \tag{8.1.2}$$

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

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

$$\psi(p) = \frac{p^2}{\eta} \tag{8.1.3}$$

which leads to

$$\frac{\partial \psi}{\partial t} = \frac{k}{\varphi\sqrt{\eta}}\sqrt{\psi}\nabla^2\psi, \quad \psi = \psi(r,t), \quad r \geq r_{0,} \quad t \geq 0 \tag{8.1.4}$$

and

$$\psi(r_0, t) = \frac{f^2}{\eta}, \quad \lim_{r\to\infty} \psi(r,t) = \frac{p_{ff}^2}{\eta}, \quad \psi(r,0) = \frac{p_{ff}^2}{\eta} \tag{8.1.5}$$

Nondimensional parameters may be defined as follows:

$$\psi = \frac{p_{ff}^2}{\eta}\Psi \quad t = t_0\tau, \quad t_0 = \frac{\varphi\eta r_0^2}{k p_{ff}} \tag{8.1.6}$$

and for cylindrical coordinates:

$$z = \ln(\frac{r}{r_0}) \tag{8.1.7}$$

which upon substitution into Eq. 8.1.4 yields the transformed equation:

$$\frac{\partial \Psi}{\partial \tau} = e^{-2z}\Psi^{1/2}\frac{\partial^2 \Psi}{\partial z^2} \tag{8.1.8}$$

Equation 8.1.8 is integrated numerically with the boundary and initial conditions

$$\Psi(0,\tau) = \frac{f^2}{p_{ff}^2}, \quad \lim_{z\to\infty}\Psi \to 1, \quad \Psi(z,0) = 1 \tag{8.1.9}$$

8.1.2.2 Spherical Geometry Equations

For the spherical problem, the cavity is hemispherical in shape with radius r_o.

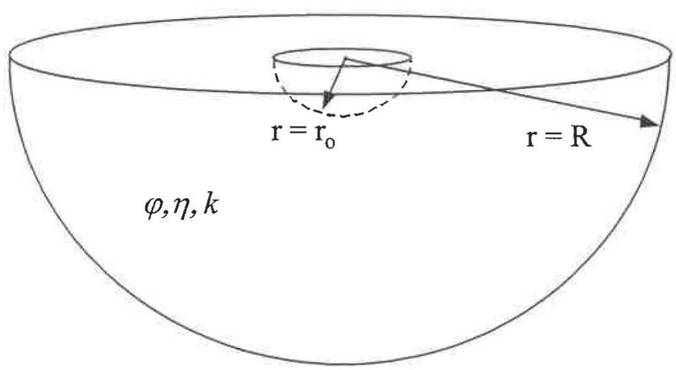


Figure 8.1-2. Schematic of spherical domain in porous flow test problem.

Eqs. 8.1.4 – 8.1.6 apply to the spherical geometry, but in order to proceed, z must be re-defined as:

$$z = \frac{r_o}{r} \tag{8.1.10}$$

The resulting transformed governing equation is then

$$\frac{\partial \Psi}{\partial \tau} = z^4\Psi^{1/2}\frac{\partial^2 \Psi}{\partial z^2} \tag{8.1.11}$$

Equation 8.1.11 is integrated numerically with the boundary conditions

$$\Psi(1,\tau) = \frac{f^2}{p_{ff}^2}, \quad \Psi(0,\tau) = 1, \quad \Psi(z,0) = 1 \tag{8.1.12}$$

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

$$\frac{R(t)}{a} = 1 + \sqrt{\frac{t}{t_o}} \qquad (8.1.13)$$

The default outer radius in DRSPALL is 19.2m. 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:

$$\frac{R(t)}{a} \cong \frac{(t/t_o)^{0.5}}{[\log(t/t_o)]^{0.5}} \qquad (8.1.14)$$

If the DRSPALL outer boundary of 19.2 m is substituted into Eq. 8.1.14 for R, and t_o is evaluated with the input values given in Table 8.1-1, 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.

8.1.2.4 Input Parameters

Relevant input parameters for this test case are given in Table 8.1-1. 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. Input files are provided in Appendix B.3.

Table 8.1-1. 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

8.1.2.5 Repository Zoning

The zoning scheme in the repository domain in DRSPALL is set to a constant zone size of 0.002 m from the cavity wall to a radius of 0.50 m, and then increased geometrically using a multiplication factor of 1.01.

8.1.3 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:

$$\zeta = \frac{\left(e^{z} - 1\right)}{\tau^{1/2}} \tag{8.1.15}$$

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:

$$DIFF(\zeta) = \left|\Psi(\zeta)_{DR\_SPALL} - \Psi(\zeta)_{Chan}\right| \tag{8.1.16}$$

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

8.1.3.1 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 8.1-3. Tabular results are given in Appendix B.2.

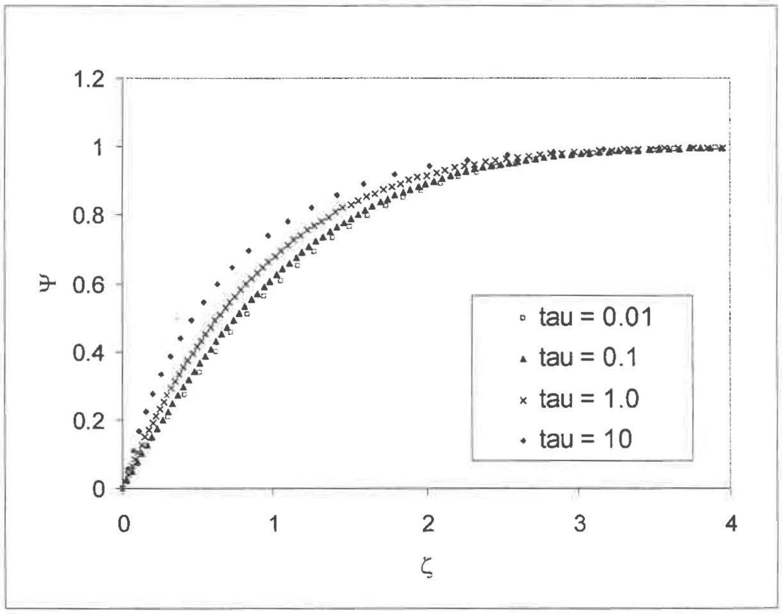


Figure 8.1-3. Numerical solutions to the dimensionless pseudopressure profiles for cylindrical geometry.

Since the numerical grid used in DRSPALL may be different from that used in the comparison solutions shown in Figure 8.1-3, a curve was fit to the comparison data to facilitate computation of the difference defined in Eq. 8.1.16. The general form of the function fit to the comparison data was:

$$\Psi(\zeta) = 1\text{-}\exp\{-(C_1\zeta + C_2\zeta^2 + C_3\zeta^3)\} \qquad \text{for } 0 \geq \zeta \geq 1 \qquad (8.1.17)$$

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

$$SUM = \sum_i \left[\Psi(\zeta)_a - \Psi(\zeta)_b\right]^2 \qquad (8.1.18)$$

where the subscript *a* denotes the solution calculated by Djordjevic and Adams (2003), the subscript *b* denotes the value of the functional fit, 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 8.1-2. Details of the fitting procedure are provided in Appendix B.6.

Table 8.1-2. 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

8.1.3.2 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 (τ = 0.01, 0.1, 1.0, 10) as for the cylindrical case. The solutions are illustrated graphically in Figure 8.1-4. Tabular results are given in Appendix B.2. Functions in the form of Eq. 8.1.17 were fit to the data using a least squares method with associated constants reported in Table 8.1-3, and details of the fitting procedure shown in Appendix B.6.

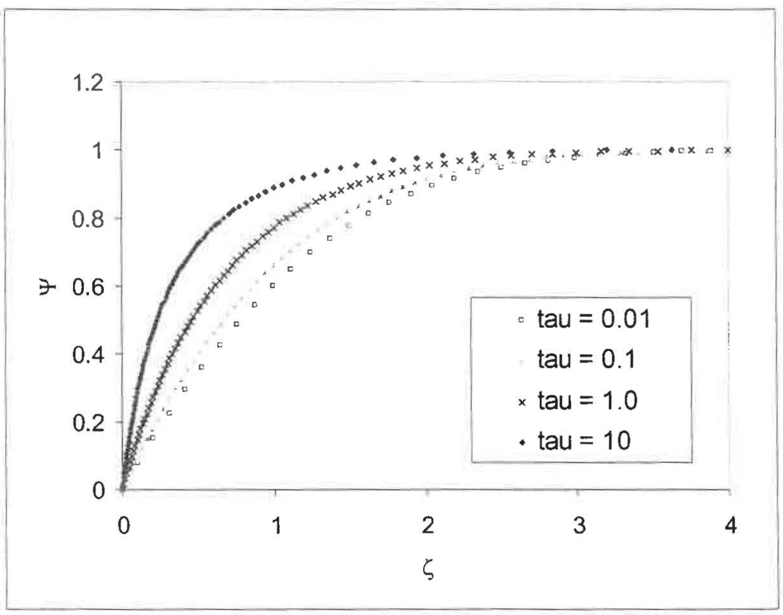


Figure 8.1-4. Numerical solutions to the dimensionless pseudopressure profiles for spherical geometry.

Table 8.1-3. 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

8.1.3.3 Test Procedure

DRSPALL is executed twice: once in cylindrical geometry and once in spherical geometry. The DRSPALL input file for each case is given in Appendix B.3. The DRSPALL results for each case are in a text file that is output for validation purposes for Test Case #1 only. The output files, given in Appendix B.4, are imported to a Microsoft EXCEL spreadsheet for post-processing and graphing. The EXCEL spreadsheet is given in Appendix B.5.

The test files associated with this test case are listed in Table 8.1-4. All test files are available in the QE0100 class of the DRS library in the SCMS. Subcase 1.1 (labeled as TC11) refers to cylindrical geometry; subcase 1.2 (labeled as TC12) refers to spherical geometry.

Table 8.1-4. Test files for Test Case #1.

Cylindrical Geometry Files	
DRSPALL Files	**Description**
DRS_TC1.COM	Procedure to run all subcases of Test Case #1
DRS_TC11.COM	Procedure to run cylindrical case
DRS_TC11.LOG	Log file for cylindrical subcase
DRS_TC11.DRS	Input file, Table B.3-1
DRS_QE0100_TC11_CHAN.DAT	Validation output file, Table B.4-1
DRS_QE0100_TC11.CDB	CAMDAT output file
DRS_QE0100_TC11.DBG	Diagnostics output file (not used)
DRS_TC1_GROPE.INP	GROPECDB input file
DRS_QE0100_TC11_GROPE.OUT	GROPECDB output file (not used)
Djordjevic and Adams (2003) Files	
DA_Cylindrical.f90	Utility program discussed in Appendix B.2
DA_CylTau0_01.inp	Input file for Tau 0.01
DA_CylTau0_01.out	Output file for Tau 0.01, Table B.2-1
DA_CylTau0_10.inp	Input file for Tau 0.10

Cylindrical Geometry Files	
DA_CylTau0_10.out	Output file for Tau 0.10, Table B.2-1
DA_CylTau1_0.inp	Input file for Tau 1.0
DA_CylTau1_0.out	Output file for Tau 1.0, Table B.2-1
DA_CylTau10_0.inp	Input file for Tau 10
DA_CylTau10_0.out	Output file for Tau 10, Table B.2-1
DA_Cylindrical.zip	WinZIP file that contains all D&A cylindrical files
EXCEL Spreadsheets:	
TC1_post_processor_v4.xls	Spreadsheet for DIFF and curve fit
Spherical Geometry Files	
DRSPALL Files	
DRS_TC1.COM	Procedure to run all subcases of Test Case #1
DRS_TC12.COM	Procedure to run spherical case
DRS_TC12.LOG	Log file for spherical case
DRS_TC12.DRS	Input file, Table B.3-2
DRS_QE0100_TC12_CHAN.DAT	Validation output file, Table B.4-2
DRS_QE0100_TC12.CDB	CAMDAT output file
DRS_QE0100_TC12.DBG	Diagnostics output file (not used)
DRS_TC1_GROPE.INP	GROPECDB input file
DRS_QE0100_TC12_GROPE.OUT	GROPECDB output file (not used)
Djordjevic and Adams (2003) Files	
DA_Spherical.f90	Utility program discussed in Appendix B.2
DA_SphTau0_01.inp	Input file for Tau 0.01
DA_SphTau0_01.out	Output file for Tau 0.01, Table B.2-2
DA_SphTau0_10.inp	Input file for Tau 0.10
DA_SphTau0_10.out	Output file for Tau 0.10, Table B.2-2
DA_SphTau1_0.inp	Input file for Tau 1.0
DA_SphTau1_0.out	Output file for Tau 1.0, Table B.2-2
DA_SphTau10_0.inp	Input file for Tau 10
DA_SphTau10_0.out	Output file for Tau 10, Table B.2-2
DA_Spherical.zip	WinZIP file that contains all D&A spherical files
EXCEL Spreadsheets:	
TC1_post_processor _v4.xls	Spreadsheet for DIFF and curve fit

8.1.4 Acceptance Criteria

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

1) Visual inspection of the pressure profiles generated by DRSPALL indicates a close approximation to the solutions by Djordjevic and Adams (2003) for corresponding dimensionless times.
2) Maximum difference for Ψ (dimensionless) between DRSPALL and Djordjevic and Adams (2003) for corresponding times does not exceed 0.1.

8.1.5 Results

8.1.5.1 Cylindrical Geometry

Figures 8.1-5 and 8.1-6 show the results of this test case in cylindrical geometry. The DRSPALL output file is given in Table B.4-1. The plots display the dimensionless pseudopressure (Ψ) versus the dimensionless plotting parameter (ζ) at four selected values of dimensionless time (τ). The comparison curves on each figure were generated from the parameters in Table 8.1-2. Conceptually, the curves represent the evolution of the pore pressure profile. The initial condition is set to Ψ = 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 (Eq. 8.1.15). For each set of axes, the results for two dimensionless times are given.

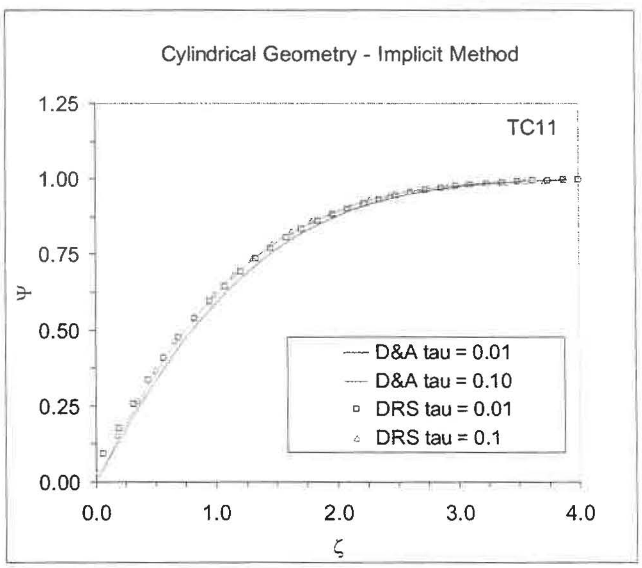


Figure 8.1-5. Overlay of DRSPALL with Djordjevic and Adams (2003) solutions for the cylindrical geometry with τ = 0.01, 0.10.

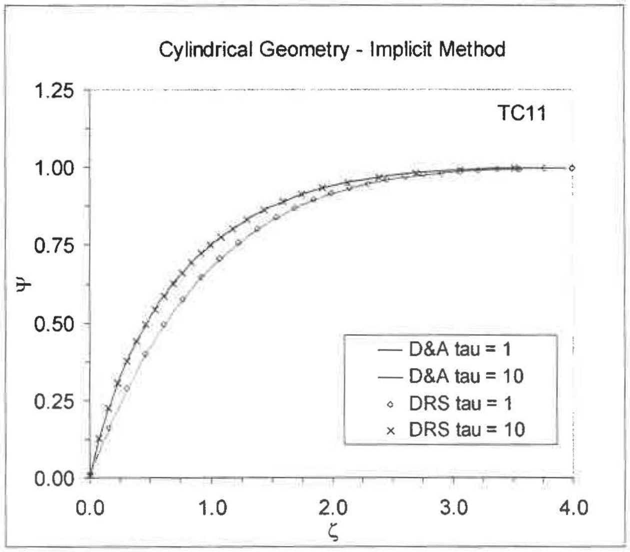


Figure 8.1-6. Overlay of DRSPALL with Djordjevic and Adams (2003) solutions for the cylindrical geometry with τ= 1.0, 10.

Visual inspection of Figures 8.1-5 and 8.1-6 indicates that the DRSPALL results overlay the Djordjevic and Adams (2003) solutions quite closely. Visual inspection of Figures 8.1-5 and 8.1-6 confirms that **Acceptance Criteria 1 is met for the cylindrical case.** The magnitude and shape of the curves match well over the entire range of interest. 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 8.1-5. DIFF values for the cylindrical case ranged from 0.009 to 0.045, representing a favorable match between DRSPALL and the comparison solution. The maximum difference of 0.045 confirms that **Acceptance Criteria 2 is met for the cylindrical case.**

Table 8.1-5. Maximum difference values calculated by Eq. 8.1.16 for implicit solution in cylindrical and spherical geometry.

τ	Cylindrical DIFF	Spherical DIFF
0.01	0.045	0.016
0.1	0.016	0.007
1	0.009	0.008
10	0.017	0.012

8.1.5.2 Spherical Geometry

Figures 8.1-7 and 8.1-8 show the results of this test case for implicit solution in the spherical geometry. The DRSPALL output file is given in Table B.4-2. A close match to the comparison solution is observed for all times, as indicated visually in Figures 8.1-7 and 8.1-8, and in the DIFF values summarized in Table 8.1-5. Visual inspection of Figures 8.1-7 and 8.1-8 confirms that **Acceptance Criteria 1 is met for the spherical case.** For all τ, max DIFF values for the implicit solution fall at 0.016 or below, indicating close agreement between solutions. The maximum difference of 0.016 confirms that **Acceptance Criteria 2 is met for the spherical case.**

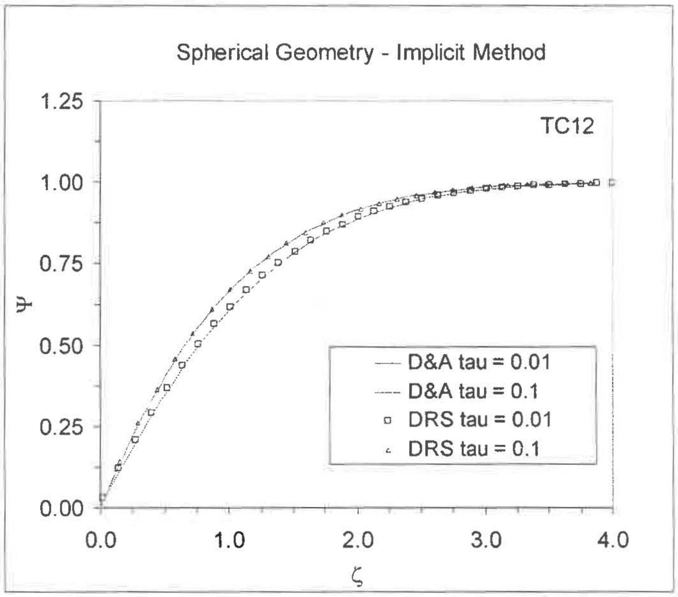


Figure 8.1-7. Overlay of DRSPALL with Djordjevic and Adams (2003) solutions for the spherical geometry with τ= 0.01, 0.10.

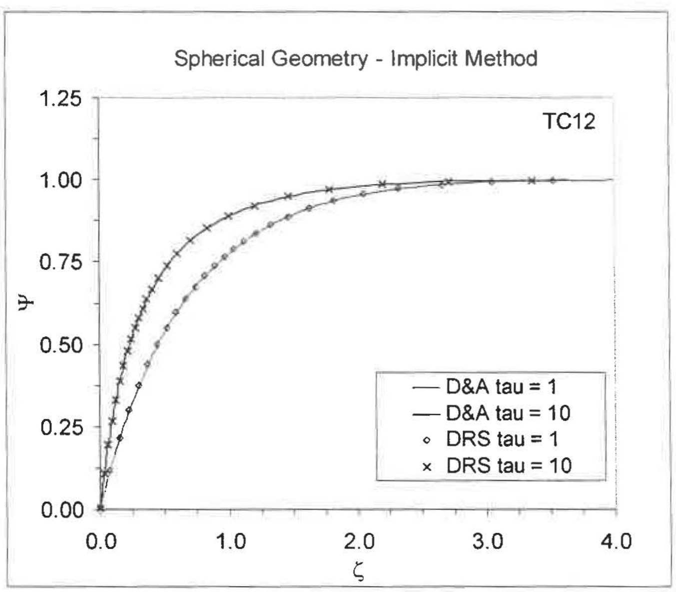


Figure 8.1-8. Overlay of DRSPALL with Djordjevic and Adams (2003) solutions for the spherical geometry with τ= 1.0, 10.

8.1.6 Conclusions

The discussion in Section 8.1.5 verifies that all acceptance criteria (Section 8.1.4) for this test case are met for both the cylindrical and spherical geometry. Thus, this test case passes.

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.

8.2 Test Case #2 – Coalbed Methane Validation

8.2.1 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 fails 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).

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 Cases 1, 4 and 5 are used to verify that DRSPALL correctly implements all requirements. Test Case 2 exercises all requirements except R.8 (input from CAMDAT file), but does not explicitly address any requirements directly. Some requirements are only partially exercised, i.e. there is no mud flow.

8.2.2 Problem Description

8.2.2.1 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 open 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.

8.2.2.2 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

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.

8.2.3 Analysis Method

8.2.3.1 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 8.2-1. The well was cavitated in July of 1991.

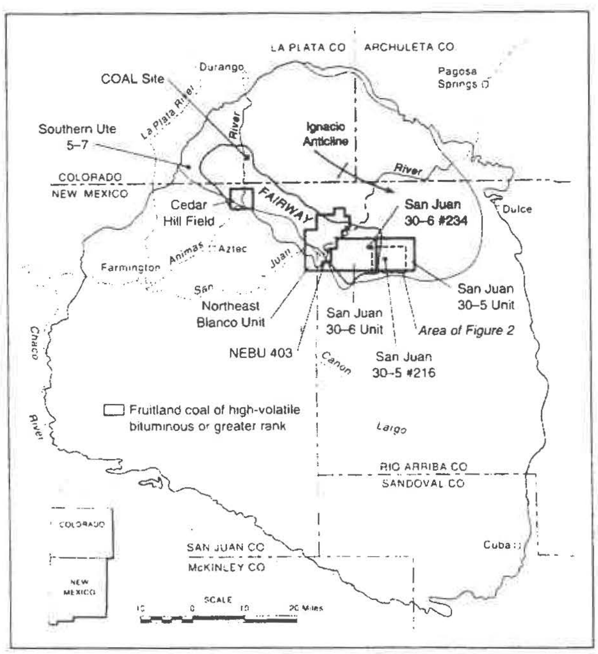


Figure 8.2-1. Location of cavitated coalbed well (Khodaverdian et al., 1996).

The key parameters, as reported by Khodaverdian et al. (1996), of the selected coal well are given in Table 8.2-1.

Table 8.2-1. 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 x 10^{-14} m^2

After all cavitation procedures were finished, the final cavity diameter was determined by sonar logging, and is shown in Figure 8.2-2.

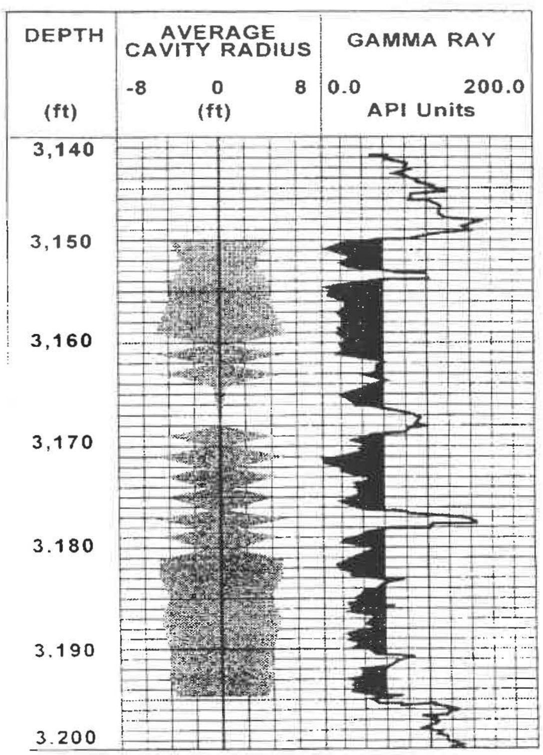


Figure 8.2-2. Cavity radius (Khodaverdian et al., 1996).

8.2.3.2 *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 8.2-3.

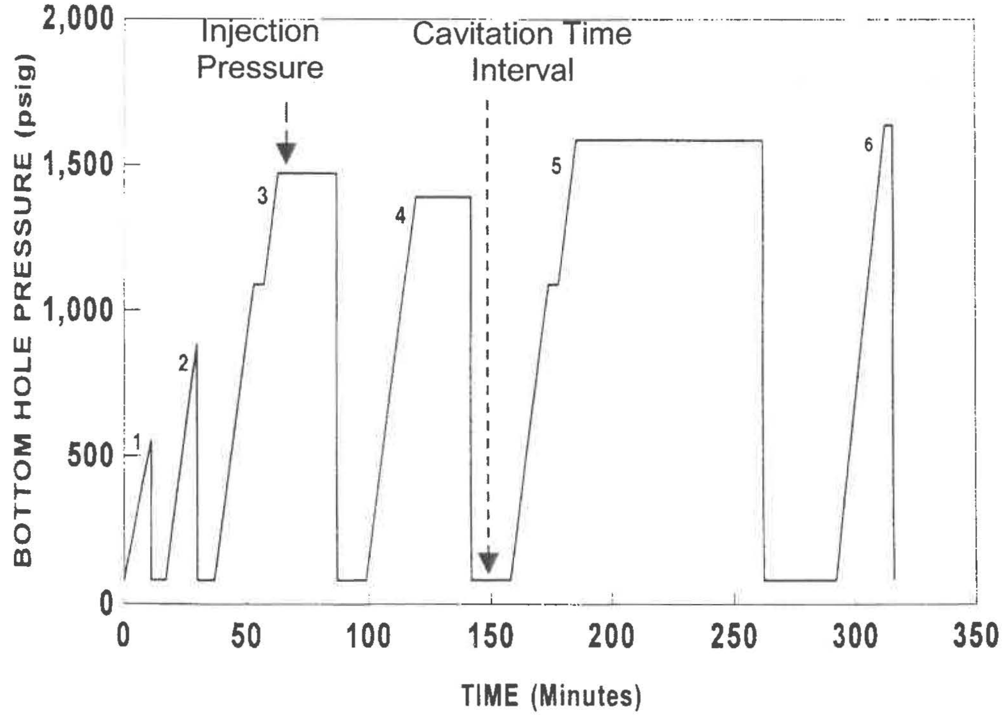


Figure 8.2-3. Cavitation times and inferred bottomhole pressures (Khodaverdian et al., 1996). Red arrows added for this report.

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 8.2-3, 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.

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 8.2-2. 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 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 8.2-2. Their final matching interpretations are shown in Figure 8.2-4. The input pressures and times, and results to compare with DRSPALL, as we obtain from the author's figures, are shown in Table 8.2-2.

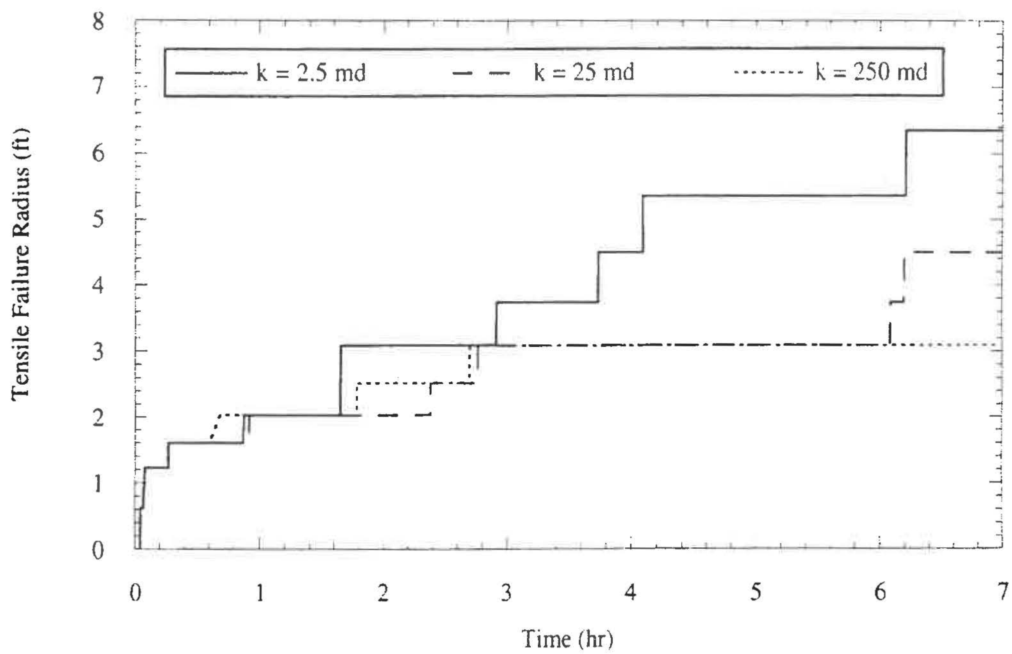


Figure 8.2-4. Interpreted cavity radii (based on tensile failure radii) from Khodaverdian et al. (1996).

Table 8.2-2. 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

8.2.3.3 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 8.2-2 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.

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. We have used a tensile strength of 0.25 MPa (36 psi) and a permeability of 3.0 md (3.0E-15 m^2) for these runs. The input file for Run 6 is shown in Table C.1-1. All other runs are the same, except for initial pressure, initial cavity size, and run time.

8.2.3.4 Test Procedure

DRSPALL is executed six times, once for each run, with the appropriate input file. The DRSPALL results for each case are in a CAMDAT file and are summarized in the diagnostic text file (*.DBG). The output data are imported to a Microsoft EXCEL spreadsheet for post-processing and graphing.

The files associated with this test case are listed in Table 8.2-3. All test files are available in the QE0100 class of the DRS library in the SCMS. Note that each of the six DRSPALL runs is a subcase (labeled as TC21 through TC26).

Table 8.2-3. Test files for Test Case #2.

DRSPALL Files:	Description
DRS_TC2.COM	Procedure to run all subcases of Test Case #2
DRS_TC21.COM	Procedure to run subcase 1
DRS_TC21.LOG	Log file for subcase 1
DRS_TC21.DRS	Input file
DRS_QE0100_TC21.CDB	CAMDAT output file (not used)
DRS_QE0100_TC21.DBG	Diagnostics output file
DRS_TC22.COM	Procedure to run subcase 2
DRS_TC22.LOG	Log file for subcase 2
DRS_TC22.DRS	Input file
DRS_QE0100_TC22.CDB	CAMDAT output file (not used)
DRS_QE0100_TC22.DBG	Diagnostics output file
DRS_TC23.COM	Procedure to run subcase 3
DRS_TC23.LOG	Log file for subcase 3
DRS_TC23.DRS	Input file
DRS_QE0100_TC23.CDB	CAMDAT output file (not used)

DRSPALL Files:	Description
DRS_QE0100_TC23.DBG	Diagnostics output file
DRS_TC24.COM	Procedure to run subcase 4
DRS_TC24.LOG	Log file for subcase 4
DRS_TC24.DRS	Input file
DRS_QE0100_TC24.CDB	CAMDAT output file (not used)
DRS_QE0100_TC24.DBG	Diagnostics output file
DRS_TC25.COM	Procedure to run subcase 5
DRS_TC25.LOG	Log file for subcase 5
DRS_TC25.DRS	Input file
DRS_QE0100_TC25.CDB	CAMDAT output file (not used)
DRS_QE0100_TC25.DBG	Diagnostics output file
DRS_TC26.COM	Procedure to run subcase 6
DRS_TC26.LOG	Log file for subcase 6
DRS_TC26.DRS	Input file
DRS_QE0100_TC26.CDB	CAMDAT output file (not used)
DRS_QE0100_TC26.DBG	Diagnostics output file
EXCEL Spreadsheets	
TC2_figure.xls	Used to create comparison figure

8.2.4 Acceptance Criteria

This test case is not explicitly used to verify any requirements. It is used as validation to show that DRSPALL can adequately simulate a drilling intrusion into the WIPP repository. The validation will be acceptable if DRSPALL reasonably predicts cavity growth over six cavitation cycles. Graphical comparisons of cavity radius as a function of time will be evaluated for consistent shape and scale.

8.2.5 Results

Table 8.2-4 and Figure 8.2-5 show the results of the DRSPALL runs and the comparison with field results. The DRSPALL results are for tensile failed and fluidized radii.

Table 8.2-4. Results comparison.

Cycle	Cavity Radius, m	
	Field Inferred	DRSPALL Calculated
1	0.31	0.30
2	0.49	0.30
3	0.61	0.58
4	0.73	0.79
5	0.91	1.01
6	1.37	1.20

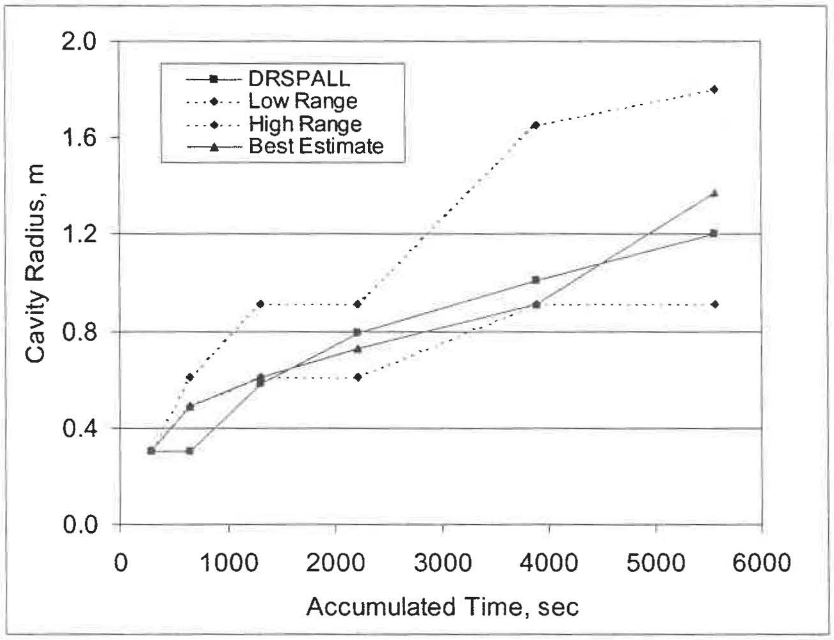


Figure 8.2-5. Reported field results and DRSPALL results compared.

8.2.6 Conclusions

As discussed in Section 8.2.2.2, 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.

The shape and scale of the cavity radius as a function of cavitation time show reasonable agreement as demonstrated in Figure 8.2-5 and, therefore, meets the acceptance criteria established in Section 8.2.4 for this test case. Thus, this test case passes.

The successful completion of this test case demonstrates that DRSPALL reasonably simulates the coalbed methane cavitation process within the ranges of uncertainties of known data and values of parameters.

8.3 No Test Case #3 is Defined

8.4 Test Case #4 – Internal Logic Checks

8.4.1 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**.

8.4.2 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 output 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) the program logic, and (2) verification or proper implementation of the mathematics outlined in the DRSPALL Design Document (WIPP PA, 2003b).

8.4.2.1 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.

8.4.2.2 Input Parameters

The input parameters for this test case are given in Table D.1-1. In order to assure a spalling event, the repository initial pressure will be near lithostatic pressure at 14.7 MPa, and the tensile strength will be set to a low value in its range, 1.2E+05 Pa (17.4 psi).

8.4.3 Analysis Methods

8.4.3.1 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)
- 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[1] (kg) – Gas removed from repository by removal of repository zones is added to "storage" before it is released to the cavity

[1] 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.

- 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.

8.4.3.2 Tensile Failure of Waste Material

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

$$\sigma_r'(r) = \sigma_{sr}(r) + \sigma_{er}(r) - \beta p(r) \tag{8.4.1}$$

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

$$\sigma_{sr}(r) = (m-1)\beta\left(\frac{1-2\upsilon}{1-\upsilon}\right)\frac{1}{r^m}\int_{r_c}^{r}(p(r) - p_{ff})r^{m-1}dr \tag{8.4.2}$$

and the radial elastic stress is evaluated as:

$$\sigma_{er}(r) = \left\{\sigma_{ff}\left[1-\left(\frac{r_c}{r}\right)^m\right] + p_c\left(\frac{r_c}{r}\right)^m\right\} \tag{8.4.3}$$

and the pore pressure, *p(r)*, is obtained from the transient solution to porous flow. The terms for Equations 8.4.1 – 8.4.3 are defined in Table 8.4-1.

Table 8.4-1. 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	–

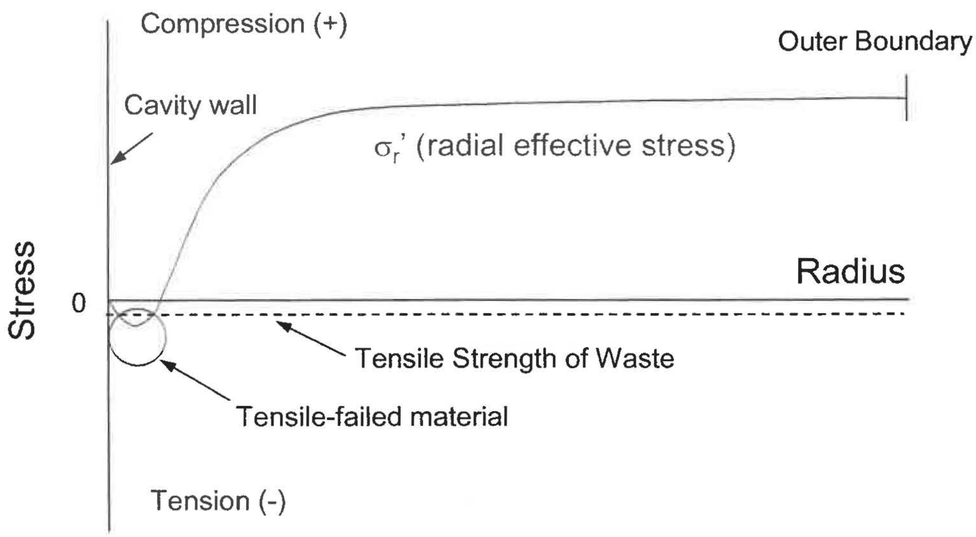


Figure 8.4-1. Drawing of a theoretical radial effective stress curve. Material is subject to tensile failure where $\sigma_r'(r)<T_s$.

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 drawing in Figure 8.4-1. 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:

$$\text{if } \frac{\sum_{i=1}^{n} \sigma'_{r,i}}{n} < T_s \text{, then failure is initiated over } L_t \qquad (8.4.4)$$

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 Eq. 8.4.4. 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, and can be confirmed in Table D.1-1. The characteristic length concept is introduced because without it, the stress formulations in Eqs. 8.4.1 – 8.4.3 preclude tensile failure in zones near the wall at small zone size. Close examination of Eqs. 8.4.1 – 8.4.3 will reveal that the radial effective stress is exactly zero at the cavity wall. This is also illustrated in Figure 8.4-1. 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:

- 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 8.4.1 – 8.4.3 in an independent spreadsheet analysis using a pore pressure profile, *p(r)*, generated by DRSPALL at one selected time. The spreadsheet values will be compared to those output from DRSPALL to verify that the stress calculations in DRSPALL are implemented correctly.

8.4.3.3 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:

$$\frac{1.75}{a\phi^3}\left(\frac{d_p U_f \rho}{\eta}\right)^2 + 150\left(\frac{1-\phi}{a^2\phi^3}\right)\left(\frac{d_p U_f \rho}{\eta}\right) = \frac{d_p^{\,3}\rho(\rho_w - \rho)g}{\eta^2} \qquad (8.4.5)$$

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 8.4.5 are defined in Table 8.4-2.

Table 8.4-2. 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

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.

$$t_f = \frac{r_{c1}}{U_s} \tag{8.4.6}$$

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)

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 8.4.5, 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 spreadsheet 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 remove 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 remove 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)

8.4.3.4 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.

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.

8.4.3.5 Test Procedure

DRSPALL is executed once to 450 seconds (TC41) with the input file given in Table D.1-1. The DRSPALL results for this test case are in the output diagnostics file and in four text files that are output for validation purposes for Test Case #4 only.

- DRS_TC41.CDB is the DRSPALL output CAMDAT file.
- DRS_QE0100_TC41_COUPLING.DAT contains coupling data at selected times.
- DRS_QE0100_TC41_STRESS.DAT contains pore pressure and stress profiles.
- DRS_QE0100_TC41_FLUIDIZATION.DAT contains fluidization data at selected times.

- DRS_QE0100_TC41_EXPULSION.DAT contains solids transport data.

The output CAMDAT file is post-processed with the BLOTCDB utility (WIPP PA, 1996b) to plot variables. The validation files DRS_QE0100_TC41_STRESS.DAT and DRS_QE0100_TC41_FLUIDIZATION.DAT are imported to a Microsoft EXCEL spreadsheet where the independent stress and fluidization calculations are done.

DRSPALL is executed again (TC42) for a short period of time to verify the external interface requirements only. This case inputs the DRSPALL parameters from the input file given in Table D.1-2 and an input CAMDAT file. The DRSPALL results for this case are in the output diagnostics file and the output CAMDAT file.

The test files associated with this test case are listed in Table 8.4-3. All test files are available in the QE0100 class of the DRS library in the SCMS.

Table 8.4-3. Test files for Test Case #4.

DRSPALL Files	Description
DRS_TC4.COM	Procedure to run Test Case #4
DRS_TC41.COM	Procedure to run subcase 1
DRS_TC41.LOG	Log file for subcase 1
DRS_TC41.DRS	Input file, Table D.1-1
DRS_QE0100_TC41_COUPLING.DAT	Coupling validation output file, excerpt in Table 8.4-4
DRS_QE0100_TC41_STRESS.DAT	Stress validation output file, excerpt in Table 8.4-5
DRS_QE0100_TC41_FLUIDIZATION.DAT	Fluidization validation output file, excerpt in Table 8.4-8
DRS_QE0100_TC41_EXPULSION.DAT	Expulsion validation output file, excerpt in Tables 8.4-12 – 8.4-14
DRS_TC41.CDB	CAMDAT output file
DRS_TC41.DBG	Diagnostics output file
DRS_TC41_SPLVOL_GROPE.INP	GROPECDB input file for verifying spall volume and mass
DRS_QE0100_TC41_SPLVOL_GROPE.OUT	GROPECDB output file for verifying spall volume and mass
DRS_TC42.COM	Procedure to run subcase 2
DRS_TC42.LOG	Log file for subcase 2
DRS_TC42.DRS	Input file, Table D.1-2

DRSPALL Files	**Description**
DRS_TC42_MS.CDB	Input CAMDAT file
DRS_QE0100_TC42_COUPLING.DAT	Validation output file (not used)
DRS_QE0100_TC42_STRESS.DAT	Validation output file (not used)
DRS_QE0100_TC42_FLUIDIZATION.DAT	Validation output file (not used)
DRS_QE0100_TC42_EXPULSION.DAT	Validation output file (not used)
DRS_QE0100_TC42.CDB	CAMDAT output file
DRS_QE0100_TC42.DBG	Diagnostics output file
EXCEL Spreadsheets	
TC4_post_processor.xls	Used to create tables from DRSPALL output files

8.4.4 Acceptance Criteria

8.4.4.1 Coupling of the Wellbore and the Repository Flow Models

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

1) Cavity pressure decreases and well bottomhole pressure increases with time (after they stabilize).
2) Repository has not yet been penetrated, indicated by the logical variable Repository Penetrated = "F" (false).
3) The total mass of gas in the bottom of the well is updated by adding gas from the waste. The total mass balance error should be less than 0.10.

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

4) Cavity pressure and well bottomhole pressure are equal.
5) Repository has been penetrated, indicated by the logical variable Repository Penetrated = "T" (true).
6) The total mass of gas in the well is updated by adding gas from the waste. The total mass balance error should be less than 0.10.

8.4.4.2 Tensile Failure of Waste Material

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

7) The radial effective stress is equal to the sum of the component stresses per Eq. 8.4.1.

8) If the average radial effective stress over characteristic length L_t = 2 cm exceeds the material tensile strength, then tensile failure is started, otherwise, tensile failure has not started.

9) Independent spreadsheet calculations of the radial effective stress, radial seepage stress, and radial elastic stress based on Equations 8.4.1 – 8.4.3 and the given DRSPALL pore pressure profile demonstrate agreement within a relative difference of 1E-4.

8.4.4.3 Fluidized Bed Transport of Disaggregated Waste Material

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

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.

11) The fluidization velocity calculated independently using the Ergun equation (8.4.4) is consistent with the value reported by DRSPALL to within a relative difference of 1E-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.

8.4.4.4 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:

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.

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.

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.

8.4.4.5 External Interfaces

The proper use of external interfaces will be verified if:

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 output diagnostics file.

17) An output CAMDAT file is generated by DRSPALL. The file must be readable by the BLOTCDB utility (WIPP PA, 1996b) or the GROPECDB utility (WIPP PA, 1996a) to confirm that it is a valid CAMDAT file.

Test Case #4 will pass if all criteria listed in Sections 8.4.4.1 – 8.4.4.5 are satisfied.

8.4.5 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 Figures 8.4-2 through 8.4-3. Note that the code was executed for 450 seconds DRSPALL time. This was sufficient time to allow for the cavity pressure to stabilize (Figure 8.4-2), drilling to complete and failure of repository material to stop and cavity radius to stabilize (Figure 8.4-3). Output variable names shown in the figures represent the CAMDAT variable names. The names are described in the User's Manual (WIPP PA, 2003d).

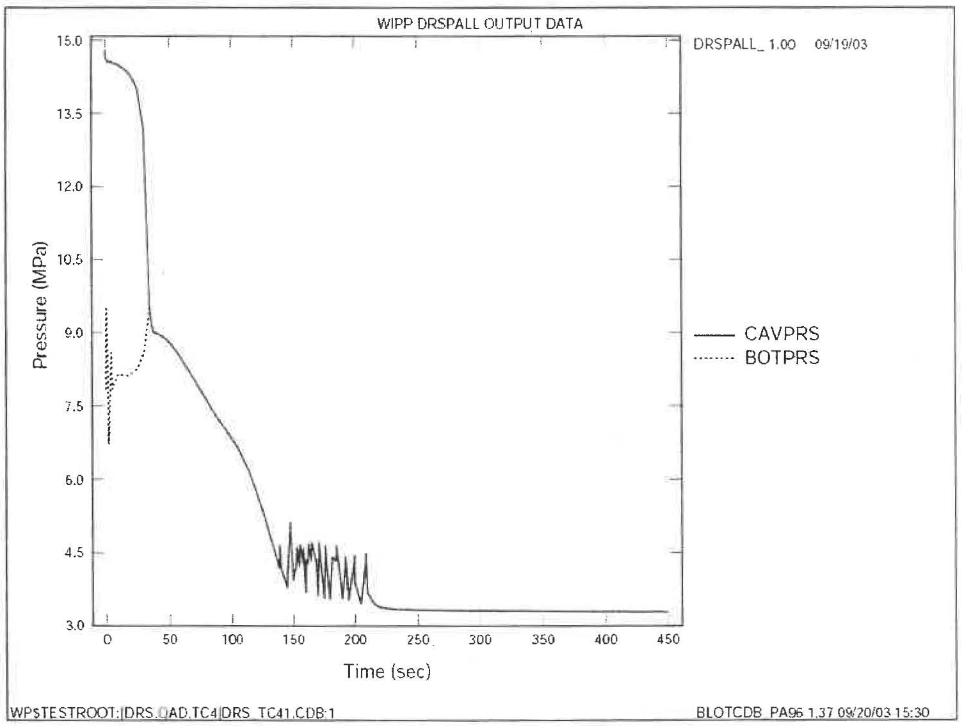


Figure 8.4-2. Pressure history plot.

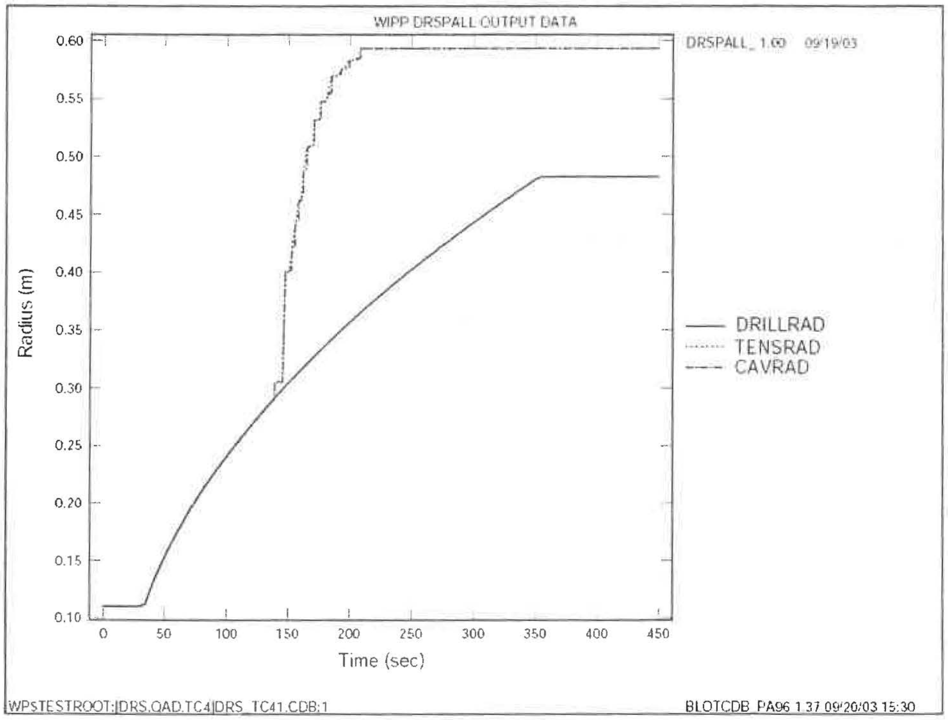


Figure 8.4-3. Radius history plot.

Understanding DRSPALL output typically begins with studying the pressure and cavity radius history plots. The pressure history plot in Figure 8.4-2 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 cause 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 3.5 MPa where it stays for the remainder of the run. The pressure spikes observed between 150 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 8.4-3. 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 8.4.3.1) created prior to bit penetration. The cavity then grows upon penetration of the repository, starting at 34 seconds. Until 150 seconds, all radial variables grow due to drilling. After 150 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 drilled radius is 0.48 m. The cavity radius and tensile-failed radius settle to a constant value near 0.59 m. The difference between these radii represents the material considered to be "spalled" in this conceptual model.

8.4.5.1 Coupling of the Wellbore and Repository Flow Models

An excerpt from the coupling file is shown in Table 8.4-4. The entire file is stored in SCMS. The information shown in this table relates to gas transport from the repository domain to the wellbore domain. Displayed output variables include run time, height of bit above repository, logical flag repository penetrated, cavity pressure, well bottom pressure, total gas in well, total gas injected, gas mass remaining in repository, gas mass from repository, gas in storage, and mass balance error. These variables are defined in Section 8.4.3.1. Also shown for this discussion is graphical output in a pressure versus time plot shown in Figure 8.4-4.

8.4.5.1.1 Coupling logic

Reporting in Table 8.4-4 starts at run time = 28.28596 seconds. The bit is 0.02427 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 = 13.61 MPa) is greater than Well Bottom Pressure at 8.43 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 9.52 MPa at ~33.79 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 8.4-4, where data from Figure 8.4-2 were plotted on a time scale from 0 to 100 seconds to zoom in on events around the time of intrusion.

An examination of Table 8.4-4 and DRS_QE0100_TC41_COUPLING.DAT confirms that **Acceptance Criteria 2 and 5 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 8.4-4 and Figures 8.4-2 and 8.4-4 confirms that **Acceptance Criteria 1 is met**: Cavity Pressure (BOTPRS) decreases and Well Bottom Pressure (CAVPRS) increases (after CAVPRS stabilizes) as the bit approaches the repository, and always "T" (true) when Bit Above Repository is less than or equal to zero. Further examination confirms that **Acceptance Criteria 5 is met**: Cavity Pressure (BOTPRS) and Well Bottom Pressure (CAVPRS) are equal when the bit intersects the repository.

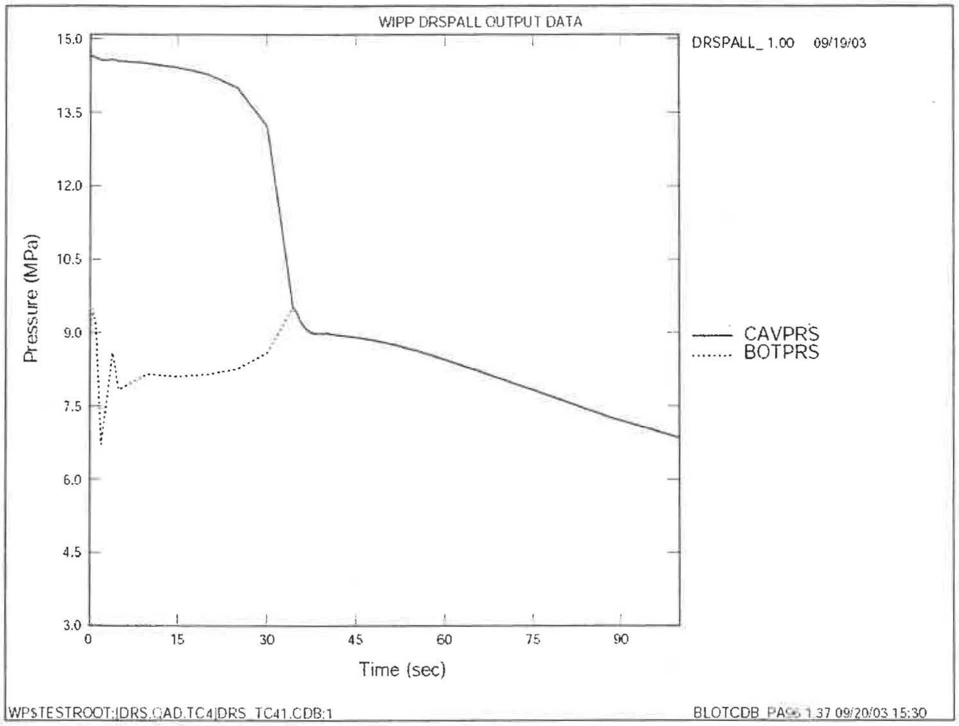


Figure 8.4-4. Pressure history plot for time = 0 to 100 sec.

In Table 8.4-4, 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 ~105 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 8.4.3.1. The global mass balance error remains on the order of 1E-04 to 1E-06 for all reported times in Table 8.4-4 and in DRS_QE0100_TC41_COUPLING.DAT, confirming that **Acceptance Criteria 3 and 6 are met**.

Table 8.4-4. Excerpt from DRS_QE0100_TC41_COUPLING.DAT.

```
Program DR_SPALL - WIPP PA 2003
ASCII Output file for Test Case #4
Verification of coupling between Repository and Wellbore

  Initial Repos Pressure (Pa)        1.480000000000000E+07
  Initial Gas in Repos (kg)          1.025939986444641E+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 Repos (kg)	Gas Mass From Repos (kg)	Gas storage (kg)	Mass Bal Error (-)
28.28596	0.02427	F	1.3614296E+07	8.4290427E+06	1.9026425E+00	1.9026425E+00	1.0259199E+05	2.0087165E+00	0.0000000E+00	1.0339199E-06
28.45051	0.02354	F	1.3584261E+07	8.4412189E+06	1.9296418E+00	1.9296418E+00	1.0259196E+05	2.0386324E+00	0.0000000E+00	1.0623486E-06
28.61514	0.02281	F	1.3552717E+07	8.4540321E+06	1.9572490E+00	1.9572490E+00	1.0259193E+05	2.0692826E+00	0.0000000E+00	1.0920098E-06
28.77983	0.02207	F	1.3519543E+07	8.4674679E+06	1.9854912E+00	1.9854912E+00	1.0259190E+05	2.1007026E+00	0.0000000E+00	1.1229838E-06
28.94460	0.02134	F	1.3484610E+07	8.4815729E+06	2.0143977E+00	2.0143977E+00	1.0259187E+05	2.1329305E+00	0.0000000E+00	1.1553582E-06
29.10945	0.02061	F	1.3447785E+07	8.4964394E+06	2.0439997E+00	2.0439997E+00	1.0259183E+05	2.1660074E+00	0.0000000E+00	1.1892283E-06
29.27438	0.01988	F	1.3408915E+07	8.5121158E+06	2.0743305E+00	2.0743305E+00	1.0259180E+05	2.1999771E+00	0.0000000E+00	1.2246980E-06
29.43940	0.01914	F	1.3367821E+07	8.5285948E+06	2.1054257E+00	2.1054257E+00	1.0259176E+05	2.2348871E+00	0.0000000E+00	1.2618808E-06
29.60450	0.01841	F	1.3324301E+07	8.5458984E+06	2.1373241E+00	2.1373241E+00	1.0259173E+05	2.2707888E+00	0.0000000E+00	1.3009016E-06
29.76971	0.01767	F	1.3278144E+07	8.5641080E+06	2.1700673E+00	2.1700673E+00	1.0259169E+05	2.3077379E+00	0.0000000E+00	1.3418977E-06
29.93501	0.01694	F	1.3229113E+07	8.5833006E+06	2.2036999E+00	2.2036999E+00	1.0259165E+05	2.3457946E+00	0.0000000E+00	1.3850199E-06
30.10042	0.01620	F	1.3176929E+07	8.6035047E+06	2.2382704E+00	2.2382704E+00	1.0259161E+05	2.3850244E+00	0.0000000E+00	1.4304344E-06
30.26595	0.01547	F	1.3121275E+07	8.6247389E+06	2.2738312E+00	2.2738312E+00	1.0259157E+05	2.4254985E+00	0.0000000E+00	1.4783256E-06
30.43159	0.01473	F	1.3061799E+07	8.6470638E+06	2.3104396E+00	2.3104396E+00	1.0259153E+05	2.4672953E+00	0.0000000E+00	1.5288980E-06
30.59736	0.01399	F	1.2998104E+07	8.6705764E+06	2.3481576E+00	2.3481576E+00	1.0259149E+05	2.5105002E+00	0.0000000E+00	1.5823791E-06
30.76326	0.01326	F	1.2929741E+07	8.6953643E+06	2.3870529E+00	2.3870529E+00	1.0259144E+05	2.5552067E+00	0.0000000E+00	1.6390221E-06
30.92930	0.01252	F	1.2856184E+07	8.7214919E+06	2.4271994E+00	2.4271994E+00	1.0259140E+05	2.6015179E+00	0.0000000E+00	1.6991099E-06
31.09549	0.01178	F	1.2776827E+07	8.7490379E+06	2.4686782E+00	2.4686782E+00	1.0259135E+05	2.6495472E+00	0.0000000E+00	1.7629598E-06
31.26185	0.01104	F	1.2690982E+07	8.7781269E+06	2.5115782E+00	2.5115782E+00	1.0259130E+05	2.6994205E+00	0.0000000E+00	1.8309287E-06
31.42837	0.01030	F	1.2597853E+07	8.8089074E+06	2.5559975E+00	2.5559975E+00	1.0259125E+05	2.7512768E+00	0.0000000E+00	1.9034185E-06
31.59508	0.00956	F	1.2496504E+07	8.8415178E+06	2.6020439E+00	2.6020439E+00	1.0259119E+05	2.8052707E+00	0.0000000E+00	1.9808831E-06
31.76199	0.00882	F	1.2385833E+07	8.8760952E+06	2.6498371E+00	2.6498371E+00	1.0259114E+05	2.8615744E+00	0.0000000E+00	2.0638375E-06
31.92911	0.00808	F	1.2264538E+07	8.9128137E+06	2.6995097E+00	2.6995097E+00	1.0259108E+05	2.9203811E+00	0.0000000E+00	2.1528679E-06
32.09645	0.00733	F	1.2131084E+07	8.9518927E+06	2.7512098E+00	2.7512098E+00	1.0259102E+05	2.9819071E+00	0.0000000E+00	2.2486434E-06
32.26405	0.00659	F	1.1983633E+07	8.9935722E+06	2.8051023E+00	2.8051023E+00	1.0259095E+05	3.0463962E+00	0.0000000E+00	2.3519299E-06
32.43191	0.00584	F	1.1819954E+07	9.0380998E+06	2.8613725E+00	2.8613725E+00	1.0259088E+05	3.1141238E+00	0.0000000E+00	2.4636075E-06
32.60006	0.00509	F	1.1637326E+07	9.0857528E+06	2.9202288E+00	2.9202288E+00	1.0259081E+05	3.1854026E+00	0.0000000E+00	2.5846915E-06
32.76853	0.00434	F	1.1432402E+07	9.1368625E+06	2.9819072E+00	2.9819072E+00	1.0259074E+05	3.2605891E+00	0.0000000E+00	2.7163569E-06
32.93735	0.00359	F	1.1201016E+07	9.1918137E+06	3.0466756E+00	3.0466756E+00	1.0259066E+05	3.3400912E+00	0.0000000E+00	2.8599679E-06
33.10655	0.00284	F	1.0937890E+07	9.2510341E+06	3.1148401E+00	3.1148401E+00	1.0259057E+05	3.4243777E+00	0.0000000E+00	3.0171123E-06
33.27617	0.00209	F	1.0636221E+07	9.3150067E+06	3.1867526E+00	3.1867526E+00	1.0259048E+05	3.5139909E+00	0.0000000E+00	3.1896439E-06
33.44625	0.00133	F	1.0287064E+07	9.3843065E+06	3.2628209E+00	3.2628209E+00	1.0259039E+05	3.6095609E+00	0.0000000E+00	3.3797297E-06
33.61685	0.00057	F	9.8783325E+06	9.4596432E+06	3.3435224E+00	3.3435224E+00	1.0259029E+05	3.7118247E+00	0.0000000E+00	3.5899015E-06
33.78802	**-0.00019**	**T**	**9.5223525E+06**	**9.5223525E+06**	**3.4287849E+00**	**3.4287849E+00**	**1.0259018E+05**	**3.8211285E+00**	**0.0000000E+00**	**3.8242352E-06**
33.95975	-0.00095	T	9.5319626E+06	9.5319626E+06	3.5140628E+00	3.5140628E+00	1.0259007E+05	3.9313310E+00	0.0000000E+00	4.0671792E-06
34.13179	-0.00172	T	9.5368221E+06	9.5368221E+06	3.5989067E+00	3.5989067E+00	1.0258996E+05	4.0409391E+00	0.0000000E+00	4.3085596E-06
34.30404	-0.00248	T	9.5331246E+06	9.5331246E+06	3.6835667E+00	3.6835667E+00	1.0258985E+05	4.1502840E+00	0.0000000E+00	4.5491680E-06
34.47643	-0.00325	T	9.5430641E+06	9.5430641E+06	3.7698590E+00	3.7698590E+00	1.0258974E+05	4.2617995E+00	3.6244251E-04	4.7914893E-06
34.64902	-0.00401	T	9.5039778E+06	9.5039778E+06	3.8569497E+00	3.8569497E+00	1.0258962E+05	4.3736670E+00	1.0789983E-04	5.0354743E-06
34.82177	-0.00478	T	9.4630241E+06	9.4630241E+06	3.9442086E+00	3.9442086E+00	1.0258951E+05	4.4860611E+00	3.1809226E-05	5.2812122E-06
34.99467	-0.00555	T	9.4218308E+06	9.4218308E+06	4.0317753E+00	4.0317753E+00	1.0258940E+05	4.5989994E+00	9.2843924E-06	5.5287332E-06
35.16771	-0.00632	T	9.4045946E+06	9.4045946E+06	4.1219710E+00	4.1219710E+00	1.0258928E+05	4.7153013E+00	2.8177944E-04	5.7805381E-06
35.34095	-0.00709	T	9.3558123E+06	9.3558123E+06	4.2125073E+00	4.2125073E+00	1.0258917E+05	4.8316869E+00	8.3710512E-05	6.0344256E-06
35.51435	-0.00786	T	9.2987700E+06	9.2987700E+06	4.3034330E+00	4.3034330E+00	1.0258905E+05	4.9488625E+00	2.4532530E-05	6.2908650E-06
35.68790	-0.00863	T	9.2422980E+06	9.2422980E+06	4.3948841E+00	4.3948841E+00	1.0258893E+05	5.0668873E+00	7.0849135E-06	6.5500526E-06
35.86161	-0.00940	T	9.2137128E+06	9.2137128E+06	4.4896482E+00	4.4896482E+00	1.0258881E+05	5.1890449E+00	2.2624075E-04	6.8149255E-06
36.03552	-0.01018	T	9.1759153E+06	9.1759153E+06	4.5842244E+00	4.5842244E+00	1.0258869E+05	5.3107994E+00	6.6250169E-05	7.0813965E-06
36.20958	-0.01095	T	9.1409044E+06	9.1409044E+06	4.6789777E+00	4.6789777E+00	1.0258857E+05	5.4330003E+00	1.9240644E-05	7.3493912E-06

8.4.5.2 Tensile Failure of Waste Material

An excerpt from the stress output file (as formatted by EXCEL) is shown in Table 8.4-5. The original file is stored in SCMS. 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, fraction of the zone fluidized and the radial effective stress calculated by the spreadsheet. Tensile strength for this test case is 0.12 MPa, and is specified in the input file (Table D.1-1) and reported in the header to DRS_QE0100_TC41_STRESS.DAT.

Acceptance Criteria 7 states that the radial effective stress must equal the sum of the component stresses as per Eq. 8.4.1. The criteria is checked by spreadsheet calculations of the radial effective stress in Table 8.4-5 for every zone (shown in last column). In each case, "EffStre" is equal to "SeepStr" + "ElastStr" – "PorePres" for all digits shown. Thus, **Acceptance Criteria 7 is met**.

8.4.5.2.1 Stress and failure logic

Reviewing Table 8.4-5 allows for an examination of the logic that controls waste material failure due to stresses in the solid. Starting with the first intact zone 103, if radial effective stress is less than tensile strength (T_s = -0.12 MPa), the material is subject to failure. Recall from Section 8.4.3.2 and Eq. 8.4.4 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. Examination of the radial effective stress "EffStre" for zones 103-113 reveals that the mean stress = -1.55932E+05 Pa, which is less than 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 103-113 (within the characteristic length), and "F" (false) for zones 114-123 (outside the characteristic length) confirms that **Acceptance Criteria 8 is met**.

8.4.5.2.2 Verification of stress calculations

The data from Table 8.4-5 were imported into an EXCEL spreadsheet (Table 8.4-6) in order to verify the stress calculations. Note that the Effective Stress formulation (Eqs. 8.4.1 – 8.4.3) requires only material properties, geometry, and the correct pore pressure profile to determine the stress state in the solid. As such, this verification will proceed by using the pore pressure profile shown in Table 8.4-5 to calculate a stress profile, which will be compared back to the stress profile calculated by DRSPALL. Table 8.4-6 displays the new stress profile calculations.

The header in Table 8.4-6 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:

$$prefactor = (m-1)\beta\left(\frac{1-2\upsilon}{1-\upsilon}\right) \tag{8.4.7}$$

The calculations start at the first intact zone 103 and are carried through to zone 123. The following notes apply:

- r_c/r denotes the ratio cavity radius to zone center radius
- The Radial Elastic Stress is calculated per Eq. 8.4.3
- The Integral Over *dr* represents the integral in Eq. 8.4.2 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 Eq. 8.4.2
- The Radial Effective Stress is calculated by Eq. 8.4.1

The spreadsheet results for the stress values are compared to DRSPALL values in the summary Table 8.4-7. The relative difference is calculated as follows:

$$\text{relative DIFF} = |(\text{DRSPALL stress} - \text{spreadsheet stress}) \div \text{DRSPALL stress}| \tag{8.4.8}$$

Relative differences for the Radial Elastic Stress were all less than 1E-12, while relative differences for Radial Seepage Stress were less than 1E-12, and for Radial Effective Stress less than 1E-10. The small DIFF values for the three stresses confirm that **Acceptance Criteria 9 was met**. These calculations verify that the stress formulation given in Section 8.4.3.2 were implemented in DRSPALL as intended.

Table 8.4-5. Excerpt from DRS_QE0100_TC41_STRESS.DAT, run time = 158.7951 sec.

Runtime(sec)	=	1.454425E+02
CavPres(Pa)	=	4.146353E+06
CavRadius(m)	=	3.128393E-01
DrilledRad(m)	=	2.989038E-01
CavityVol(m^3)	=	1.136522E-01
Pff(Pa)	=	1.479203E+07
FirstIntactZone=		103

zone index	Radius(m)	PorePres(Pa)	ElastStr(Pa)	SeepStr(Pa)	EffStre(Pa)	Failed(T/F)	Fluidized(-)	Spreadsheet EffStre(Pa)
93	2.939482E-01	4.661860E+06	4.757951E+06	-1.571180E-01	9.609117E+04	T	1	9.609117E+04
94	2.959367E-01	4.686087E+06	4.779872E+06	-1.353646E+00	9.378394E+04	T	1	9.378394E+04
95	2.979252E-01	4.709829E+06	4.801601E+06	-3.319853E+00	9.176842E+04	T	1	9.176842E+04
96	2.999138E-01	4.733570E+06	4.823510E+06	-1.972065E+00	8.993815E+04	T	1	8.993815E+04
97	3.019023E-01	4.756543E+06	4.844462E+06	-2.779430E-01	8.791859E+04	T	1	8.791859E+04
98	3.038909E-01	4.767929E+06	4.850089E+06	-2.456990E+00	8.215786E+04	T	1	8.215786E+04
99	3.058794E-01	4.161419E+06	4.242081E+06	-4.044156E+00	8.065736E+04	T	1	8.065736E+04
100	3.078679E-01	4.217049E+06	4.305268E+06	-2.508475E+00	8.821718E+04	T	1	8.821718E+04
101	3.098565E-01	4.253661E+06	4.338075E+06	-3.641354E+00	8.441047E+04	T	1	8.441047E+04
102	3.118450E-01	4.273342E+06	4.350736E+06	-2.401319E+00	7.739207E+04	T	1	7.739207E+04
103	3.138336E-01	4.408686E+06	4.349476E+06	-5.124927E+04	-1.104600E+05	T	0	-1.104600E+05
104	3.158221E-01	4.597200E+06	4.547514E+06	-1.001251E+05	-1.498110E+05	T	0	-1.498110E+05
105	3.178107E-01	4.759872E+06	4.740627E+06	-1.469404E+05	-1.661846E+05	T	0	-1.661846E+05
106	3.197992E-01	4.910351E+06	4.928967E+06	-1.918497E+05	-1.732335E+05	T	0	-1.732335E+05
107	3.217877E-01	5.052969E+06	5.112680E+06	-2.349590E+05	-1.752475E+05	T	0	-1.752475E+05
108	3.237763E-01	5.189360E+06	5.291908E+06	-2.763567E+05	-1.738092E+05	T	0	-1.738092E+05
109	3.257648E-01	5.320327E+06	5.466786E+06	-3.161218E+05	-1.696637E+05	T	0	-1.696637E+05
110	3.277534E-01	5.446384E+06	5.637445E+06	-3.543279E+05	-1.632669E+05	T	0	-1.632669E+05
111	3.297419E-01	5.567924E+06	5.804013E+06	-3.910434E+05	-1.549543E+05	T	0	-1.549543E+05
112	3.317304E-01	5.685275E+06	5.966610E+06	-4.263329E+05	-1.449976E+05	T	0	-1.449976E+05
113	3.337190E-01	5.798725E+06	6.125356E+06	-4.602571E+05	-1.336264E+05	T	0	-1.336264E+05
114	3.357075E-01	5.908527E+06	6.280362E+06	-4.928735E+05	-1.210386E+05	F	0	-1.21039E+05

115	3.376961E-01	6.014908E+06	6.431739E+06	-5.242363E+05	-1.074060E+05	F	0	-1.07406E+05
116	3.396846E-01	6.118073E+06	6.579591E+06	-5.543969E+05	-9.287909E+04	F	0	-9.28791E+04
117	3.416731E-01	6.218207E+06	6.724022E+06	-5.834042E+05	-7.758968E+04	F	0	-7.75897E+04
118	3.436617E-01	6.315479E+06	6.865129E+06	-6.113045E+05	-6.165392E+04	F	0	-6.16539E+04
119	3.456502E-01	6.410040E+06	7.003008E+06	-6.381416E+05	-4.517429E+04	F	0	-4.51743E+04
120	3.476388E-01	6.502034E+06	7.137750E+06	-6.639575E+05	-2.824140E+04	F	0	-2.82414E+04
121	3.496273E-01	6.591587E+06	7.269444E+06	-6.887921E+05	-1.093553E+04	F	0	-1.09355E+04
122	3.516158E-01	6.678820E+06	7.398175E+06	-7.126832E+05	6.672114E+03	F	0	6.67211E+03
123	3.536044E-01	6.763842E+06	7.524027E+06	-7.356671E+05	2.451825E+04	F	0	2.45182E+04

Table 8.4-6. EXCEL spreadsheet showing independent calculations of stress profiles from pore pressure data obtained from Table 8.4-5.

Far-field stress	1.4900E+07
Tensile strength	1.2000E+05
Poisson's ratio	3.8000E-01
Geometry index	3
Far-field pressure	1.4792E+07
Biot Beta	1.0000E+00
Prefactor	3.8710E-01

RADIAL S

Zone Index	r_c/r	Rad El Stress	*Seepage stress* Integral over dr	Sum	RadSeepStr	Radial Effective Stress
				0		
103	9.936637E-01	4.349476E+06	-2.046144E+03	-2.046144E+03	-5.124927E+04	-1.104600E+05
104	9.874072E-01	4.547514E+06	-2.027855E+03	-4.074000E+03	-1.001251E+05	-1.498110E+05
105	9.812290E-01	4.740627E+06	-2.018522E+03	-6.092522E+03	-1.469404E+05	-1.661846E+05
106	9.751276E-01	4.928967E+06	-2.012303E+03	-8.104825E+03	-1.918497E+05	-1.732335E+05
107	9.691017E-01	5.112680E+06	-2.007501E+03	-1.011233E+04	-2.349590E+05	-1.752475E+05
108	9.631497E-01	5.291908E+06	-2.003567E+03	-1.211589E+04	-2.763567E+05	-1.738092E+05
109	9.572704E-01	5.466786E+06	-2.000295E+03	-1.411619E+04	-3.161218E+05	-1.696637E+05
110	9.514625E-01	5.637445E+06	-1.997583E+03	-1.611377E+04	-3.543279E+05	-1.632669E+05
111	9.457246E-01	5.804013E+06	-1.995367E+03	-1.810914E+04	-3.910434E+05	-1.549543E+05
112	9.400555E-01	5.966610E+06	-1.993601E+03	-2.010274E+04	-4.263329E+05	-1.449976E+05
113	9.344540E-01	6.125356E+06	-1.992244E+03	-2.209498E+04	-4.602571E+05	-1.336264E+05
114	9.289188E-01	6.280362E+06	-1.991262E+03	-2.408625E+04	-4.928735E+05	-1.210386E+05
115	9.234488E-01	6.431739E+06	-1.990627E+03	-2.607687E+04	-5.242363E+05	-1.074060E+05

116	9.180429E-01	6.579591E+06	-1.990312E+03	-2.806719E+04	-5.543969E+05	-9.287909E+04
117	9.126999E-01	6.724022E+06	-1.990294E+03	-3.005748E+04	-5.834042E+05	-7.758968E+04
118	9.074187E-01	6.865129E+06	-1.990552E+03	-3.204803E+04	-6.113045E+05	-6.165392E+04
119	9.021983E-01	7.003008E+06	-1.991067E+03	-3.403910E+04	-6.381416E+05	-4.517429E+04
120	8.970376E-01	7.137750E+06	-1.991822E+03	-3.603092E+04	-6.639575E+05	-2.824140E+04
121	8.919356E-01	7.269444E+06	-1.992802E+03	-3.802372E+04	-6.887921E+05	-1.093553E+04
122	8.868913E-01	7.398175E+06	-1.993993E+03	-4.001772E+04	-7.126832E+05	6.672114E+03
123	8.819037E-01	7.524027E+06	-1.995382E+03	-4.201310E+04	-7.356671E+05	2.451825E+04

Table 8.4-7. Summary of differences between DRSPALL and spreadsheet calculations for stress verification.

	Absolute DIFF			Relative DIFF		
	Rad El Stress	*Rad Seep Stress*	*Rad Eff Stress*	*Rad El Stress*	*Rad Seep Stress*	*Rad Eff Stress*
103	7.90693E-07	2.01580E-07	6.11835E-07	1.81790E-13	3.93333E-12	5.53898E-12
104	6.05360E-07	1.45184E-07	4.30213E-07	1.33119E-13	1.45003E-12	2.87170E-12
105	3.94881E-07	9.11823E-08	2.72732E-07	8.32972E-14	6.20539E-13	1.64114E-12
106	1.41561E-07	4.94183E-08	1.32335E-07	2.87202E-14	2.57589E-13	7.63912E-13
107	6.51926E-08	3.87081E-09	9.97388E-08	1.27512E-14	1.64744E-14	5.69131E-13
108	6.72415E-07	1.61584E-07	4.50411E-07	1.27065E-13	5.84695E-13	2.59141E-12
109	3.87430E-07	1.16357E-07	2.91184E-07	7.08698E-14	3.68077E-13	1.71624E-12
110	2.30968E-07	7.17700E-08	1.18191E-07	4.09703E-14	2.02553E-13	7.23911E-13
111	6.79865E-08	3.38769E-08	3.35567E-08	1.17137E-14	8.66320E-14	2.16559E-13
112	7.54371E-08	2.56114E-09	1.12836E-07	1.26432E-14	6.00736E-15	7.78189E-13
113	4.61005E-07	1.28988E-07	3.92058E-07	7.52617E-14	2.80252E-13	2.93398E-12
114	3.34345E-07	9.74978E-08	2.56216E-07	5.32366E-14	1.97815E-13	2.11681E-12
115	2.03960E-07	6.23404E-08	1.21334E-07	3.17114E-14	1.18917E-13	1.12967E-12
116	7.45058E-09	2.73576E-08	5.26779E-09	1.13238E-15	4.93466E-14	5.67167E-14
117	5.05708E-07	1.46101E-07	4.28394E-07	7.52092E-14	2.50429E-13	5.52127E-12
118	4.36790E-07	1.10245E-07	2.97128E-07	6.36245E-14	1.80344E-13	4.81929E-12
119	2.76603E-07	7.68341E-08	1.56950E-07	3.94977E-14	1.20403E-13	3.47431E-12
120	1.22935E-07	5.28526E-08	2.70993E-08	1.72232E-14	7.96023E-14	9.59559E-13
121	4.09782E-08	2.66591E-08	1.07364E-07	5.63705E-15	3.87041E-14	9.81791E-12
122	4.55417E-07	1.24564E-07	2.98014E-07	6.15580E-14	1.74782E-13	4.46656E-11
123	3.11993E-07	9.25502E-08	2.32299E-07	4.14662E-14	1.25804E-13	9.47455E-12

8.4.5.3 Fluidized Bed Transport of Disaggregated Waste Material

An excerpt from the fluidization output file is shown in Table 8.4-8. The entire file is stored in SCMS. 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. Shown are the 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 -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.

Table 8.4-8. Excerpt from DRS_QE0100_TC41_FLUIDIZATION.DAT, run time = 145.8678 sec.

```
Runtime (sec)                 = 1.4586779704775E+02
Cavity Pressure(Pa)           = 4.3556358551769E+06
Cavity Radius(m)              = 3.3471325039864E-01
Gas Density (kg/m^3)          = 3.6760607574864E+00
Fluidization Velocity(m)      = 5.7394912081331E-01
Superficial Gas Velocity(m)
          (First Intact Zone)= 1.1524586428985E+00
Waste In Well (kg)            = 4.1079099663678E+01
      FirstIntactZone           114
```

Cell index	Radius(m)	Failure Completed(T/F)	Fluidization Start(T/F)	Fluidization Complete(T/F)	Fraction Fluidized
104	3.1582211225086E-01	T	T	T	1.0000
105	3.1781065306987E-01	T	T	T	1.0000
106	3.1979919388888E-01	T	T	T	1.0000
107	3.2178773470789E-01	T	T	T	1.0000
108	3.2377627552691E-01	T	T	T	1.0000
109	3.2576481634592E-01	T	T	T	1.0000
110	3.2775335716493E-01	T	T	T	1.0000
111	3.2974189798394E-01	T	T	T	1.0000
112	3.3173043880295E-01	T	T	T	1.0000
113	3.3371897962197E-01	T	T	T	1.0000
114	3.3570752044098E-01	T	T	F	0.0002
115	3.3769606125999E-01	T	T	F	0.0002
116	3.3968460207900E-01	T	T	F	0.0001
117	3.4167314289802E-01	T	T	F	0.0001
118	3.4366168371703E-01	F	F	F	0.0000
119	3.4565022453604E-01	F	F	F	0.0000
120	3.4763876535505E-01	F	F	F	0.0000
121	3.4962730617406E-01	F	F	F	0.0000
122	3.5161584699308E-01	F	F	F	0.0000
123	3.5360438781209E-01	F	F	F	0.0000
124	3.5559292863110E-01	F	F	F	0.0000
125	3.5758146945011E-01	F	F	F	0.0000
126	3.5957001026913E-01	F	F	F	0.0000
127	3.6155855108814E-01	F	F	F	0.0000
128	3.6354709190715E-01	F	F	F	0.0000
129	3.6553563272616E-01	F	F	F	0.0000
130	3.6752417354517E-01	F	F	F	0.0000
131	3.6951271436419E-01	F	F	F	0.0000
132	3.7150125518320E-01	F	F	F	0.0000
133	3.7348979600221E-01	F	F	F	0.0000
134	3.7547833682122E-01	F	F	F	0.0000

8.4.5.3.1 Fluidization logic

At the point in the code execution shown in Table 8.4-8, 113 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 114. Zones 104-113 were completely removed by tensile failure and fluidization (Fraction Fluidized = 1.0). Zones 114-117 have failed in tension (Failure Completed = T), and zones 114-117 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. This condition can be confirmed by examining the header in Table 8.4-8. The Superficial Gas Velocity at the first intact zone (114) = 1.152 m/s, while the Fluidization Velocity = 0.5738 m/s. As such, the failed zone 114 is subject to fluidization, and fluidization is currently in process. **Acceptance Criteria 10 is met** because the Fluidization Start = "T" (True) in zone 114 confirms that fluidization has started in the first intact zone. Zones must complete fluidization in sequence such that zone 115 cannot completely fluidize until after zone 114 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 (not fluidized) to 1.0 (fully fluidized). Notice that zones 114-117 are just starting to fluidize in Table 8.4-8. Eventual fluidization of failed zones 115 and 116 can be confirmed by looking at the subsequent data snapshots in DRS_QE0100_TC41_FLUIDIZATION.DAT for run times > 145 seconds.

8.4.5.3.2 Verification of fluidization velocity

Data from Table 8.4-8 were imported into an EXCEL spreadsheet (Table 8.4-9) in order to verify proper calculation of Ergun's minimum fluidization velocity (Eq. 2.4). The dependent variable in Ergun's formula is U_f, which can be solved for by the quadratic formula:

$$AU_f^2 + BU_f + C = 0 \tag{8.4.9}$$

$$U_f = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{8.4.10}$$

Eq. 2.4. was rearranged to form the constants A, B, and C, defined in Eq. 8.4.9, which are evaluated in Table 8.4-9. The two lines preceding the last in Table 8.4-9 compare the fluidization velocity calculated by the spreadsheet to that calculated by DRSPALL for the given input conditions. The relative difference [(DRSPALL *Uf* – spreadsheet *Uf*)/DRSPALL *Uf*] evaluated to 5.417e-15. This small relative difference is less than 1E-4, confirming that **Acceptance Criteria 11 is met**.

Table 8.4-9. Spreadsheet solution for minimum fluidization velocity U_f.

Parameters	*Value*	*Units*
run time	1.4586777E+02	sec
gas density	3.6766585E+00	kg/m3
porosity	5.7500000E-01	-
waste density	2.6500000E+03	kg/m3
gas viscosity	8.9339000E-06	Pa*sec
particle diameter	1.0000000E-03	m
shape factor	5.5000000E-01	-
gravity	9.8067000E+00	m/sec2
a	2.8346290E+06	
b	4.5620861E+05	
c	-1.1954651E+06	
b^2-4ac	1.3762927E+13	
spreadsheet fluidization vel	5.7390813E-01	m/s
DRSPALL fluidization vel	5.7390813E-01	m/s
Relative difference	5.4165890E-15	

8.4.5.3.3 Verification of fluidization time

The spreadsheet calculation of the fluidization time is shown in Table 8.4-10. For the given conditions, the fluidization time calculated by Eq. 8.4.6 using r_{c1} and U_s from runtime = 1.58797E+02 sec was t_f = 0.292 seconds. For comparison, t_f (FLUIDTIM) was extracted from the CAMDAT file for several runtimes near 145.87 seconds, and are shown in Table 8.4-10, showing values of t_f = 0.245 to 0.292 sec.

Confirmation of proper implementation of t_f in DRSPALL is possible by examining the amount of time required to completely fluidize zone 114 that started to fluidize near runtime = 1.4587E+02 sec. The reporting frequency in DRS_QE0100_TC41_FLUIDIZATION.DAT is not sufficient to capture both the beginning and ending of fluidization for zone 114, 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 8.4-10, with runtime #1 and runtime #2 representing the two selected runtime reports from which the fluidization time is extrapolated. The projected fluidization time from this coarse method is 0.307 sec. This compares favorably with the values calculated by spreadsheet (t_f = 0.291 sec) and extracted from the CAMDAT file using GROPECDB, Table 8.4-11 (step 208, t_f = 0.291).

Table 8.4-10. Spreadsheet solution for fluidization time, t_f.

Fluidization Time, t_f

Parameter	*Value*	*Units*
run time	1.4586777E+02	sec
radius to cell center first intact zone	3.3471325E-01	m
superficial gas velocity	1.1519070E+00	m/sec
fluidization time	2.9057316E-01	sec
From DRS_TC41_FLUIDIZATION.DAT		
runtime #1	1.4586777E+02	sec
fraction fluidized #1	0.0001	-
runtime #2	1.4586790E+02	sec
fraction fluidized #2	0.0005	-
projected fluidization time	3.07E-01	sec

Table 8.4-11. Fluidization time values extracted from CAMDAT file.

CDB Step Index	Time (Sec)	Fluidization Time (sec)
207	1.45866E+02	4.21058E-01
208	1.46159E+02	2.91436E-01
209	1.46159E+02	2.91436E-01
210	1.46177E+02	3.09156E-01
211	1.46177E+02	3.09156E-01

Note: Consecutive times can appear to be equal because times listed by the GROPECDB utility do not have enough precision to capture the DRSPALL time step. Fluidization Times on the CDB are for the first intact zone minus 1 or the last zone fluidized. Therefore, step 207 gives Fluidization Time for zone 113; steps 208 and 209 for zone 114.

8.4.5.3.4 Verification of Drilling and Spall Volumes and Masses

The spreadsheet calculations of waste volumes and masses removed from the repository due to drilling and spall (failure and fluidization) are shown in Table 8.4-12. The table also gives the values that were extracted from the diagnostic output (.DBG) and the CAMDAT output files listed in Table 8-4.3. The difference in CAVRAD0 between the .DBG and CAMDAT files is due the precision in the displayed number not the actual value. The maximum relative difference [ABS(DRSPALL – spreadsheet)/DRSPALL] evaluated to 4.28E-05 for SPLVOLEQ. This small relative difference is less than 1E-4, confirming that **Acceptance Criteria 12 is met.**

Table 8.4-12. Drilling and Spall Volumes and Masses from CAMDAT file

CAMDAT Variable Name	Description	Value from .DBG File	Value from CAMDAT Output File	Spreadsheet Calculation	Relative Difference
CAVRAD0	Initial psuedo-Cavity Radius	0.1100	1.10008E-01	1.10008E-01	1.25E-06
CUTMASS	Cuttings mass	2.6078E+02	2.60779E+02	2.60779E+02	4.52E-07
TOTMASS	Total mass	4.8930E+02	4.89296E+02	4.89285E+02	2.15E-05
SPLMASS	Spall mass	2.2852E+02	2.28516E+02	2.28507E+02	4.11E-05
SPLMAS2	Incremental spall mass	4.3433E+02	4.34330E+02	4.34329E+02	2.54E-06
CUTVOLEQ	Equivalent uncompacted cuttings volume	6.56050E-01	6.56049E-01	6.56048E-01	2.28E-06
TOTVOLEQ	Equivalent uncompacted total volume	1.23090E+00	1.23093E+00	1.23091E+00	1.88E-05
SPLVOLEQ	Equivalent uncompacted spall volume	5.74880E-01	5.74884E-01	5.74859E-01	4.28E-05
SPLVOL2EQ	Equivalent uncompacted incremental spall volume	1.09270E+00	1.09266E+00	1.09265E+00	7.95E-06

8.4.5.4 Expulsion of Disaggregated Waste Material

Excerpts from the expulsion output file are shown in Tables 8.4-13, 8.4-14 and 8.4-15. The entire file is stored in SCMS. Shown are:

a) data near the time of penetration (run time = 33.5 to 35.2 sec)

b) data exhibiting early waste expulsion (run time = 113.1 to 115.4 sec)

c) late time waste expulsion data approaching steady conditions (400 to 407 sec)

8.4.5.4.1 Near bit penetration

Table 8.4-13 shows the expulsion output file (as formatted by EXCEL) at several times near bit penetration at 33.8 sec. Prior to bit penetration, the logical variable Repository Penetrated = 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 (33.8 sec) and the removal of the first zone (34.4 sec). The total waste in well reflects the sum: Waste in Store + Total Waste In Well. An explanation of the Waste in Store variable is given in Section 8.4.3.1. Waste Ejected is still zero since it has not had time to transport 653 m to the land surface, and Waste Position In Well shows that the location of the waste front moves upward with time.

8.4.5.4.2 Early waste expulsion at surface

Table 8.4-14 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 114.8 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 [Mass Waste Removed – (Waste in Store + Waste In Well + Waste Ejected)]/ Mass Waste Removed.

8.4.5.4.3 Late time waste expulsion

Data at late time (run time > 400 sec) show steady state behavior with a total of 243 zones removed, corresponding to 489.3 kg of waste removed from the repository and an identical 489.3 kg of waste expelled to the surface. The mass balance error is reported as 4.666e-7 kg.

8.4.5.4.4 Summary

The acceptance criteria for the expulsion of disaggregated waste material will be confirmed by examining DRS_QE0100_TC41_EXPULSION.DAT (excerpts of which are shown in Tables 8.4-13, 8.4-14, and 8.4-15). Waste Position in Well decreases from -653 to 0, confirming that **Acceptance Criteria 13 is met**. Waste Mass Ejected is very small (<0.2 kg) before z = 0 (when Waste Position in Well reaches 0), then it monotonically increases, confirming the **Acceptance Criteria 14 is met**. The Mass Balance Error is small (<2e-6) for all times, confirming that **Acceptance Criteria 15 is met**.

Table 8.4-13. Excerpt from DRS_QE0100_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 (-)
33.53346	F	0	0.00000000	0.00000000	0.00000000	0.00000000	-653.0	0.0000E+00
33.70435	F	0	0.00000000	0.00000000	0.00000000	0.00000000	-653.0	0.0000E+00
33.87582	T	0	0.00000000	0.00000000	0.00000000	0.00000000	-653.0	0.0000E+00
34.04774	T	0	0.00000000	0.00000000	0.00000000	0.00000000	-653.0	0.0000E+00
34.21989	T	0	0.00000000	0.00000000	0.00000000	0.00000000	-653.0	0.0000E+00
34.39221	T	1	0.17339133	0.16359581	0.00979530	0.00000000	-652.0	1.2450E-06
34.5647	T	1	0.17339133	0.04880662	0.12458449	0.00000000	-650.0	1.2450E-06
34.73738	T	1	0.17339133	0.01445852	0.15893259	0.00000000	-647.9	1.2450E-06
34.91021	T	1	0.17339133	0.00424100	0.16915011	0.00000000	-646.9	1.2450E-06
35.08317	T	2	0.35304977	0.12847249	0.22457760	0.00000000	-644.8	9.0138E-07
35.25632	T	2	0.35304977	0.03836360	0.31468649	0.00000000	-643.7	9.0138E-07

Table 8.4-14. Excerpt from DRS_QE0100_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 (-)
113.0545	T	74	36.974594	0.02251904	36.925244	0.02685049	-37.9	5.4274E-07
113.2676	T	74	36.974594	0.01143368	36.930135	0.03304494	-33.8	5.4274E-07
113.4807	T	75	37.912394	0.64644939	37.225537	0.04043085	-29.8	5.9635E-07
113.6942	T	75	37.912394	0.32907453	37.534149	0.04919306	-24.7	5.9635E-07
113.9079	T	75	37.912394	0.16726158	37.685637	0.059518681	-19.8	5.9635E-07
114.1216	T	75	37.912394	0.08486001	37.755945	0.07161157	-13.9	5.9635E-07
114.3354	T	75	37.912394	0.04296723	37.783760	0.08569012	-7.3	5.9635E-07
114.5494	T	75	37.912394	0.02170973	37.788722	0.10198504	-2.0	5.9635E-07
114.7634	T	75	37.912394	0.01094530	37.780734	0.12073749	0.0	5.9635E-07
114.9775	T	76	38.864707	0.65317080	38.069350	0.14220226	0.0	4.1577E-07
115.1920	T	76	38.864707	0.33004099	38.368021	0.16666177	0.0	4.1577E-07
115.4066	T	76	38.864707	0.16648808	38.503872	0.19436304	0.0	4.1577E-07

Table 8.4-15. Excerpt from DRS_QE0100_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 (m)
400.49056	T	243	489.29551	8.7577036-119	2.2632195E-12	489.29574	-653.0	4.6660E-07
401.10618	T	243	489.29551	3.6294466-119	2.2632195E-12	489.29574	-653.0	4.6660E-07
401.72180	T	243	489.29551	1.5041855-119	2.2632195E-12	489.29574	-653.0	4.6660E-07
402.33742	T	243	489.29551	6.2340912-120	2.2632195E-12	489.29574	-653.0	4.6660E-07
402.95304	T	243	489.29551	2.5837810-120	2.2632195E-12	489.29574	-653.0	4.6660E-07
403.56866	T	243	489.29551	1.0709003-120	2.2632195E-12	489.29574	-653.0	4.6660E-07
404.18428	T	243	489.29551	4.4386733-121	2.2632195E-12	489.29574	-653.0	4.6660E-07
404.79990	T	243	489.29551	1.8397893-121	2.2632195E-12	489.29574	-653.0	4.6660E-07
405.41551	T	243	489.29551	7.6259470-122	2.2632195E-12	489.29574	-653.0	4.6660E-07
406.03113	T	243	489.29551	3.1610419-122	2.2632195E-12	489.29574	-653.0	4.6660E-07
406.64675	T	243	489.29551	1.3103204-122	2.2632195E-12	489.29574	-653.0	4.6660E-07

8.4.5.5 External Interfaces

The GROPECDB excerpt of all properties for all element blocks of the input CAMDAT file is shown in Table 8.4-16. The input control file for Test Case 4.2 is shown in Table 8.4-17. 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 output diagnostics file for this test case is shown in Table 8.4-18. An examination of this file confirms that the DRSPALL parameters are being read correctly from the input control file and the input CAMDAT file.

The output diagnostics file contains a direct echo of the input control file; the value of each CAMDAT property read; and a listing of each DRSPALL parameter value. With two exceptions ("Total Thickness" and "First Wellbore Zone"), the value of each DRSPALL parameter listed in the output diagnostics file equals the value given in the input control file, if any, or the value of the CAMDAT property referenced in the input control file, or the default value. For example, waste parameter "Failure characteristic length" is given a value of "0.02" in the input control file, as confirmed on the output diagnostics file. (This parameter is called "Lt" in the input control file, but this is just a comment, as the parameter are listed in order within category, as explained in the DRSPALL User's Manual, WIPP PA, 2003d.) In another example, parameter "Gas Constant" (under "Parameters") is read from the CAMDAT property RGAS of element block BLOWOUT, as requested by the input control file. The value in the output diagnostics file (4.1160E+03) matches the CAMDAT value shown for property RGAS under block BLOWOUT in Table 8.4-16.

The input parameters "Tensile Velocity", Bit Nozzle Number", 'Bit Nozzle Diameter", and "Choke Efficiency" were set to DEFAULT. The default values as specified in the DRSPALL Users' Manual (WIPP PA, 2003d) are: 1000.0, 3.0, 0.011112 and 0.9, respectively.

If the parameter "Total Thickness" is specified as 0.0 by the user, then it is calculated internally from the initial repository height (H), the uncompacted waste porosity (φ_u) and the input initial porosity (φ_i) as follows:

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

The parameter "First Wellbore Zone" is a flag indicating whether downward flow inside of the pipe is modeled. If greater that 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 291 for this problem.

Several remaining parameters are listed in the output file but not in the input control file. "Gas Density at STP" is calculated internally from input parameters and echoed to the output diagnostic file for user convenience. "Initial Cavity Radius", "Min Characteristic Velocity" and "Min Number Zones/Lt" are optional input parameters that were not specified in the input control and were set to default values.

Comparisons of the input CAMDAT file, and input control file with the excerpt from the output diagnostic 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 Criteria 16 is met**.

Finally, the output CAMDAT file from Test Case 4.1 was successfully examined with the GROPECDB utility (WIPP PA, 1996a) in the analysis presented above (Section 8.5.4), confirming that the output file is in the proper CAMDAT file format and that **Acceptance Criteria 17 is met**.

Table 8.4-16. Properties from input CAMDAT file.

```
Element Block 2)    "DRSPALL "     2=ID     0 elements
      0-node     0 attributes    44 properties
SURFELEV     REPOSTOP     REPOSTCK     DRZTCK       DRZPERM      REPOTRAD
REPIPRES     FFPORPRS     FFSTRESS     REPIPOR      REPIPERM     BIOTBETA
POISRAT      COHESION     FRICTANG     TENSLSTR     PARTDIAM     GASBSDEN
GASVISCO     INITMDEN     MUDVISCO     ANNUROUG     MUDSOLMX     MUDSOLVE
BITDIAM      PIPEDIAM     COLRDIAM     PIPEID       COLRLNGT     DRILRATE
INITBAR      MUDPRATE     DDZTHICK     DDZPERM      STPDVOLR     STPPVOLR
STPDTIME     SHAPEFAC     FRCHBETA     CHARLEN      PIPEROUG     EXITPLEN
EXITPDIA     MAXPPRES
1.0373E+03   3.8531E+02   1.4200E+00   8.5000E-01   1.0000E-15   1.9200E+01
1.4800E+07   1.4800E+07   1.4900E+07   5.7500E-01   1.7000E-13   1.0000E+00
3.8000E-01   1.3000E+05   4.5800E+01   1.2000E+05   1.0000E-03   8.2000E-02
8.9339E-06   1.2100E+03   1.1000E-02   3.9400E-04   6.1500E-01   -1.5000E+00
3.1115E-01   1.1430E-01   2.0320E-01   9.7180E-02   1.8290E+02   4.4450E-03
1.5000E-01   2.0181E-02   1.6000E-01   1.0000E-14   1.0000E+03   1.0000E+03
1.0000E+03   5.5000E-01   1.1500E-06   2.0000E-02   5.0000E-05   0.0000E+00
2.0320E-01   2.7500E+07

Element Block 3)    "REFCON  "     3=ID     0 elements
      0-node     0 attributes     2 properties
PI           GRAVACC
3.14159E+00  9.80665E+00

Element Block 4)    "BLOWOUT "     4=ID     0 elements
      0-node     0 attributes     3 properties
RGAS         TREPO        RHOS
4.1160E+03   3.0000E+02   2.6500E+03

Element Block 5)    "BRINESAL"     5=ID     0 elements
      0-node     0 attributes     1 properties
COMPRES
3.1000E-10
```

Table 8.4-17. Input control file for Test Case 4.2.

```
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

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, 1.01
Wellbore Cell Length             (m):   1.0
wellbore Zone Growth Rate        (-):   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
```

Table 8.4-18. Excerpts from DRS_QE0100_TC42.OUT, output diagnostics file for Test Case 4.2

```
FROM CDB, DRSPALL  SURFELEV       :   1.0373E+03
FROM CDB, DRSPALL  REPOSTOP       :   3.8531E+02
FROM CDB, DRSPALL  DRZTCK         :   8.5000E-01
FROM CDB, DRSPALL  DRZPERM        :   1.0000E-15
FROM CDB, DRSPALL  REPIPRES       :   1.4800E+07
FROM CDB, DRSPALL  FFSTRESS       :   1.4900E+07
FROM CDB, DRSPALL  REPIPOR        :   5.7500E-01
FROM CDB, DRSPALL  REPIPERM       :   1.7000E-13
FROM CDB, DRSPALL  FRCHBETA       :   1.1500E-06
FROM CDB, DRSPALL  BIOTBETA       :   1.0000E+00
FROM CDB, DRSPALL  POISRAT        :   3.8000E-01
FROM CDB, DRSPALL  COHESION       :   1.3000E+05
FROM CDB, DRSPALL  FRICTANG       :   4.5800E+01
FROM CDB, DRSPALL  TENSLSTR       :   1.2000E+05
FROM CDB, DRSPALL  PARTDIAM       :   1.0000E-03
FROM CDB, DRSPALL  GASVISCO       :   8.9339E-06
FROM CDB, DRSPALL  INITMDEN       :   1.2100E+03
FROM CDB, DRSPALL  MUDVISCO       :   1.1000E-02
FROM CDB, DRSPALL  PIPEROUG       :   5.0000E-05
FROM CDB, DRSPALL  ANNUROUG       :   3.9400E-04
FROM CDB, DRSPALL  MUDSOLMX       :   6.1500E-01
FROM CDB, DRSPALL  MUDSOLVE       :  -1.5000E+00
FROM CDB, DRSPALL  BITDIAM        :   3.1115E-01
FROM CDB, DRSPALL  PIPEDIAM       :   1.1430E-01
FROM CDB, DRSPALL  COLRDIAM       :   2.0320E-01
```

```
FROM CDB, DRSPALL  PIPEID          :  9.7180E-02
FROM CDB, DRSPALL  COLRLNGT        :  1.8290E+02
FROM CDB, DRSPALL  EXITPLEN        :  0.0000E+00
FROM CDB, DRSPALL  EXITPDIA        :  2.0320E-01
FROM CDB, DRSPALL  DRILRATE        :  4.4450E-03
FROM CDB, DRSPALL  INITBAR         :  1.5000E-01
FROM CDB, DRSPALL  MUDPRATE        :  2.0181E-02
FROM CDB, DRSPALL  DDZTHICK        :  1.6000E-01
FROM CDB, DRSPALL  DDZPERM         :  1.0000E-14
FROM CDB, DRSPALL  STPDVOLR        :  1.0000E+03
FROM CDB, DRSPALL  STPPVOLR        :  1.0000E+03
FROM CDB, DRSPALL  STPDTIME        :  1.0000E+03

 VALIDATION TEST CASE:      4 SUBCASE:       2

FROM CDB, REFCON   PI              :  3.1416E+00
FROM CDB, REFCON   GRAVACC         :  9.8067E+00
FROM CDB, BLOWOUT  RGAS            :  4.1160E+03
FROM CDB, BLOWOUT  TREPO           :  3.0000E+02
FROM CDB, BLOWOUT  RHOS            :  2.6500E+03
FROM CDB, DRSPALL  SHAPEFAC        :  5.5000E-01


****************************************************************
*
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 Pore 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 Density at STP             (kg/m^3):  8.2362E-02
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
Max Solids Vol. Frac.             (Pa-s):  6.1500E-01
Solids Viscosity Exp.             (Pa-s): -1.5000E+00

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   1.010
Wellbore Cell Length               (m):  1.0000E+00
Wellbore Cell Growth Rate          (-):  1.0100E+00
First Wellbore Zone                (-): 291
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
Min Characteristic Velocity        (-):  1.0000E-06
Min 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
```

8.4.6 Conclusions

The discussion in Section 8.4.5 verifies that all acceptance criteria (Section 8.4.4) for this test case are met. Thus, this test case passes.

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 and BLOTCDB utilities verifies the external interfaces to CAMDAT files.

8.5 Test Case #5 – Wellbore Flow Verification

8.5.1 Test Objective

The objective of this test case is to verify the wellbore flow model against an independent computational fluid dynamics model FLUENT.

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

8.5.2 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 and gas and solids

Independent calculations will be run in parallel with the commercial computational fluid dynamics code FLUENT (FLUENT 6.1 User's Guide, 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 (Hansen et al., 2003), and default values are used for most DRSPALL parameters. A schematic of the domain is shown in Figure 8.5-1.

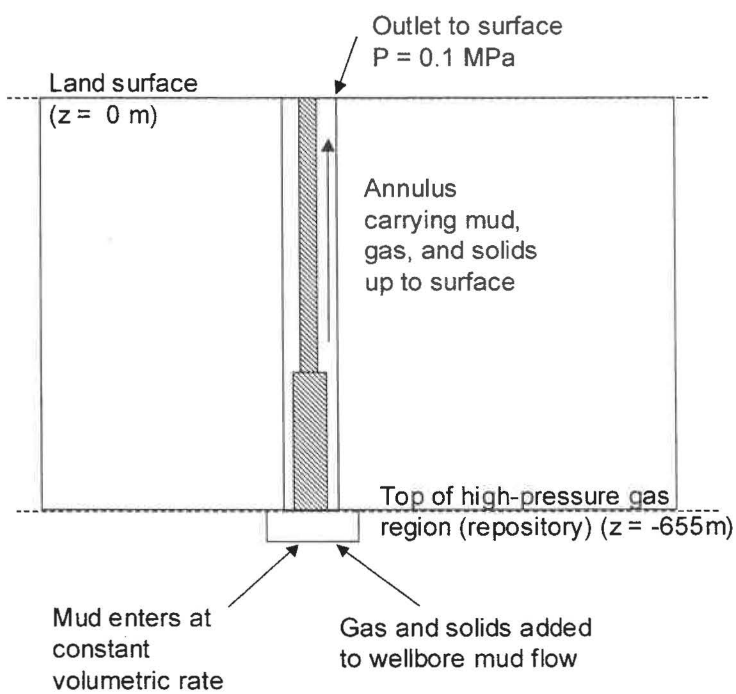


Figure 8.5-1. Schematic of Wellbore Flow Test Problem domain.

8.5.2.1 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 to 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.

8.5.2.2 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. Input files are provided in Appendix E.1.

8.5.3 Analysis Method

Six runs will be executed under this test case. The run matrix is shown in Table 8.5-1. More detailed descriptions are given in the text that follows.

Table 8.5-1. 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	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

<u>Steady-state runs.</u> 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 and 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.

8.5.3.1 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.

8.5.3.2 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.

8.5.3.3 Case 5.3 – Mud-only, steady flow, high-end mud density

This test run is the same as Case 5.2, Section 8.5.3.2 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.

8.5.3.4 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.

8.5.3.5 Case 5.6 – Gas added to flow at medium, constant rate

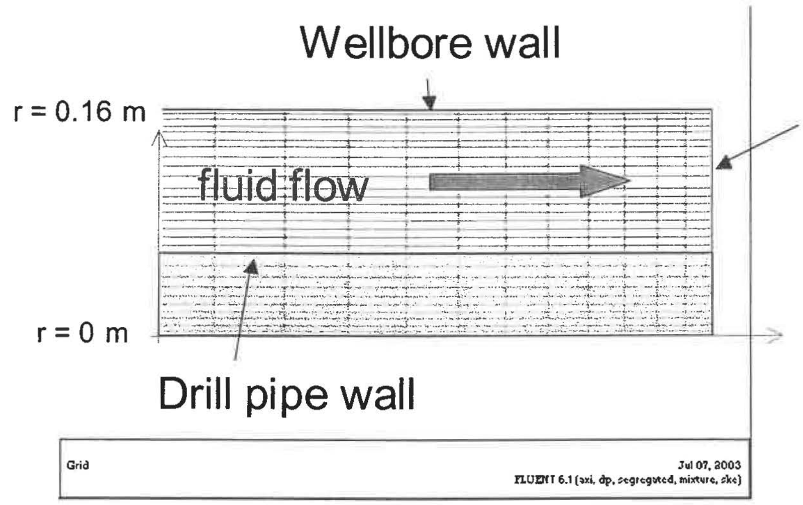
This test run will add hydrogen gas to the flow stream at the bottom of the well. Mud flow and physical properties are set to defaults as in Case 5.2. The hydrogen mass flow rate = 2.5 kg/sec, a value representative of the gas flow rate into the wellbore during a blowout while the mud column is accelerating.

8.5.3.6 Case 5.7 – Gas added to flow at medium, constant rate; solids added at low, constant rate

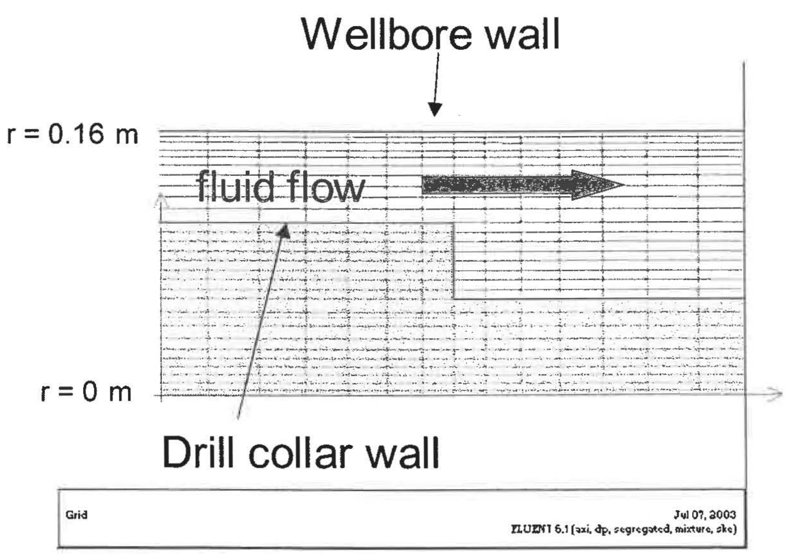
This test run is the same as Case 5.6, Section 8.5.3.5, with gas flowing into the well bottom, except solids are also added. A solids loading rate of 2.5 kg/sec is selected to represent a slow, steady material failure case. In normal model executions where a spalling event occurs, this mass loading rate tends to spike early and diminish to zero. The constant rate was selected here for simplicity in implementation and comparison between models.

8.5.3.7 Test Procedure

FLUENT runs were executed independently and the data captured in tabular form. 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. Two sections of the computational grid are shown in Figure 8.5-2 and illustrate the level of detail in the FLUENT models. Details of the FLUENT calculations are documented in a memo Webb, 2003).



(a) Drill pipe grid section near outlet



(b) Grid section at collar drill pipe transition

Figure 8.5-2. FLUENT computational grid

DRSPALL is run with the wellbore decoupled from the repository, and the mass loading function specific to the test case is specified internal to the code. DRSPALL is executed once for each of the six cases, with the appropriate DRSPALL input file defining the case. Each execution results in an output CAMDAT file. This file contains the data needed to generate the graphs of the pressure, fluid velocities and volume fraction profiles in the wellbore. Pertinent data was extracted from the CAMDAT file and converted to tabular form using the GROPECDB utility (WIPP PA, 1996a). These data are compared with the corresponding data generated from FLUENT. The comparisons were generated with basic Microsoft EXCEL capabilities. The tabular data from FLUENT and the GROPECDB output files were copied into EXCEL spreadsheets; pertinent data for comparison were referenced on a separate spreadsheet; data from FLUENT was sorted to get time in ascending order; DRSPALL coordinates were converted so the wellbore bottom is at z=0; and a chart for graphical display of the comparisons was defined. The error bars capability in EXCEL was used to present the acceptance criteria on the resulting figures.

The test files associated with this test case are listed in Table 8.5-2. All test files are available in the QE0100 class of the DRS library in the SCMS.

Table 8.5-2. Test files for Test Case #5.

DRSPALL Files	Description
DRS_TC5.COM	Procedure to run all subcases of Test Case #5
DRS_TC51.COM	Procedure to run Case 5.1
DRS_TC51.LOG	Log file for Case 5.1
DRS_TC51.DRS	Input file, Table E.1-1
DRS_QE0100_TC51_WELLBORE.DAT	Validation file (not used)
DRS_QE0100_TC51.CDB	CAMDAT output file
DRS_QE0100_TC51.DBG	Diagnostics output file (not used)
DRS_TC5_GROPE.INP	GROPECDB input file
DRS_QE0100_TC51_GROPE.OUT	GROPECDB output file
DRS_TC52.COM	Procedure to run Case 5.2
DRS_TC52.LOG	Log file for Case 5.2
DRS_TC52.DRS	Input file, Table E.1-2
DRS_QE0100_TC52_WELLBORE.DAT	Validation file (not used)
DRS_QE0100_TC52.CDB	CAMDAT output file
DRS_QE0100_TC52.DBG	Diagnostics output file (not used)
DRS_TC5_GROPE.INP	GROPECDB input file
DRS_QE0100_TC52_GROPE.OUT	GROPECDB output file
DRS_TC53.COM	Procedure to run Case 5.3
DRS_TC53.LOG	Log file for Case 5.3

DRS_TC53.DRS	Input file, Table E.1-3
DRS_QE0100_TC53_WELLBORE.DAT	Validation file (not used)
DRS_QE0100_TC53.CDB	CAMDAT output file
DRS_QE0100_TC53.DBG	Diagnostics output file (not used)
DRS_TC5_GROPE.INP	GROPECDB input file
DRS_QE0100_TC53_GROPE.OUT	GROPECDB output file
DRS_TC55.COM	Procedure to run Case 5.5
DRS_TC55.LOG	Log file for Case 5.5
DRS_TC55.DRS	Input file, Table E.1-4
DRS_ QE0100_TC55_WELLBORE.DAT	Validation file (not used)
DRS_QE0100_TC55.CDB	CAMDAT output file
DRS_QE0100_TC55.DBG	Diagnostics output file (not used)
DRS_TC5_GROPE.INP	GROPECDB input file
DRS_QE0100_TC55_GROPE.OUT	GROPECDB output file
DRS_TC56.COM	Procedure to run Case 5.6
DRS_TC56.LOG	Log file for Case 5.6
DRS_TC56.DRS	Input file, Table E.1-5
DRS_ QE0100_TC56_WELLBORE.DAT	Validation file (not used)
DRS_QE0100_TC56.CDB	CAMDAT output file
DRS_QE0100_TC56.DBG	Diagnostics output file (not used)
DRS_TC5_GROPE.INP	GROPECDB input file
DRS_QE0100_TC56_GROPE.OUT	GROPECDB output file
DRS_TC57.COM	Procedure to run Case 5.7
DRS_TC57.LOG	Log file for Case 5.7
DRS_TC57.DRS	Input file, Table E.1-6
DRS_TC57_WELLBORE.DAT	Validation file (not used)
DRS_QE0100_TC57.CDB	CAMDAT output file
DRS_QE0100_TC57.DBG	Diagnostics output file (not used)
DRS_TC57_GROPE.INP	GROPECDB input file
DRS_QE0100_TC57_GROPE.OUT	GROPECDB output file
FLUENT Results	(as provided by the modeler in FLUENT_RESULTS.ZIP)
Case1-P	Pressure results for Case 5.1
Case2-P	Pressure results for Case 5.2
Case3-P	Pressure results for Case 5.3

Case5-P	Pressure results for Case 5.5
Case5-Mud	Mud volume fraction results for Case 5.5
Case5-Gas	Gas volume fraction results for Case 5.5
Case6-P	Pressure results for Case 5.6
Case6-Gas	Gas volume fraction results for Case 5.6
Case6-Mud	Mud volume fraction results for Case 5.6
Case7-P	Pressure results for Case 5.7
Case7-Gas	Gas volume fraction results for Case 5.7
Case7-Mud	Mud volume fraction results for Case 5.7
Case7-Solid	Solid volume fraction results for Case 5.7
EXCEL Spreadsheets	
TC5_figures.xls	Graphical comparisons

8.5.4 Acceptance Criteria

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

1) The fluid pressure agrees within 20%.
2) The volume fraction of gas in two- and three-phase runs (Cases 5.5, 5.6, 5.7) agrees within 0.02.
3) The volume fraction of waste in the three-phase run (Case 5.7) agrees within 20%.
4) The velocity of the mixture agrees within 25%. 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).

Verification will be evaluated by visual comparison of graphical results that contain error bounds consistent with the acceptance criteria.

8.5.5 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), 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

8.5.5.1 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 8.5-3. 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 percent error bounds, confirming that **Acceptance Criteria 1 is met** for this case. A simple hydrostatic model gives the expected bottomhole pressure as $\rho gh = 7.7$ MPa, where $\rho = 1210$ 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 Figure 8.5-3 are well below 1e-4 confirming that **Acceptance Criteria 4 is met** for 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. (**Acceptance Criteria 2, and 3 do not apply** to this case.)

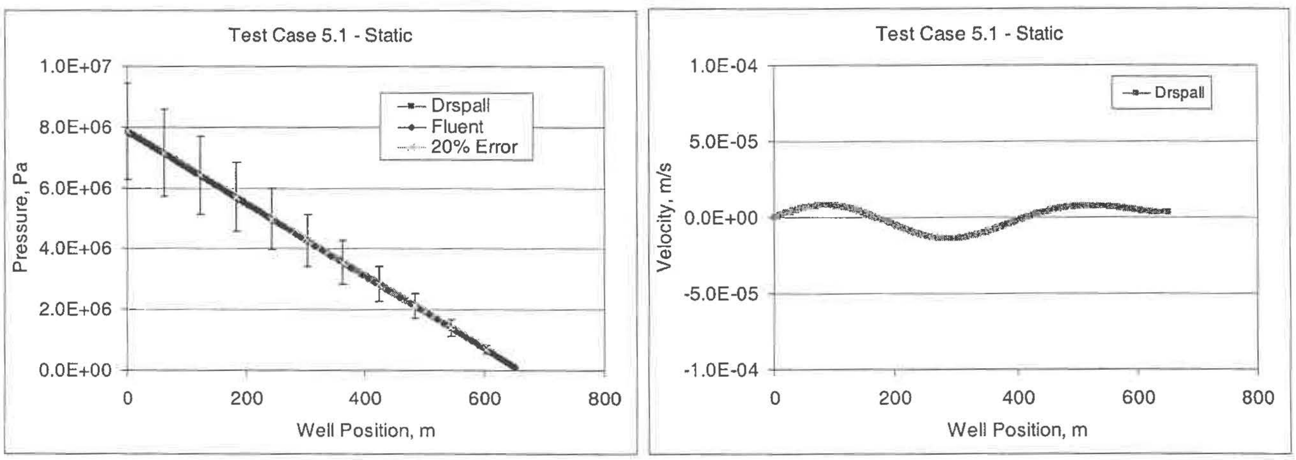
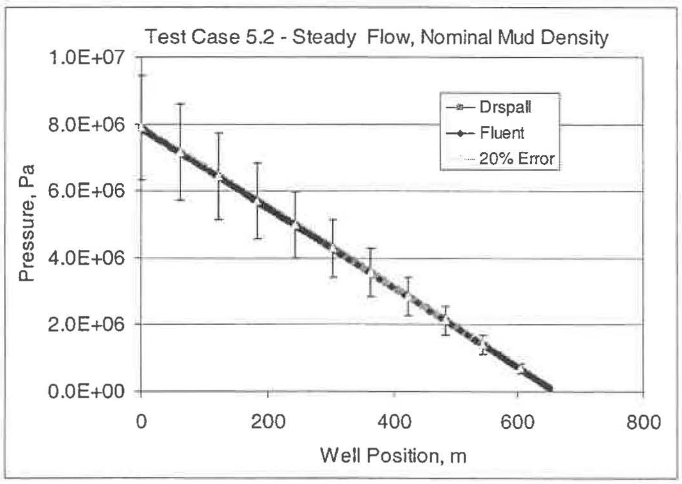


Figure 8.5-3. Pressure and velocity profiles for static wellbore, Case 5.1

8.5.5.2 Case 5.2 – Steady Flow, Nominal Mud Density

The results for Case 5.2 (mud pumping rate = 0.02018 m^3/s and mud density = 1210 m) are summarized by the pressure and fluid velocity profiles at 90 s shown in Figure 8.5-4. The results from FLUENT and DRSPALL visually overlay. The pressure profiles are similar to Test Case 5.1, Section 8.5.5.1, with only very minor differences due to dynamic effects. Pressures are within the 20% error bars, confirming that **Acceptance Criteria 1 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 the another for the drill pipe extending to the land surface. Velocities are within the 25% error bars, confirming that **Acceptance Criteria 4 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 0.46 m/s and 0.31 m/s for the collar and drill pipe regions, respectively. (**Acceptance Criteria 2 and 3 do not apply** to this case.)



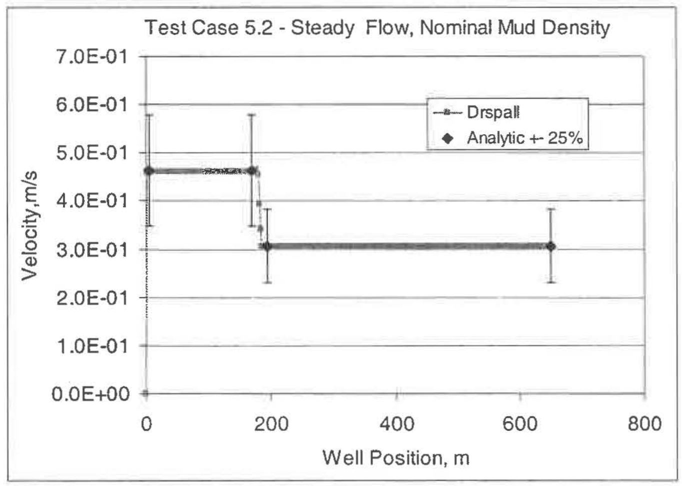
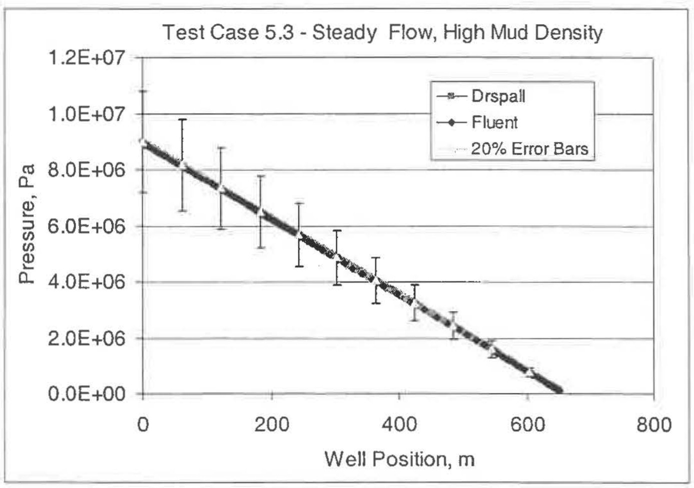


Figure 8.5-4. Pressure and velocity profiles for steady state and nominal mud density Case 5.2.

8.5.5.3 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 8.5-5. The results from FLUENT and DRSPALL visually overlay. The pressure profiles are similar to Test Case 5.2, Section 8.5.5.2, except for an increase in bottom hole pressure due the increase in mud density. Pressures are within the 20% error bars, confirming that **Acceptance Criteria 1 is met** for this case. The estimated value of bottomhole pressure is ρgh = 8.83 MPa, where ρ = 1380 kg/m^3 is the mud density, g = 9.82 m/s^2, and h = 653 m is the wellbore height. The calculated values for bottom hole pressure were 8.84 MPa and 8.95 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 25% error bars, confirming that **Acceptance Criteria 4 is met** for this case. The expected values of fluid velocities are the same as in Test Case 5.2. (**Acceptance Criteria 2 and 3 do not apply** to this case.)



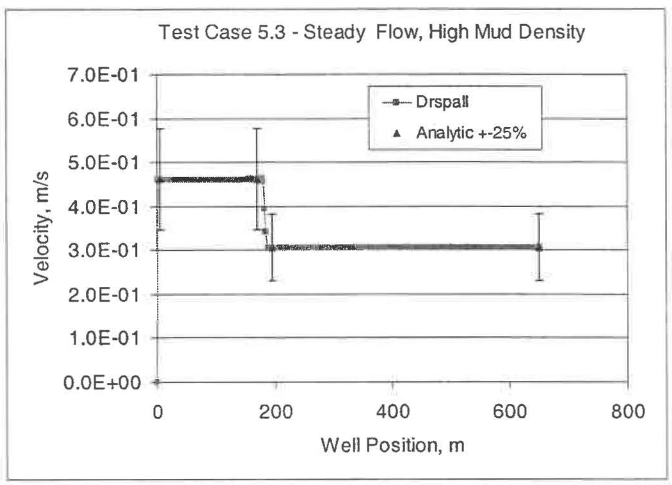
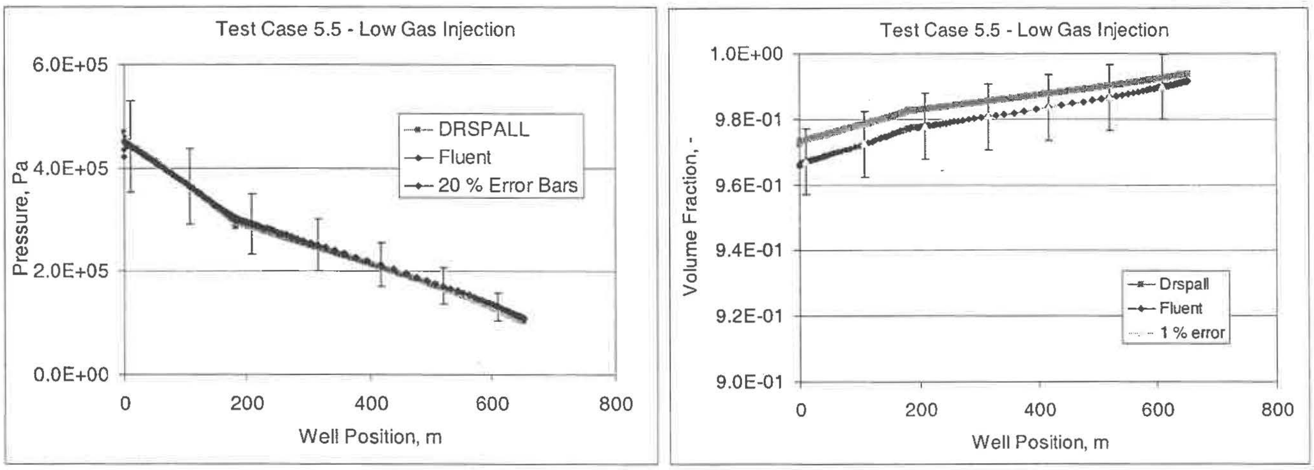


Figure 8.5-5. Pressure and velocity profiles for steady state and high mud density, Case 5.3.

8.5.5.4 Case 5.5 – Low Gas Injection Rate

The results for Case 5.5 (constant mud pumping rate = 0.02018 m^3/s, mud density = 1210 kg/m^3 and 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 8.5-6. The pressure profile results from FLUENT and DRSPALL visually overlay. Pressures are within the 20% error bars, confirming that **Acceptance Criteria 1 is met** for this case. Note that the bottom hole pressures have dropped from 8 MPa to 0.4 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 1% error bars, confirming that **Acceptance Criteria 2 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 20 percent error bounds, confirming that **Acceptance Criteria 4 is met** for this case. (**Acceptance Criteria 3 does not apply** to this case.)



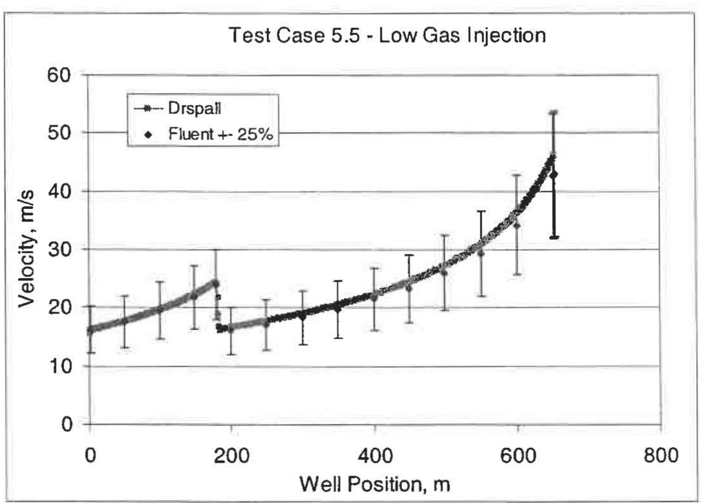


Figure 8.5-6. Pressure, gas volume fraction and velocity profiles for steady state, nominal mud density and low gas injection rate, Case 5.5.

8.5.5.5 Case 5.6 – Medium Gas Injection

The results for Case 5.6 (constant mud pumping rate = 0.02018 m3/s; mud density = 1210 kg/m^3; and a gas injection rate = 2.5 kg/s) are summarized by the pressure, fluid velocity and gas volume fraction profiles at 450s shown in Figure 8.5-7. The gas injection rate was ten times larger than in Case 5.5, Section 8.5.5.4. 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, confirming that **Acceptance Criteria 1 is met** for this case. Gas volume fractions are above 99% for both DRSPALL and FLUENT. Gas volume fractions are within the 1% error bars, confirming that **Acceptance Criteria 2 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 25% error bars, confirming that **Acceptance Criteria 4 is met** for this case. (**Acceptance Criteria 3 does not apply** to this case.)

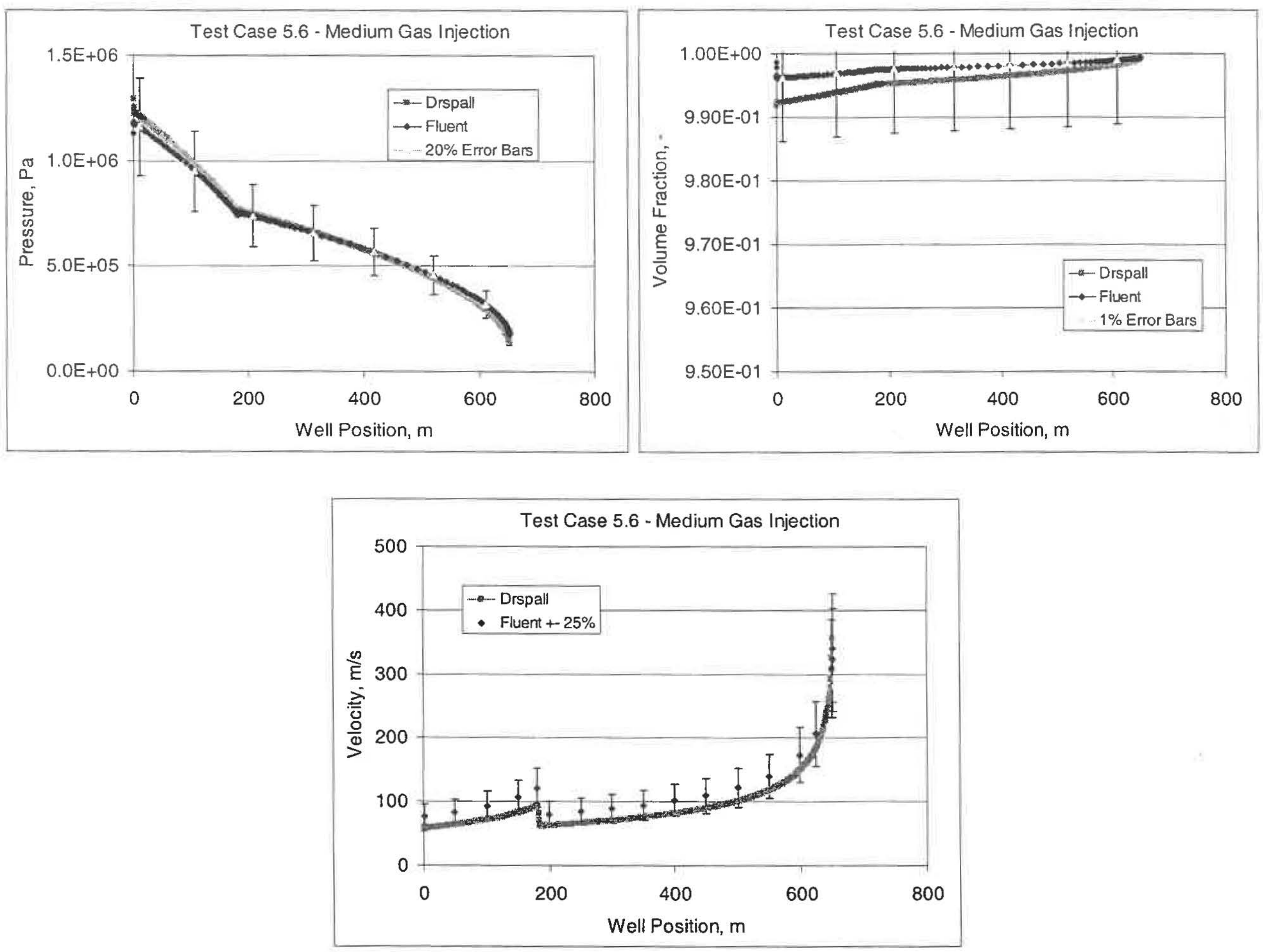


Figure 8.5-7. Pressure, gas volume fraction and velocity profiles for steady state, nominal mud density and medium gas injection rate, Case 5.6.

8.5.5.6 Case 5.7 – Medium Gas and Low Solid Injection

The results for Case 5.7 (constant mud pumping rate = 0.02018 m^3/s; mud density = 1210 kg/m^3; gas injection rate = 2.5 kg/s; and low solid injection rate = 2.5kg/s) are summarized by the pressure, fluid velocity and gas and solid volume fraction profiles at 450 s shown in Figure 8.5-8. The gas injection rate was the same as in Case 5.6, Section 8.5.5.5. 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, confirming that **Acceptance Criteria 1 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 1% error bars, confirming that **Acceptance Criteria 2 is met** for this case. Solid volume fractions are very small, near 5×10^{-4}. Solid volume fractions are within the 20% error bars, confirming that **Acceptance Criteria 3 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 25% error bars, confirming that **Acceptance Criteria 4 is met** for this case.

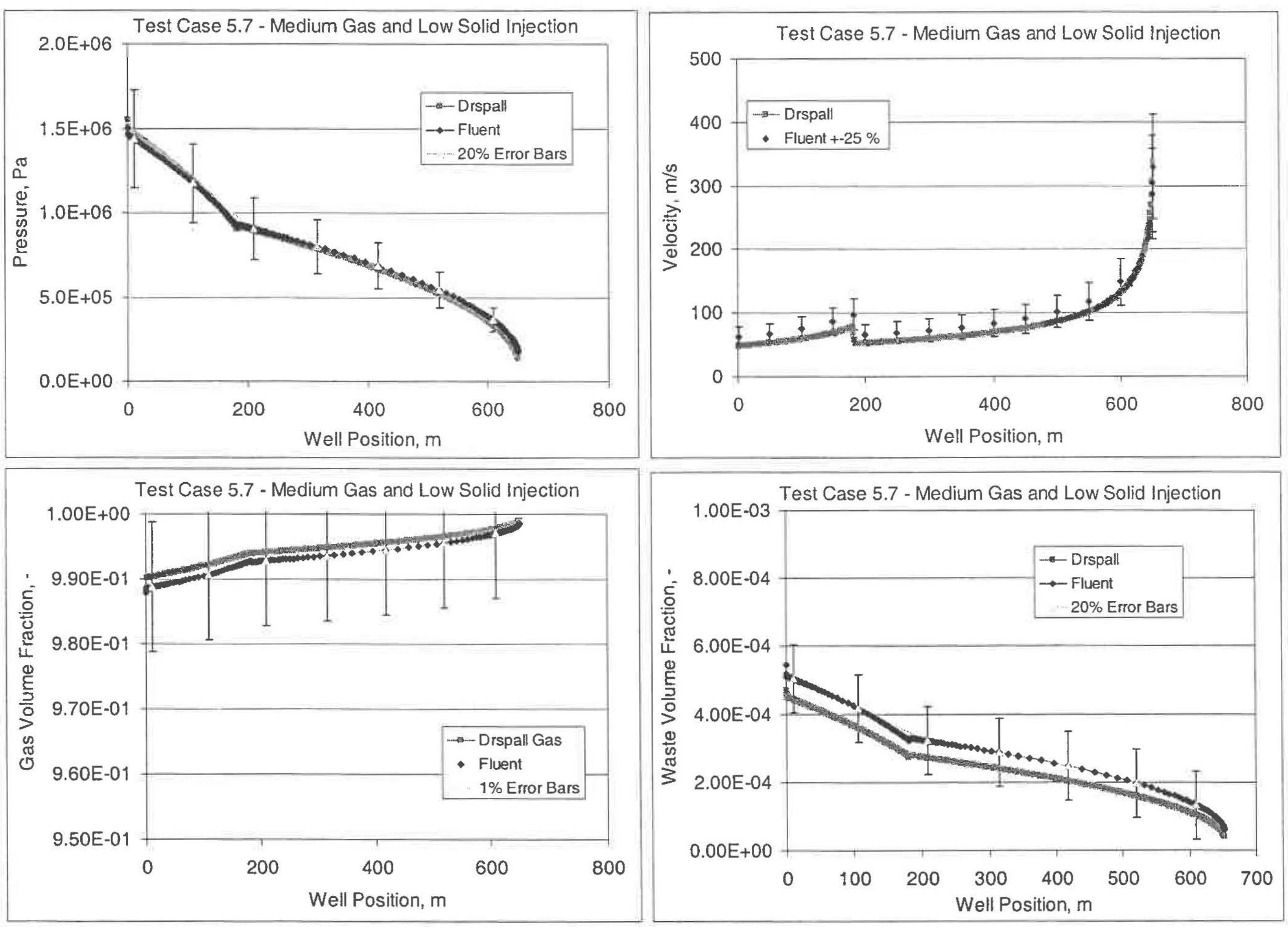


Figure 8.5-8. Pressure, velocity and volume fraction profiles for steady state, nominal mud density, medium gas and low solid injection rate, Case 5.7.

8.5.6 Conclusions

The discussion in Section 8.5.5 verifies that all acceptance criteria (Section 0) for this test case are met. Thus, this test case passes.

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.

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

9 CONCLUSION

Testing for DRSPALL Version 1.00 has been completed and the acceptance criteria for all test cases have been successfully met. The testing verifies that DRSPALL satisfies all the requirements listed in the DRSPALL Requirements Document (WIPP PA, 2003a).

10 INSTALLATION TESTING AND REGRESSION TESTING

Test Case #4 is suitable for regression and installation testing. Although Test Case #4 does not seek to specifically validate all the functional requirements of the code, it does exercise all of the major features of the model: repository flow, wellbore flow, repository and wellbore boundary conditions, tensile failure of waste, and fluidization of waste.

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APPENDIX A SAMPLE TEST COMMAND PROCEDURES

The test procedure shown in Table A.1-1 was executed with the following parameters:

```
@DRS_TC5.COM BTO QE0100
```

Table A.1-1. Test procedure for Test Case #5 (DRS_TC5.COM)

```
$!=====================================================================
$! Script:      DRS_TC5.COM
$! Purpose:     Run  DRSPALL Test Case #5 Wellbore Flow
$!                   5.1 - Static flow
$!                   5.2 - Mud Only, steady flow, nominal mud density
$!                   5.3 - Mud only, steady flow, high mud density
$!                   5.4 - Not Used
$!                   5.5 - Mud with low gas injection, steady flow
$!                   5.6 - Mud with med gas injection, steady flow
$!                   5.7 - Mud with gas and solid injection, steady flow
$!
$! Execution:   @DRS_TC5  node  output_class
$!              node - batch queue node name ("NO" for interactive)
$!              output_class - class name for storing output files
$!
$! Date:        4/23/03
$! By:          David K Rudeen
$!=====================================================================
$
$! set cms library for fetch
$ LIBDRS
$
$! set output class for CMS store, and output name
$ output_class = "''p2'"
$ output_name = output_class
$ fetch_class = ""
$ IF output_class .nes. "" THEN fetch_class = "/gen=''output_class'"
$
$! set batch queue node name
$ IF "''p1'" .EQS. "NO"
$ THEN
$   node = ""
$ ELSE
$   IF "''p1'" .EQS. ""
$   THEN
$     node = "CCR"
$   ELSE
$     node = "''p1'"
$   ENDIF
$   IF output_class .nes. ""
$   THEN
$     node = node + "$CCA"
$   ELSE
$     node = node + "$BATCH"
$   ENDIF
$ ENDIF
$
```

```
$! loop over subcases 1..7, but skip 4
$ n = 1
$START:
$ IF n .le. 7
$ THEN
$   IF n .eq. 4 THEN GOTO SKIP
$   tc = "TC5''n'"
$
$!   create subdirectory for subcase
$   IF f$search("''tc'.DIR") .eqs. ""
$   THEN
$     CREATE/DIR [.'tc']
$   ENDIF
$
$!   switch to subdirectory
$   SET DEFAULT [.'tc']
$
$!   fetch command procedure from CMS
$   IF f$search("DRS_''tc'.COM") .eqs. ""
$   THEN
$     CMS FETCH 'fetch_class' DRS_'tc'.COM
$   ENDIF
$
$   default_dir = f$environment("default")
$   IF node .eqs. ""
$   THEN
$!     execute subcase interactively
$     @DRS_'tc' "''default_dir'" "''output_name'" "''output_class'"
$   ELSE
$!     submit subcase to specified batch queue
$     SUBMIT/NOTIFY/NOPRINT/LOG='default_dir'/QUEUE='node' -
         /PARAM=("''default_dir'","''output_name'","''output_class'")
DRS_'tc'
$   ENDIF
$
$!   move up a directory for next subcase
$   SET DEFAULT [-]
$
$   SKIP:
$!   execute next subcase
$   n = n + 1
$   GOTO START
$ ENDIF
$
$! End of script
```

Table A.1-2. Test procedure for Case 5.1 (DRS_TC51.COM)

```
$!=====================================================================
$! Script:       DRS_TC51.COM
$! Purpose:      Run  DRSPALL Test Case #5.1
$!
$! Execution:    @DRS_TC51  directory  output_name  output_class
$!               directory - optional directory name. Defaults to
$!                  current directory.
$!               output_name - name to be inserted in output file names
$!                  for uniqueness (do not include leading "_").
$!               output_class - class name for storing output files.
$!                  Defaults to no class (no store in CMS).
$!
$! Date:         5/1/03
$! By:           David K Rudeen
$!=====================================================================
$
$ WRITE sys$output ""
$ WRITE sys$output "*** DRSPALL Test Case 5.1 ***"
$ WRITE sys$output ""
$
$ write sys$output "Node ''f$getsyi ("nodename")' - ''f$getsyi ("hw_name")'"
$
$! set up output name insert, output class and fetch class
$ output_name = "_test"
$ IF p2 .nes. "" THEN output_name = "_" + p2
$ output_class = p3
$ fetch_class = ""
$ IF p3 .nes. "" THEN fetch_class = "/gen=''p3'"
$
$! set default directory, if specified
$ IF "''p1'" .NES. ""
$ THEN
$   SET DEFAULT 'p1'
$   WRITE sys$output "''p1'"
$ ENDIF
$
$! set cms library for fetch and store
$ LIBDRS
$
$! define drspall executable
$ DRSPALL :== $wp$prodroot:[drs.exe]drspall_QE0100.exe
$ x = DRSPALL - "$"
$ @wp$ref:wp_get_image_id 'x'
$
$! fetch drspall input file
$ IF f$search("DRS_TC51.DRS") .eqs. ""
$ THEN
$   CMS FETCH 'fetch_class' DRS_TC51.DRS
$ ENDIF
$
$! execute drspall
$ DRSPALL DRS_TC51.DRS -
          DRS'output_name'_TC51.DBG -
          cancel -
          DRS'output_name'_TC51.CDB
```

```
$
$! rename validation file to include output_name
$ IF output_name .nes. ""
$ THEN
$   RENAME DRS_TC51_WELLBORE.DAT DRS'output_name'_TC51_WELLBORE.DAT
$ ENDIF
$
$! fetch the GROPECDB input file
$ IF f$search("DRS_TC5_GROPE.INP") .eqs. ""
$ THEN
$   CMS FETCH 'fetch_class' DRS_TC5_GROPE.INP
$ ENDIF
$
$! run GROPECDB utility
$ GROPECDB DRS'output_name'_TC51.CDB -
           DRS_TC5_GROPE.INP -
           DRS'output_name'_TC51_GROPE.OUT
$
$! store output files in CMS
$ IF output_class .nes. ""
$ THEN
$   c_create = "cms create element /noconc"
$   c_insert = "cms insert gen/always"
$   cmt = "Test output for DRSPALL 1.00."
$   'c_create' DRS'output_name'_TC51_WELLBORE.DAT "''cmt'"
$   'c_insert' DRS'output_name'_TC51_WELLBORE.DAT 'output_class' "''cmt'"
$   'c_create' DRS'output_name'_TC51.CDB "''cmt'"
$   'c_insert' DRS'output_name'_TC51.CDB 'output_class' "''cmt'"
$   'c_create' DRS'output_name'_TC51.DBG "''cmt'"
$   'c_insert' DRS'output_name'_TC51.DBG 'output_class' "''cmt'"
$   'c_create' DRS'output_name'_TC51_GROPE.OUT "''cmt'"
$   'c_insert' DRS'output_name'_TC51_GROPE.OUT 'output_class' "''cmt'"
$ ENDIF
$
$! End of Script
```

APPENDIX B TEST CASE #1

B.1 Chan et al. (1993) Solution to Porous Flow Problem

Chan et al. (1993) solved the porous flow problem in cylindrical geometry and reported the following graphical results using dimensionless pseudopressure Ψ versus dimensionless plotting parameter ζ.

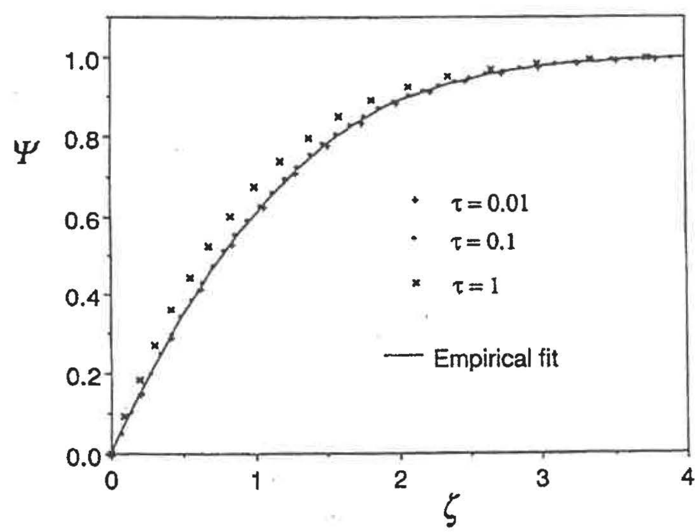

Figure B.1-1. Chan et al. (1993) solution to the porous flow problem in cylindrical geometry for τ = 0.01, 0.1, 1.

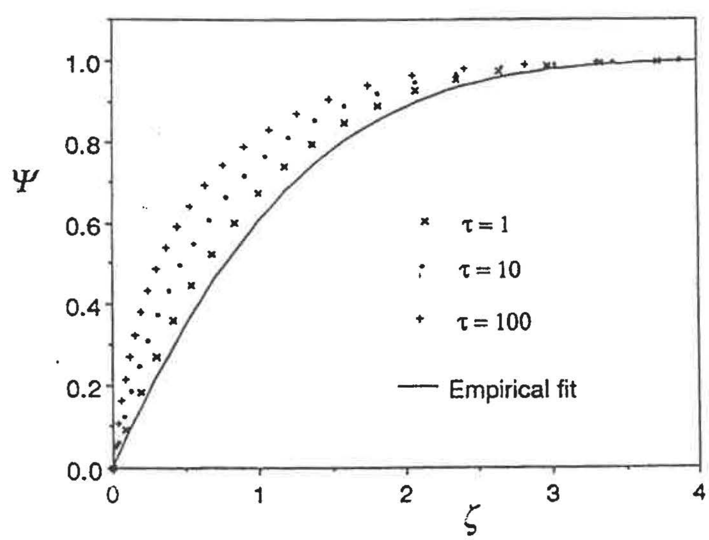

Figure B.1-2. Chan et al. (1993) solution to the porous flow problem in cylindrical geometry for τ = 1, 10, 100.

The data in Figure B.1-1 and B.1-2 were digitized so that X-Y data could be captured and the curves could be reproduced for comparison to the Djordjevic and Adams (2003) solutions in the cylindrical geometry. Table B.1-1 presents the results of the digitization of Chan's $\tau = 1$ and 10 data. Chan et al. (1993) provided fitting parameters to their $\tau = 0.01$ and 0.1 data, so no digitization of these data were necessary.

Table B.1-1. Digitized values from Chan (1993) figures.

$\tau = 1$		$\tau = 10$	
ζ	Ψ	ζ	Ψ
0.000	0.000	0.000	0.000
0.083	0.089	0.077	0.123
0.189	0.184	0.124	0.186
0.296	0.271	0.182	0.248
0.414	0.360	0.241	0.310
0.537	0.446	0.309	0.373
0.684	0.522	0.387	0.432
0.839	0.600	0.462	0.494
1.002	0.673	0.560	0.548
1.181	0.738	0.666	0.607
1.370	0.794	0.783	0.663
1.594	0.846	0.907	0.715
1.824	0.887	1.051	0.764
2.080	0.924	1.210	0.810
2.360	0.952	1.391	0.853
2.654	0.972	1.594	0.887
2.987	0.985	1.824	0.918
3.735	0.995	2.084	0.945
3.342	0.991	2.358	0.965
		2.674	0.982
		3.037	0.988
		3.429	0.994

B.2 Djordjevic and Adams (2003) Results

The utility code developed by Djordjevic and Adams (2003) 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 Tables B.2-2 through B.2-9. The input file for the 0.01 cylindrical case is shown in Table B.2-1. Examination of the input file and the corresponding output reveals that the input file is essentially echoed in the output. Thus, the input files for the other cases will not be shown.

Table B.2-1. Input file for cylindrical case, Tau = 0.01 (DA_CylTau0_01.inp)

```
Simulation of Cylindrical Gas Flow with Dimensionless Pseudopressure
Comparison of Numerical Chan et. al. and DRSPALL - WIPP PA
delz (length step size)
0.01
delt (time step size)
0.0001
Taumax (simulation duration)
0.01
zetamax
4
phi (Repository porosity, dimensionless)
0.05
eta (Gas viscosity, Pa s)
0.00002
r0 (borehole radius, m)
0.0000476
kperm (Repository permeability, m^2)
0.064E-12
pff (Repository initial or far field pore pressure, Pa)
10.135E6
NPCavsTpts (Number of Cavity Pressure versus Time Data Points)
1
Time (s)  Cavity Pressure (Pa)
  0           0
```

Table B.2-2. 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 DRSPALL - 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
```

0.3700000000	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 B.2-4. 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 DRSPALL - WIPP PA
delz
     0.020000
delt
     0.010000
Taumax
     1.000000
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)
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
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 B.2-5. 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 DRSPALL - 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)
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 B.2-6. 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 DRSPALL - 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)
  0.0000000000           Infinity                    1.0000000000
  0.0100000000          990.0000000000               0.9999980000
  0.0200000000          490.0000000000               1.0000000000
  0.0300000000          323.3333333333               1.0000000000
  0.0400000000          240.0000000000               1.0000000000
  0.0500000000          190.0000000000               1.0000000000
  0.0600000000          156.6666666667               1.0000000000
  0.0700000000          132.8571428571               1.0000000000
  0.0800000000          115.0000000000               1.0000000000
  0.0900000000          101.1111111111               1.0000000000
  0.1000000000           90.0000000000               1.0000000000
  0.1100000000           80.9090909091               1.0000000000
  0.1200000000           73.3333333333               1.0000000000
  0.1300000000           66.9230769231               1.0000000000
  0.1400000000           61.4285714286               1.0000000000
  0.1500000000           56.6666666667               1.0000000000
  0.1600000000           52.5000000000               1.0000000000
  0.1700000000           48.8235294118               1.0000000000
  0.1800000000           45.5555555556               1.0000000000
  0.1900000000           42.6315789474               1.0000000000
  0.2000000000           40.0000000000               1.0000000000
  0.2100000000           37.6190476190               1.0000000000
  0.2200000000           35.4545454545               1.0000000000
  0.2300000000           33.4782608696               1.0000000000
  0.2400000000           31.6666666667               1.0000000000
  0.2500000000           30.0000000000               1.0000000000
  0.2600000000           28.4615384615               1.0000000000
  0.2700000000           27.0370370370               1.0000000000
  0.2800000000           25.7142857143               1.0000000000
  0.2900000000           24.4827586207               1.0000000000
  0.3000000000           23.3333333333               1.0000000000
  0.3100000000           22.2580645161               1.0000000000
  0.3200000000           21.2500000000               1.0000000000
  0.3300000000           20.3030303030               1.0000000000
  0.3400000000           19.4117647059               1.0000000000
  0.3500000000           18.5714285714               1.0000000000
  0.3600000000           17.7777777778               1.0000000000
  0.3700000000           17.0270270270               1.0000000000
  0.3800000000           16.3157894737               1.0000000000
```

0.3900000000	15.6410256410	1.0000000000
0.4000000000	15.0000000000	1.0000000000
0.4100000000	14.3902439024	1.0000000000
0.4200000000	13.8095238095	1.0000000000
0.4300000000	13.2558139535	1.0000000000
0.4400000000	12.7272727273	1.0000000000
0.4500000000	12.2222222222	1.0000000000
0.4600000000	11.7391304348	1.0000000000
0.4700000000	11.2765957447	1.0000000000
0.4800000000	10.8333333333	1.0000000000
0.4900000000	10.4081632653	1.0000000000
0.5000000000	10.0000000000	1.0000000000
0.5100000000	9.6078431373	0.9999999999
0.5200000000	9.2307692308	0.9999999996
0.5300000000	8.8679245283	0.9999999984
0.5400000000	8.5185185185	0.9999999945
0.5500000000	8.1818181818	0.9999999823
0.5600000000	7.8571428571	0.9999999465
0.5700000000	7.5438596491	0.9999998479
0.5800000000	7.2413793103	0.9999995914
0.5900000000	6.9491525424	0.9999989613
0.6000000000	6.6666666667	0.9999974938
0.6100000000	6.3934426230	0.9999942461
0.6200000000	6.1290322581	0.9999873993
0.6300000000	5.8730158730	0.9999736158
0.6400000000	5.6250000000	0.9999470580
0.6500000000	5.3846153846	0.9998979713
0.6600000000	5.1515151515	0.9998107522
0.6700000000	4.9253731343	0.9996614595
0.6800000000	4.7058823529	0.9994147931
0.6900000000	4.4927536232	0.9990206459
0.7000000000	4.2857142857	0.9984104319
0.7100000000	4.0845070423	0.9974934796
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
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 B.2-7. Spherical solution for Tau = 0.10 (DA_SphTau0_1.out)

```
Simulation of Spherical Gas Flow with Dimensionless Pseudopressure
Comparison of Numerical Chan et. al. and DRSPALL - 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)
  0.0000000000          Infinity                     1.0000000000
  0.0100000000         313.0654883567                0.9999800003
  0.0200000000         154.9516053483                0.9999999982
  0.0300000000         102.2469776788                1.0000000000
  0.0400000000          75.8946638440                1.0000000000
  0.0500000000          60.0832755432                1.0000000000
  0.0600000000          49.5423500093                1.0000000000
  0.0700000000          42.0131174851                1.0000000000
  0.0800000000          36.3661930919                1.0000000000
  0.0900000000          31.9741407861                1.0000000000
  0.1000000000          28.4604989415                1.0000000000
  0.1100000000          25.5857010686                1.0000000000
  0.1200000000          23.1900361746                1.0000000000
  0.1300000000          21.1629351104                1.0000000000
  0.1400000000          19.4254199125                1.0000000000
  0.1500000000          17.9195734076                1.0000000000
  0.1600000000          16.6019577159                1.0000000000
  0.1700000000          15.4393556349                1.0000000000
  0.1800000000          14.4059315630                1.0000000000
  0.1900000000          13.4812889723                1.0000000000
  0.2000000000          12.6491106407                1.0000000000
  0.2100000000          11.8961873883                0.9999999999
  0.2200000000          11.2117117042                0.9999999997
  0.2300000000          10.5867556449                0.9999999989
  0.2400000000          10.0138792572                0.9999999956
  0.2500000000           9.4868329805                0.9999999848
  0.2600000000           9.0003287251                0.9999999525
  0.2700000000           8.5498618219                0.9999998640
  0.2800000000           8.1315711261                0.9999996411
  0.2900000000           7.7421280646                0.9999991201
  0.3000000000           7.3786478737                0.9999979819
  0.3100000000           7.0386180178                0.9999956433
  0.3200000000           6.7198400279                0.9999910991
  0.3300000000           6.4203819161                0.9999827069
  0.3400000000           6.1385389874                0.9999679093
  0.3500000000           5.8728013689                0.9999428975
  0.3600000000           5.6218269514                0.9999022236
  0.3700000000           5.3844187187                0.9998383801
  0.3800000000           5.1595056561                0.9997413677
```

0.3900000000	4.9461265967	0.9995982816
0.4000000000	4.7434164903	0.9993929436
0.4100000000	4.5505946817	0.9991056105
0.4200000000	4.3669548640	0.9987127829
0.4300000000	4.1918564332	0.9981871332
0.4400000000	4.0247170220	0.9974975644
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
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 B.2-8. 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 DRSPALL - WIPP PA
delz
     0.010000
delt
     0.010000
Taumax
     1.000000
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	Infinity	1.0000000000
0.0100000000	99.0000000000	0.9998000303
0.0200000000	49.0000000000	0.9999998386
0.0300000000	32.3333333333	0.9999999996
0.0400000000	24.0000000000	1.0000000000
0.0500000000	19.0000000000	1.0000000000
0.0600000000	15.6666666667	1.0000000000
0.0700000000	13.2857142857	1.0000000000
0.0800000000	11.5000000000	1.0000000000
0.0900000000	10.1111111111	1.0000000000
0.1000000000	9.0000000000	0.9999999993
0.1100000000	8.0909090909	0.9999999903
0.1200000000	7.3333333333	0.9999999094
0.1300000000	6.6923076923	0.9999993959
0.1400000000	6.1428571429	0.9999969924
0.1500000000	5.6666666667	0.9999883007
0.1600000000	5.2500000000	0.9999629734
0.1700000000	4.8823529412	0.9999012292
0.1800000000	4.5555555556	0.9997711968
0.1900000000	4.2631578947	0.9995282306
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
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 B.2-9. 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 DRSPALL - 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)
  0.0000000000          Infinity                  1.0000000000
  0.0100000000          31.3065488357             0.9980030205
  0.0200000000          15.4951605348             0.9999840290
  0.0300000000          10.2246977679             0.9999995756
  0.0400000000           7.5894663844             0.9999998900
  0.0500000000           6.0083275543             0.9999972481
  0.0600000000           4.9542350009             0.9999653860
  0.0700000000           4.2013117485             0.9997872725
  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
  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
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

B.3 DRSPALL Input for Test Case #1

Table B.3-1. DRSPALL input for Test Case #1, cylindrical case (DRS_TC11.DRS)

```
REPOSITORY                                          :
 Land Elevation                  m                  : 1.0373E+03
 Repository Top                  m                  : 3.8531E+02
 Total Thickness                 m                  : 1.42
 DRZ Thickness                   m                  : 0.85
 DRZ Permeability                m^2                : 0.10E-14
 Outer Radius                    m                  : 19.2
 Initial Gas Pressure            Pa                 : 0.145E+08
 Far-Field In-Situ Stress        Pa                 : 0.149E+08
                                                    :
                                                    :
WASTE                                               :
 Porosity                        -                  : 0.575
 Permeability                    m^2                : 2.400E-13
 ForchHeimer Beta                -                  : 0.0
 Biot Beta                       -                  : 1.0
 Poisson's Ratio                 -                  : 0.38
 Cohesion                        Pa                 : 0.130E+06
 Friction Angle                  deg                : 44.4
 Tensile Strength                Pa                 : 0.690E+06
 Lt                              -                  : 0.02
 Particle Diameter               m                  : 0.0010
 Gas Viscosity                   Pa-s               : 0.8934E-05
                                                    :
MUD                                                 :
 Density                         kg/m^3             : 1.21E+03
 Viscosity                       Pa-s               : 0.110E-01
 Wall Roughness Pipe             m                  : 0.001
 Wall Roughness Annulus          m                  : 0.001
 Max. Solids Vol. Fraction       -                  : 0.615
 Solids Viscosity Exponent       -                  : -1.5
                                                    :
WELLBORE/DRILLING                                   :
 Bit Diameter                    m                  : 0.3112
 Pipe Diameter                   m                  : 0.1143
 Collar Diameter                 m                  : 0.2032
 Pipe Inside Diameter            m                  : 0.09178
 Collar Length                   m                  : 182.90
 Exit Pipe Length                m                  : 0.0
 Exit Pipe Diameter              m                  : 0.2032
 Drilling Rate                   m/s                : 0.005
 Bit Above Repository (Init.)    m                  : 0.15
 Mud Pump Rate                   m^3/s              : 2.018E-02
 Maximum Pump Pressure           m^3/s              : 27.5E+06
 DDZ Thickness                   m                  : 0.16
 DDZ Permeability                m^2                : 0.10E-13
 Stop Drilling Exit Vol. Rate    m^3/s              : 1000.0
 Stop Pumping Exit Vol. Rate     m^3/s              : 1000.0
 Stop DrillingTime               s                  : 1000.0
                                                    :
COMPUTATIONAL                                       :
 Spherical/Cylindrical           S/C                : C
 Allow Fluidization?             Y/N                : N
 Maximum Run Time                s                  : 6.0
 Repository Cell Length          m                  : 0.002
 Repository Radius, Growth       m,-                : 0.5, 1.01
 Wellbore Cell Length            m                  : 4.0
 Wellbore Zone Growth Rate       -                  : 1.0
 First Wellbore Zone             -                  : 2
 Well Stability Factor           -                  : 0.1
 Repository Stability Factor     -                  : 5.0
 Mass Diffusion Factor           -                  : 0.02
 Momentum Diffusion Factor       -                  : 0.002

VALIDATION
 Validation Test Case            -                  : 1.1
```

Table B.3-2. DRSPALL input for Test Case #1, spherical case (DRS_TC12.DRS)

```
REPOSITORY                                   :
 Land Elevation                  m           : 1.0373E+03
 Repository Top                  m           : 3.8531E+02
 Total Thickness                 m           : 1.42
 DRZ Thickness                   m           : 0.85
 DRZ Permeability                m^2         : 0.10E-14
 Outer Radius                    m           : 19.2
 Initial Gas Pressure            Pa          : 0.145E+08
 Far-Field In-Situ Stress        Pa          : 0.149E+08
                                             :
WASTE                                        :
 Porosity                        -           : 0.575
 Permeability                    m^2         : 2.4E-13
 Forchheimer Beta                -           : 0.0
 Biot Beta                       -           : 1.0
 Poisson's Ratio                 -           : 0.38
 Cohesion                        Pa          : 0.130E+06
 Friction Angle                  deg         : 44.4
 Tensile Strength                Pa          : 0.690E+06
 Lt                              -           : 0.02
 Particle Diameter               m           : 0.0010
 Gas Viscosity                   Pa-s        : 0.8934E-05
                                             :
MUD                                          :
 Density                         kg/m^3      : 1.21E+03
 Viscosity                       Pa-s        : 0.110E-01
 Wall Roughness Pipe             m           : 0.001
 Wall Roughness Annulus          m           : 0.001
 Max. Solids Vol. Fraction       -           : 0.615
 Solids Viscosity Exponent       -           : -1.5
                                             :
WELLBORE/DRILLING                            :
 Bit Diameter                    m           : 0.3112
 Pipe Diameter                   m           : 0.1143
 Collar Diameter                 m           : 0.2032
 Pipe Inside Diameter            m           : 0.09178
 Collar Length                   m           : 182.90
 Exit Pipe Length                m           : 0.0
 Exit Pipe Diameter              m           : 0.2032
 Drilling Rate                   m/s         : 0.005
 Bit Above Repository (Init.)    m           : 0.15
 Mud Pump Rate                   m^3/s       : 2.018E-02
 Maximum Pump Pressure           m^3/s       : 27.5E+06
 DDZ Thickness                   m           : 0.16
 DDZ Permeability                m^2         : 0.10E-13
 Stop Drilling Exit Vol. Rate    m^3/s       : 1000.0
 Stop Pumping Exit Vol. Rate     m^3/s       : 1000.0
 Stop DrillingTime               s           : 1000.0
                                             :
COMPUTATIONAL                                :
 Spherical/Cylindrical           S/C         : S
 Allow Fluidization?             Y/N         : N
 Maximum Run Time                s           : 6.0
 Repository Cell Length          m           : 0.002
 Repository Radius, Growth       m,-         : 0.5, 1.01
 Wellbore Cell Length            m           : 4.0
 Wellbore Zone Growth Rate       -           : 1.0
 First Wellbore Zone             -           : 2
 Well Stability Factor           -           : 0.1
 Repository Stability Factor     -           : 5.0
 Mass Diffusion Factor           -           : 0.02
 Momentum Diffusion Factor       -           : 0.002

VALIDATION
 Validation Test Case            -           : 1.2
```

B.4 DRSPALL Results for Test Case #1

Table B.4-1. DRSPALL results for Test Case #1, cylindrical case (DRS_QE0100_TC11_CHAN.DAT)

```
DRSPALL_QE0100 1.00 PROD QE0100 09/17/2003                    09/19/2003 01:30:42


                                 DRSPALL_QE0100

DDDDDD  RRRRRR   SSSSSS PPPPPP   AAAAA  LL       LL               QQQQQ  EEEEEEE
DD   DD RR    RR SS      PP    PP AA    AA LL       LL             QQ    QQ EE
DD   DD RR    RR SS      PP    PP AA    AA LL       LL             QQ    QQ EE
DD   DD RRRRRR   SSSSS  PPPPPP  AAAAAAA LL       LL             QQ    QQ EEEEE
DD   DD RRRRR        SS PP      AA    AA LL       LL             QQ Q QQ EE
DD   DD RR   RR       SS PP      AA    AA LL       LL             QQ   QQQ EE
DDDDDD  RR    RR SSSSSS  PP      AA    AA LLLLLLL LLLLLLL _______  QQQQQQ EEEEEEE

                           DRSPALL_QE0100 Version 1.00
                           PROD QE0100 Built 09/17/2003
                              Written by John Schatz
                            Sponsored by David Rudeen

                          Run on 09/19/2003 at 01:30:42
                        Run on ALPHA AXP BTO OpenVMS V7.3-1

              **************************************************************

              Prepared for
              Sandia National Laboratories
              Albuquerque, New Mexico 87185-5800
              for the United States Department of Energy
              under Contract DE-AC04-76DP00789

              **************************************************************

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              of their contractors or subcontractors.

              **************************************************************


     Run time (s):        3.60000E-04
          Tau(-):        1.00728E-02
       Radius (m)   PorePressure (Pa)          Zeta(-)             Psi(-)
   1.5659190E-01      4.3390643E+06       6.3515847E-02      8.9548057E-02
   1.5857569E-01      6.0774916E+06       1.9054754E-01      1.7567612E-01
   1.6055948E-01      7.3593099E+06       3.1757924E-01      2.5759545E-01
   1.6254327E-01      8.3902394E+06       4.4461093E-01      3.3482101E-01
   1.6452706E-01      9.2511102E+06       5.7164263E-01      4.0705370E-01
```

1.6651085E-01	9.9842829E+06	6.9867432E-01	4.7413034E-01
1.6849465E-01	1.0615689E+07	8.2570601E-01	5.3599458E-01
1.7047844E-01	1.1162896E+07	9.5273771E-01	5.9267659E-01
1.7246223E-01	1.1638700E+07	1.0797694E+00	6.4427743E-01
1.7444602E-01	1.2052945E+07	1.2068011E+00	6.9095593E-01
1.7642981E-01	1.2413536E+07	1.3338328E+00	7.3291736E-01
1.7841360E-01	1.2727031E+07	1.4608645E+00	7.7040336E-01
1.8039740E-01	1.2999012E+07	1.5878962E+00	8.0368281E-01
1.8238119E-01	1.3234327E+07	1.7149279E+00	8.3304363E-01
1.8436498E-01	1.3437248E+07	1.8419596E+00	8.5878540E-01
1.8634877E-01	1.3611575E+07	1.9689913E+00	8.8121269E-01
1.8833256E-01	1.3760716E+07	2.0960230E+00	9.0062932E-01
1.9031635E-01	1.3887740E+07	2.2230547E+00	9.1733327E-01
1.9230015E-01	1.3995411E+07	2.3500863E+00	9.3161248E-01
1.9428394E-01	1.4086221E+07	2.4771180E+00	9.4374143E-01
1.9626773E-01	1.4162414E+07	2.6041497E+00	9.5397839E-01
1.9825152E-01	1.4225997E+07	2.7311814E+00	9.6256354E-01
2.0023531E-01	1.4278765E+07	2.8582131E+00	9.6971767E-01
2.0221910E-01	1.4322312E+07	2.9852448E+00	9.7564150E-01
2.0420290E-01	1.4358043E+07	3.1122765E+00	9.8051562E-01
2.0618669E-01	1.4387192E+07	3.2393082E+00	9.8450084E-01
2.0817048E-01	1.4410833E+07	3.3663399E+00	9.8773890E-01
2.1015427E-01	1.4429894E+07	3.4933716E+00	9.9035357E-01
2.1213806E-01	1.4445173E+07	3.6204033E+00	9.9245189E-01
2.1412185E-01	1.4457348E+07	3.7474350E+00	9.9412558E-01
2.1610565E-01	1.4466993E+07	3.8744667E+00	9.9545254E-01
2.1808944E-01	1.4474591E+07	4.0014984E+00	9.9649832E-01

Run time (s): 3.59700E-03
Tau(-): 1.00644E-01

Radius (m)	PorePressure (Pa)	Zeta(-)	Psi(-)
1.5659190E-01	2.5948079E+06	2.0093853E-02	3.2023915E-02
1.6452706E-01	5.7007397E+06	1.8084467E-01	1.5457043E-01
1.7246223E-01	7.4971740E+06	3.4159549E-01	2.6733707E-01
1.8039740E-01	8.8185929E+06	5.0234632E-01	3.6988147E-01
1.8833256E-01	9.8578473E+06	6.6309714E-01	4.6219811E-01
1.9626773E-01	1.0699908E+07	8.2384796E-01	5.4453288E-01
2.0420290E-01	1.1392431E+07	9.8459878E-01	6.1730071E-01
2.1213806E-01	1.1966106E+07	1.1453496E+00	6.8103536E-01
2.2007323E-01	1.2442601E+07	1.3061004E+00	7.3635348E-01
2.2800840E-01	1.2838244E+07	1.4668512E+00	7.8392633E-01
2.3594356E-01	1.3165937E+07	1.6276021E+00	8.2445616E-01
2.4387873E-01	1.3436237E+07	1.7883529E+00	8.5865617E-01
2.5181390E-01	1.3657994E+07	1.9491037E+00	8.8723331E-01
2.5974906E-01	1.3838757E+07	2.1098545E+00	9.1087370E-01
2.6768423E-01	1.3985028E+07	2.2706053E+00	9.3023067E-01
2.7561940E-01	1.4102435E+07	2.4313562E+00	9.4591523E-01
2.8355456E-01	1.4195857E+07	2.5921070E+00	9.5848919E-01
2.9148973E-01	1.4269507E+07	2.7528578E+00	9.6846053E-01
2.9942490E-01	1.4327007E+07	2.9136086E+00	9.7628122E-01
3.0736006E-01	1.4371445E+07	3.0743595E+00	9.8234690E-01
3.1529523E-01	1.4405431E+07	3.2351103E+00	9.8699853E-01
3.2323040E-01	1.4431145E+07	3.3958611E+00	9.9052526E-01
3.3116556E-01	1.4450387E+07	3.5566119E+00	9.9316856E-01
3.3910073E-01	1.4464627E+07	3.7173627E+00	9.9512695E-01
3.4703590E-01	1.4475047E+07	3.8781136E+00	9.9656116E-01
3,5497106E-01	1.4482585E+07	4.0388644E+00	9.9759934E-01

Run time (s): 3.57609E-02
Tau(-): 1.00059E+00

Radius (m)	PorePressure (Pa)	Zeta(-)	Psi(-)
1.5659190E-01	1.6842862E+06	6.3727839E-03	1.3492604E-02
1.8039740E-01	5.8420566E+06	1.5931960E-01	1.6232878E-01
2.0420290E-01	7.8068689E+06	3.1226641E-01	2.8987968E-01
2.2800840E-01	9.1662944E+06	4.6521322E-01	3.9962404E-01
2.5181390E-01	1.0193610E+07	6.1816004E-01	4.9421963E-01
2.7561940E-01	1.1002291E+07	7.7110685E-01	5.7574514E-01
2.9942490E-01	1.1653202E+07	9.2405366E-01	6.4588399E-01
3.2323040E-01	1.2183832E+07	1.0770005E+00	7.0604408E-01
3.4703590E-01	1.2619457E+07	1.2299473E+00	7.5743489E-01
3.7084140E-01	1.2978248E+07	1.3828941E+00	8.0111740E-01
3.9464690E-01	1.3273927E+07	1.5358409E+00	8.3803634E-01

4.1845240E-01	1.3517245E+07	1.6887877E+00	8.6904114E-01
4.4225790E-01	1.3716873E+07	1.8417345E+00	8.9489941E-01
4.6606340E-01	1.3879960E+07	1.9946814E+00	9.1630575E-01
4.8986890E-01	1.4012489E+07	2.1476282E+00	9.3388751E-01
5.1367440E-01	1.4119523E+07	2.3005750E+00	9.4820890E-01
5.3747990E-01	1.4205369E+07	2.4535218E+00	9.5977409E-01
5.6128540E-01	1.4273703E+07	2.6064686E+00	9.6903015E-01
5.8509090E-01	1.4327657E+07	2.7594154E+00	9.7636985E-01
6.0889640E-01	1.4369894E+07	2.9123622E+00	9.8213482E-01
6.3270190E-01	1.4402661E+07	3.0653091E+00	9.8661900E-01
6.5650740E-01	1.4427845E+07	3.2182559E+00	9.9007241E-01
6.8179264E-01	1.4448041E+07	3.3807098E+00	9.9284603E-01
7.1028468E-01	1.4464573E+07	3.5637670E+00	9.9511953E-01
7.4239023E-01	1.4477374E+07	3.7700403E+00	9.9688166E-01
7.7856756E-01	1.4486642E+07	4.0024743E+00	9.9815834E-01

Run time (s):	3.57421E-01		
Tau(-):	1.00006E+01		
Radius (m)	PorePressure (Pa)	Zeta(-)	Psi(-)
1.5659190E-01	1.2194914E+06	2.0157812E-03	7.0732907E-03
1.9428394E-01	5.1590457E+06	7.8615467E-02	1.2659097E-01
2.3197598E-01	6.8689751E+06	1.5521515E-01	2.2441293E-01
2.6966802E-01	8.0325530E+06	2.3181484E-01	3.0688185E-01
3.0736006E-01	8.9130844E+06	3.0841452E-01	3.7785053E-01
3.4505210E-01	9.6164059E+06	3.8501421E-01	4.3983478E-01
3.8274415E-01	1.0197223E+07	4.6161390E-01	4.9457010E-01
4.2043619E-01	1.0687852E+07	5.3821358E-01	5.4330648E-01
4.5812823E-01	1.1109086E+07	6.1481327E-01	5.8697637E-01
4.9582027E-01	1.1475136E+07	6.9141295E-01	6.2629603E-01
5.3351231E-01	1.1796171E+07	7.6801264E-01	6.6182954E-01
5.7120435E-01	1.2079735E+07	8.4461233E-01	6.9403096E-01
6.0889640E-01	1.2331590E+07	9.2121201E-01	7.2327280E-01
6.4658844E-01	1.2556246E+07	9.9781170E-01	7.4986597E-01
6.8630823E-01	1.2767522E+07	1.0785323E+00	7.7531329E-01
7.3400095E-01	1.2991369E+07	1.1754559E+00	8.0273798E-01
7.9161896E-01	1.3224702E+07	1.2925501E+00	8.3183227E-01
8.6121738E-01	1.3461213E+07	1.4339916E+00	8.6185144E-01
9.3721738E-01	1.3672779E+07	1.5884426E+00	8.8915528E-01
1.0133984E+00	1.3844825E+07	1.7432615E+00	9.1167270E-01
1.0995932E+00	1.4000228E+07	1.9184309E+00	9.3225390E-01
1.2037258E+00	1.4143650E+07	2.1300547E+00	9.5145219E-01
1.3295295E+00	1.4267443E+07	2.3857192E+00	9.6818034E-01
1.4815139E+00	1.4365121E+07	2.6945898E+00	9.8148253E-01
1.6651277E+00	1.4433315E+07	3.0677391E+00	9.9082319E-01
1.8869532E+00	1.4473515E+07	3.5185442E+00	9.9635027E-01

Run time (s):	3.57401E+00		
Tau(-):	1.00001E+02		
Radius (m)	PorePressure (Pa)	Zeta(-)	Psi(-)
1.5659190E-01	9.7166783E+05	6.3746335E-04	4.4905511E-03
2.0618669E-01	4.6169250E+06	3.2510631E-02	1.0138405E-01
2.5578148E-01	6.1045303E+06	6.4383798E-02	1.7724276E-01
3.0537627E-01	7.0968668E+06	9.6256966E-02	2.3955062E-01
3.5497106E-01	7.8405329E+06	1.2813013E-01	2.9238505E-01
4.0456585E-01	8.4326463E+06	1.6000330E-01	3.3821414E-01
4.5416065E-01	8.9224595E+06	1.9187647E-01	3.7864582E-01
5.0375544E-01	9.3385654E+06	2.2374964E-01	4.1478623E-01
5.5335023E-01	9.6990688E+06	2.5562280E-01	4.4742895E-01
6.0294502E-01	1.0016160E+07	2.8749597E-01	4.7716271E-01
6.5253981E-01	1.0298434E+07	3.1936914E-01	5.0443638E-01
7.0777826E-01	1.0579465E+07	3.5486932E-01	5.3234281E-01
7.7856756E-01	1.0897938E+07	4.0036360E-01	5.6487545E-01
8.6921738E-01	1.1251509E+07	4.5862167E-01	6.0212346E-01
9.6921738E-01	1.1586415E+07	5.2288884E-01	6.3850187E-01
1.0753078E+00	1.1892471E+07	5.9107012E-01	6.7267951E-01
1.2097709E+00	1.2223695E+07	6.7748578E-01	7.1067166E-01
1.3822108E+00	1.2577276E+07	7.8830799E-01	7.5237987E-01
1.6033532E+00	1.2943261E+07	9.3042993E-01	7.9680385E-01
1.8869532E+00	1.3308013E+07	1.1126917E+00	8.4234579E-01
2.2506510E+00	1.3653989E+07	1.3464299E+00	8.8671309E-01
2.7170687E+00	1.3960267E+07	1.6461834E+00	9.2693963E-01
3.3152177E+00	1.4205100E+07	2.0305968E+00	9.5973781E-01

4.0823031E+00	1.4372329E+07	2.5235808E+00	9.8246778E-01
5.0660380E+00	1.4461420E+07	3.1557994E+00	9.9468577E-01
6.3276110E+00	1.4493390E+07	3.9665766E+00	9.9908849E-01

Table B.4-2. DRSPALL results for Test Case #1, spherical case (DRS_QE0100_TC12_CHAN.DAT)

```
DRSPALL_QE0100 1.00 PROD QE0100 09/17/2003                    09/19/2003 01:31:26


                              DRSPALL_QE0100

 DDDDDD   RRRRRR    SSSSSS PPPPPP    AAAAA  LL       LL                QQQQQ   EEEEEEE
 DD    DD RR    RR SS       PP    PP AA    AA LL       LL             QQ    QQ EE
 DD    DD RR    RR SS       PP    PP AA    AA LL       LL             QQ    QQ EE
 DD    DD RRRRRR    SSSSS  PPPPPP  AAAAAAA LL       LL             QQ    QQ EEEEE
 DD    DD RRRRR          SS PP       AA    AA LL       LL             QQ Q QQ EE
 DD    DD RR   RR        SS PP       AA    AA LL       LL             QQ   QQQ EE
 DDDDDD   RR    RR SSSSSS  PP       AA    AA LLLLLLL LLLLLLL _______  QQQQQQ EEEEEEE

                      DRSPALL_QE0100 Version 1.00
                      PROD QE0100 Built 09/17/2003
                         Written by John Schatz
                       Sponsored by David Rudeen

                     Run on 09/19/2003 at 01:31:26
                  Run on ALPHA AXP BTO OpenVMS V7.3-1

      ************************************************************

      Prepared for
      Sandia National Laboratories
      Albuquerque, New Mexico 87185-5800
      for the United States Department of Energy
      under Contract DE-AC04-76DP00789

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      of any information, apparatus, product, or process disclosed
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      contractors  or  subcontractors.   The  views  and  opinions
      expressed  herein  do not necessarily state or reflect those
      of the United States Government, any agency thereof  or  any
      of their contractors or subcontractors.

      ************************************************************


   Run time (s):           3.26417E-03
         Tau(-):           1.00078E-02
     Radius (m)     PorePressure (Pa)            Zeta(-)              Psi(-)
  4.7103083E-01       2.5628559E+06      2.0745145E-02       3.1240096E-02
  4.7688394E-01       5.0735320E+06      1.4521601E-01       1.2242914E-01
  4.8273705E-01       6.6307290E+06      2.6968688E-01       2.0911566E-01
  4.8859016E-01       7.8189446E+06      3.9415775E-01       2.9077714E-01
  4.9444326E-01       8.7856718E+06      5.1862862E-01       3.6712499E-01
  5.0029637E-01       9.5965292E+06      6.4309949E-01       4.3801842E-01
  5.0614948E-01       1.0288107E+07      7.6757036E-01       5.0342522E-01
  5.1200259E-01       1.0883675E+07      8.9204123E-01       5.6339776E-01
  5.1785570E-01       1.1399398E+07      1.0165121E+00       6.1805597E-01
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5.2370880E-01	1.1847254E+07	1.1409830E+00	6.6757401E-01
5.2956191E-01	1.2236567E+07	1.2654538E+00	7.1216922E-01
5.3541502E-01	1.2574874E+07	1.3899247E+00	7.5209250E-01
5.4126813E-01	1.2868453E+07	1.5143956E+00	7.8761995E-01
5.4712123E-01	1.3122662E+07	1.6388664E+00	8.1904526E-01
5.5297434E-01	1.3342152E+07	1.7633373E+00	8.4667304E-01
5.5882745E-01	1.3531015E+07	1.8878082E+00	8.7081272E-01
5.6468056E-01	1.3692893E+07	2.0122790E+00	8.9177326E-01
5.7053366E-01	1.3831043E+07	2.1367499E+00	9.0985844E-01
5.7638677E-01	1.3948389E+07	2.2612208E+00	9.2536295E-01
5.8223988E-01	1.4047566E+07	2.3856917E+00	9.3856894E-01
5.8809299E-01	1.4130943E+07	2.5101625E+00	9.4974345E-01
5.9394610E-01	1.4200648E+07	2.6346334E+00	9.5913630E-01
5.9979920E-01	1.4258586E+07	2.7591043E+00	9.6697866E-01
6.0565231E-01	1.4306454E+07	2.8835751E+00	9.7348218E-01
6.1150542E-01	1.4345760E+07	3.0080460E+00	9.7883865E-01
6.1735853E-01	1.4377831E+07	3.1325169E+00	9.8322004E-01
6.2321163E-01	1.4403829E+07	3.2569877E+00	9.8677908E-01
6.2906474E-01	1.4424767E+07	3.3814586E+00	9.8965001E-01
6.3491785E-01	1.4441517E+07	3.5059295E+00	9.9194969E-01
6.4077096E-01	1.4454827E+07	3.6304003E+00	9.9377889E-01
6.4662407E-01	1.4465330E+07	3.7548712E+00	9.9522364E-01
6.5247717E-01	1.4473562E+07	3.8793421E+00	9.9635671E-01
6.5833028E-01	1.4479970E+07	4.0038130E+00	9.9723909E-01

Run time (s): 3.26196E-02
Tau(-): 1.00011E-01

Radius (m)	PorePressure (Pa)	Zeta(-)	Psi(-)
4.7103083E-01	1.6230765E+06	6.5624045E-03	1.2529737E-02
4.9249223E-01	5.4827673E+06	1.5093530E-01	1.4297616E-01
5.1395362E-01	7.3939850E+06	2.9530820E-01	2.6002860E-01
5.3541502E-01	8.7526062E+06	4.3968110E-01	3.6436678E-01
5.5687641E-01	9.8006611E+06	5.8405400E-01	4.5685117E-01
5.7833781E-01	1.0639347E+07	7.2842689E-01	5.3838625E-01
5.9979920E-01	1.1323718E+07	8.7279979E-01	6.0987677E-01
6.2126060E-01	1.1888306E+07	1.0171727E+00	6.7220846E-01
6.4272199E-01	1.2356841E+07	1.1615456E+00	7.2623793E-01
6.6418339E-01	1.2746700E+07	1.3059185E+00	7.7278651E-01
6.8564478E-01	1.3071217E+07	1.4502914E+00	8.1263598E-01
7.0710618E-01	1.3340988E+07	1.5946643E+00	8.4652538E-01
7.2856757E-01	1.3564658E+07	1.7390372E+00	8.7514836E-01
7.5002897E-01	1.3749419E+07	1.8834101E+00	8.9915116E-01
7.7149036E-01	1.3901342E+07	2.0277830E+00	9.1913114E-01
7.9295176E-01	1.4025600E+07	2.1721559E+00	9.3563588E-01
8.1441315E-01	1.4126624E+07	2.3165288E+00	9.4916289E-01
8.3587455E-01	1.4208225E+07	2.4609017E+00	9.6016002E-01
8.5733594E-01	1.4273676E+07	2.6052746E+00	9.6902654E-01
8.7879734E-01	1.4325786E+07	2.7496475E+00	9.7611480E-01
9.0025873E-01	1.4366951E+07	2.8940204E+00	9.8173260E-01
9.2172013E-01	1.4399207E+07	3.0383933E+00	9.8614588E-01
9.4318152E-01	1.4424272E+07	3.1827662E+00	9.8958197E-01
9.6464292E-01	1.4443580E+07	3.3271391E+00	9.9223304E-01
9.8674249E-01	1.4458703E+07	3.4758051E+00	9.9431193E-01
1.0113018E+00	1.4471118E+07	3.6410182E+00	9.9602020E-01
1.0387019E+00	1.4480881E+07	3.8253413E+00	9.9736460E-01

Run time (s): 3.26175E-01
Tau(-): 1.00004E+00

Radius (m)	PorePressure (Pa)	Zeta(-)	Psi(-)
4.7103083E-01	1.1860607E+06	2.0752833E-03	6.6907961E-03
5.0614948E-01	4.9850363E+06	7.6785481E-02	1.1819542E-01
5.4126813E-01	6.7215651E+06	1.5149568E-01	2.1488436E-01
5.7638677E-01	7.9329649E+06	2.2620588E-01	2.9931954E-01
6.1150542E-01	8.8616724E+06	3.0091608E-01	3.7350410E-01
6.4662407E-01	9.6075052E+06	3.7562627E-01	4.3902096E-01
6.8174271E-01	1.0223652E+07	4.5033647E-01	4.9713707E-01
7.1686136E-01	1.0742525E+07	5.2504667E-01	5.4887915E-01
7.5198000E-01	1.1185591E+07	5.9975687E-01	5.9508897E-01
7.8709865E-01	1.1567912E+07	6.7446707E-01	6.3646410E-01
8.2221730E-01	1.1900503E+07	7.4917727E-01	6.7358848E-01
8.5733594E-01	1.2191693E+07	8.2388746E-01	7.0695546E-01
8.9245459E-01	1.2447939E+07	8.9859766E-01	7.3698547E-01

9.2757324E-01	1.2674358E+07	9.7330786E-01	7.6403972E-01
9.6269188E-01	1.2875076E+07	1.0480181E+00	7.8843082E-01
9.9980480E-01	1.3062995E+07	1.1269708E+00	8.1161396E-01
1.0440141E+00	1.3258844E+07	1.2210201E+00	8.3613290E-01
1.0968949E+00	1.3459080E+07	1.3335168E+00	8.6157824E-01
1.1601481E+00	1.3658066E+07	1.4680796E+00	8.8724270E-01
1.2358083E+00	1.3849052E+07	1.6290365E+00	9.1222947E-01
1.3263090E+00	1.4024571E+07	1.8215647E+00	9.3549866E-01
1.4345613E+00	1.4177190E+07	2.0518568E+00	9.5597009E-01
1.5640469E+00	1.4300662E+07	2.3273201E+00	9.7269407E-01
1.7189309E+00	1.4391418E+07	2.6568148E+00	9.8507925E-01
1.9041949E+00	1.4450012E+07	3.0509392E+00	9.9311701E-01
2.1257980E+00	1.4481689E+07	3.5223700E+00	9.9747588E-01

Run time (s): 3.26162E+00
Tau(-): 1.00000E+01

Radius (m)	PorePressure (Pa)	Zeta(-)	Psi(-)
4.7103083E-01	1.0164413E+06	6.5627457E-04	4.9139259E-03
5.1590466E-01	4.7578873E+06	3.0844905E-02	1.0766940E-01
5.6077849E-01	6.3858948E+06	6.1033535E-02	1.9395792E-01
6.0565231E-01	7.4984769E+06	9.1222165E-02	2.6742999E-01
6.5052614E-01	8.3388292E+06	1.2141080E-01	3.3073043E-01
6.9539996E-01	9.0066131E+06	1.5159943E-01	3.8582202E-01
7.4027379E-01	9.5545208E+06	1.8178806E-01	4.3419200E-01
7.8514761E-01	1.0014325E+07	2.1197669E-01	4.7698785E-01
8.3002144E-01	1.0406810E+07	2.4216532E-01	5.1510910E-01
8.7489527E-01	1.0746358E+07	2.7235395E-01	5.4927087E-01
9.1976909E-01	1.1043336E+07	3.0254258E-01	5.8004884E-01
9.6464292E-01	1.1305460E+07	3.3273121E-01	6.0791169E-01
1.0136707E+00	1.1558908E+07	3.6571438E-01	6.3547377E-01
1.0751979E+00	1.1836981E+07	4.0710650E-01	6.6641673E-01
1.1525477E+00	1.2135798E+07	4.5914314E-01	7.0048800E-01
1.2497889E+00	1.2449021E+07	5.2456167E-01	7.3711351E-01
1.3720370E+00	1.2768565E+07	6.0680343E-01	7.7543996E-01
1.5257228E+00	1.3085079E+07	7.1019474E-01	8.1436043E-01
1.7189309E+00	1.3388556E+07	8.4017446E-01	8.5257282E-01
1.9618249E+00	1.3668987E+07	1.0035802E+00	8.8866207E-01
2.2671824E+00	1.3916950E+07	1.2090078E+00	9.2119622E-01
2.6510664E+00	1.4124220E+07	1.4672638E+00	9.4883984E-01
3.1336713E+00	1.4284634E+07	1.7919336E+00	9.7051499E-01
3.7403843E+00	1.4395638E+07	2.2000966E+00	9.8565704E-01
4.5031214E+00	1.4460487E+07	2.7132240E+00	9.9455737E-01
5.4620063E+00	1.4489678E+07	3.3583087E+00	9.9857682E-01

B.5 DIFF Calculation

The difference calculations used to generate Table 8.1-5 are detailed here. The DRSPALL output and comparison data were aligned in an EXCEL table, and the difference between Ψ at corresponding ζ were calculated. The "MAX" worksheet function was then used to select and report the maximum DIFF for each τ. For each τ, the maximum DIFF is highlighted.

Table B.5-1. DIFF calculation for cylindrical case

Tau	0.01		
	DRSPALL	D&A	
Zeta	Ψ	Ψ	DIFF
6.35E-02	8.95E-02	4.50E-02	4.45E-02
1.91E-01	1.76E-01	1.33E-01	4.30E-02
3.18E-01	2.58E-01	2.16E-01	4.12E-02
4.45E-01	3.35E-01	2.96E-01	3.89E-02
5.72E-01	4.07E-01	3.71E-01	3.63E-02
6.99E-01	4.74E-01	4.41E-01	3.35E-02
8.26E-01	5.36E-01	5.05E-01	3.05E-02
9.53E-01	5.93E-01	5.65E-01	2.76E-02
1.08E+00	6.44E-01	6.20E-01	2.47E-02
1.21E+00	6.91E-01	6.69E-01	2.19E-02
1.33E+00	7.33E-01	7.14E-01	1.93E-02
1.46E+00	7.70E-01	7.54E-01	1.69E-02
1.59E+00	8.04E-01	7.89E-01	1.47E-02
1.71E+00	8.33E-01	8.20E-01	1.27E-02
1.84E+00	8.59E-01	8.48E-01	1.09E-02
1.97E+00	8.81E-01	8.72E-01	9.36E-03
2.10E+00	9.01E-01	8.93E-01	8.00E-03
2.22E+00	9.17E-01	9.11E-01	6.79E-03
2.35E+00	9.32E-01	9.26E-01	5.76E-03
2.48E+00	9.44E-01	9.39E-01	4.87E-03
2.60E+00	9.54E-01	9.50E-01	4.11E-03
2.73E+00	9.63E-01	9.59E-01	3.44E-03
2.86E+00	9.70E-01	9.67E-01	2.88E-03
2.99E+00	9.76E-01	9.73E-01	2.40E-03
3.11E+00	9.81E-01	9.79E-01	1.99E-03
3.24E+00	9.85E-01	9.83E-01	1.64E-03
3.37E+00	9.88E-01	9.86E-01	1.35E-03
3.49E+00	9.90E-01	9.89E-01	1.09E-03
3.62E+00	9.92E-01	9.92E-01	8.88E-04
3.75E+00	9.94E-01	9.93E-01	7.22E-04
3.87E+00	9.95E-01	9.95E-01	5.71E-04
4.00E+00	9.97E-01	9.96E-01	4.58E-04

Tau	0.10		
	DRSPALL	D&A	
Zeta	Ψ	Ψ	DIFF
2.01E-02	3.20E-02	1.61E-02	1.60E-02
1.81E-01	1.55E-01	1.40E-01	1.50E-02
3.42E-01	2.67E-01	2.54E-01	1.37E-02
5.02E-01	3.70E-01	3.58E-01	1.21E-02
6.63E-01	4.62E-01	4.52E-01	1.03E-02
8.24E-01	5.45E-01	5.36E-01	8.58E-03
9.85E-01	6.17E-01	6.10E-01	7.01E-03
1.15E+00	6.81E-01	6.75E-01	5.70E-03
1.31E+00	7.36E-01	7.32E-01	4.61E-03
1.47E+00	7.84E-01	7.80E-01	3.79E-03
1.63E+00	8.24E-01	8.21E-01	3.23E-03
1.79E+00	8.59E-01	8.56E-01	2.83E-03
1.95E+00	8.87E-01	8.85E-01	2.57E-03
2.11E+00	9.11E-01	9.08E-01	2.39E-03
2.27E+00	9.30E-01	9.28E-01	2.28E-03
2.43E+00	9.46E-01	9.44E-01	2.17E-03
2.59E+00	9.58E-01	9.56E-01	2.06E-03
2.75E+00	9.68E-01	9.67E-01	1.93E-03
2.91E+00	9.76E-01	9.74E-01	1.79E-03
3.07E+00	9.82E-01	9.81E-01	1.63E-03
3.24E+00	9.87E-01	9.86E-01	1.46E-03
3.40E+00	9.91E-01	9.89E-01	1.28E-03
3.56E+00	9.93E-01	9.92E-01	1.11E-03
3.72E+00	9.95E-01	9.94E-01	9.37E-04
3.88E+00	9.97E-01	9.96E-01	7.76E-04
4.04E+00	9.98E-01	9.97E-01	6.36E-04

Tau	1.00		
	DRSPALL	D&A	
Zeta	Ψ	Ψ	DIFF
6.37E-03	1.35E-02	6.56E-03	6.93E-03
1.59E-01	1.62E-01	1.54E-01	8.56E-03
3.12E-01	2.90E-01	2.83E-01	7.30E-03
4.65E-01	4.00E-01	3.95E-01	4.98E-03
6.18E-01	4.94E-01	4.92E-01	2.60E-03
7.71E-01	5.76E-01	5.75E-01	6.65E-04
9.24E-01	6.46E-01	6.47E-01	6.38E-04
1.08E+00	7.06E-01	7.07E-01	1.29E-03
1.23E+00	7.57E-01	7.59E-01	1.39E-03
1.38E+00	8.01E-01	8.02E-01	1.09E-03
1.54E+00	8.38E-01	8.39E-01	4.98E-04
1.69E+00	8.69E-01	8.69E-01	2.05E-04
1.84E+00	8.95E-01	8.94E-01	9.64E-04
1.99E+00	9.16E-01	9.15E-01	1.66E-03
2.15E+00	9.34E-01	9.32E-01	2.26E-03
2.30E+00	9.48E-01	9.46E-01	2.70E-03
2.45E+00	9.60E-01	9.57E-01	3.01E-03
2.61E+00	9.69E-01	9.66E-01	3.17E-03
2.76E+00	9.76E-01	9.73E-01	3.20E-03
2.91E+00	9.82E-01	9.79E-01	3.12E-03
3.07E+00	9.87E-01	9.84E-01	2.96E-03
3.22E+00	9.90E-01	9.87E-01	2.73E-03
3.38E+00	9.93E-01	9.90E-01	2.46E-03
3.56E+00	9.95E-01	9.93E-01	2.11E-03
3.77E+00	9.97E-01	9.95E-01	1.73E-03
4.00E+00	9.98E-01	9.97E-01	1.34E-03

Tau	10.00		
	DRSPALL	D&A	
Zeta	Ψ	Ψ	DIFF
2.02E-03	7.07E-03	3.03E-03	4.04E-03
7.46E-02	1.21E-01	1.06E-01	1.51E-02
1.47E-01	2.15E-01	1.97E-01	1.74E-02
2.20E-01	2.95E-01	2.79E-01	1.55E-02
2.92E-01	3.64E-01	3.52E-01	1.16E-02
3.65E-01	4.24E-01	4.17E-01	7.11E-03
4.37E-01	4.78E-01	4.75E-01	2.64E-03
5.10E-01	5.26E-01	5.27E-01	1.37E-03
5.83E-01	5.69E-01	5.74E-01	4.72E-03
6.55E-01	6.08E-01	6.16E-01	7.38E-03
7.28E-01	6.44E-01	6.53E-01	9.32E-03
8.00E-01	6.76E-01	6.86E-01	1.06E-02
8.73E-01	7.05E-01	7.16E-01	1.13E-02
9.45E-01	7.32E-01	7.43E-01	1.14E-02
1.02E+00	7.56E-01	7.68E-01	1.12E-02
1.10E+00	7.81E-01	7.91E-01	1.04E-02
1.19E+00	8.07E-01	8.16E-01	9.13E-03
1.31E+00	8.35E-01	8.42E-01	7.16E-03
1.44E+00	8.63E-01	8.68E-01	4.47E-03
1.60E+00	8.92E-01	8.93E-01	1.15E-03
1.80E+00	9.19E-01	9.16E-01	2.52E-03
2.03E+00	9.43E-01	9.37E-01	6.07E-03
2.31E+00	9.64E-01	9.55E-01	8.88E-03
2.64E+00	9.80E-01	9.69E-01	1.03E-02
3.04E+00	9.90E-01	9.80E-01	1.01E-02
3.52E+00	9.96E-01	9.88E-01	8.35E-03

Table B.5-2. DIFF calculation for spherical case

Tau	0.01		
	DRSPALL	D&A	
Zeta	Ψ	Ψ	DIFF
2.07E-02	3.12E-02	1.57E-02	1.55E-02
1.45E-01	1.22E-01	1.08E-01	1.47E-02
2.70E-01	2.09E-01	1.95E-01	1.38E-02
3.94E-01	2.91E-01	2.78E-01	1.28E-02
5.19E-01	3.67E-01	3.55E-01	1.17E-02
6.43E-01	4.38E-01	4.28E-01	1.05E-02
7.68E-01	5.03E-01	4.94E-01	9.31E-03
8.92E-01	5.63E-01	5.55E-01	8.14E-03
1.02E+00	6.18E-01	6.11E-01	7.07E-03
1.14E+00	6.68E-01	6.61E-01	6.08E-03
1.27E+00	7.12E-01	7.07E-01	5.24E-03
1.39E+00	7.52E-01	7.48E-01	4.55E-03
1.51E+00	7.88E-01	7.84E-01	3.97E-03
1.64E+00	8.19E-01	8.16E-01	3.51E-03
1.76E+00	8.47E-01	8.44E-01	3.16E-03
1.89E+00	8.71E-01	8.68E-01	2.88E-03
2.01E+00	8.92E-01	8.89E-01	2.66E-03
2.14E+00	9.10E-01	9.07E-01	2.50E-03
2.26E+00	9.25E-01	9.23E-01	2.36E-03
2.39E+00	9.39E-01	9.36E-01	2.24E-03
2.51E+00	9.50E-01	9.48E-01	2.11E-03
2.63E+00	9.59E-01	9.57E-01	2.01E-03
2.76E+00	9.67E-01	9.65E-01	1.89E-03
2.88E+00	9.73E-01	9.72E-01	1.76E-03
3.01E+00	9.79E-01	9.77E-01	1.64E-03
3.13E+00	9.83E-01	9.82E-01	1.50E-03
3.26E+00	9.87E-01	9.85E-01	1.37E-03
3.38E+00	9.90E-01	9.88E-01	1.23E-03
3.51E+00	9.92E-01	9.91E-01	1.10E-03
3.63E+00	9.94E-01	9.93E-01	9.66E-04
3.75E+00	9.95E-01	9.94E-01	8.37E-04
3.88E+00	9.96E-01	9.96E-01	7.30E-04
4.00E+00	9.97E-01	9.97E-01	6.21E-04

Tau	0.10		
	DRSPALL	D&A	
Zeta	Ψ	Ψ	DIFF
6.56E-03	1.25E-02	6.22E-03	6.31E-03
1.51E-01	1.43E-01	1.36E-01	6.60E-03
2.95E-01	2.60E-01	2.54E-01	6.22E-03
4.40E-01	3.64E-01	3.59E-01	5.38E-03
5.84E-01	4.57E-01	4.53E-01	4.33E-03
7.28E-01	5.38E-01	5.35E-01	3.29E-03
8.73E-01	6.10E-01	6.08E-01	2.38E-03
1.02E+00	6.72E-01	6.71E-01	1.66E-03
1.16E+00	7.26E-01	7.25E-01	1.21E-03
1.31E+00	7.73E-01	7.72E-01	9.39E-04
1.45E+00	8.13E-01	8.12E-01	8.48E-04
1.59E+00	8.47E-01	8.46E-01	8.94E-04
1.74E+00	8.75E-01	8.74E-01	1.04E-03
1.88E+00	8.99E-01	8.98E-01	1.22E-03
2.03E+00	9.19E-01	9.18E-01	1.40E-03
2.17E+00	9.36E-01	9.34E-01	1.58E-03
2.32E+00	9.49E-01	9.47E-01	1.71E-03
2.46E+00	9.60E-01	9.58E-01	1.79E-03
2.61E+00	9.69E-01	9.67E-01	1.82E-03
2.75E+00	9.76E-01	9.74E-01	1.79E-03
2.89E+00	9.82E-01	9.80E-01	1.72E-03
3.04E+00	9.86E-01	9.85E-01	1.63E-03
3.18E+00	9.90E-01	9.88E-01	1.49E-03
3.33E+00	9.92E-01	9.91E-01	1.35E-03
3.48E+00	9.94E-01	9.93E-01	1.19E-03
3.64E+00	9.96E-01	9.95E-01	1.01E-03
3.83E+00	9.97E-01	9.97E-01	8.23E-04

Tau	1.00		
	DRSPALL	D&A	
Zeta	Ψ	Ψ	DIFF
2.08E-03	6.69E-03	3.19E-03	3.51E-03
7.68E-02	1.18E-01	1.11E-01	7.03E-03
1.52E-01	2.15E-01	2.07E-01	7.72E-03
2.26E-01	2.99E-01	2.93E-01	6.80E-03
3.01E-01	3.74E-01	3.68E-01	5.05E-03
3.76E-01	4.39E-01	4.36E-01	3.00E-03
4.50E-01	4.97E-01	4.96E-01	9.70E-04
5.25E-01	5.49E-01	5.50E-01	8.59E-04
6.00E-01	5.95E-01	5.97E-01	2.37E-03
6.74E-01	6.36E-01	6.40E-01	3.53E-03
7.49E-01	6.74E-01	6.78E-01	4.32E-03
8.24E-01	7.07E-01	7.12E-01	4.76E-03
8.99E-01	7.37E-01	7.42E-01	4.90E-03
9.73E-01	7.64E-01	7.69E-01	4.78E-03
1.05E+00	7.88E-01	7.93E-01	4.42E-03
1.13E+00	8.12E-01	8.15E-01	3.87E-03
1.22E+00	8.36E-01	8.39E-01	2.99E-03
1.33E+00	8.62E-01	8.63E-01	1.78E-03
1.47E+00	8.87E-01	8.87E-01	2.51E-04
1.63E+00	9.12E-01	9.11E-01	1.56E-03
1.82E+00	9.36E-01	9.32E-01	3.44E-03
2.05E+00	9.56E-01	9.51E-01	5.10E-03
2.33E+00	9.73E-01	9.67E-01	6.19E-03
2.66E+00	9.85E-01	9.79E-01	6.41E-03
3.05E+00	9.93E-01	9.87E-01	5.67E-03
3.52E+00	9.97E-01	9.93E-01	4.22E-03

Tau	10.00		
	DRSPALL	D&A	
Zeta	Ψ	Ψ	DIFF
6.56E-04	4.91E-03	2.29E-03	2.62E-03
3.08E-02	1.08E-01	1.00E-01	7.23E-03
6.10E-02	1.94E-01	1.86E-01	8.21E-03
9.12E-02	2.67E-01	2.60E-01	7.25E-03
1.21E-01	3.31E-01	3.25E-01	5.37E-03
1.52E-01	3.86E-01	3.83E-01	3.18E-03
1.82E-01	4.34E-01	4.33E-01	1.02E-03
2.12E-01	4.77E-01	4.78E-01	8.97E-04
2.42E-01	5.15E-01	5.18E-01	2.49E-03
2.72E-01	5.49E-01	5.53E-01	3.70E-03
3.03E-01	5.80E-01	5.85E-01	4.56E-03
3.33E-01	6.08E-01	6.13E-01	5.08E-03
3.66E-01	6.35E-01	6.41E-01	5.28E-03
4.07E-01	6.66E-01	6.72E-01	5.09E-03
4.59E-01	7.00E-01	7.05E-01	4.29E-03
5.25E-01	7.37E-01	7.40E-01	2.71E-03
6.07E-01	7.75E-01	7.76E-01	2.42E-04
7.10E-01	8.14E-01	8.12E-01	2.85E-03
8.40E-01	8.53E-01	8.47E-01	5.77E-03
1.00E+00	8.89E-01	8.82E-01	6.91E-03
1.21E+00	9.21E-01	9.17E-01	4.11E-03
1.47E+00	9.49E-01	9.53E-01	3.70E-03
1.79E+00	9.71E-01	9.83E-01	1.21E-02
2.20E+00	9.86E-01	9.98E-01	1.20E-02
2.71E+00	9.95E-01	1.00E+00	5.40E-03
3.36E+00	9.99E-01	1.00E+00	1.42E-03

B.6 Curve Fits

The curve fits to the Djordjevic and Adams (2003) solutions are shown graphically in Figures B.7-1 and B.7-2. These fits were obtained by a least-squares routine. The EXCEL spreadsheet used to generate these fits follow the figures.

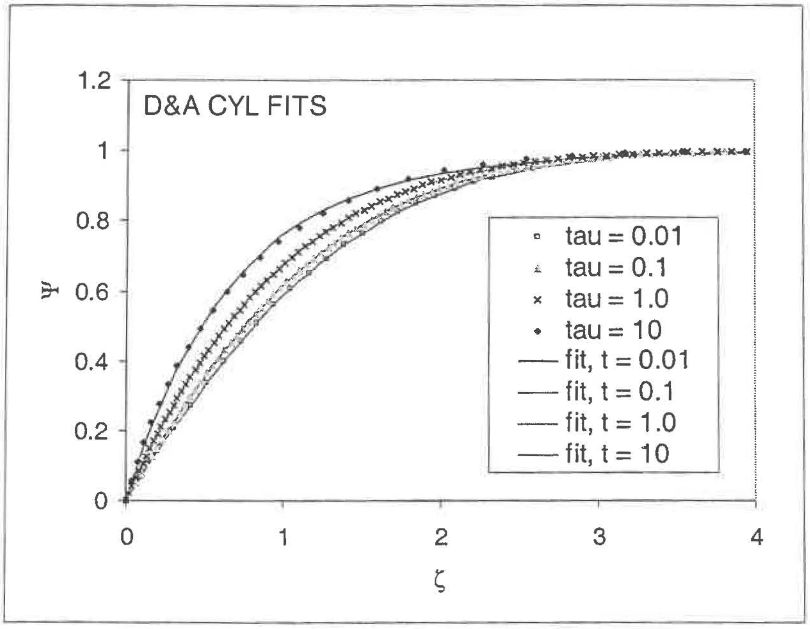

Figure B.7-1. Graphical representation of curve fits to Djordjevic and Adams (2003) cylindrical geometry solutions.

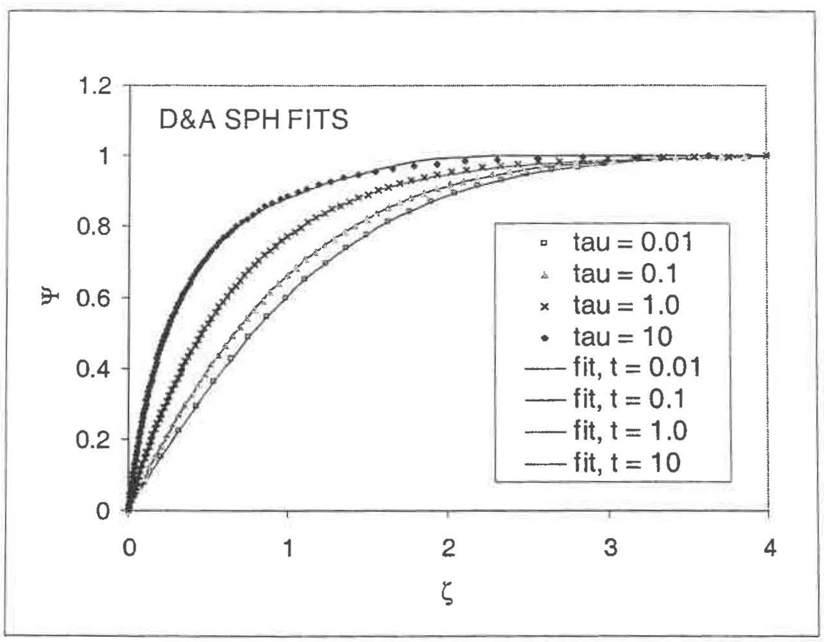

Figure B.7-2. Graphical representation of curve fits to Djordjevic and Adams (2003) spherical geometry solutions.

Table B.7-1. 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 B.7-2. 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 spreadsheets used to generate the least square fits are shown in Tables B.7-3 and B.7-4. The "Solver" worksheet function was used to minimize the SUM for each Tau. Resulting a, b, and c-values correspond to the C_1, C_2, and C_3 listed in Tables B.7-1 and B.7-2.

Table B.7-3. Spreadsheet excerpts showing least squares fits for cylindrical geometry.

	a		0.715023	
	b		0.166805	
Tau = 0.01				
Z	ζ	Ψ	proposed f(ζ)	(Ψ-f)^2
0	0	0	0	0
0.01	0.100502	0.070962	0.070906	3.11962E-09
0.02	0.202013	0.140635	0.140368	7.10137E-08
0.03	0.304545	0.208485	0.208027	2.09692E-07
0.04	0.408108	0.274117	0.273552	3.19248E-07
0.05	0.512711	0.337219	0.336647	3.27067E-07
0.06	0.618365	0.397542	0.397054	2.38218E-07
0.07	0.725082	0.454887	0.454551	1.12767E-07
0.08	0.832871	0.509102	0.50896	2.0282E-08
0.09	0.941743	0.560077	0.560142	4.17448E-09
0.1	1.051709	0.607741	0.608002	6.79678E-08
0.11	1.162781	0.652058	0.652484	1.81568E-07
0.12	1.274969	0.693028	0.693574	2.98958E-07
0.13	1.388284	0.730681	0.731295	3.77723E-07
0.14	1.502738	0.765078	0.765705	3.93252E-07
0.15	1.618342	0.796306	0.796892	3.44263E-07

0.16	1.735109	0.824475	0.824975	2.49935E-07
0.17	1.853049	0.849718	0.850094	1.41355E-07
0.18	1.972174	0.872184	0.87241	5.10192E-08
0.19	2.092496	0.892038	0.892099	3.75946E-09
0.2	2.214028	0.909456	0.909349	1.13109E-08
0.21	2.336781	0.924621	0.924354	7.12263E-08
0.22	2.460767	0.937723	0.937311	1.69523E-07
0.23	2.586	0.94895	0.948416	2.85618E-07
0.24	2.712492	0.958492	0.957861	3.97843E-07
0.25	2.840254	0.966531	0.965832	4.88112E-07
0.26	2.969301	0.973244	0.972506	5.44821E-07
0.27	3.099645	0.9788	0.978049	5.63763E-07
0.28	3.231298	0.983354	0.982614	5.47325E-07
0.29	3.364275	0.987052	0.986343	5.02586E-07
0.3	3.498588	0.990024	0.989362	4.39005E-07
0.31	3.634251	0.992389	0.991784	3.66298E-07
0.32	3.771278	0.994252	0.993711	2.9286E-07
0.33	3.909681	0.995703	0.995229	2.24896E-07
			SUM	8.32057E-06
			AVG	2.44723E-07

a	0.802918
b	0.156586

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	5.65331E-09
0.02	0.063882	0.050779	0.050606	3.01326E-08
0.03	0.096306	0.076035	0.075755	7.83613E-08
0.04	0.129055	0.101166	0.100781	1.48308E-07
0.05	0.162133	0.126152	0.125669	2.33401E-07
0.06	0.195544	0.150973	0.150403	3.24778E-07
0.07	0.229291	0.175612	0.174969	4.13099E-07
0.08	0.263377	0.20005	0.199351	4.89863E-07
0.09	0.297805	0.224273	0.223533	5.4829E-07
0.1	0.33258	0.248264	0.2475	5.83804E-07
0.11	0.367704	0.272008	0.271237	5.94208E-07
0.12	0.40318	0.295491	0.29473	5.79616E-07
0.13	0.439014	0.3187	0.317963	5.42189E-07
0.14	0.475207	0.341619	0.340922	4.85763E-07
0.15	0.511765	0.364237	0.363592	4.15395E-07
0.16	0.54869	0.38654	0.38596	3.36877E-07
0.17	0.585985	0.408517	0.408011	2.56264E-07
0.18	0.623656	0.430155	0.429732	1.79432E-07
0.19	0.661705	0.451444	0.45111	1.11692E-07
0.2	0.700137	0.472372	0.472133	5.74884E-08
0.21	0.738955	0.492929	0.492787	2.01608E-08

0.22	0.778163	0.513105	0.513063	1.81026E-09
0.23	0.817765	0.532891	0.532948	3.2406E-09
0.24	0.857765	0.552277	0.552431	2.39836E-08
0.25	0.898167	0.571254	0.571504	6.23956E-08
0.26	0.938975	0.589816	0.590156	1.15815E-07
0.27	0.980194	0.607954	0.608379	1.80766E-07
0.28	1.021826	0.625661	0.626164	2.53198E-07
0.29	1.063877	0.642932	0.643505	3.2874E-07
0.3	1.106351	0.65976	0.660395	4.02963E-07
0.31	1.149251	0.676141	0.676828	4.71627E-07
0.32	1.192583	0.69207	0.692799	5.30912E-07
0.33	1.23635	0.707543	0.708303	5.77609E-07
0.34	1.280557	0.722557	0.723337	6.09278E-07
0.35	1.325208	0.737109	0.737899	6.24355E-07
0.36	1.370308	0.751198	0.751987	6.22208E-07
0.37	1.415861	0.764823	0.765599	6.03143E-07
0.38	1.461872	0.777982	0.778736	5.68368E-07
0.39	1.508346	0.790677	0.791398	5.19902E-07
0.4	1.555286	0.802909	0.803587	4.60453E-07
0.41	1.602699	0.814678	0.815305	3.93266E-07
0.42	1.650587	0.825988	0.826555	3.21942E-07
0.43	1.698957	0.836841	0.837342	2.50255E-07
0.44	1.747814	0.847243	0.847669	1.81959E-07
0.45	1.797161	0.857196	0.857543	1.20609E-07
0.46	1.847004	0.866706	0.866969	6.93874E-08
0.47	1.897348	0.87578	0.875956	3.09686E-08
0.48	1.948198	0.884423	0.884509	7.40104E-09
0.49	1.999559	0.892644	0.892638	2.89666E-11
0.5	2.051437	0.900449	0.900352	9.45023E-09
0.51	2.103835	0.907849	0.90766	3.55104E-08
0.52	2.156761	0.91485	0.914572	7.73331E-08
0.53	2.210218	0.921464	0.921099	1.33383E-07
0.54	2.264213	0.9277	0.927251	2.01558E-07
0.55	2.31875	0.933569	0.933041	2.79299E-07
0.56	2.373835	0.939082	0.938479	3.63726E-07
0.57	2.429474	0.94425	0.943578	4.51771E-07
0.58	2.485672	0.949085	0.94835	5.40316E-07
0.59	2.542435	0.9536	0.952808	6.26332E-07
0.6	2.599768	0.957806	0.956965	7.06999E-07
0.61	2.657677	0.961716	0.960832	7.79812E-07
0.62	2.716169	0.965342	0.964424	8.42663E-07
0.63	2.775248	0.968698	0.967753	8.93909E-07
0.64	2.834921	0.971797	0.970831	9.32399E-07
0.65	2.895194	0.974651	0.973672	9.57495E-07
0.66	2.956073	0.977273	0.976288	9.69054E-07
0.67	3.017563	0.979676	0.978692	9.67395E-07
0.68	3.079672	0.981872	0.980896	9.53254E-07
0.69	3.142404	0.983874	0.982911	9.27713E-07
0.7	3.205768	0.985695	0.98475	8.92131E-07
0.71	3.269767	0.987345	0.986424	8.48064E-07

0.72	3.334411	0.988837	0.987944	7.97186E-07
0.73	3.399703	0.990182	0.989321	7.41215E-07
0.74	3.465652	0.991391	0.990565	6.81843E-07
0.75	3.532264	0.992474	0.991686	6.20675E-07
0.76	3.599545	0.993441	0.992693	5.59182E-07
0.77	3.667503	0.994302	0.993596	4.98665E-07
0.78	3.736143	0.995067	0.994403	4.40225E-07
0.79	3.805474	0.995743	0.995122	3.84757E-07
0.8	3.875501	0.996339	0.995762	3.32945E-07
0.81	3.946232	0.996862	0.996328	2.85264E-07
			SUM	3.35029E-05
			AVG	4.08572E-07

a	1.031861
b	0.101224

Tau = 1.0

Z	ζ	Ψ	proposed f(ζ)	(Ψ-f)^2
0	0	0	0	0
0.02	0.020201	0.021332	0.02067	4.38995E-07
0.04	0.040811	0.042644	0.041398	1.55178E-06
0.06	0.061837	0.063926	0.062177	3.05894E-06
0.08	0.083287	0.085169	0.082995	4.72515E-06
0.1	0.105171	0.106367	0.103845	6.36168E-06
0.12	0.127497	0.127511	0.124714	7.82503E-06
0.14	0.150274	0.148595	0.145593	9.01374E-06
0.16	0.173511	0.169612	0.166471	9.86426E-06
0.18	0.197217	0.190553	0.187336	1.03463E-05
0.2	0.221403	0.211412	0.208178	1.04576E-05
0.22	0.246077	0.232181	0.228984	1.02195E-05
0.24	0.271249	0.252853	0.249743	9.67138E-06
0.26	0.29693	0.273419	0.270441	8.86597E-06
0.28	0.32313	0.293871	0.291067	7.86506E-06
0.3	0.349859	0.314202	0.311607	6.73511E-06
0.32	0.377128	0.334403	0.332049	5.54353E-06
0.34	0.404948	0.354465	0.352378	4.35531E-06
0.36	0.433329	0.37438	0.372582	3.23022E-06
0.38	0.462285	0.394137	0.392647	2.22051E-06
0.4	0.491825	0.413729	0.412559	1.36906E-06
0.42	0.521962	0.433146	0.432304	7.08235E-07
0.44	0.552707	0.452377	0.451868	2.59087E-07
0.46	0.584074	0.471414	0.471237	3.1198E-08
0.48	0.616074	0.490245	0.490397	2.29436E-08
0.5	0.648721	0.508861	0.509333	2.22205E-07
0.52	0.682028	0.527252	0.528032	6.07471E-07
0.54	0.716007	0.545407	0.546479	1.14926E-06
0.56	0.750673	0.563315	0.564661	1.81183E-06
0.58	0.786038	0.580966	0.582564	2.55502E-06

0.6	0.822119	0.598348	0.600175	3.33628E-06
0.62	0.858928	0.615451	0.617479	4.11266E-06
0.64	0.896481	0.632265	0.634466	4.84281E-06
0.66	0.934792	0.648778	0.65112	5.48885E-06
0.68	0.973878	0.664979	0.667432	6.01798E-06
0.7	1.013753	0.680858	0.683388	6.40396E-06
0.72	1.054433	0.696403	0.698978	6.62817E-06
0.74	1.095936	0.711606	0.714191	6.68036E-06
0.76	1.138276	0.726455	0.729016	6.55902E-06
0.78	1.181472	0.74094	0.743445	6.27134E-06
0.8	1.225541	0.755053	0.757468	5.83279E-06
0.82	1.2705	0.768783	0.771077	5.26627E-06
0.84	1.316367	0.782121	0.784266	4.60105E-06
0.86	1.363161	0.79506	0.797028	3.87123E-06
0.88	1.4109	0.807592	0.809357	3.11414E-06
0.9	1.459603	0.81971	0.821248	2.36848E-06
0.92	1.50929	0.831406	0.832699	1.67243E-06
0.94	1.559981	0.842675	0.843706	1.06184E-06
0.96	1.611696	0.853514	0.854267	5.68383E-07
0.98	1.664456	0.863916	0.864383	2.18084E-07
1	1.718282	0.873879	0.874053	3.00055E-08
1.02	1.773195	0.883402	0.883278	1.53318E-08
1.04	1.829217	0.892482	0.892062	1.7684E-07
1.06	1.886371	0.901121	0.900407	5.08799E-07
1.08	1.94468	0.909318	0.908319	9.97305E-07
1.1	2.004166	0.917077	0.915804	1.62104E-06
1.12	2.064854	0.924401	0.922867	2.35239E-06
1.14	2.126768	0.931294	0.929517	3.15894E-06
1.16	2.189933	0.937763	0.935762	4.00515E-06
1.18	2.254374	0.943815	0.941612	4.85415E-06
1.2	2.320117	0.949458	0.947077	5.66972E-06
1.22	2.387188	0.954703	0.952169	6.41797E-06
1.24	2.455613	0.959559	0.9569	7.06907E-06
1.26	2.525421	0.964039	0.961283	7.59858E-06
1.28	2.59664	0.968156	0.96533	7.98844E-06
1.3	2.669297	0.971924	0.969056	8.22762E-06
1.32	2.743421	0.975359	0.972475	8.31235E-06
1.34	2.819044	0.978474	0.975603	8.24581E-06
1.36	2.896193	0.981288	0.978453	8.03764E-06
1.38	2.974902	0.983817	0.981042	7.70291E-06
1.4	3.0552	0.986079	0.983384	7.26095E-06
1.42	3.13712	0.98809	0.985495	6.73404E-06
1.44	3.220696	0.989869	0.98739	6.14596E-06
1.46	3.30596	0.991434	0.989085	5.5206E-06
1.48	3.392946	0.992803	0.990593	4.88075E-06
1.5	3.481689	0.993991	0.991931	4.24703E-06
1.52	3.572225	0.995017	0.99311	3.63709E-06
1.54	3.66459	0.995897	0.994146	3.06509E-06
1.56	3.758821	0.996646	0.995052	2.54149E-06
1.58	3.854956	0.997279	0.995839	2.07303E-06

1.6	3.953032	0.99781	0.99652	1.66302E-06
			SUM	0.000356762
			AVG	4.40447E-06

	a	1.505438		
	b	-0.070611		
Tau = 10	c	0		
			proposed	
Z	ζ	Ψ	f(ζ)	(Ψ-f)^2
0	0	0	0	0
0.1	0.033258	0.055757	0.048761	4.8941E-05
0.2	0.070014	0.111444	0.099725	0.000137338
0.3	0.110635	0.167013	0.152691	0.000205126
0.4	0.155529	0.222406	0.207395	0.000225315
0.5	0.205144	0.277551	0.26351	0.000197145
0.6	0.259977	0.33236	0.320642	0.000137331
0.7	0.320577	0.386726	0.378334	7.0438E-05
0.8	0.38755	0.440515	0.436071	1.97452E-05
0.9	0.461567	0.493561	0.49329	7.34409E-08
1	0.543368	0.545668	0.549393	1.38789E-05
1.1	0.633773	0.596594	0.603763	5.14023E-05
1.2	0.733685	0.646057	0.655792	9.47677E-05
1.3	0.844106	0.693726	0.704899	0.000124834
1.4	0.966139	0.739224	0.750564	0.000128598
1.5	1.101007	0.78213	0.79235	0.000104453
1.6	1.250059	0.821993	0.82993	6.30003E-05
1.7	1.414786	0.85835	0.863104	2.26043E-05
1.8	1.596839	0.890759	0.891813	1.10999E-06
1.9	1.798038	0.918842	0.916136	7.32387E-06
2	2.020397	0.942338	0.936286	3.66284E-05
2.1	2.266142	0.961165	0.95259	7.35271E-05
2.2	2.537732	0.975468	0.965461	0.000100139
2.3	2.837886	0.985646	0.975365	0.000105707
2.4	3.169607	0.992335	0.98279	9.11107E-05
2.5	3.536215	0.996326	0.988211	6.58612E-05
2.6	3.94138	0.998449	0.992066	4.07379E-05
			SUM	0.002167135
			AVG	8.02643E-05

Table B.7-4. Spreadsheet excerpts showing least squares fits for spherical geometry.

	a	0.761335		
	b	0.16477		
Tau = 0.01				
			proposed	
Z	ζ	Ψ	f(ζ)	(Ψ-f)^2
0.72	3.888889	0.996154	0.995715	1.9256E-07

0.73	3.69863	0.994248	0.993717	2.81726E-07
0.74	3.513514	0.991603	0.990986	3.80533E-07
0.75	3.333333	0.988018	0.987331	4.7319E-07
0.76	3.157895	0.983266	0.982531	5.38951E-07
0.77	2.987013	0.977093	0.976346	5.57456E-07
0.78	2.820513	0.96923	0.968512	5.16125E-07
0.79	2.658228	0.959395	0.95875	4.1705E-07
0.8	2.5	0.9473	0.946771	2.80151E-07
0.81	2.345679	0.932659	0.932285	1.40057E-07
0.82	2.195122	0.915197	0.915006	3.63914E-08
0.83	2.048193	0.894656	0.894663	4.64249E-11
0.84	1.904762	0.870802	0.871003	4.04612E-08
0.85	1.764706	0.843433	0.843806	1.3953E-07
0.86	1.627907	0.81238	0.812886	2.55941E-07
0.87	1.494253	0.777516	0.778099	3.39835E-07
0.88	1.363636	0.738755	0.739349	3.53082E-07
0.89	1.235955	0.696056	0.696592	2.87067E-07
0.9	1.111111	0.649422	0.649834	1.69482E-07
0.91	0.989011	0.598903	0.599138	5.492E-08
0.92	0.869565	0.544594	0.544619	5.99527E-10
0.93	0.752688	0.486634	0.486444	3.61738E-08
0.94	0.638298	0.425207	0.42483	1.42344E-07
0.95	0.526316	0.360541	0.360037	2.53404E-07
0.96	0.416667	0.292906	0.292366	2.91133E-07
0.97	0.309278	0.222622	0.222153	2.20252E-07
0.98	0.204082	0.150061	0.14976	9.06745E-08
0.99	0.10101	0.075667	0.075575	8.33359E-09
1	0	0	0	0
			SUM	6.49747E-06
			AVG	2.24051E-07

	a	0.950459
	b	0.138708
Tau = 0.1		

Z	ζ	Ψ	proposed f(ζ)	(Ψ-f)^2
0.45	3.865006	0.997546	0.996803	5.51486E-07
0.46	3.712239	0.99654	0.99566	7.74016E-07
0.47	3.565973	0.995235	0.994219	1.03304E-06
0.48	3.425801	0.99358	0.992433	1.31466E-06
0.49	3.29135	0.991519	0.990254	1.59875E-06
0.5	3.162278	0.988997	0.987633	1.86102E-06
0.51	3.038267	0.98596	0.98452	2.07589E-06
0.52	2.919026	0.982356	0.980866	2.2201E-06
0.53	2.804284	0.978135	0.976627	2.27604E-06
0.54	2.693792	0.973251	0.971756	2.23452E-06
0.55	2.587318	0.967661	0.966213	2.09635E-06
0.56	2.484647	0.961328	0.95996	1.87254E-06

0.57	2.385578	0.954219	0.952961	1.58315E-06
0.58	2.289925	0.946308	0.945187	1.25492E-06
0.59	2.197515	0.93757	0.936612	9.18148E-07
0.6	2.108185	0.92799	0.927214	6.032E-07
0.61	2.021784	0.917555	0.916975	3.37165E-07
0.62	1.93817	0.906258	0.905882	1.4106E-07
0.63	1.857211	0.894095	0.893928	2.78698E-08
0.64	1.778781	0.881068	0.881108	1.58228E-09
0.65	1.702765	0.867182	0.867422	5.72696E-08
0.66	1.629052	0.852445	0.852872	1.821E-07
0.67	1.55754	0.836869	0.837467	3.57105E-07
0.68	1.488131	0.820469	0.821217	5.5945E-07
0.69	1.420733	0.80326	0.804135	7.64936E-07
0.7	1.355262	0.785263	0.786238	9.50475E-07
0.71	1.291635	0.766497	0.767544	1.09628E-06
0.72	1.229775	0.746986	0.748075	1.18762E-06
0.73	1.16961	0.726751	0.727854	1.21598E-06
0.74	1.111071	0.705819	0.706905	1.17958E-06
0.75	1.054093	0.684214	0.685255	1.08327E-06
0.76	0.998614	0.661962	0.66293	9.37768E-07
0.77	0.944576	0.639089	0.63996	7.58525E-07
0.78	0.891924	0.615622	0.616373	5.64092E-07
0.79	0.840605	0.591587	0.592199	3.74336E-07
0.8	0.790569	0.56701	0.567467	2.08575E-07
0.81	0.741769	0.541919	0.542208	8.37855E-08
0.82	0.694159	0.516339	0.516453	1.30298E-08
0.83	0.647695	0.490296	0.490231	4.22261E-09
0.84	0.602339	0.463816	0.463572	5.93187E-08
0.85	0.558049	0.436923	0.436506	1.73993E-07
0.86	0.514789	0.409644	0.409063	3.37844E-07
0.87	0.472524	0.382001	0.38127	5.3512E-07
0.88	0.43122	0.354019	0.353156	7.45951E-07
0.89	0.390843	0.325722	0.324748	9.48005E-07
0.9	0.351364	0.297131	0.296074	1.11852E-06
0.91	0.312753	0.268271	0.267159	1.23658E-06
0.92	0.274981	0.239162	0.238029	1.28549E-06
0.93	0.238021	0.209828	0.208707	1.25509E-06
0.94	0.201848	0.180289	0.179219	1.14391E-06
0.95	0.166436	0.150567	0.149587	9.60786E-07
0.96	0.131762	0.120684	0.119832	7.25781E-07
0.97	0.097802	0.090661	0.089976	4.70037E-07
0.98	0.064536	0.060523	0.060039	2.34032E-07
0.99	0.031942	0.030293	0.030041	6.33646E-08
1	0	0	0	0
			SUM	4.76477E-05
			AVG	8.50853E-07

a	1.537306
b	-0.033499

Tau = 1.0

Z	ζ	Ψ	proposed f(ζ)	(Ψ-f)^2
0.2	4	0.999117	0.996351	7.6495E-06
0.21	3.761905	0.998473	0.995054	1.16901E-05
0.22	3.545455	0.997531	0.993457	1.65938E-05
0.23	3.347826	0.996225	0.99153	2.20425E-05
0.24	3.166667	0.994495	0.989243	2.75802E-05
0.25	3	0.992289	0.986572	3.26854E-05
0.26	2.846154	0.989565	0.983494	3.68566E-05
0.27	2.703704	0.98629	0.97999	3.96872E-05
0.28	2.571429	0.982442	0.976045	4.09192E-05
0.29	2.448276	0.978006	0.971645	4.04669E-05
0.3	2.333333	0.97298	0.966782	3.84134E-05
0.31	2.225806	0.967364	0.961449	3.49859E-05
0.32	2.125	0.961168	0.955644	3.05162E-05
0.33	2.030303	0.954404	0.949365	2.53966E-05
0.34	1.941176	0.94709	0.942614	2.00357E-05
0.35	1.857143	0.939245	0.935395	1.48209E-05
0.36	1.777778	0.93089	0.927713	1.0089E-05
0.37	1.702703	0.922048	0.919577	6.10603E-06
0.38	1.631579	0.912743	0.910995	3.05741E-06
0.39	1.564103	0.902999	0.901977	1.04525E-06
0.4	1.5	0.89284	0.892535	9.29413E-08
0.41	1.439024	0.882287	0.88268	1.54409E-07
0.42	1.380952	0.871365	0.872427	1.1265E-06
0.43	1.325581	0.860095	0.861787	2.86301E-06
0.44	1.272727	0.848498	0.850776	5.18903E-06
0.45	1.222222	0.836595	0.839408	7.91469E-06
0.46	1.173913	0.824403	0.827697	1.08475E-05
0.47	1.12766	0.811942	0.815658	1.3803E-05
0.48	1.083333	0.799229	0.803305	1.66132E-05
0.49	1.040816	0.786279	0.790653	1.9133E-05
0.5	1	0.773109	0.777718	2.12449E-05
0.51	0.960784	0.759731	0.764512	2.28609E-05
0.52	0.923077	0.74616	0.751051	2.3924E-05
0.53	0.886792	0.732408	0.737349	2.44068E-05
0.54	0.851852	0.718488	0.723418	2.43104E-05
0.55	0.818182	0.704409	0.709273	2.36614E-05
0.56	0.785714	0.690182	0.694927	2.25082E-05
0.57	0.754386	0.675818	0.680391	2.09178E-05
0.58	0.724138	0.661324	0.66568	1.89713E-05
0.59	0.694915	0.64671	0.650804	1.67597E-05
0.6	0.666667	0.631983	0.635775	1.43801E-05
0.61	0.639344	0.61715	0.620604	1.19317E-05
0.62	0.612903	0.602218	0.605303	9.51234E-06
0.63	0.587302	0.587195	0.589881	7.21504E-06
0.64	0.5625	0.572085	0.574349	5.12541E-06
0.65	0.538462	0.556895	0.558716	3.31918E-06

0.66	0.515152	0.541629	0.542993	1.86036E-06
0.67	0.492537	0.526292	0.527186	7.99684E-07
0.68	0.470588	0.51089	0.511306	1.73707E-07
0.69	0.449275	0.495426	0.495361	4.1609E-09
0.7	0.428571	0.479904	0.479358	2.97819E-07
0.71	0.408451	0.464328	0.463305	1.04671E-06
0.72	0.388889	0.448702	0.447209	2.22868E-06
0.73	0.369863	0.433028	0.431077	3.80826E-06
0.74	0.351351	0.417311	0.414916	5.73788E-06
0.75	0.333333	0.401552	0.398731	7.9592E-06
0.76	0.315789	0.385755	0.38253	1.04048E-05
0.77	0.298701	0.369923	0.366317	1.29998E-05
0.78	0.282051	0.354056	0.350098	1.56641E-05
0.79	0.265823	0.338158	0.333879	1.83142E-05
0.8	0.25	0.322232	0.317664	2.08653E-05
0.81	0.234568	0.306278	0.301458	2.32337E-05
0.82	0.219512	0.290299	0.285265	2.53386E-05
0.83	0.204819	0.274296	0.26909	2.71048E-05
0.84	0.190476	0.258272	0.252936	2.84647E-05
0.85	0.176471	0.242227	0.236808	2.93603E-05
0.86	0.162791	0.226163	0.22071	2.97457E-05
0.87	0.149425	0.210083	0.204643	2.95888E-05
0.88	0.136364	0.193986	0.188613	2.88735E-05
0.89	0.123596	0.177875	0.172621	2.76016E-05
0.9	0.111111	0.16175	0.156671	2.57943E-05
0.91	0.098901	0.145613	0.140766	2.34944E-05
0.92	0.086957	0.129464	0.124907	2.07674E-05
0.93	0.075269	0.113306	0.109099	1.77032E-05
0.94	0.06383	0.097139	0.093342	1.44174E-05
0.95	0.052632	0.080963	0.077639	1.10522E-05
0.96	0.041667	0.06478	0.061991	7.77789E-06
0.97	0.030928	0.048592	0.046402	4.79307E-06
0.98	0.020408	0.032398	0.030873	2.32556E-06
0.99	0.010101	0.0162	0.015405	6.32517E-07
1	0	0	0	0
			SUM	0.001289658
			AVG	1.59217E-05

	a	3.499587
	b	-2.228657
Tau = 10	c	0.858206

Z	ζ	Ψ	proposed f(ζ)	(Ψ-f)^2
0.07	4.201312	0.999787	1	4.5253E-08
0.08	3.636619	0.999217	1	6.12872E-07
0.09	3.197414	0.997966	1	4.13654E-06
0.1	2.84605	0.995816	0.999992	1.74363E-05
0.11	2.55857	0.992662	0.99984	5.15257E-05

0.12	2.319004	0.988495	0.998922	0.000108735
0.13	2.116294	0.983371	0.996147	0.000163242
0.14	1.942542	0.977376	0.990712	0.000177858
0.15	1.791957	0.97061	0.982628	0.000144427
0.16	1.660196	0.963172	0.972521	8.74053E-05
0.17	1.543936	0.955152	0.961191	3.64598E-05
0.18	1.440593	0.946633	0.949313	7.18452E-06
0.19	1.348129	0.937684	0.937348	1.13103E-07
0.2	1.264911	0.928368	0.925555	7.91225E-06
0.21	1.189619	0.918737	0.914052	2.19472E-05
0.22	1.121171	0.908835	0.902866	3.56348E-05
0.23	1.058676	0.8987	0.891973	4.52592E-05
0.24	1.001388	0.888364	0.881327	4.95232E-05
0.25	0.948683	0.877853	0.870873	4.8728E-05
0.26	0.900033	0.867191	0.860557	4.40161E-05
0.27	0.854986	0.856398	0.85033	3.68211E-05
0.28	0.813157	0.84549	0.840149	2.85251E-05
0.29	0.774213	0.83448	0.829977	2.02808E-05
0.3	0.737865	0.823383	0.819785	1.29416E-05
0.31	0.703862	0.812207	0.80955	7.06112E-06
0.32	0.671984	0.800963	0.799252	2.92631E-06
0.33	0.642038	0.789657	0.788877	6.07985E-07
0.34	0.613854	0.778298	0.778416	1.39162E-08
0.35	0.58728	0.76689	0.767859	9.38759E-07
0.36	0.562183	0.755439	0.757202	3.10734E-06
0.37	0.538442	0.74395	0.746442	6.21007E-06
0.38	0.515951	0.732426	0.735578	9.93062E-06
0.39	0.494613	0.720872	0.724609	1.39664E-05
0.4	0.474342	0.709289	0.713537	1.8043E-05
0.41	0.455059	0.697682	0.702364	2.19235E-05
0.42	0.436695	0.686051	0.691092	2.54132E-05
0.43	0.419186	0.6744	0.679726	2.83623E-05
0.44	0.402472	0.662731	0.668268	3.06645E-05
0.45	0.386501	0.651044	0.656724	3.22553E-05
0.46	0.371224	0.639342	0.645096	3.31079E-05
0.47	0.356597	0.627626	0.633391	3.32294E-05
0.48	0.34258	0.615898	0.621612	3.26553E-05
0.49	0.329135	0.604157	0.609765	3.1445E-05
0.5	0.316228	0.592406	0.597854	2.96765E-05
0.51	0.303827	0.580645	0.585884	2.74417E-05
0.52	0.291903	0.568875	0.57386	2.48418E-05
0.53	0.280428	0.557097	0.561786	2.19832E-05
0.54	0.269379	0.545312	0.549667	1.89736E-05
0.55	0.258732	0.533519	0.537509	1.59189E-05
0.56	0.248465	0.52172	0.525314	1.29203E-05
0.57	0.238558	0.509915	0.513088	1.00719E-05
0.58	0.228993	0.498104	0.500835	7.45881E-06
0.59	0.219751	0.486289	0.488559	5.15532E-06
0.6	0.210819	0.474468	0.476264	3.22419E-06
0.61	0.202178	0.462644	0.463954	1.71558E-06

0.62	0.193817	0.450815	0.451632	6.66759E-07
0.63	0.185721	0.438983	0.439302	1.01865E-07
0.64	0.177878	0.427147	0.426968	3.20992E-08
0.65	0.170276	0.415308	0.414633	4.56071E-07
0.66	0.162905	0.403467	0.4023	1.36038E-06
0.67	0.155754	0.391622	0.389973	2.72039E-06
0.68	0.148813	0.379775	0.377653	4.5011E-06
0.69	0.142073	0.367926	0.365345	6.65826E-06
0.7	0.135526	0.356074	0.353051	9.13943E-06
0.71	0.129163	0.34422	0.340773	1.18853E-05
0.72	0.122977	0.332365	0.328514	1.48308E-05
0.73	0.116961	0.320507	0.316276	1.79068E-05
0.74	0.111107	0.308648	0.304061	2.10411E-05
0.75	0.105409	0.296788	0.291872	2.41599E-05
0.76	0.099861	0.284926	0.279711	2.71895E-05
0.77	0.094458	0.273063	0.26758	3.00572E-05
0.78	0.089192	0.261198	0.25548	3.2693E-05
0.79	0.084061	0.249333	0.243414	3.50307E-05
0.8	0.079057	0.237466	0.231382	3.70095E-05
0.81	0.074177	0.225598	0.219387	3.85749E-05
0.82	0.069416	0.21373	0.20743	3.96802E-05
0.83	0.06477	0.20186	0.195513	4.02877E-05
0.84	0.060234	0.18999	0.183636	4.03692E-05
0.85	0.055805	0.178119	0.171802	3.9908E-05
0.86	0.051479	0.166247	0.160011	3.88991E-05
0.87	0.047252	0.154375	0.148264	3.73507E-05
0.88	0.043122	0.142503	0.136562	3.52844E-05
0.89	0.039084	0.130629	0.124908	3.2737E-05
0.9	0.035136	0.118755	0.1133	2.97601E-05
0.91	0.031275	0.106881	0.101741	2.64218E-05
0.92	0.027498	0.095007	0.090231	2.28068E-05
0.93	0.023802	0.083132	0.078771	1.9017E-05
0.94	0.020185	0.071256	0.067361	1.51721E-05
0.95	0.016644	0.059381	0.056003	1.14102E-05
0.96	0.013176	0.047505	0.044696	7.8879E-06
0.97	0.00978	0.035629	0.033442	4.78096E-06
0.98	0.006454	0.023753	0.022241	2.28435E-06
0.99	0.003194	0.011876	0.011094	6.12605E-07
1	0	0	0	0
			SUM	0.0024227
			AVG	2.57734E-05

APPENDIX C TEST CASE #2

C.1 DRSPALL Input for Test Case #2

Table C.1-1. DRSPALL input for Test Case #2, Run 6 (DRS_TC26.DRS)

```
REPOSITORY                                  :
 Land Elevation                 m           :   960.000
 Repository Top                 m           :     0.000
 Total Thickness                m           :    13.7
 DRZ Thickness                  m           :     0.850
 DRZ Permeability               m^2         :  1.000E-15
 Outer Radius                   m           :    15.000
 Initial Gas Pressure           Pa          :  11.4E+06
 Far-Field In-Situ Stress       Pa          :  15.3E+06
                                            :
WASTE                                       :
 Porosity                       -           : 0.05
 Permeability                   m^2         : 0.30E-14
 Forchheimer Beta               -           : 1.15e-6
 Biot Beta                      -           : 1.0000
 Poisson's Ratio                -           : 0.3000
 Cohesion                       Pa          : 1.000E+04
 Friction Angle                 deg         :  45.000
 Tensile Strength               Pa          : 2.500E+05
 Characteristic Length          m           : 0.01
 Particle Diameter              m           : 0.001
 Gas Viscosity                  Pa-s        : 2.000E-05
                                            :
MUD                                         :
 Density                        kg/m^3      : 1210.000
 Viscosity                      Pa-s        :  1.000E-02
 Wall Roughness Pipe            m           :  1.000E-05
 Wall Roughness Annulus         m           :  0.100E-05
 Max. Solids Vol. Fraction      -           :  0.6000
 Solids Viscosity Exponent      -           : -1.8000
 Choke Efficiency               -           :  0.9000
                                            :
WELLBORE/DRILLING                           :
 Bit Diameter                   m           : 0.30
 Pipe Diameter                  m           : default
 Collar Diameter                m           : default
 Pipe Inside Diameter           m           : default
 Collar Length                  m           : 0.0000
 Exit Pipe Length               m           : 0.0000
 Exit Pipe Diameter             m           : 0.3048
 Drilling Rate                  m/s         : 0.0000
 Bit Above Repository (Init.)   m           : -13.7
 Mud Pump Rate                  m^3/s       : 0.0000
 Max Pump Pressure              Pa          :  2.750E+07
 DDZ Thickness                  m           :  0.150
 DDZ Permeability               m^2         :  1.000E-14
 Stop Drilling Exit Vol. Rate   m^3/s       : 1000.000
 Stop Pumping Exit Vol. Rate    m^3/s       : 1000.000
 Stop DrillingTime              s           : 1000.000
                                            :
COMPUTATIONAL                               :
 Spherical/Cylindrical          S/C         : C
 Allow Fluidization?            Y/N         : Y
 Maximum Run Time               s           : 1680.0
 Repository Cell Length         m           : 0.002
 Radius, Growth Rate            m,-         : 0.500 1.020
 Wellbore Cell Length           m           : 2.0000
 Wellbore ZoneGrowth Rate       --          : 1.010E+00
 First Wellbore Zone            --          : 2
 Well Stability Factor          --          : 1.000E-01
 Repository Stability Factor    --          : 5.000E+00
 Mass Diffusion Factor          --          : 1.000E-03
```

```
 Momentum Diffusion Factor     --         : 4.000E-03

VALIDATION
 Validation Test Case          --         : 2.6
 Initial cavity radius         m          : 1.01
 Minimum Characteristic Velocity  m/s     : 0.5
```

APPENDIX D TEST CASE #4

D.1 DRSPALL Input for Test Case #4

Table D.1-1. DRSPALL input for Case 4.1 (DRS_TC41.DRS)

```
REPOSITORY
 Land Elevation                 m          : 1.0373E+03
 Repository top                 m          : 3.8531E+02
 Total Thickness                m          : 1.4200E+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               -          : 1.15e-6
 Biot Beta                      -          : 1.0000E+00
 Poisson's Ratio                -          : 3.8000E-01
 Cohesion                       Pa         : 1.3000E+05
 Friction Angle                 deg        : 4.5800E+01
 Tensile Strength               Pa         : 0.1200E+06
 Lt                             -          : 0.02
 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
 Max Solids Vol. Frac.          Pa-s       : 6.1500E-01
 Solids Viscosity Exp.          Pa-s       : -1.5000E+00

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          : 0.0
 Exit Pipe Diameter             m          : 0.2032
 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        : Y
 Max Run Time                   s          : 4.5000E+02
 Respository Cell Length        m          : 2.0000E-03
 Repository Radius, Growth      m,-        : 0.500  1.010
 Wellbore Cell Length           m          : 1.0000E+00
```

```
 Wellbore Zone Growth Rate     -          : 1.01
 First Wellbore Zone           -          : 2
 Well Stability factor         -          : 0.05
 Repository Stability factor   -          : 2.0000E+00
 Mass Diffusion factor         -          : 2.0000E-03
 Momentum Diffusion factor     -          : 2.0000E-03

VALIDATION
 Validation Test Case          -          : 4.1

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
 Water Compressibility         1/Pa       : 12.4e-10   !3.1000E-10
 Waste Density                 kg/m^3     : 2.6500E+03
 Salt Density                  kg/m^3     : 2.1800E+03
 Shape Factor                  -          : 0.5500E+00
 Tensile Velocity              m/s        : 1.0000E+03
 Bit Nozzle Number             -          : 3.0000E+00
 Bit Nozzle Diameter           m          : 1.1113E-02
 Choke Efficiency              -          : 9.0000E-01
```

Table D.1-2. DRSPALL input for Case 4.2 (DRS_TC42.DRS)

```
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

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, 1.01
Wellbore Cell Length              (m):  1.0
wellbore Zone Growth Rate         (-):  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
```

APPENDIX E TEST CASE #5

E.1 DRSPALL Input for Test Case #5

Table E.1-1. DRSPALL input for Case 5.1 (DRS_TC51.DRS)

```
REPOSITORY                                  :
 Land Elevation                m            : 1037.300
 Repository Top                m            : 385.310
 Total Thickness               m            : 1.420
 DRZ Thickness                 m            : 0.850
 DRZ Permeability              m^2          : 1e-20
 Outer Radius                  m            : 19.200
 Initial Gas Pressure          Pa           : 8e6
 Far-Field In-Situ Stress      Pa           : 1.480E+07
                                            :
WASTE                                       :
 Porosity                      -            : 0.5750
 Permeability                  m^2          : 1.700E-13
 Forchheimer Beta              -            : 1.15e-6
 Biot Beta                     -            : 1.0000
 Poisson's Ratio               -            : 0.3800
 Cohesion                      Pa           : 1.300E+05
 Friction Angle                deg          : 45.000
 Tensile Strength              Pa           : 6.895E+03
 Lt                            m            : 0.2
 Particle Diameter             m            : 0.0010
 Gas Viscosity                 Pa-s         : 8.934e-6
                                            :
MUD                                         :
 Density                       kg/m^3       : 1210.000
 Viscosity                     Pa-s         : 1.100E-02
 Wall Roughness Pipe           m            : 5.0000E-05
 Wall Roughness Annulus        m            : 5.0000E-05
 Max. Solids Vol. Fraction     -            : 0.6000
 Solids Viscosity Exponent     -            : -1.8000
                                            :
WELLBORE/DRILLING                           :
 Bit Diameter                  m            : 0.3112
 Pipe Diameter                 m            : 0.1143
 Collar Diameter               m            : 0.2032
 Pipe Inside Diameter          m            : 9.718e-2
 Collar Length                 m            : 182.9000
 Exit Pipe Length              m            : 0.0
 Exit Pipe Diameter            m            : 0.2032
 Drilling Rate                 m/s          : 5.0e-3
 Bit Above Repository (Init.)  m            : 0.150
 Mud Pump Rate                 m^3/s        : 0.0
 Max Pump Pressure             Pa           : 2.750E+07
 DDZ Thickness                 m            : 0.150
 DDZ Permeability              m^2          : 1e-15
 Stop Drilling Exit Vol. Rate  m^3/s        : 0.100
 Stop Pumping Exit Vol. Rate   m^3/s        : 10000.
 Stop DrillingTime             s            : 0.1
                                            :
COMPUTATIONAL                               :
 Spherical/Cylindrical         S/C          : S
 Allow Fluidization?           Y/N          : N
 Maximum Run Time              s            : 90.0
 Repository Cell Length        m            : 0.0100
 Radius, Growth Rate           m,-          : 0.500 1.010
 Wellbore Cell Length          m            : 2.0000
```

```
 Wellbore Zone Growth Rate    -          : 1.0
 First Wellbore Zone          -          : 2
 Well Stability Factor        -          : 0.05
 Repository Stability Factor  -          : 5.000E+00
 Mass Diffusion Factor        -          : 0.0
 Momentum Diffusion Factor    -          : 0.004

VALIDATION
 Validation Test Case         -          : 5.1
                                         :
```

Table E.1-2. DRSPALL input for Case 5.2 (DRS_TC52.DRS)

```
REPOSITORY                                     :
 Land Elevation                 m              : 1037.300
 Repository Top                 m              : 385.310
 Total Thickness                m              : 1.420
 DRZ Thickness                  m              : 0.850
 DRZ Permeability               m^2            : 1e-20
 Outer Radius                   m              : 19.200
 Initial Gas Pressure           Pa             : 8e6
 Far-Field In-Situ Stress       Pa             : 1.480E+07
                                               :
WASTE                                          :
 Porosity                       -              : 0.5750
 Permeability                   m^2            : 1.700E-13
 Forchheimer Beta               -              : 0.0000
 Biot Beta                      -              : 1.0000
 Poisson's Ratio                -              : 0.3800
 Cohesion                       Pa             : 1.300E+05
 Friction Angle                 deg            : 45.000
 Tensile Strength               Pa             : 6.895E+03
 Lt                             m              : 0.2
 Particle Diameter              m              : 0.0010
 Gas Viscosity                  Pa-s           : 8.934e-6
                                               :
MUD                                            :
 Density                        kg/m^3         : 1210.000
 Viscosity                      Pa-s           : 1.100E-02
 Wall Roughness Pipe            m              : 5.0000E-05
 Wall Roughness Annulus         m              : 5.0000E-05
 Max. Solids Vol. Fraction      -              : 0.6000
 Solids Viscosity Exponent      -              : -1.8000
                                               :
WELLBORE/DRILLING                              :
 Bit Diameter                   m              : 0.3112
 Pipe Diameter                  m              : 0.1143
 Collar Diameter                m              : 0.2032
 Pipe Inside Diameter           m              : 9.718e-2
 Collar Length                  m              : 182.9000
 Exit Pipe Length               m              : 0.0
 Exit Pipe Diameter             m              : 0.2032
 Drilling Rate                  m/s            : 5.0e-3
 Bit Above Repository (Init.)   m              : 0.150
 Mud Pump Rate                  m^3/s          : 0.02018
 Max Pump Pressure              Pa             : 2.750E+07
 DDZ Thickness                  m              : 0.150
 DDZ Permeability               m^2            : 1e-15
 Stop Drilling Exit Vol. Rate   m^3/s          : 1000.
 Stop Pumping Exit Vol. Rate    m^3/s          : 10000.
 Stop DrillingTime              s              : 1000.
                                               :
COMPUTATIONAL                                  :
 Spherical/Cylindrical          S/C            : S
 Allow Fluidization?            Y/N            : N
 Maximum Run Time               s              : 90.0
 Repository Cell Length         m              : 0.0100
 Radius, Growth Rate            m,-            : 0.500 1.010
 Wellbore Cell Length           m              : 2.0000
 Wellbore Zone Growth Rate      -              : 1.0
 First Wellbore Zone            -              : 2
 Well Stability Factor          -              : 0.05
 Repository Stability Factor    -              : 5.000E+00
 Mass Diffusion Factor          -              : 0.004
 Momentum Diffusion Factor      -              : 0.004

VALIDATION
 Validation Test Case           -              : 5.2
                                                    :
```

Table E.1-3. DRSPALL input for Case 5.3 (DRS_TC53.DRS)

```
REPOSITORY                               :
 Land Elevation               m          : 1037.300
 Repository Top               m          : 385.310
 Total Thickness              m          : 1.420
 DRZ Thickness                m          : 0.850
 DRZ Permeability             m^2        : 1e-20
 Outer Radius                 m          : 19.200
 Initial Gas Pressure         Pa         : 8e6
 Far-Field In-Situ Stress     Pa         : 1.480E+07
                                         :
WASTE                                    :
 Porosity                     -          : 0.5750
 Permeability                 m^2        : 1.700E-13
 Forchheimer Beta             -          : 0.0000
 Biot Beta                    -          : 1.0000
 Poisson's Ratio              -          : 0.3800
 Cohesion                     Pa         : 1.300E+05
 Friction Angle               deg        : 45.000
 Tensile Strength             Pa         : 6.895E+03
 Lt                           m          : 0.2
 Particle Diameter            m          : 0.0010
 Gas Viscosity                Pa-s       : 8.934e-6
                                         :
MUD                                      :
 Density                      kg/m^3     : 1380.000
 Viscosity                    Pa-s       : 1.100E-02
 Wall Roughness Pipe          m          : 5.0000E-05
 Wall Roughness Annulus       m          : 5.0000E-05
 Max. Solids Vol. Fraction    -          : 0.6000
 Solids Viscosity Exponent    -          : -1.8000
                                         :
WELLBORE/DRILLING                        :
 Bit Diameter                 m          : 0.3112
 Pipe Diameter                m          : 0.1143
 Collar Diameter              m          : 0.2032
 Pipe Inside Diameter         m          : 9.718e-2
 Collar Length                m          : 182.9000
 Exit Pipe Length             m          : 0.0
 Exit Pipe Diameter           m          : 0.2032
 Drilling Rate                m/s        : 5.0e-3
 Bit Above Repository (Init.) m          : 0.150
 Mud Pump Rate                m^3/s      : 0.02018
 Max Pump Pressure            Pa         : 2.750E+07
 DDZ Thickness                m          : 0.150
 DDZ Permeability             m^2        : 1e-15
 Stop Drilling Exit Vol. Rate m^3/s      : 1000.
 Stop Pumping Exit Vol. Rate  m^3/s      : 10000.
 Stop DrillingTime            s          : 1000.
                                         :
COMPUTATIONAL                            :
 Spherical/Cylindrical        S/C        : S
 Allow Fluidization?          Y/N        : N
 Maximum Run Time             s          : 90.0
 Repository Cell Length       m          : 0.0100
 Radius, Growth Rate          m,-        : 0.500 1.010
 Wellbore Cell Length         m          : 2.0000
 Wellbore Zone Growth Rate    -          : 1.0
 First Wellbore Zone          -          : 2
 Well Stability Factor        -          : 0.05
 Repository Stability Factor  -          : 5.000E+00
 Mass Diffusion Factor        -          : 0.004
 Momentum Diffusion Factor    -          : 0.004

VALIDATION
 Validation Test Case         -          : 5.3
                                              :
```

Table E.1-4. DRSPALL input for Case 5.5 (DRS_TC55.DRS)

```
REPOSITORY                                 :
 Land Elevation               m            : 1037.300
 Repository Top               m            : 385.310
 Total Thickness              m            : 1.420
 DRZ Thickness                m            : 0.850
 DRZ Permeability             m^2          : 1e-20
 Outer Radius                 m            : 19.200
 Initial Gas Pressure         Pa           : 8e6
 Far-Field In-Situ Stress     Pa           : 1.480E+07
                                           :
WASTE                                      :
 Porosity                     -            : 0.5750
 Permeability                 m^2          : 1.700E-13
 Forchheimer Beta             -            : 0.0000
 Biot Beta                    -            : 1.0000
 Poisson's Ratio              -            : 0.3800
 Cohesion                     Pa           : 1.300E+05
 Friction Angle               deg          : 45.000
 Tensile Strength             Pa           : 6.895E+03
 Lt                           m            : 0.2
 Particle Diameter            m            : 0.0010
 Gas Viscosity                Pa-s         : 8.934e-6
                                           :
MUD                                        :
 Density                      kg/m^3       : 1210.000
 Viscosity                    Pa-s         : 8.934e-6      !1.100E-02
 Wall Roughness Pipe          m            : 5.0000E-05
 Wall Roughness Annulus       m            : 1.0000E-05
 Max. Solids Vol. Fraction    -            : 0.6000
 Solids Viscosity Exponent    -            : -1.8000
                                           :
WELLBORE/DRILLING                          :
 Bit Diameter                 m            : 0.3112
 Pipe Diameter                m            : 0.1143
 Collar Diameter              m            : 0.2032
 Pipe Inside Diameter         m            : 9.718e-2
 Collar Length                m            : 182.9000
 Exit Pipe Length             m            : 0.0
 Exit Pipe Diameter           m            : 0.2032
 Drilling Rate                m/s          : 5.0e-3
 Bit Above Repository (Init.) m            : 0.150
 Mud Pump Rate                m^3/s        : 0.02018
 Max Pump Pressure            Pa           : 2.750E+07
 DDZ Thickness                m            : 0.150
 DDZ Permeability             m^2          : 1e-15
 Stop Drilling Exit Vol. Rate m^3/s        : 1000.
 Stop Pumping Exit Vol. Rate  m^3/s        : 10000.
 Stop DrillingTime            s            : 1000.
                                           :
COMPUTATIONAL                              :
 Spherical/Cylindrical        S/C          : S
 Allow Fluidization?          Y/N          : N
 Maximum Run Time             s            : 450.0
 Repository Cell Length       m            : 0.0100
 Radius, Growth Rate          m,-          : 0.500 1.010
 Wellbore Cell Length         m            : 1.0
 Wellbore Zone Growth Rate    -            : 1.01
 First Wellbore Zone          -            : 2
 Well Stability Factor        -            : 0.05
 Repository Stability Factor  -            : 5.000E+00
 Mass Diffusion Factor        -            : 0.001
 Momentum Diffusion Factor    -            : 0.004

VALIDATION
 Validation Test Case         -            : 5.5
                                           :
```

Table E.1-5. DRSPALL input for Case 5.6 (DRS_TC56.DRS)

```
REPOSITORY                                         :
 Land Elevation                    m               : 1037.300
 Repository Top                    m               : 385.310
 Total Thickness                   m               : 1.420
 DRZ Thickness                     m               : 0.850
 DRZ Permeability                  m^2             : 1e-20
 Outer Radius                      m               : 19.200
 Initial Gas Pressure              Pa              : 8e6
 Far-Field In-Situ Stress          Pa              : 1.480E+07
                                                   :
WASTE                                              :
 Porosity                          -               : 0.5750
 Permeability                      m^2             : 1.700E-13
 Forchheimer Beta                  -               : 0.0000
 Biot Beta                         -               : 1.0000
 Poisson's Ratio                   -               : 0.3800
 Cohesion                          Pa              : 1.300E+05
 Friction Angle                    deg             : 45.000
 Tensile Strength                  Pa              : 6.895E+03
 Lt                                m               : 0.2
 Particle Diameter                 m               : 0.0010
 Gas Viscosity                     Pa-s            : 8.934e-6
                                                   :
MUD                                                :
 Density                           kg/m^3          : 1210.000
 Viscosity                         Pa-s            : 8.934e-6     !1.100E-02
 Wall Roughness Pipe               m               : 5.0000E-05
 Wall Roughness Annulus            m               : 1.0000E-05
 Max. Solids Vol. Fraction         -               : 0.6000
 Solids Viscosity Exponent         -               : -1.8000
                                                   :
WELLBORE/DRILLING                                  :
 Bit Diameter                      m               : 0.3112
 Pipe Diameter                     m               : 0.1143
 Collar Diameter                   m               : 0.2032
 Pipe Inside Diameter              m               : 9.718e-2
 Collar Length                     m               : 182.9000
 Exit Pipe Length                  m               : 0.0
 Exit Pipe Diameter                m               : 0.2032
 Drilling Rate                     m/s             : 5.0e-3
 Bit Above Repository (Init.)      m               : 0.150
 Mud Pump Rate                     m^3/s           : 0.02018
 Max Pump Pressure                 Pa              : 2.750E+07
 DDZ Thickness                     m               : 0.150
 DDZ Permeability                  m^2             : 1e-15
 Stop Drilling Exit Vol. Rate      m^3/s           : 1000.
 Stop Pumping Exit Vol. Rate       m^3/s           : 10000.
 Stop DrillingTime                 s               : 1000.
                                                   :
COMPUTATIONAL                                      :
 Spherical/Cylindrical             S/C             : S
 Allow Fluidization?               Y/N             : N
 Maximum Run Time                  s               : 120.0
 Repository Cell Length            m               : 0.0100
 Radius, Growth Rate               m,-             : 0.500 1.010
 Wellbore Cell Length              m               : 1.0
 Wellbore Zone Growth Rate         -               : 1.01
 First Wellbore Zone               -               : 2
 Well Stability Factor             -               : 0.05
 Repository Stability Factor       -               : 5.000E+00
 Mass Diffusion Factor             -               : 0.001
 Momentum Diffusion Factor         -               : 0.004

VALIDATION
 Validation Test Case              -               : 5.6
                                                   :
```

Table E.1-6. DRSPALL input for Case 5.7 (DRS_TC57.DRS)

```
REPOSITORY                                  :
 Land Elevation               m             : 1037.300
 Repository Top               m             : 385.310
 Total Thickness              m             : 1.420
 DRZ Thickness                m             : 0.850
 DRZ Permeability             m^2           : 1e-20
 Outer Radius                 m             : 19.200
 Initial Gas Pressure         Pa            : 8e6
 Far-Field In-Situ Stress     Pa            : 1.480E+07
                                            :
WASTE                                       :
 Porosity                     -             : 0.5750
 Permeability                 m^2           : 1.700E-13
 Forchheimer Beta             -             : 0.0000
 Biot Beta                    -             : 1.0000
 Poisson's Ratio              -             : 0.3800
 Cohesion                     Pa            : 1.300E+05
 Friction Angle               deg           : 45.000
 Tensile Strength             Pa            : 6.895E+03
 Lt                           m             : 0.2
 Particle Diameter            m             : 0.0010
 Gas Viscosity                Pa-s          : 8.934e-6
                                            :
MUD                                         :
 Density                      kg/m^3        : 1210.000
 Viscosity                    Pa-s          : 8.934e-6     !1.100E-02
 Wall Roughness Pipe          m             : 5.0000E-05
 Wall Roughness Annulus       m             : 5.0000E-05
 Max. Solids Vol. Fraction    -             : 0.6000
 Solids Viscosity Exponent    -             : -1.8000
                                            :
WELLBORE/DRILLING                           :
 Bit Diameter                 m             : 0.3112
 Pipe Diameter                m             : 0.1143
 Collar Diameter              m             : 0.2032
 Pipe Inside Diameter         m             : 9.718e-2
 Collar Length                m             : 182.9000
 Exit Pipe Length             m             : 0.0
 Exit Pipe Diameter           m             : 0.2032
 Drilling Rate                m/s           : 5.0e-3
 Bit Above Repository (Init.) m             : 0.150
 Mud Pump Rate                m^3/s         : 0.02018
 Max Pump Pressure            Pa            : 2.750E+07
 DDZ Thickness                m             : 0.150
 DDZ Permeability             m^2           : 1e-15
 Stop Drilling Exit Vol. Rate m^3/s         : 1000.
 Stop Pumping Exit Vol. Rate  m^3/s         : 10000.
 Stop DrillingTime            s             : 1000.
                                            :
COMPUTATIONAL                               :
 Spherical/Cylindrical        S/C           : S
 Allow Fluidization?          Y/N           : N
 Maximum Run Time             s             : 100.0
 Repository Cell Length       m             : 0.0100
 Radius, Growth Rate          m,-           : 0.500 1.010
 Wellbore Cell Length         m             : 1.0
 Wellbore Zone Growth Rate    -             : 1.01
 First Wellbore Zone          -             : 2
 Well Stability Factor        -             : 0.05
 Repository Stability Factor  -             : 5.000E+00
 Mass Diffusion Factor        -             : 0.001
 Momentum Diffusion Factor    -             : 0.004

VALIDATION
 Validation Test Case         -             : 5.7
                                            :
```