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SUMMARY OF 1988 WIPP FACILITY HORIZON GAS FLOW MEASUREMENTS

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ABSTRACT

Numerous gas flow measurements have been made at the Waste Isolation Pilot Plant (WIPP) Facility horizon during 1988. All tests have been pressure decay or constant pressure tests from single boreholes drilled from the underground excavations. The test fluid has been nitrogen. The data have been interpreted as permeabilities and porosities by means of a transient numerical solution method. A closed-form steady-state approximation provides a reasonable order-of-magnitude permeability estimate. The effective resolution of the measurement system is less than 10^{-20} m².

Results indicate that beyond 1 to 5 m from an excavation, the gas flow is very small and the corresponding permeability is below the system resolution. Within the first meter of an excavation, the interpreted permeabilities can be 5 orders of magnitude greater than the undisturbed or far-field permeability. The interpreted permeabilities in the region between the undisturbed region and the first meter from an excavation are in the range of 10^{-16} to 10^{-20} m². Measurable gas flow occurs to a greater depth into the roof above WIPP excavations of different sizes and ages than into the ribs and floor. The gas flows into the formation surrounding the smallest excavation tested are consistently lower than those at similar locations surrounding larger excavations of comparable age. Gas flow measured in the interbed layers near the WIPP excavations is highly variable. Generally, immediately above and below excavations, relatively large gas flow is measured in the interbed layers. These results are consistent with previous measurements and indicate a limited disturbed zone surrounding WIPP excavations.

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1.0 INTRODUCTION

This report describes the objectives, equipment, techniques, analysis methods and results of injected gas flow measurements made throughout the underground workings of the Waste Isolation Pilot Plant (WIPP) Facility from May through October, 1988. Gas flow measurements made from 1984 through 1986 were summarized by Stormont et al. (1987), and those made in 1987 are given by Borns and Stormont (1988).

The Waste Isolation Pilot Plant (WIPP) is being developed by the Department of Energy (DOE) to demonstrate safe disposal in rock salt of radioactive waste from US defense programs. A part of the WIPP Research and Development Program conducted by Sandia National Laboratories (SNL) is directed toward developing acceptable sealing technology for man-made WIPP penetrations (boreholes, shafts, and drifts). The basic goal of sealing is to limit fluid migration in, through, and out of the repository. In support of developing seal designs, measurements are being made from which estimates of the host rock permeability are made.

Previous measurements indicate that the gas permeability of undisturbed rock salt (more than 5 m from an excavation) is typically below the measurement system resolution (Stormont et al., 1987; Borns and Stormont, 1988). Stormont et al. (1987) have argued that the gas permeability of undisturbed rock salt is most likely effectively zero due to the probability that the porosity of undisturbed rock salt ($<<1\%$) is saturated with brine under relatively great pressures. The gas pressure required to displace pore brine was estimated to range from <1 MPa to 100 MPa by Stormont et al. (1987). Within about 5 m of WIPP excavations, however, injected gas flow into rock salt intervals was measured which corresponds to permeabilities for rock salt which range from 10^{-15} to 10^{-21} m². Further, gas flow into intervals containing horizontally-layered interbed materials (anhydrite and clay) was found to be measurable only in the immediate vicinity (within 2 m in all cases) of excavations.

The previous gas flow/permeability measurements have proven to be useful for delineation of a zone of rock surrounding the WIPP excavations in which the hydraulic and mechanical properties have been altered - the so-called Disturbed Rock Zone (DRZ). Although the gas permeability is not a measure of the intrinsic or liquid permeability of the undisturbed rock surrounding WIPP excavations, the gas permeability of the DRZ is an important parameter in its own right. The gas permeability in the DRZ affects the buildup and dissipation of natural and waste-generated gases in the repository, and may also be important in determining the influx of brine from the surrounding rock. Furthermore, the gas permeability of the DRZ is an important consideration in the development of sealing strategy and designs, because flow through a seal system is partially dependent on the permeability of the rock adjacent to the seal.

The objectives of the gas flow/permeability measurements reported here were:

1. Determine the gas permeability in the undisturbed far-field.
2. Determine the gas permeability variations in the DRZ.
3. Provide data for developing a better understanding of the creation and nature of the DRZ.

2.0 FACILITY LAYOUT AND SURROUNDING STRATIGRAPHY

The WIPP Facility is located in a bedded salt formation approximately 650 m below the ground surface (see Figure 2.1). The underground development can be separated into areas north and south of the shafts: to the north are the experimental areas and to the south are the disposal rooms. Areas where flow measurements were conducted are indicated on Figure 2.1.

The WIPP facility is being developed at two levels: the disposal level and the simulated-waste experimental area level. The immediate stratigraphy (see Figure 2.2) contains numerous horizontal layers of anhydrite and clay, as well as halite containing various impurities. Of particular note are the non-salt layers immediately above and below the disposal horizon. Marker Bed 139 (MB 139), described in detail by Borns (1984), is a nominally 1-m thick anhydrite layer about 2 to 3 m below the disposal level invert. Seam B is a 6-cm thick clay/anhydrite layer about 2 m above the disposal level back.

For the purposes of this report, "salt" refers to the rock at the facility horizon that is predominantly halite (from argillaceous to polyhalitic to clear halite). The interbed materials are the horizontal anhydrite and clay layers (e.g., MB 139 and Seam B) present in the vicinity of the WIPP horizon.

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Figure 2.1. The WIPP Facility.

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Figure 2.2. The WIPP Facility stratigraphy.

3.0 TESTING DESCRIPTION

3.1 Test Locations

Gas flow measurements were made at four stations or locations in the WIPP underground workings: Room G, Room D, Room 2, and the E-140 drift at the N-1266 station (see Figure 2.1). The locations of the measurement stations were selected to be near deformation measurements being made with multi-point borehole extensometers. Section and plan views of the boreholes drilled for these gas flow measurements are given in Figures 3.1 through 3.4. The 4.76 cm diameter boreholes were drilled dry (air was used as the drilling fluid).

3.2 Test Equipment

The equipment used for the measurements reported herein is referred to as the high-resolution gas flow tool to distinguish it from previous measurement systems with lower effective resolution (see Stormont et al.(1987) for a discussion of gas flow measurement systems used previously). The system was designed and fabricated by the S-CUBED Division of Maxwell Laboratories, La Jolla, California.

The measurement system has three basic components: a four-packer assembly, a flow control system, and a data acquisition system. These components are illustrated in Figure 3.5. The packer assembly was used to isolate a region of interest within a test borehole. Typically, the region of the borehole between the inner two packers was used as the test interval, so that the intervals between these packers and the outside packers served as the guard zones. The guard zones are used to identify packer bypass due to less-than-perfect seating of the packer and to allow flow along the axis of the borehole to be distinguished from radial flow. The packers were designed for a nominal borehole diameter of 5 cm. The mandrel diameter was 4.3 cm. The length of the region between the inner two packers was 59.0 cm and the length of the region between the inner and outer packers was 46.7 cm. The volume between the inner two packers, including the tubing volume for introducing and measuring the gas pressure, was 398 cm³. The volumes of each of the guard regions are 187 cm³. The reservoir tank volume for constant pressure tests was 5890 cm³. The packer assembly was connected by means of a pneumatic/electrical conduit to the flow control and data acquisition systems. A schematic tubing diagram is given in Figures 3.6. Nitrogen for packer inflation and test zone injection was controlled by means of the flow manifold. Measurements were made of the test zone or reservoir tank pressure, guard zone pressure, packer pressures, and test interval temperature. The pressures were measured with Sensotec pressure transducers and temperature was measured with a resistive temperature detector (RTD). The data acquisition system consisted of a dedicated microcomputer, a display screen, and two floppy disk drives. The system is menu driven, and allows logging of the measured values onto floppy disks. Time is recorded from the microcomputer's internal clock.

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Figure 3.1. Gas flow/permeability testing boreholes associated with Room D station.

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Figure 3.2. Gas flow/permeability testing boreholes associated with Room G station.

TRI-6346-19-0

Figure 3.3. Gas flow/permeability testing boreholes associated with SPDV Room 2 station.

TRI-6346-20-0

Figure 3.4. Gas flow/permeability testing boreholes associated with E140/N1266 station

TRI-6346-21-0

Figure 3.5. Schematic of the components of the high-resolution gas flow/permeability test equipment (modified from Peterson et al., 1985).

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Figure 3.6. Schematic of tubing diagram for the high-resolution gas flow/permeability test equipment (modified from Peterson, 1988).

The measurement system is designed to be used in three different configurations. Most often, all four packers were inflated and pressures were monitored in both upper and lower guard regions in addition to the test region. This configuration is referred to as the 4-Pack configuration. In instances when it was desired to test the rock as near to the excavation as possible, the Collar configuration was employed where the upper packer was not inflated and only the test region and lower guard region were utilized. A third configuration employs only the upper two packers so the test region extends from the bottom of the borehole to the second packer. Only the upper guard region is employed in this configuration. This configuration, referred to as the Whole Hole configuration, was not used during any of the tests reported herein.

3.3 Test Technique

Two types of tests were utilized: the constant pressure flow test, and the shut-in or pressure decay test. Constant pressure flow tests measured the flow rate from an external gas reservoir required to maintain a desired constant pressure in the test interval. For a shut-in test, the test region was filled to a desired initial pressure and subsequent pressure decay was measured with time. The flow into the formation was then calculated from the measured pressure drop. The shut-in test was usually performed when flow rates became so small that flow into the formation could be more accurately determined from the measured pressure drop in the test interval rather than in the much larger reservoir volume. At permeabilities below about 10^{-18} m^2 , the reservoir (tank) pressure changes very little during a constant pressure test, and consequently, the flow rate from the reservoir to the test interval is so small it is difficult to resolve. Conversely, at permeabilities above 10^{-18} m^2 , the pressure drop in the test interval during a pressure decay test is very fast and difficult to accurately record. Therefore, the approximate permeability below which pressure decay tests were conducted and above which constant pressure tests were conducted was about 10^{-18} m^2 .

Detailed test or operating procedures were followed for each test. The usual procedure involved placing the packer system in the borehole, and pressurizing the packers. The packer pressure would be as great as 4.3 MPa when the test interval was more than 5 m from the excavation, and as low as 0.8 MPa when the test interval was in the first meter of the borehole. The packers were allowed to seat under pressure for a minimum of 15 minutes. The test and guard zones are then monitored for 5 minutes to ensure there is not gas production from the formation into the borehole. (Some previous tests in which the test interval included Seam B had no gas flow into the borehole.) For test intervals within the first 5 m of the excavation, the first test attempted was often a constant pressure test. If the gas flow into the formation did not result in measurable reservoir pressure decay for 10 minutes or more, then either a constant pressure test at a greater pressure or a pressure decay test was conducted.

A number of sequential tests were conducted. In these instances, a number of tests were conducted at the same location without deflating the packers or

moving the test system. Typically, successive test were conducted at increasingly greater test interval pressures. In these cases, the successive tests were identified by including an additional letter on the test number (e.g., TEST 41A, TEST 41B, etc.).

The ultimate test duration varied from a few minutes to a few days, depending on numerous factors as diverse as the measured response and underground access.

3.4 Quality Assurance (QA) and Documentation

All tasks were carried out in accordance with the Sandia National Laboratories Department 6340 WIPP Quality Assurance Program Plan. This document is approved by DOE/WPO for all WIPP activities assigned to Sandia. The WIPP QAPP meets the requirements of the WIPP Operations Quality Assurance Program Plan (DOE-WIPP 87-007) and the Basic and DOE selected Supplementary requirements of ANSI/SNME NQA-1-1986. Specific applications of the WIPP QAPP to this test have been incorporated throughout the testing.

Documentation relevant to this experiment includes:

- Test plan (reference: J. C. Stormont, "TEST PLAN: WIPP Horizon Gas Flow/Permeability Measurements," Sandia National Laboratories, April, 1988).
- Instrumentation schematics, specifications, and calibrations.
- Procedures.
- System test conduct.
- Raw data on floppy disks and accompanying field notes, including completed testing procedures.
- Reduced data¹ on floppy disks. This data has been converted to appropriate units and screened to ensure coherence and completeness. A listing of the program used to reduce the data is included.
- Listing of the transient flow codes used to interpret the tests.
- Summary of relevant numerical simulations, including the output on floppy disks.

All of the above documentation is contained in the WIPP QA system, a copy of which is physically located at the WIPP Site.

1. A discussion of the test interpretation methodology is given in chapter 4.

4.0 INTERPRETATION OF GAS FLOW MEASUREMENTS

The methodology used to interpret the in situ gas flow data is summarized by the flow chart in Figure 4.1. Data is received from the field on floppy disks with accompanying field notes. The measured quantities during the pressure decay or shut-in gas flow test are time, test zone pressure, guard zone pressures, packer pressure and test zone temperature. In the case of constant pressure tests, the gas reservoir (tank) pressure is monitored instead of the test zone pressure. A working data file with desired units (e.g., Pascals or psi, absolute or gage pressure) is created from the raw data. The data is then evaluated or screened to assess the completeness, reasonableness and consistency of the data, as well as to determine if a correction for leakage along the packer-rock contact is warranted. An equivalent steady-state permeability is then calculated from a closed-form solution using the most linear portion of the pressure vs. time data. A system test which most closely matches the field test condition is selected and compared to the data. If the data is clearly within the system resolution, a transient analysis is conducted utilizing a finite-difference numerical solution. The numerical solution requires the permeability and porosity to be assumed, and provides a simulation of the pressure vs. time data. The permeability and porosity are adjusted until a reasonable agreement between the numerical simulation and the measured response is obtained. In some instances, an enhanced permeability and porosity in the vicinity of borehole was used to obtain a better match between the numerical simulation and the measured response. In the following sections, different aspects of the interpretation process are discussed.

4.1 Packer Bypass Correction

The first step in the analysis of the field data is to determine whether there was measurable gas flow from the test zone into the guard zone(s) along the packer-rock contact. If the guard zone pressure(s) increased relatively rapidly after the introduction of gas into the test interval, then it is likely that gas is leaking past the packer(s). If, on the other hand, there is a substantial time delay between introduction of gas into the test zone and when guard zone pressure(s) begin to increase, then it is more likely that flow in the rock along the axis of the borehole is responsible for the pressure increase. Therefore, a pressure increase in the guard zone does not necessarily imply leakage past the packers.

A correction for packer bypass can be applied if so desired. The correction assumes that the change in pressure in the guard zones is due solely to packer bypass. A test zone pressure correction is calculated based on the guard zone pressure changes and the difference between the test and guard zone volumes. For the pressure decay test data, the test zone pressure data is adjusted as follows

$$P_{ctz} = P_{tz} + (V_{lgz}/V_{tz}) \Delta P_{lgz} + (V_{ugz}/V_{tz}) \Delta P_{ugz} , \quad (4.1)$$

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Figure 4.1. Flow chart of data reduction methodology.

where P_{ctz} is the corrected test zone pressure, P_{tz} is the uncorrected test zone pressure, ΔP_{lgz} is the change in the lower guard zone pressure, ΔP_{ugz} is the change in the upper guard zone pressure, V_{tz} is the test zone volume, V_{lgz} is the lower guard zone volume, and V_{ugz} is the upper guard zone volume. For constant pressure test data, the test zone pressure and volume is replaced by that of the gas reservoir.

4.2 Calculation of Volumetric Flow Rates

The measured pressure changes in the test zone, guard zones and gas reservoir can be converted to volumetric flow rates. For an isothermal process, the volumetric flow rate (dV/dt) at standard conditions of an ideal gas can be calculated from

$$dV/dt = (V/P_a) dP/dt, \quad (4.2)$$

where V is the applicable volume (test zone, guard zones or gas reservoir), P_a is standard (atmospheric) pressure, and dP/dt is the time rate of change of the pressure.

The flow rate from the test interval is not a constant during a transient test. However, as will be subsequently discussed, the flow rate will often approach a constant value. The single flow rate obtained from the most linear portion of the test zone pressure history can be assigned as "the result" for a particular test. Stormont et al. (1987) presented gas flow test data both as flow rates and permeabilities. Their rationale for this approach was that the volumetric flow rates were derived directly from measured values, and had minimal uncertainty associated with them. Permeabilities, on the other hand, are interpreted from a model of porous flow which includes many assumptions (see discussion in the next section). However, the principal objective of the gas flow testing is to provide estimates of the gas permeability and porosity of the disturbed rock zone as these quantities are more useful and meaningful for various analyses than a flow rate. Therefore, the results herein will be given as permeabilities and porosities.

4.3 Transient Gas Flow in a Porous Medium

4.3.1 Development of Governing Equations

The mathematical expression which describes gas flow through a porous medium is derived by combining the continuity equation, the equation of state, and Darcy's law. The flow will be assumed to be radial, applicable for flow to or from a borehole. The continuity equation is derived by considering the mass balance over a representative elementary volume of the porous medium (Katz et al., 1959, p. 407)

$$\frac{\partial(\rho\phi)}{\partial t} = \frac{\partial(\rho v)}{\partial r} \frac{\rho v}{r} \quad (4.3)$$

where ρ is the gas density, v is the gas velocity, ϕ is the porosity of the porous medium, t is time and r is the radial coordinate. Expanding the first term yields

$$-\phi \frac{\partial \rho}{\partial t} - \rho \frac{\partial \phi}{\partial t} = \frac{\partial(\rho v)}{\partial r} + \frac{\rho v}{r}. \quad (4.4)$$

From Walsh (1965), the time rate of change of the porosity can be expressed in terms of the compressibility of the solid material (β_s) and the bulk material (β_{eff})

$$\frac{\partial \phi}{\partial t} = -\phi \beta_s \frac{\partial P}{\partial t} - [\beta_s - \beta_{eff}] \frac{\partial P}{\partial t}. \quad (4.5)$$

The velocity of a fluid through a porous medium can be related to the pressure gradient ($\partial P/\partial r$) and the ratio of the permeability of the porous medium (k) to the viscosity of the fluid (μ) by means of Darcy's law

$$v = -\frac{k}{\mu} \frac{\partial P}{\partial r}. \quad (4.6)$$

The equation of state for an ideal gas is

$$\rho = \frac{PM}{RT}, \quad (4.7)$$

where M is the molecular weight, R is the gas constant, T is the temperature.

Combining equations (4.4), (4.5), (4.6), and (4.7) yields the governing differential equation for isothermal radial gas flow through a porous medium

$$\frac{\partial P^2}{\partial t} \frac{\mu}{kP} [\phi(1 - P\beta_s) - P(\beta_s - \beta_{eff})] = \frac{\partial^2 P^2}{\partial r^2} + \frac{1}{r} \frac{\partial P^2}{\partial r}. \quad (4.8)$$

Often the rock is assumed to be incompressible, and Equation (4.8) reduces to

$$\frac{\partial P^2}{\partial t} \frac{\mu\phi}{kP} = \frac{\partial^2 P^2}{\partial r^2} + \frac{1}{r} \frac{\partial P^2}{\partial r}. \quad (4.9)$$

Equation (4.8) and (4.9) may appear with P replaced by $1/\beta$, where β is the compressibility of an ideal gas.

For the constant pressure tests, the applicable boundary conditions are

$$\frac{\partial P^2}{\partial t} = 0 \quad \text{at borehole wall}, \quad (4.10)$$

$$\frac{\partial P^2}{\partial t} = 0 \quad \text{at remote boundary}. \quad (4.11)$$

For the pressure decay test, the rate of pressure change in the borehole due to the volumetric flux from the borehole is given by

$$\frac{\partial P}{\partial t} = \frac{P}{V} \frac{\partial V}{\partial t} \quad (4.12)$$

Combining equation (4.12) with an expression for the borehole volumetric flux (the velocity from Equation (4.6) times the borehole surface area) yields the boundary condition for the pressure decay test in terms of P^2

$$\frac{\partial P^2}{\partial t} = - \frac{kA}{\mu V} P \frac{\partial P^2}{\partial r} \quad (4.13)$$

where A is the borehole surface area.

In either case, the initial condition is a specified pressure at all locations including the borehole.

The assumptions which are inherent in the equation (4.8) are discussed below.

1. Isothermal conditions - The temperature of the gas in the test zone is measured during all tests. The experimental data reveal that the temperature changes are quite small, typically considerably less than 0.1°C . The corresponding thermally-induced pressure change is less than 300 Pa, well below the usual minimum measured pressure change of 7 kPa.
2. The flow is laminar - When streamlines become distorted, Darcy's law breaks down (Dullien, 1979, p. 164). A lowest critical Reynolds number above which Darcy's law is no longer valid is 1 to 10 (Bear, 1979, p.65). The Reynolds number is calculated from Bear (1979, p. 65)

$$\text{Re} = \frac{(q d)}{\nu} \quad (4.14)$$

where q is the specific discharge, d is some representative length of the porous medium (often taken as the grain size), and ν is the kinematic viscosity. Extreme conditions with respect to the validity of Darcy's law exist when there is a relatively great specific discharge, that is, a large flow at high pressures. For a 100 SCCM flow rate at 2.17 MPa gas pressure (a much larger flow rate at this pressure than measured), the Reynolds number is 0.75. Therefore, Darcy's law should be valid for the measurements reported here.

3. The fluid is an ideal gas - The gas used for all of the gas flow test was nitrogen. The assumption of an ideal gas is important because of the simplifications which follow when the viscosity is independent of pressure and the real gas correction factor equals unity in the equation of state. The use of reduced state variables

permits the deviation from ideal behavior to be assessed. The reduced pressure P_r is given by

$$P_r = P/P_c , \quad (4.15)$$

and the reduced temperature T_r is given by

$$T_r = T/T_c , \quad (4.16)$$

where P is the pressure, P_c is the critical pressure, T is the temperature, and T_c is the critical temperature. The behavior of all gases is the same with respect to the reduced state variables. The critical pressure and temperature for nitrogen were obtained from The Handbook of Chemistry and Physics (Weast, 1978, p. F-90). At extreme values of the reduced pressure and temperature applicable for the gas flow tests described herein, the viscosity change from standard conditions is <1% (Katz et al., 1959, Figure 4-102 and Fig 4-103, p 173) and the real gas correction factor is between 0.99 and 1.00 (Katz et al., 1959, Table A-2, p. 710). Therefore, the assumption that the injected fluid is an ideal gas is justified.

4. The flowing fluid is a single phase, nonreactive gas - Only a single gas is injected into the formation, but pre-existing water in the flow path can greatly affect the resulting gas flow and consequently the calculated permeability. It is unlikely that the injected gas will displace pre-existing brine or water because of the capillary forces in the water due to the small flow paths assumed to exist in intact rock salt. Stormont et al. (1987) argued that injected gas should not displace pore brine unless the pores are much greater than that typically assumed for intact rock salt or the rock tested was not completely saturated. Because there is no data on water displacement by injected gas, it will be assumed that only the injected gas is flowing. The implication of this assumption is if the formation was originally fully saturated, the gas will be flowing through porosity which has been created subsequent to the excavation process. The dissolution of nitrogen in the brine is believed to be small and not accounted for.
5. Permeability is independent of pressure - Permeability can be a function of pressure for a number of fundamentally different reasons. Gas permeability measurements may be affected by the Klinkenberg or slip phenomenon. When the mean free path of the gas molecule is on the order of the size of the flow path, then substantial interaction between the gas molecule and the flow path surface will occur. This interaction will result in a component of flow in addition to that due to a pressure gradient (Darcy flow). The apparent or Klinkenberg permeability can be up to an order of magnitude greater than the intrinsic or liquid permeability. Because the mean free path of a gas molecule is inversely proportional to its pressure, tests conducted at different pressures will have varying contributions of slip to the total gas flow and consequently the calculated permeability. A correction for gas slip can be derived experimentally but requires

many tests to be conducted at various pressures. Sutherland and Cave (1980) and Peach et al. (1987) interpret their laboratory data as indicating there is no significant Klinkenberg correction required for rock salt for permeabilities of about 10^{-19} m². Thus, while there may be Klinkenberg effects inherent in the data, there is no information regarding a relevant correction.

Another way in which pressure can affect the permeability is by alteration of pore structure. In response to changes in the pore pressure, the effective stress on the rock may change. Effective stresses control the volume changes in geomaterials, and volume changes are due in part to changes in the pore structure. The permeability of a porous medium is some function of the pore geometry and structure. Therefore, changes in gas pressure can result in a change in permeability. Peach et al. (1987) indicate that alteration of pore structure due to pressure changes does affect the permeability of rock salt, but discount these changes as insignificant.

6. The flow is perfectly radial - With this assumption, the component of flow parallel to the borehole axis is ignored. The validity of this assumption is a function of the length to diameter ratio of the test interval (Marinelli, 1984). A series of finite element calculation performed by Peterson (personal communication, 1989) with the dimensions of the gas flow test system previously described compared the pressure and flow rate histories for perfectly radial (one-dimensional) and cylindrical (two-dimensional) flow geometry. The difference in calculated volumetric flow rates for different permeabilities, porosities, test pressures and test durations are given in the following table.

Table 4.1
Comparison of Flow Rates Calculated Assuming
Radial (1-D) and Cylindrical (2-D) Flow Geometries

Maximum Difference Between Flow Rates for Radial and Cylindrical Flow Geometries (%)	Permeability (m ²)	Porosity	Test Zone Pressure (Pa)	Test Duration (hr)
5	10^{-20}	0.001	2,171,430	24.0
20	10^{-18}	0.005	791,430	4.0
25	10^{-15}	0.01	239,430	.25

Marinelli (1984) investigated the influence of assuming perfectly radial flow on the interpretation of constant pressure borehole tests. For test conditions and durations applicable to the gas flow tests, the maximum difference between one- and two-dimensional flow geometries is less than 30%.

A study of the influence of anisotropic permeability on borehole test interpretation conducted by Braester and Thunvik (1984) can be used to provide an indication of the validity of the radial flow assumption. They compared the results of numerically simulated borehole tests with different radial and vertical (along borehole axis) permeabilities. For the case of a radial permeability 100 times the vertical permeability, flow will be essentially radial. The difference between such a case and that of isotropic permeability was found to be on the order of 30% for their boundary and initial conditions.

Zeigler (1976) compared closed-form permeability equations based on radial and various two-dimensional flow geometries. For the test geometry and assumed depth of penetration of the test fluid applicable for these gas flow tests, the one- and two-dimensional solutions compare to within 10%.

The above discussion suggests that the validity of the radial flow assumption depends on the test configuration and conditions, as well as the properties of the formation. However, all available information suggests the maximum error due to the assumption of radial flow for the tests reported herein is about 25%.

7. The rock salt is homogeneous - In reality, the rock is clearly a bedded, inhomogeneous medium. Within the rocks termed rock salt, there is a considerable variation in grain size and impurity content. However, the only study which addressed the hydraulic properties of samples from different beds found no discernible differences (Black et al, 1979).

4.3.2 Numerical Simulation of Gas Flow

A finite difference solution to Equations (4.8) or (4.9) was developed in order to simulate the field measurements of gas flow. The finite difference method involves discretization of the domain into a number of finite lengths connected by nodes. Approximations to derivatives of functions are made at nodes, substituted into the differential equation, and the resulting system of equations is solved. In essence, the governing partial differential equation (Equation (4.8)) is approximated by a series of ordinary differential equations.

Equations (4.8) and (4.9) can be written as

$$\frac{\partial p^2}{\partial t} = B \frac{1}{r} \frac{\partial}{\partial r} \left[C r \frac{\partial p^2}{\partial r} \right], \quad (4.17)$$

where $B = [(\beta\phi - \beta_s(1+\phi) + \beta_{eff})]^{-1}$ for Equation (4.8) and $B = [\beta\phi]^{-1}$ for Equation (4.9), and C is the conductivity k/μ . A central difference approximation to the spatial derivative of the term in brackets gives

$$\frac{dp_i^2}{dt} \approx B_i \frac{1}{r_i} \left[\frac{r_{i+1/2}}{\Delta} C_{i+1/2} \frac{\partial p_{i+1/2}^2}{\partial r} - \frac{r_{i-1/2}}{\Delta} C_{i-1/2} \frac{\partial p_{i-1/2}^2}{\partial r} \right], \quad (4.18)$$

where i refers to the node number and Δ is the distance between nodes i and $i+1$. The remaining spatial derivatives can then be approximated by a central difference approximation, yielding a set of ordinary differential equations in time,

$$\begin{aligned} \frac{dp_i^2}{dt} \approx B_i \frac{1}{r_i} & \left[\frac{r_{i+1/2}}{\Delta^2} C_{i+1/2} (p_{i+1}^2 - p_i^2) \right. \\ & \left. - \frac{r_{i-1/2}}{\Delta^2} C_{i-1/2} (p_i^2 - p_{i-1}^2) \right], \end{aligned} \quad (4.19)$$

where $C_{i+1/2}$ is calculated at the midpoint between nodes i and $i+1$, and B_i is calculated at node i . Both B_i and C_i can be a function of position, pressure and/or time as desired.

A position-dependent permeability and porosity allows the modeling of a so-called Disturbed Rock Zone (DRZ) surrounding the test borehole. For our purposes, the DRZ is assumed to be a volume of rock in which the gas flow properties are increased above the far-field values. In the DRZ, the permeability is assumed to vary as (McTigue, 1988)

$$k = k_a \exp [D(z-r)], \quad (4.20)$$

where D is proportional to the increase in permeability at the borehole wall, k_a is the far-field permeability, and z is the distance at which the permeability decreases to the far-field permeability. The porosity in the DRZ is assumed to vary according to a form of the the Carmen-Kozeny relation (McKee et al., 1988)

$$\phi = \phi_a \left(K/K_a \right)^{1/3}, \quad (4.21)$$

where ϕ_a is the far-field porosity.

The exponential form for the permeability changes in the DRZ model is qualitatively consistent with measured permeabilities about excavations in rock salt (Stormont et al., 1987). An exponential form for the position-

dependent permeability of rock salt was developed by Kelsall et al (1982) based on the laboratory permeability measurements of Lai (1971).

The resulting system of equations is solved using a backward differencing solver subroutine (available from Sandia National Laboratories' technical library) which is unconditionally stable and optimizes the time step for accuracy (Shampine and Watts, 1979). The value of the independent variable (P^2 in this case) is calculated and given at discrete times on the way to the final time. Other quantities such as the flowrate and flux can be calculated as desired.

The discretization of the domain should consider a number of factors. First, the number of nodes should be minimized in order to limit the size of the system of equations which is to be solved. Next, the location of the remote boundary (or last node) should be sufficiently far from the borehole so Equation (4.11) remains valid at all times. Also, calculated pressure gradients in the vicinity of the borehole will be relatively great, and the accuracy of the approximation is improved if discretization is fine in this region. Finally, the discretization should be suitable for wide ranges of permeabilities, pressures and times. In order to best accommodate these factors, the following coordinate transformation given by Nowak and McTigue (1987) was employed

$$x = 1 - e^{-\zeta(r/a-1)}, \quad (4.22)$$

where x is the transformed coordinate, r is the radial coordinate, a is the borehole radius, and ζ is the stretch factor. The transformed coordinate varies from $x=0$ at the borehole wall to $x=1$ at infinity. In the transformed space, the distance between nodes is uniform. In the original coordinate system, the distance between nodes increases with increasing distance from the borehole by an amount which depends on the value of the stretch factor. This transformation permits nodes to be concentrated in the vicinity of the borehole while the remote boundary is at infinity. The numerical solution is derived in x coordinates, and transformed to r coordinates.

In order to ensure the accuracy of the numerical simulation, it is desirable to compare the numerical solution to an analytical solution. However, the only analytical solutions available apply to linear forms of the governing differential equation, such as which result when water is the fluid. (This subject will be discussed further in the subsequent section.) Therefore, a linearized form of equation (4.18) was numerically solved for comparison with the analytical solution of Cooper et al. (1967) for the borehole pressure history during a water pressure pulse test. The numerical solution was found to be essentially identical for simulations with 100 to 200 nodes and stretch factors of 0.1 to 0.01. The numerical results and analytical solutions are seen to compare very well (Figure 4.2).

4.3.3 Interpretation of Permeability and Porosity from Transient Gas Flow Data

Determination of gas flow properties from transient gas flow tests is referred to as an inverse problem (Bear, 1979, p. 463). The independent

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Figure 4.2. Comparison of analytical and numerical solutions to slug test using water.

variable is pressure squared, and the gas flow properties (permeability and porosity) are required as input to a numerical or analytical solution. To estimate the gas flow properties from test data, initial values of the gas flow properties are assumed and the initial conditions are imposed. The calculated pressure history is then compared to the measured data. The assumed gas flow properties are adjusted and the process is repeated until the calculated and measured pressures histories agree, at which time the associated gas flow properties are assumed satisfactory.

A fundamental difficulty with the inverse problem is that the solution is not necessarily unique (Bear, 1979, p. 464): different combinations of permeability and porosity can provide essentially identical pressure histories. In Figure 4.3, similar pressure histories from simulations with three different combinations of permeability and porosity are given. As a practical matter, the resolution of the measurements and/or the precision of the subjective matching method may result in numerous apparently equally good solutions. Perhaps the most important factor which generates non-uniqueness is the contribution of factors to the measured response which are not included in the model (Bear, 1979, p. 465).

In order to aid interpretation of transient gas flow tests, the flow equation has often been cast into dimensionless form (e.g., Energy Resources Conservation Board, 1979, pp. 2-33).

$$\frac{\partial^2}{\partial r^2} (\Delta P_d) = \frac{d}{dt_d} (\Delta P_d) , \quad (4.23)$$

where ΔP_d and t_d are dimensionless relative pressure change and time. Equation (4.23) is directly analogous to the standard equation of heat conduction, for which solutions are available for certain boundary conditions (Carslaw and Jaeger, 1959, p. 29). Dimensionless analyses have been used to determine gas permeability from well tests (e.g., Katz et al, 1959; Energy Resources Conservation Board, 1979; Hagoort, 1988). However, in order to utilize a dimensionless approach, Equation (4.8) has to be linearized. Linearization of the flow equation for an ideal gas requires a constant compressibility be assumed. (For non-ideal or real gases, further assumptions are required). Except for cases where the pressure differences are in a fairly narrow range, linearization of the flow equation is not advisable (Hagoort, 1988, p. 133). For many of the field tests, the compressibility at different locations and different times can vary by more than a factor of 20.

An alternative approach for determining the permeability from gas flow test data is to assume a value for the porosity, and find by trial and error the permeability which provides the best match with the measured pressure and/or flow history (Peterson et al., 1985). The rationale for this approach is that (1) the permeability is usually a more important parameter for most applications which use the gas flow properties, and (2) the measured response during a gas flow test is much more sensitive to the value of permeability than the porosity. This approach necessitates estimates of an appropriate porosity to be made. The few laboratory measurements of porosity on bedded salt indicate an interconnected porosity between 0.005 and 0.010 (Wawersik and Hannum, 1980; Gloyna and Reynolds, 1959; Aufricht and Howard, 1960). These

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Figure 4.3. Illustration of various combinations of permeability and porosity which produce similar numerically-generated pressure histories.

measurements were made at zero confining pressure, so the porosity would tend to correspond to the "unhealed" condition. Upon application of confining pressure, the porosity will be reduced as evidenced by the decrease of permeability of more than an order of magnitude (e.g., Sutherland and Cave, 1980). The nominal undisturbed or healed gas-accessible porosity was assumed to be 0.001 in previous analyses (Peterson et al., 1985; Stormont et al., 1987).

The approach for interpreting the gas flow measurements given here provides both a permeability and porosity. This approach utilizes the phenomenon of quasi-steady flow: when the storage of fluid in the rock becomes negligible, the flow from the borehole approaches steady-state. Quasi-steady flow will be discussed further in a subsequent section. The consequences of quasi-steady flow are that (1) the late-time slope of the pressure-time data is nearly solely a function of the permeability of the medium, and (2) the value of the porosity principally affects the initial rate of change of the pressure.

The method for deriving the permeability and porosity from the transient data uses these observations, and is summarized as follows:

1. An initial permeability is estimated from the steady-state flow equation (discussed subsequently) and an initial porosity is assumed.
2. A numerical simulation is conducted with the initial permeability and porosity, and applicable initial and boundary conditions. The resulting pressure vs. time history is compared to the field data.
3. The measured time rate of change of the pressure is compared to that from the numerical simulation and their difference is used to adjust the permeability for the subsequent iteration.
4. The final value of the pressure data is compared to that from the numerical simulation, and their difference is used to adjust the porosity for the subsequent iteration.
5. The updated permeability and porosity are used in another numerical simulation of the field test, and the output is used to adjust the permeability and porosity values in the same fashion as in (3) and (4) above.
6. The iterative process continues until the calculated rate of pressure change and final pressure match the field data to within about 5%.

It was not always possible to obtain a reasonable fit of the data, or the derived values were unrealistic (e.g., $k < 10^{-20}$ m², $\phi = 20\%$). Typically, the cause for the inability to match the field data was due to a steep initial drop in the pressure. The possible causes of this initial drop include, but are not limited to,:

1. A DRZ surrounding the test borehole;
2. Compliance of test system; and

3. A temperature change (decrease) of the gas in the test interval.

Without attempting to definitely specify the cause of the initial drop each time it was observed, simulations incorporating a DRZ were used to provide an improved fit to the field data. The DRZ model used in the numerical simulations (Equations 4.20 and 4.21) incorporated a constant depth of the DRZ (one borehole diameter) in order to reduce the number of additional parameters introduced to one. It must be emphasized that while permeability increases in the vicinity of boreholes are reasonable, the use of a DRZ model serves as an expedient device to obtain a better fit between field data and predictions, and does not necessarily prove the concept of a DRZ surrounding the test borehole.

4.4 Quasi-Steady Gas Flow

4.4.1 Development of Quasi-Steady Gas Flow

Steady-state flow is never achieved in the field tests, but transient flow often approaches steady-state flow. This behavior is referred to as quasi- or pseudo-steady flow, and is a result of fluid storage in the rock becoming negligible (Hsieh et al, 1981). The approach of quasi-steady flow depends on the term which specifies the storage capacity of the rock and fluid approaching zero

$$\left(\frac{\beta_{eff} - \beta_s}{\beta} \right) + \phi(1 - \beta_s/\beta) \rightarrow 0 . \quad (4.24)$$

Bulk and matrix compressibility of rock salt are assumed to be $4.83E-11 \text{ Pa}^{-1}$ and $4.26E-11 \text{ Pa}^{-1}$, respectively (Nowak, McTigue and Beraun, 1988). The first term in the brackets will vary from $1.4E-6$ to $1.2E-5$ at a gas pressure of .24 MPa and 2.17 MPa, respectively. The second term will simply approach the porosity. For rock salt, the porosity is generally assumed to be between 0.01 and 0.001, and Equation (4.24) essentially reduces to the porosity. The transient response, then, is a function of the porosity of the rock salt, and the storage will be small when the test fluid is nitrogen gas.

The development of quasi-steady flow is illustrated in Figure 4.4, where the calculated flow rates from boreholes for various combinations of permeability and porosity are given as a function of time. The following comments pertain to the results given in this figure:

1. The smaller the porosity, the faster a nearly constant or quasi-steady flow rate is established.
2. The quasi-steady flow rates are much more sensitive to the value of the permeability than of the porosity.

Gas is more conducive to establishing quasi-steady flow than water in low porosity media. The flow rates of gas and water from the test borehole calculated for pressure decay tests under similar conditions are given in

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Figure 4.4. Volumetric flow rate vs. time from numerical simulations using various combinations of permeability and porosity.

Figure 4.5. After the initial transient, the flow rate of gas changes by less than a factor of two while that for water changes by more than an order of magnitude. Further, note the much greater flow rate for gas for the same permeability, making gas flow more "measurable" in field tests.

4.4.2 Steady-State Flow Approximation

Quasi-steady flow conditions suggest closed-form steady-state flow equations may provide reasonable first estimates of permeability. For steady-state radial gas flow governed by Darcy's law in a uniform, homogeneous, isotropic medium, the permeability is given by (Zeigler, 1976)

$$K = \frac{V\mu}{\pi L} \frac{\ln(r_a/a)}{p^2 - p_a^2} \frac{dp}{dt}, \quad (4.25)$$

where r_a is the assumed depth of fluid penetration into the formation, p_a is atmospheric pressure, and a is the radius of the borehole. All of the parameters in Equation (4.25) are constant or can be measured with the exception of $\ln(r_a/a)$ which must be assumed. A value of 3, corresponding to a depth of penetration of gas of about 50 cm into the rock, will be assumed for the subsequent steady-state permeability calculations. This value was selected principally because it corresponds fairly closely to the depth of penetration anticipated for typical test duration and pressures. A number of numerical simulations were conducted for various test conditions, from which the time derivatives of the borehole pressures (dp/dt) were computed and used to calculate the steady-state permeability with $\ln(r_a/a)$ assumed to equal 3. Comparison between the calculated steady-state permeability and the permeability used as input to the numerical simulation are given in Figures 4.6 and 4.7. For permeabilities on the order of 10^{-18} m², the steady-state permeability is a good approximation for typical test pressures and assumed porosities when the test duration exceeds about 2 hours. When the permeability is on the order of 10^{-20} m², the steady-state permeability approximation quickly becomes valid within a factor of 2; however, the test duration required for the steady-state approximation to be within 25% or so becomes prohibitive (more than 48 hrs). The necessary test duration is increased as the test pressure is reduced. These results illustrate that the steady-state approximation depends on the permeability, porosity, test pressure and test duration. While the accuracy of the approximation varies with the test condition, the steady-state permeability calculation provides a reasonable order-of-magnitude approximation.

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Figure 4.5. Flow rate vs. time for comparable gas and brine test simulations.

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Figure 4.6. Calculated steady-state permeability vs. time for various porosities and test pressures for a permeability of 10^{-18} m^2 .

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Figure 4.7. Calculated steady-state permeability vs. time for two test pressures for a permeability of 10^{-20} m^2 and a porosity of 0.005.

5.0 MEASUREMENT UNCERTAINTY AND RESOLUTION

Uncertainties in the interpreted gas flow properties are the result of three factors:

1. Error in the measured data.
2. Limitations in the measurement system (e.g., system leakage and compliance).
3. Shortcomings in the flow model.

The last factor was discussed in the previous section, and the conclusion was reached that uncertainties as a result of the assumed flow model may be large, but are very difficult to quantify. The measurements of pressure and time are made quite accurately, and relatively little error results from this factor. The measurement system was determined to be able to resolve permeabilities below 10^{-20} m².

5.1 Error in the Measured Values

The test zone, guard zone and tank pressures are measured with Sensotec transducers with an accuracy of 0.1% of the full-scale reading. The packer pressures are measured with Sensotec transducers with an accuracy of 1.0% of the full-scale reading. The temperature is measured with a Resistive Temperature Detector (RTD) with an accuracy of 1.0%. Signal amplification and conditioning introduced an additional error of 0.1% of the full-scale output of the transducers.

Various dimensions are required analysis of the data. Fixed test dimensions and the associated uncertainties are: borehole radius, 2.38 cm, 0.1 cm; tool diameter, 1.88 cm, 0.1 cm; test zone length, 59.1 cm, 0.1 cm; guard zone length, 46.7 cm, 0.1 cm; tubing volume, 2.0 cc per m, 0.1 cc per m; reservoir tank volume, 5890 cc, 100 cc.

To obtain an estimate of the relative magnitude of the error in the measured values, the uncertainty in the calculated volumetric flow rate was determined by means of an uncertainty analysis (Benedict, 1977). The standard volumetric flow rate during a pressure decay test can be calculated from the measured pressure change in the borehole

$$\frac{dv}{dt} = \frac{V}{P_a} \frac{dP}{dt}, \quad (5.1)$$

where P_a is atmospheric pressure, and V is the test zone volume.

The relative error in the volumetric flow rate is the root mean sum of the error associated with the test zone volume, the atmospheric or standard pressure, and the pressure decay rate

$$\left| \frac{\delta dV}{dV} \right| = \left[\left(\frac{\delta V}{V} \right)^2 + \left(\frac{\delta P_a}{P_a} \right)^2 + \left(\frac{\delta(dP)}{dP} \right)^2 + \left(\frac{\delta(dt)}{dt} \right)^2 \right]^{1/2}, \quad (5.2)$$

where δ indicates the uncertainty associated with a value.

For a time in excess of 100 seconds and the test configuration for the test system used here, the relative error in the flow rate is essentially a function of the magnitude of the pressure change. For example, for a pressure change of 6900 Pa, the measured pressure change contributes more than 90% of the 10% relative error of the flow rate. For relatively great pressure changes (more than 69 kPa), the probable relative error associated with the calculated flow rates is less than 1%. In Table 5.1, the calculated flow rates and the probable relative error are given for a range of measured values (time and pressure). When the measured pressure change is at the target minimum value (here assumed to be 6.9 kPa)², the calculated flow rate defines the effective resolution of the measurement. These results illustrate an important point about flow testing in a very low permeability medium; namely, that the resolution of the measurement is often limited principally by the test duration.

If the flow model is assumed to be correct, then the uncertainties in the calculated permeability will be proportional to those of the calculated flow rates. Thus, the error in measured values (principally pressure) is expected to contribute less than 10% to the uncertainty in the calculated flow rates and permeabilities.

5.2 Test System Resolution

A key aspect of the HRGFT testing program is the conduct of system tests. System tests are designed to measure the response of the test system in an impermeable medium, and thereby establish the limitations and effective resolution of the test system. With a perfect test system, there would be no change in the test zone, guard zones or packer pressures if the test system was utilized in an impermeable medium. As a practical matter, however, all test systems are imperfect and changes in pressure result.

A system test is conducted following the normal test sequence and procedures, except the packer assembly is placed in a 5-cm diameter aluminum tube rather than a borehole. The packers are inflated, and a pressure is introduced to the test interval. The packer, guard zone and test zone pressures are monitored, as well as the test zone temperature. From the

2. In low permeability media, there is typically a minimum pressure change that is considered desirable to measure in order to avoid subtle temperature and system compliance effects as well as to increase the depth of penetration of the gas. For the tests reported herein, the target minimum pressure change was 6.9 kPa (1 psi).

TABLE 5.1
Results of Uncertainty Analysis
for Volumetric Flow Rates

Measured Pressure Change (kPa)	Test Duration (sec) (hrs)	Volumetric Flow Rate (SCCM)	Relative Probable Error of Flow Rate (%)
0.69	100 (0.3)	2.69×10^{-2}	100
6.9	100 (0.3)	2.69×10^{-1}	10
6.9	10,000 (2.8)	2.69×10^{-3}	10
6.9	100,000 (27.7)	2.69×10^{-4}	10
69.0	10,000 (2.8)	2.69×10^{-2}	1
69.0	100,000 (27.7)	2.69×10^{-3}	1

measured values, some indication of the system resolution can be estimated. For example, a loss of pressure in the test zone can be interpreted as if radial flow out of the test zone was occurring, and an equivalent permeability can be calculated. Assuming the pressure loss was inherent in the system, this background or system flow rate or permeability defines the resolution of the test system.

Factors which render a test system less than perfect include packer bypass; packer leakage; packer system compliance; leakage through fittings, valves and tubing; and temperature effects. The system tests conducted with the HRGFT system revealed that a slow but persistent leak through the tubing was most often the limiting factor of the system resolution. There were also a few system tests where packer bypass and packer leakage appreciably affected the test system resolution. The resolution of the system was found to depend on the test zone pressure and to a lesser degree on the test duration. At test zone pressures of 0.24 MPa to 2.17 MPa, the equivalent system permeability was found to decrease from about 10^{-20} to 10^{-21} m², respectively. A brief discussion of the factors affecting the system resolution follows.

5.2.1 Tubing Leakage

During numerous system checks, a consistent pressure decay has been measured. After much effort, the nylon tubing used to connect the packers and test intervals to the gas supply and pressure transducers was identified as the source of the slow leak. A majority of the pressure changes observed during system tests have been attributed to the tubing leakage. While the tubing leak limits the system resolution, the flexible nylon tubing is a fundamental feature of the HRGFT as it permits the system to be extremely portable.

5.2.2 Temperature Effects

Thermally induced pressure changes can result when the gas temperature changes as it equilibrates with the ambient or surrounding temperature. If there is no flow from the test interval during a system test, then the pressure change brought about by a temperature change for an ideal gas is

$$P_2 = \left(\frac{T_2}{T_1} \right) P_1 , \quad (5.3)$$

where the subscripts 1 and 2 refer to conditions before and after the temperature change, respectively.

Conversely, the temperature of the gas can change from pressure changes in response to mass flow, such as a gas bottle cooling as gas is expelled from it.

During system tests, the greatest rate of temperature changes (both increases and decreases) were measured within the first few hours of test initiation. These changes were most often only a few tenths of a degree

centigrade, but on a few occasions were as great as 1°C . These temperature changes can be largely attributed to the gas equilibrating with the aluminum tubing and the surrounding air. After these initial change, the temperature would change less than 0.1°C . Often the change in temperature could be approximately correlated to the diurnal temperature variation in the mine ventilation. The conclusion from the system tests is that the maximum thermally induced pressure changes are less than 5% of the measured pressure changes. Further, as will be shown, the temperature changes during tests in boreholes are typically much less than during the system tests. In general, therefore, correction to pressure data for thermal effects is not warranted.

5.2.3 Packer Bypass

Packer bypass can be discerned during system tests by guard zone pressure increases and a corresponding pressure decrease in the test zone. When substantial packer bypass occurred, remedial action (such as cleaning of the packer element and the aluminum tube) greatly reduced the amount of packer bypass. If so desired, the test zone pressure during system tests as well as borehole tests can be corrected for guard zone pressure increases.

5.2.4 Packer Leakage

After a period of use, the HRGFT packers began to leak small amounts of gas as evidenced by simultaneous pressure increases in both the test and guard zones. Packer leakage was observed in system tests 54 and 73. In these tests, the packers were set without pressurizing the test or guard zones. After about 12 hours, the pressure in the test and guard zones was seen to increase. Inspection of the packers subsequently revealed blemishes on the packer surface. In these cases, the packer elements were replaced.

5.2.5 Packer System Compliance

Because the packer system is not rigid, the test zone volume changes in response to internal pressure changes. In essence, the packer system contributes a component of compressibility in addition to that of the test fluid, although for systems with gas as the test fluid it will be much less important than for water. The packer system compliance is obscured by the background tubing leak during most system tests. The system tests in which there was no initial pressure (TEST 54 and TEST 73) were designed to provide a measure of the system compliance. However, the pressure changes in the test and guard zones due to the movement and/or contraction/expansion of the packers was negligible when compared to the leakage from the packers.

Table 5.2 provides a summary of system tests conducted to date. As a result of leakage through the tubing, pressure decays were measured in most tests. The pressure decay rates in Table 5.2 were obtained from the most linear portion of the pressure-time data. As with tests in boreholes, the pressure-time data slopes usually become increasingly linear with time. Volumetric flow rates and steady-state permeabilities were calculated directly from these pressure decay rates as if flow was into the formation. In a few

TABLE 5.2
Summary of System Tests

Test No.	Pressure (MPa)	Time** (sec)	Pressure* Decay Rate (Pa/sec)	Flow* Rate (SCCM)	Steady State* Permeability (m ²)	
9	2.16	7200	0.3125	4.6E-4	7.9E-22	
15	2.02	400,000	0.202	3.4E-4	5.8E-22	
	1.49	13,000	-1.667	-5.2E-3	-8.9E-21	
	0.81	150,000	0.090	9.6E-4	1.7E-21	
16	2.02	90,000	0.28	4.6E-4	8.0E-22	Guard Zone Only
	1.74	90,000	0.15	3.4E-4	5.8E-22	Guard Zone Only
19	2.11	60,000	0.39	6.0E-4	1.0E-21	Includes Guard Zones
21	2.05	200,000	0.27	6.4E-4	1.1E-21	
29	0.24	10,000	-0.10	-1.5E-2	-2.5E-20	
	0.77	60,000	-0.02	-1.9E-4	-3.3E-22	
33	0.24	9,000	0.086	1.2E-2	2.0E-20	
	0.44	15,000	0.150	5.5E-3	9.5E-21	
	0.77	50,000	0.167	1.9E-3	3.3E-21	
36	2.08	65,000	0.625	7.9E-4	1.3E-21	
44	0.49	72,000	0.10	3.6E-3	6.2E-21	
	0.49	100,000	-0.03	-1.0E-3	-1.8E-21	
	0.24	72,000	0.02	2.5E-3	4.3E-21	

* Negative values indicate pressure increases. Corresponding flow rates and permeabilities consequently assume negative values.

** 86,400 sec = 1 day.

TABLE 5.2 (concluded)
Summary of System Tests

Test No.	Pressure (MPa)	Time** (sec)	Pressure* Decay Rate (Pa/sec)	Flow* Rate (SCCM)	Steady State* Permeability (m ²)
45	0.78	60,000	0.10	1.1E-3	2.0E-21
46	1.11	60,000	0.20	1.1E-3	1.9E-21
47	.432	60,000	0.02	8.1E-4	1.4E-21
	.434	150,000	-0.06	-2.2E-3	-3.7E-21
54	0.0	60,000	~0	N/A	N/A
	0.0	200,000	-0.09	N/A	N/A
58	0.44	72,000	0.02	7.2E-4	1.2E-21
	0.77	20,000	0.06	7.0E-4	1.2E-21
	1.12	60,000	-0.08	-4.4E-4	-7.6E-22
73	0.0	50,000	~0	N/A	N/A
	0.0	200,000	-0.10	N/A	N/A

instances, the test zone pressure actually increased; in these tests, a permeability which would negate this pressure increase was calculated. The calculated permeabilities are effectively a measure of the system resolution. Therefore, the system resolution is between 10^{-20} and 10^{-22} m², with a trend of better resolution (lower system permeability) with increased pressure.

6.0 EXPERIMENTAL RESULTS

The experimental results are given in Appendix A. For each test, the borehole pressure history, guard zone histories, and temperature history are given. For constant pressure tests, the reservoir tank pressure history is given instead of the borehole pressure history. For some of the tests, the results of the numerical simulation used to interpret the gas permeability and porosity of the rock tested are also given. For successive tests, only those tests which were conducted with sufficient duration are included in the experimental results. For example, results from TEST 1C are given but not from TEST 1A or TEST 1B. All data can be found in the raw data files.

A summary of the experimental results and the derived permeabilities and porosities is given in Table 6.1.

6.1 Discussion of Transient Analyses

In general, reasonable agreement was found between the field data and the output from a numerical simulation. A few examples illustrating some findings from the transient analyses are given below.

6.1.1 Sensitivity to Permeability

Two examples of the sensitivity of the numerical test simulations to the assumed permeability are given in Figures 6.1 and 6.2. These typical results confirm the relatively great sensitivity of the simulated response to the value of the permeability as predicted in Chapter 4. Also, the results given in these figures illustrate that the assumed permeability influences the late-time slope of the pressure - time history.

6.1.2 Sensitivity to Porosity

The sensitivity of the numerical test simulations to the assumed porosity are illustrated by examples in Figures 6.3 and 6.4. It is apparent that the pressure - time history, particularly the late-time response, is relatively insensitive to the value of the porosity.

6.1.3 Application of the Local DRZ Model

Two examples of the use of the DRZ model to obtain a better match between the field data and a numerical simulation are given in Figures 6.5 and 6.6. Without the DRZ model, the porosity would have to be unrealistically great (>20% in some cases). In these examples, the DRZ model provides an initial pressure drop in the numerical simulation which improves the agreement with the field data.

TABLE 6.1
Summary of Experimental Results

Test No.	Borehole No.	Mean Test Interval depth (m)	Test Type* /Pressure (kPa)	Permeability** (m ²)	Porosity***	D Disturbed Zone Parameter***
1C	DP02	7.5	P.D./2171	$<7.9 \times 10^{-22}$		
2	DP02	3.6	P.D./791	$<9.4 \times 10^{-22}$		
3	DP02	7.5	P.D./2171	$<7.9 \times 10^{-22}$		
4	DP02	1.8	P.D./234	5.0×10^{-19}	0.01	5
5	DP02	15.0	P.D./2171	$<7.9 \times 10^{-22}$		
6	DP02	6.1	P.D./446	$<9.5 \times 10^{-21}$		
7	DP02	0.9	C.P./170	1.7×10^{-15}	0.004	1
8	DP01	15.0	P.D./2171	$<7.9 \times 10^{-22}$		
9	System Test		P.D./2171	7.9×10^{-22}		
10	DP01	7.5	P.D./2171	$<5.8 \times 10^{-22}$		
11A	DP01	1.8	P.D./234	6.2×10^{-19}	0.02	1
12	DP03	14.6	P.D./2171	$<5.8 \times 10^{-22}$		
13	DP03	3.9	P.D./791	$<7.9 \times 10^{-22}$		
14	DP03	1.5	P.D./234	3.2×10^{-20}	.005	100
15A	System Test		P.D./2171	5.8×10^{-22}		
15B			P.D./1481	8.9×10^{-21}		
15C			P.D./791	1.7×10^{-21}		
16	System Test		P.D./2021	7.0×10^{-22}		
17	D001	0.9	C.P./170	1.9×10^{-14}	0.005	1
18	DP04	0.9	C.P./170	6.3×10^{-16}	0.006	1
19	System Test		P.D./2110	1.1×10^{-21}		
20	DP03	0.9	P.D./171	1.0×10^{-18}	0.01	20
21	System Test		P.D./2050	$<1.1 \times 10^{-21}$		
23	GAP02	0.9	P.D./234	8.3×10^{-19}	0.026	1
24	GAP01	0.9	C.P./234	2.3×10^{-16}	0.003	1
25	GAP06	0.9	P.D./234	$<2.0 \times 10^{-20}$		

* P.D. = pressure decay test, C.P. = constant pressure test.

** Permeability were determined by comparison with applicable system test, steady-state flow analysis, and/or transient flow analysis.

*** Porosity and disturbed zone parameter "D" were determined from transient flow analysis.

TABLE 6.1 (Continued)
Summary of Experimental Results

Test No.	Borehole No.	Mean Test Interval depth (m)	Test Type* /Pressure (kPa)	Permeability** (m ²)	Porosity***	D Disturbed Zone Parameter***
26	GAP05	0.9	P.D./234	$<2.0 \times 10^{-20}$		
27	GAP06	1.8	P.D./791	$<3.3 \times 10^{-21}$		
28B	GAP01	1.8	P.D./791	2.2×10^{-20}	0.021	1
29	System Test		P.D./234	2.5×10^{-20}		
			P.D./791	3.3×10^{-22}		
30A	GAP02	1.8	P.D./491	$<4.7 \times 10^{-20}$		
30B			P.D./791	2.0×10^{-21}	0.001	5
31A	GAP03	1.8	P.D./239	4.3×10^{-19}	0.020	10
31B			P.D./491	3.3×10^{-18}	0.014	1
31C			C.P./491	4.3×10^{-18}	0.010	1
31D			C.P./791	2.1×10^{-18}	0.014	1
32	GAP04	1.8	P.D./491	$<2.6 \times 10^{-21}$		
33	System Test		P.D./240	2.0×10^{-20}		
			P.D./440	9.5×10^{-21}		
			P.D./770	3.3×10^{-21}		
34C	GAP05	1.8	P.D./791	$<1.2 \times 10^{-21}$		
35C	GAP01	4.8	P.D./1100	$<1.5 \times 10^{-21}$		
36	System Test		P.D./2080	1.3×10^{-21}		
37A	GAP03	0.9	P.D./239	1.1×10^{-18}	0.013	10
38	GAP03	4.8	P.D./791	1.0×10^{-21}	0.002	1
39A	GAP01	0.9	C.P./170	8.0×10^{-16}	0.015	1
39B			C.P./239	5.4×10^{-16}	0.005	1
39C			C.P./791	2.8×10^{-16}	0.005	1
40A	GAP02	0.9	P.D./170	9.0×10^{-15}	0.008	1
40B			C.P./170	1.0×10^{-16}	0.005	1
40C			C.P./239	1.8×10^{-16}	0.003	1
40D			C.P./446	1.3×10^{-16}	0.002	1
41	GAP04	0.9	P.D./239	1.0×10^{-19}	0.015	100
42C	2P01	1.8	P.D./791	$<8.0 \times 10^{-22}$		
43C	2P04	1.8	P.D./791	$<1.6 \times 10^{-21}$		
44	System Test		P.D./490	6.2×10^{-21}		
			P.D./234	4.3×10^{-21}		
45	System Test		P.D./791	2.0×10^{-21}		
46	System Test		P.D./1110	1.9×10^{-21}		
47	System Test		P.D./432	1.4×10^{-21}		
			P.D./432	3.7×10^{-21}		
48	2P02	1.8	P.D./446	$>1.0 \times 10^{-12}$		

TABLE 6.1 (Concluded)
Summary of Experimental Results

Test No.	Borehole No.	Mean Test Interval depth (m)	Test Type* /Pressure (kPa)	Permeability** (m ²)	Porosity***	D Disturbed Zone Parameter***
49C	2P01	3.6	P.D./791	$<9.5 \times 10^{-22}$		
50B	2P04	0.9	P.D./239	$<9.0 \times 10^{-21}$		
50C			P.D./446	1.8×10^{-20}	0.005	20
51A	2P01	0.9	C.P./165	1.1×10^{-16}	0.011	1
51B			C.P./239	6.0×10^{-18}	0.010	1
51C			C.P./446	5.9×10^{-18}	0.010	1
52	2P02	2.7	P.D./446	2.4×10^{-20}	0.003	1
53	2P02	4.5	P.D./791	5.7×10^{-20}	0.017	10
54	System Test		N/A	N/A		
55	2P02	4.5	P.D./791	6.4×10^{-20}	0.005	10
56	2P02	0.9	P.D./239	2.5×10^{-17}	0.005	1
57	2P02	2.7	P.D./446	1.1×10^{-20}	0.001	1
58A	System Test		P.D./440	1.2×10^{-21}		
58B			P.D./770	1.2×10^{-21}		
58C			P.D./1120	7.6×10^{-22}		
59	2P03	0.9	P.D./239	1.0×10^{-17}	0.01	1
60	2P03	2.1	C.P./446	$>1.0 \times 10^{-12}$		
61	2P05	0.9	P.D./170	7.0×10^{-18}	0.005	1
62	2P05	3.6	P.D./446	1.6×10^{-20}	0.004	50
63	2P05	1.8	P.D./446	$<2.0 \times 10^{-22}$		
64	EP02	1.8	P.D./446	$<1.1 \times 10^{-21}$		
65	EP01	1.8	P.D./446	$<2.6 \times 10^{-21}$		
66	EP03	1.8	P.D./446	$<2.4 \times 10^{-21}$		
67	EP03	0.9	P.D./239	9.5×10^{-20}	0.005	100
68	EP04	1.8	P.D./446	$<2.0 \times 10^{-21}$		
69	EP04	0.9	P.D./239	$<6.8 \times 10^{-21}$		
70	EP05	0.9	P.D./239	$<8.3 \times 10^{-21}$		
71	EP02	0.9	P.D./239	$<1.0 \times 10^{-20}$		
72	EP01	0.9	P.D./239	$<1.0 \times 10^{-20}$		
73	System Test		N/A	N/A

TRI-6346-37-0

Figure 6.1. Sensitivity of transient response to assumed permeability value using results of Test 7.

TRI-6346-38-0

Figure 6.2. Sensitivity of transient response to assumed permeability using results of Test 38.

TRI-6346-39-0

Figure 6.3. Sensitivity of transient response to assumed porosity using results of Test 57.

TRI-6346-40-0

Figure 6.4. Sensitivity of transient response to assumed porosity using results of Test 40D

TRI-6346-41-0

Figure 6.5. Illustration of the application of the DRZ model to improve the match with the initial data. Test data is from Test 4.

TRI-6346-42-0

Figure 6.6. Illustration of the application of the DRZ model to improve the match with initial data. Test data is from Test 37A.

6.1.4 Influence of the Initial Pressure Field

The influence of the assumed initial pressure field in the rock is illustrated in Figure 6.7. In one case, the initial pressure field in the rock is assumed to be at atmospheric pressure. The other simulation incorporates the pressure field in the rock due to a previous test. Because sequential tests generally involved successively greater test pressures, the influence of the remnant pressure due to previous testing is small.

6.2 Discussion of Results

6.2.1 Results From Tests at the Same Test Location

The results from analyses of measurements conducted at the same test location (both borehole and mean test interval depth) are given in Table 6.2. Not included are tests in which the response was below the system resolution. In general, the derived permeabilities and porosities are repeatable. In some cases, the initial measurement of a series of sequential test results in a greater permeability compared to subsequent measurements (Test 40A, Test 51A). A possible cause for this is that the first measurements during sequence tests were of relatively short duration and at a lower pressure, and therefore have a limited depth of penetration relative to the subsequent measurements. In such cases, if there was a substantial DRZ, the initial measurement may only be testing the rock of enhanced permeability. In one instance (Test 31A), a much lower permeability was derived from the first test compared to subsequent tests. In two of the three cases where measurements were repeated at the same location but after some period of time (non-sequential tests), good agreement was found between derived permeabilities (Test 24 and Test 39, Test 53 and Test 55). In one case (Test 23 and Test 40), the permeability derived from the first test was much lower than that derived from the subsequent test.

6.2.2 Results as a Function of Position

In general, the distributions of derived permeabilities about Room D, Room G and Room 2 (Figures 6.8 through 6.11) are consistent with previous measurements (Stormont et al., 1987; Borns and Stormont, 1988). Within the first meter in the ribs, permeabilities from 10^{-14} to 10^{-18} m² were measured. At a depth of 1.8 m, the permeability decreased by at least 2 orders of magnitude. There was no measurable permeability at greater depths into the ribs. In the floor, the permeability at a mean test interval depth of 0.9 m was between 10^{-17} and 10^{-15} m². At 1.8 m into the floor, the permeability was too great to measure in the floor of Room 2 and too small to measure in the floor of Room G. These test intervals included the MB139 anhydrite layer.

Measurable gas flow occurred to the greatest depth in the rock above the roof of Room G and Room 2. At a depth of almost 5 m, measurable gas flow occurred. The test intervals which included Seam B allow a very large gas flow for Room 2, and a smaller but still measurable gas flow above Room G. There were insufficient measurements to draw a similar conclusion about the gas permeabilities above the back of Room D.

TRI-6346-43-0

Figure 6.7. Illustration of the influence of the initial pressure field in the rock using results of Test 40C.

TABLE 6.2
Results From Tests at Same Locations

<u>Borehole number</u>	<u>Mean test interval depth (m)</u>	<u>Test number</u>	<u>Test* type</u>	<u>Test pressure (kPa)</u>	<u>Permeability (m²)</u>	<u>Porosity</u>	<u>D Disturbed Zone Parameter</u>
GAP02	0.9	23	P.D.	234	2.3×10^{-19}	0.026	21
		40A	P.D.	170	9.0×10^{-15}	0.007	1
		40B	C.P.	170	1.0×10^{-16}	0.005	1
		40C	C.P.	239	1.8×10^{-16}	0.003	1
		40D	C.P.	446	1.3×10^{-16}	0.002	1
GAP01	0.9	24	C.P.	234	8.3×10^{-16}	0.003	1
		39A	C.P.	170	8.0×10^{-16}	0.015	1
		39B	C.P.	239	5.4×10^{-16}	0.005	1
		39C	C.P.	791	2.8×10^{-16}	0.005	1
GAP03	1.8	31A	P.D.	239	4.3×10^{-19}	0.020	1
		31B	P.D.	491	3.3×10^{-18}	0.014	1
		31C	C.P.	491	4.3×10^{-18}	0.010	10
		31D	C.P.	791	2.1×10^{-18}	0.015	1
2P01	0.9	51A	C.P.	165	1.1×10^{-16}	0.011	1
		51B	C.P.	239	6.0×10^{-18}	0.010	1
		51C	C.P.	446	5.9×10^{-18}	0.010	1
2P02	4.5	53	P.D.	791	4.1×10^{-20}	0.022	100
		55	P.D.	791	6.4×10^{-20}	0.005	10

*P.D. = pressure decay test, C.P. = constant pressure test

- Notes:
1. All permeabilities are in m^2 units.
 2. Room D is 5.6 m wide by 5.6 m high. Tests were conducted at mid-length of Room D.
 3. Room D was excavated in March 1984. Tests were conducted during June through July 1988.

TRI-6346-25-0

Figure 6.8. Distribution of permeabilities surrounding Room D.

- Notes:
1. All permeabilities are in m^2 units.
 2. Room 2 is 10.0 m wide by 3.9 m high. Tests were conducted at mid-length of Room 2.
 3. Room 2 was excavated in March 1983. Tests were conducted during September through October 1988.

TRI-6346-26-0

Figure 6.9. Distribution of permeabilities surrounding Room 2.

- Notes:
1. All permeabilities are in m^2 units.
 2. Room G is 6.0 m wide by 3.0 m high. Tests were conducted at Room G's "A" station.
 3. Room G was excavated in December 1984. Tests were conducted July through August 1988.

TRI-6346-27-0

Figure 6.10. Distribution of permeabilities surrounding Room G.

- Notes:
1. All permeabilities are in m^2 units.
 2. E-140 drift is 4.2 m wide by 2.4 m high. Tests were made at the N-1266 station.
 3. The E-140 drift at N-1266 station was excavated in February 1983. Tests were conducted during October 1988.

TRI-6346-28-0

Figure 6.11. Distribution of permeabilities surrounding the E140 drift at the N1266 station.

The results in the boreholes angled up and down reveal that the permeabilities at these locations are very low. In the one instance of measurable gas flow in a vertically down hole in Room 2, the test interval included anhydrite layer MB139. In two instances where the initial flow was relatively great but eventually decreased to essentially zero were measured in angled holes.

The results from boreholes in the E140 drift at the N1266 station indicate systematically lower permeabilities than from other locations. Recall that the E140 drift has the smallest cross-section of all the excavations from which tests were made. The only measurable gas flow occurred at 0.9 m into the roof. In the sense that the greatest depth of measurable gas permeability occurred in the rock above the roof of the E140 drift, these results are consistent with those from Room 2 and Room G.

7.0 CONCLUSIONS

A method for interpreting gas permeability and porosity from gas flow measurements has been developed. A transient numerical simulation is used to match the field results. As a result of quasi-steady flow developed during gas flow tests, a closed-form steady-state approximation provides a reasonable order-of-magnitude permeability estimate.

The uncertainty of the interpreted permeabilities is probably mostly due to the simplifications and assumptions made in developing the flow model. Shortcomings of the test equipment limits the system resolution to below 10^{-20} m². Error in the measured values (principally pressure) typically introduces less than 10% uncertainty in the calculated permeability.

For the gas flow measurements conducted in the formation surrounding various WIPP Facility excavations, the following conclusions have been drawn.

1. Gas flow in rock salt undisturbed by the presence of the excavation is very low, corresponding to a gas permeability of less than 10^{-21} m². The boundary of the undisturbed region is 1 to 5 meters from the excavation. Within the first meter of an excavation, the interpreted permeabilities can be 5 orders of magnitude greater than the undisturbed or far-field permeability. The interpreted permeabilities in the region between the undisturbed region and the first meter are in the range of 10^{-16} to 10^{-20} m².
2. Measurable gas flow occurs to a greater depth into the roof above WIPP excavations of different sizes and ages than into the ribs. There are insufficient data to draw similar conclusions regarding gas flows in the floor.
3. The gas flows into the formation surrounding the smallest excavation tested (2.4 m high by 3.6 m wide) are consistently lower than those at comparable locations surrounding larger excavations of comparable age.
4. Gas flow measured in the interbed layers near the WIPP excavations is highly variable. Generally, immediately above and below excavations, relatively great gas flow is measured in the interbed layers.

The conclusions from the gas flow/permeability measurements conducted during 1988 are consistent with those made from previous measurements. Therefore, these results substantiate the existence and nature of a limited Disturbed Rock Zone (DRZ) surrounding WIPP excavations as previously proposed by Stormont et al. (1987) and Borns and Stormont (1988).

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APPENDIX A. EXPERIMENTAL DATA

In this appendix, plots of the experimental data are given. Data given includes borehole pressure history for pressure decay test or tank pressure history for constant pressure test, temperature history and guard zone(s) history. Also given is a brief summary of the location, depth and orientation of the tests and relevant notes pertaining to the test. The appendix is arranged so that data records from the same test are contained on facing pages. When numerical simulations were used to interpret permeability and porosity from a test, the results of these simulations are also given. Only TEST 22, in which a regulator failure precluded a meaningful test, is not included.

TEST 1C

Borehole: DP02

Orientation: Horizontal

Mean test interval depth (m): 7.5

Notes: Guard zones not operable.

This test was preceded by 0.79 MPa and 1.48 MPa pressure decay tests.

This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 7.9 \times 10^{-22} \text{ m}^2$.

TEST 2

Borehole: DP02 Orientation: Horizontal

Mean test interval depth (m): 3.6

Notes: Guard zones not operable.

This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 9.4 \times 10^{-22} \text{ m}^2$.

TEST 3

Borehole: DP02

Orientation: Horizontal

Mean test interval depth (m): 7.5

Notes: Guard zones not operable.

This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 7.9 \times 10^{-22} \text{ m}^2$.

TEST 4

Borehole: DP02

Orientation: Horizontal

Mean test interval depth (m): 1.8

Notes: Guard zones not operable.

TEST 5

Borehole: DP02

Orientation: Horizontal

Mean test interval depth (m): 15.0

Notes: This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 7.9 \times 10^{-22} \text{ m}^2$.

TEST 6

Borehole: DP02

Orientation: Horizontal

Mean test interval depth (m): 6.1

Notes: Pressure increased in both test zones and guard zones, possibly due to backflow from previous tests in vicinity or packer-leakage.

This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 9.5 \times 10^{-21} \text{ m}^2$.

TEST 7

Borehole: DP02

Orientation: Horizontal

Mean test interval depth (m): 0.9

Notes: Employed collar configuration.

Constant borehole pressure of 0.17 MPa.

TEST 8

Borehole: DP01

Orientation: Horizontal

Mean test interval depth (m): 15.0

Notes: This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 7.9 \times 10^{-22} \text{ m}^2$.

Correction for possible guard zone leakage would lower the maximum equivalent permeability by about 25%.

TEST 9

System test

Notes: Equivalent permeability of system
estimated to be $7.9 \times 10^{-22} \text{ m}^2$.

TEST 10

Borehole: DP01

Orientation: Horizontal

Mean test interval depth (m): 7.5

Notes: This test was preceded by a constant pressure test at 2.17 MPa in which no pressure change was measured.

This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 5.8 \times 10^{-22} \text{ m}^2$.

Correction for possible guard zone leakage would lower the maximum equivalent permeability by less than 20%.

TEST 11A

Borehole: DP01

Orientation: Horizontal

Mean test interval depth (m): 1.8

Notes: The pressure asymptotically approached atmospheric pressure. The given history was truncated.

Borehole pressure was corrected for leakage in guard zones.

TEST 12

Borehole: DP03

Orientation: Vertical up

Mean test interval depth (m): 14.6

Notes: The test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 5.8 \times 10^{-22} \text{ m}^2$.

Borehole pressure corrected for leakage in guard zones.

TEST 13

Borehole: DP03

Orientation: Vertical up

Mean test interval depth (m): 3.9

Notes: This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 7.9 \times 10^{-22} \text{ m}^2$.

Borehole pressure corrected for leakage into guard zones.

TEST 14

Borehole: DP03

Orientation: Vertical up

Mean test interval depth (m): 1.5

Notes: This test was preceded by a 0.23 MPa constant pressure test in which no tank pressure change was measured.

Pressure increase in guard zone could be a result of "backflow" from previous constant pressure test or leakage into the guard zone. Correction for possible leakage into guard zone would lower permeability by about 50%.

TEST 15A

System Test

Notes: Equivalent permeability of system
estimated to be $5.8 \times 10^{-22} \text{ m}^2$.

TEST 15B

System Test

Notes: Equivalent permeability of system
estimated to be $8.9 \times 10^{-21} \text{ m}^2$.

TEST 15C

System Test

Notes: Equivalent permeability of system estimated to be $1.7 \times 10^{-21} \text{ m}^2$.

Correction for guard zone leakage would reduce system permeability by about an order of magnitude.

TEST 16

System Test

Notes: This test was conducted by pressurizing the guard zones and observing their response.

Equivalent permeability of system estimated to be $7.0 \times 10^{-22} \text{ m}^2$, calculated from pressure changes in guard zones.

Pressure increase in test interval possibly due to packer system compliance.

TEST 17

Borehole: DP01

Orientation: Horizontal

Mean test interval depth (m): 0.9

Notes: Employed collar configuration.

Constant borehole pressure of 0.17 MPa.

TEST 18

Borehole: DP04 Orientation: Vertical down

Mean test interval depth (m): 0.9

Notes: Employed collar configuration.

Constant borehole pressure of 0.17 MPa.

TEST 19

System Test

Notes: Equivalent permeability of system
estimated to be $1.1 \times 10^{-21} \text{ m}^2$.

TEST 20

Borehole: DP03

Orientation: Vertical up

Mean test interval depth (m): 0.9

Notes: This test was preceded by a 0.17 MPa constant pressure test. There was a problem with the regulator during this test.

This test utilized the collar configuration.

TEST 21

System Test

Notes: Only packers 1 and 4 were inflated during this system test; therefore, test and guard zones are in communication.

Equivalent permeability of system estimated to be $1.1 \times 10^{-21} \text{ m}^2$.

TEST 23

Borehole: GAP02 Orientation: Horizontal

Mean test interval depth (m): 0.9

Notes: This test utilized the collar configuration.

This test was preceded by a 0.23 MPa constant pressure test. There was a problem with the regulator during this test.

TEST 24

Borehole: GAP01 Orientation: Horizontal

Mean test interval depth (m): 0.9

Notes: This test utilized the collar configuration.

Constant borehole pressure of 0.23 MPa.

TEST 25

Borehole: GAP06

Orientation: Angled down

Mean test interval depth (m): 0.9

Notes: This test utilized the collar configuration.

This pressure during this test eventually reaches a value at which it essentially does not change. This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 2.0 \times 10^{-20} \text{ m}^2$.

TEST 26

Borehole: GAP05

Orientation: Angled up

Mean test interval depth (m): 0.9

Notes: This test utilizes the collar configuration.

This test was preceded by a 0.23 MPa constant pressure test, which did not result in a measurable tank pressure change.

This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 2.0 \times 10^{-20} \text{ m}^2$.

The borehole pressure was corrected for leakage into the guard zone.

TEST 27

Borehole: GAP06

Orientation: Angled up

Mean test interval depth (m): 1.8

Notes: This test was preceded by a 0.23 MPa pressure decay test, in which no measurable pressure change was observed.

This pressure during this test eventually reaches a value at which it essentially does not change. This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 3.3 \times 10^{-21} \text{ m}^2$.

Moisture on tool was observed at the end of the test.

The borehole pressure was corrected for leakage into the guard zones.

TEST 28B

Borehole: GAP01 Orientation: Horizontal

Mean test interval depth (m): 1.8

Notes: This test was preceded by a 0.23 MPa pressure decay test, during which insufficient pressure change was measured to continue the test.

This test was followed by a 0.44 MPa pressure decay test, during which insufficient pressure change was measured.

TEST 29A

System Test

Notes: The borehole pressure was corrected for leakage into the guard zones, packer leakage suspected.

Equivalent permeability of system estimated to be $2.5 \times 10^{-20} \text{ m}^2$.

TEST 29B

System Test

Notes: The borehole pressure was corrected for leakage into the guard zones. Packer leakage suspected.

Equivalent permeability of system estimated to be $3.3 \times 10^{-22} \text{ m}^2$.

TEST 30B

Borehole: GAP02

Orientation: Horizontal

Mean test interval depth (m): 1.8

Notes: This test was preceded by a 0.49 MPa pressure decay test. The resulting pressure change was interpreted as at or below the system resolution, with an estimated permeability of $\leq 4.7 \times 10^{-20} \text{ m}^2$.

TEST 31A

Borehole: GAP03 Orientation: Vertical up

Mean test interval depth (m): 1.8

Notes: Sequential test

Correction for possible guard zone leakage
would lower the maximum equivalent
permeability by less than 20%.

TEST 31B

Borehole: GAP03

Orientation: Vertical up

Mean test interval depth (m): 1.8

Notes: Sequential test

TEST 31C

Borehole: GAP03 Orientation: Vertical up

Mean test interval depth (m): 1.8

Notes: Sequential test.

Constant borehole pressure of 0.49 MPa.

Possible leakage into guard zone will
alter computed permeability by less than
10%.

TEST 31D

Borehole: GAP03

Orientation: Vertical up

Mean test interval depth (m): 1.8

Notes: Sequential test.

Constant borehole pressure of 0.79 MPa.

TEST 32

Borehole: GAP04 Orientation: Vertical down

Mean test interval depth (m): 1.8

Notes: This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 2.6 \times 10^{-21}$.

TEST 33A

System Test

Notes: Equivalent permeability of system estimated to be $2.0 \times 10^{-20} \text{ m}^2$.

Test zone pressure corrected for leakage into the guard zones.

TEST 33B

System Test

Notes: Equivalent permeability of system
estimated to be $9.5 \times 10^{-21} \text{ m}^2$.

TEST 33C

System Test

Notes: Equivalent permeability of system
estimated to be $3.3 \times 10^{-21} \text{ m}^2$.

TEST 34C

Borehole: GAP05

Orientation: Angled up.

Mean test interval depth (m): 1.8

Notes: This test was preceded by pressure decay tests at 0.23 and 0.44 MPa, during which no significant pressure change was measured.

This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 1.2 \times 10^{-21} \text{ m}^2$.

Pressure changes in guard zones may be a result of "backflow" of residual pressure from previous pressure decay tests. Correction for the guard zone pressure increases as if there was leakage would lower the maximum permeability by about one order of magnitude.

TEST 35C

Borehole: GAP01 Orientation: Horizontal

Mean test interval depth (m): 4.8

Notes: This test was preceded by pressure decay tests at 0.44 MPa and 0.79 MPa, during which no significant pressure changes were measured.

This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 1.5 \times 10^{-21} \text{ m}^2$.

TEST 36

System Test

Notes: Equivalent permeability of system estimated to be $1.0 \times 10^{-21} \text{ m}^2$.

The test interval pressure was corrected for guard zone leakage.

TEST 37A

Borehole: GAP03

Orientation: Vertical up

Mean test interval depth (m): 0.9

Notes: This test utilized the collar configuration.

Constant borehole pressure was 0.24 MPa.

TEST 38

Borehole: GAP03

Orientation: Vertical up

Mean test interval depth (m): 4.8

Notes:

TEST 39A

Borehole: GAP01 Orientation: Horizontal

Mean test interval depth (m): 0.9

Notes: This test employed the collar configuration.

This was a sequential test.

Constant borehole pressure of 0.17 MPa.

TEST 39B

Borehole: GAP01 Orientation: Horizontal

Mean test interval (m): 0.9

Notes: This test employed the collar configuration

This was a sequential test.

Constant borehole pressure of 0.24 MPa.

TEST 39C

Borehole: GAP01 Orientation: Horizontal

Mean test interval depth (m): 0.9

Notes: This test employed the collar configuration.

This was a sequential test.

Constant borehole pressure of 0.79 MPa.

TEST 40A

Borehole: GAP02 Orientation: Horizontal

Mean test interval (m): 0.9

Notes: This test employed the collar configuration.

This was a sequential test.

TEST 40B

Borehole: GAP02

Orientation: Horizontal

Mean test interval depth (m): 0.9

Notes: This test employed the collar configuration.

This was a sequential test.

Constant borehole pressure of 0.17 MPa.

TEST 40C

Borehole: GAP02

Orientation: Horizontal

Mean test interval depth (m): 0.9

Notes: This test employed the collar configuration

This was a sequential test.

Constant borehole pressure of 0.24 MPa.

TEST 40D

Borehole: GAP02

Orientation: Horizontal

Mean test interval depth (m): 0.9

Notes: This test employed the collar configuration.

This was a sequential test.

Constant borehole pressure of 0.45 MPa.

TEST 41

Borehole: GAP04 Orientation: Vertical down

Mean test interval depth (m): 0.9

Notes: This test employed the collar configuration.

TEST 42C

Borehole: 2P01

Orientation: Horizontal

Mean test interval depth (m): 1.8

Notes: This test was preceded by 0.24 MPa and 0.45 MPa pressure decay tests, during which no significant pressure change was measured.

This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 8.0 \times 10^{-22} \text{ m}^2$.

TEST 43C

Borehole: 2P04

Orientation:

Mean test interval depth (m): 1.8

Notes: This test was preceded by 0.24 MPa and 0.45 MPa pressure decay tests, during which no significant pressure change was measured.

This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 1.6 \times 10^{-21} \text{ m}^2$.

TEST 44A

System Test

Notes: Equivalent permeability of system estimated to be $6.2 \times 10^{-21} \text{ m}^2$. This corresponds to the pressure decay observed during the first 24 hours.

TEST 44B

System Test

Notes: Equivalent permeability estimated from pressure increase, about $4.3 \times 10^{-21} \text{ m}^2$.

Increase of both test zone and guard zone pressures may be attributable to previous system test (TEST 44A) run at greater pressure.

TEST 45

System Test

Notes: The test interval pressure was corrected for leakage into the guard zones.

Equivalent permeability of system estimated to be $2.0 \times 10^{-21} \text{ m}^2$.

TEST 46

System Test

Notes: Equivalent permeability of system
estimated to be $1.9 \times 10^{-21} \text{ m}^2$.

TEST 47

System Test

Notes: Equivalent permeability of system
estimated to be $1.4 \times 10^{-21} \text{ m}^2$.

Possible packer leakage into guard zones
after 50,000 seconds.

TEST 48

Borehole: 2P02 Orientation: Vertical up

Mean test interval depth (m): 1.8

Notes: The test interval included Seam B.

The flow into the formation was so great that a pressure could not be sustained. The estimated permeability associated with this response is $\geq 10^{-12}$ m².

TEST 49C

Borehole: 2P01

Orientation: Horizontal

Mean test interval depth (m): 3.6

Notes: This test was preceded by 0.44 MPa and 0.79 MPa pressure decay tests, during which no significant pressure decay was measured.

This test was determined to be at or below the resolution of the test system with an equivalent permeability of $\leq 9.5 \times 10^{-22} \text{ m}^2$.

TEST 50C

Borehole: 2P04

Orientation: Angled up

Mean test interval depth (m): 0.9

Notes: This test was preceded by 0.17 MPa and 0.24 MPa pressure decay tests, during which insufficient pressure change was measured.

This test employed the collar configuration.

TEST 51A

Borehole: 2P01

Orientation: Horizontal

Mean test interval depth (m): 0.9

Notes: This test employed the collar configuration.

This was a sequential test.

Constant borehole pressure of 0.17 MPa.

TEST 51B

Borehole: 2P01 Orientation: Horizontal

Mean test interval depth (m): 0.9

Notes: This test employed the collar configuration.

This was a sequential test.

Constant borehole pressure of 0.24 MPa.

TEST 51C

Borehole: 2P01

Orientation: Horizontal

Mean test interval depth (m): 0.9

Notes: This test employed the collar configuration.

This was a sequential test.

Constant borehole pressure of 0.45 MPa.

TEST 52

Borehole: 2P02 Orientation: Vertical up

Mean test interval depth (m): 2.7

Notes:

TEST 53

Borehole: 2P02

Orientation: Vertical up

Mean test interval depth (m): 4.5

Notes:

TEST 54

System Test

Notes: Initially, the test and guard zones were set with no pressure. Subsequent pressure increases attributed to packer leakage, and confirmed by inspection of packers.

No equivalent permeability was estimated for this system test.

TEST 55

Borehole: 2P02

Orientation: Vertical up

Mean test interval depth (m): 4.5

Notes:

TEST 56

Borehole: 2P02

Orientation: Vertical up

Mean test interval depth (m): 0.9

Notes: This test employed the collar configuration.

TEST 57

Borehole: 2P02

Orientation: Vertical up

Mean test interval depth (m): 2.7

Notes:

TEST 58A

System Test

Notes: The test interval pressure was corrected for leakage into the guard zones

Equivalent permeability of system estimated to be $1.2 \times 10^{-21} \text{ m}^2$.

TEST 58B

System Test

Notes: The test interval pressure was corrected for leakage into the guard zones.

Equivalent permeability of system estimated to be $1.2 \times 10^{-21} \text{ m}^2$.

TEST 58C

System Test

Notes: The test interval pressure was corrected for leakage into the guard zones.

Equivalent permeability of system estimated to be $7.6 \times 10^{-22} \text{ m}^2$.

TEST 59

Borehole: 2P03

Orientation: Vertical down

Mean test interval depth (m): 0.9

Notes: This test employed the collar configuration.

TEST 60

Borehole: 2P03 Orientation: Vertical down

Mean test interval depth (m): 2.1

Notes: This test interval included MB 139.

The flow into the formation was so great that a pressure could not be sustained. The estimated permeability associated with this response is $> 10^{-12} \text{ m}^2$.

TEST 61

Borehole: 2P05

Orientation: Angled down

Mean test interval depth (m): 0.9

Notes: This test employed the collar configuration.

TEST 62

Borehole: 2P05

Orientation: Angled down

Mean test interval depth (m): 3.6

Notes: The test interval included MB 139.

TEST 63

Borehole: 2P05

Orientation: Angled down

Mean test interval depth (m): 1.8

Notes: This test was determined to be at or below the system resolution, estimated to be $\leq 2.0 \times 10^{-22} \text{ m}^2$.

TEST 64

Borehole: EP02 Orientation: Horizontal

Mean test interval depth (m): 1.8

Notes: This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 1.1 \times 10^{-21} \text{ m}^2$.

TEST 65

Borehole: EP01

Orientation: Horizontal

Mean test interval depth (m): 1.8

Notes: This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 2.6 \times 10^{-21} \text{ m}^2$.

TEST 66

Borehole: EP03 Orientation: Vertical up

Mean test interval depth (m): 1.8

Notes: This test was determined to be at or below
the system resolution, with an equivalent
permeability of $\leq 2.4 \times 10^{-21} \text{ m}^2$.

TEST 67

Borehole: EP03 Orientation: Vertical up

Mean test interval depth (m): 0.9

Notes: This test employed the collar configuration.

TEST 08

Borehole: EP04

Orientation: Angled up

Mean test interval depth (m): 1.8

Notes: This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 2.0 \times 10^{-21} \text{ m}^2$.

TEST 69

Borehole: EP04

Orientation: Angled up

Mean test interval depth (m): 0.9

Notes: This test employed the collar configuration.

This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 6.8 \times 10^{-21} \text{ m}^2$.

TEST 70

Borehole: EP05

Orientation: Angled up

Mean test interval depth (m): 0.9

Notes: This test employed the collar configuration.

This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 8.3 \times 10^{-21} \text{ m}^2$.

Correction for possible guard zone leakage would lower the maximum permeability by about 50%.

TEST 71

Borehole: EP02

Orientation: Horizontal

Mean test interval depth (m): 0.9

Notes: This test employed the collar configuration.

This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 1.0 \times 10^{-20} \text{ m}^2$.

TEST 72

Borehole: EP01 Orientation: Horizontal

Mean test interval depth (m): 0.9

Notes: This test employed the collar configuration.

This test was determined to be at or below the system resolution, with an equivalent permeability of $\leq 1.0 \times 10^{-20} \text{ m}^2$.

TEST 73

System Test

Notes: Initially, the test and guard zones were set with no pressure. Subsequent pressure increases attributed to packer leakage, and confirmed by inspection of the packers.

No equivalent permeability was estimated for this system test.

END

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