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Literature Review and Recommendation of Methods for Measuring Relative Permeability of Anhydrite from the Salado Formation at the Waste Isolation Pilot Plant

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Literature Review and Recommendation of Methods for Measuring Relative Permeability of Anhydrite from the Salado Formation at the Waste Isolation Pilot Plant

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ABSTRACT

This report documents a literature review of methods for measuring relative permeability as applied to low permeability anhydrite rock samples from the Salado Formation. About one hundred papers were reviewed, and four methods were identified as promising techniques for measuring the relative permeability of the Salado anhydrite: 1) the unsteady-state high-rate method, 2) the unsteady-state stationary-liquid method, 3) the unsteady-state centrifuge method, and 4) the unsteady-state low-rate method. Except for the centrifuge method, all have been used for low permeability rocks. The unsteady-state high-rate method is preferred for measuring relative permeability of Salado anhydrite, and the unsteady-state stationary-liquid method could be well suited for measuring gas relative permeability of Salado anhydrite. The unsteady-state low-rate method, which combines capillary pressure effects with relative permeability concepts may also prove effective. Likewise, the unsteady-state centrifuge method may be an efficient means for measuring brine relative permeability for Salado anhydrite, especially at high gas saturations.

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1. SUMMARY

The objective of this report is to document a literature review of methods for measuring relative permeability as applied to low permeability anhydrite rock samples from the Salado Formation at the Waste Isolation Pilot Plant (WIPP) site. The anhydrite interbeds are considered to be the most permeable of the Salado stratigraphic layers. Relative permeability measurements are necessary for performance assessment predictions of the potential for flow of waste-generated gas from and brine inflow into the WIPP repository. Salado anhydrite porosity is expected to range between 1 and 3 percent, and undisturbed permeability is expected to vary from 1×10^{-16} to $1 \times 10^{-21} \text{ m}^2$ ($\sim 1 \times 10^{-4} \text{ D}$ to $1 \times 10^{-9} \text{ D}$). With these parameter ranges in mind, this survey of current technology for measuring relative permeability was undertaken, and in all, about one hundred papers were reviewed. The survey began with a database literature search by Sandia National Laboratories. Then, the most relevant papers identified by the search were obtained and evaluated, and from the reference lists in these papers, other pertinent papers were found. Additional references were identified through reviews of recent technical conference programs.

As a result of the evaluation of the technology described in the papers, four methods were identified as promising techniques for measuring the relative permeability of the Salado anhydrite. Listed in order of most promising for this application, they are: 1) the unsteady-state high-rate method, 2) the unsteady-state stationary-liquid method, 3) the unsteady-state centrifuge method, and 4) the unsteady-state low-rate method. Each method, except for unsteady-state centrifuge, has been used for low permeability rocks. The unsteady-state low-rate and unsteady-state centrifuge methods are the newest and least proven of the four. Because of its well-documented, successful applications cited in the literature, the unsteady-state high-rate method is the first choice for measuring relative permeability of Salado anhydrite and is expected to yield accurate measurements, especially at moderate gas saturation values. The unsteady-state stationary-liquid method could be well suited for measuring gas relative permeability of Salado anhydrite.

The unsteady-state low-rate method may also prove to be an effective technique for Salado anhydrite because it integrates capillary pressure and relative permeability effects. In addition, the relative permeability estimates obtained from the unsteady-state low-rate displacements may be more pertinent for evaluation of the potential for transport of waste-generated gas from, and brine inflow to, the WIPP repository than two-phase relationships obtained using high-rate displacements. Likewise, the unsteady-state centrifuge method may prove to be an efficient means for measuring brine relative permeability for Salado anhydrite, especially at high gas saturations.

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2. INTRODUCTION

Technology for safe disposal of radioactive wastes in bedded salt deposits is being developed at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico. A significant objective of this effort is the prediction of the long-term performance of the repository. These predictions focus on structural changes as the halite flows to fill the excavated waste-storage rooms, and on the potential for flow of gas and brine through the anhydrite, clay, and/or halite beds of the Salado Formation which surrounds the repository. In situ tests indicate that the anhydrite layers, such as the 1-m thick Marker Bed 139 (MB 139), have permeabilities that are one to two orders of magnitude greater than the halite layers, so the anhydrite layers may provide a primary flow path for brine into, and gas out of, the repository. Currently, program emphasis is on collecting rock and flow data for the higher permeability anhydrite interbed layers, and this literature review was directed toward evaluating current laboratory technology for measuring relative permeabilities of the Salado anhydrite.

While two-phase rock-fluid properties such as relative permeability are routinely measured on rock samples from hydrocarbon reservoirs, measurement methodologies are not standardized. For studies of hydrologic properties of low permeability rock such as the anhydrite from the Salado Formation, modifications of techniques used for high permeability rock may be required due to difficulties associated with measuring ultra-low flow rates and fluid saturation in tight rocks.

The test flow rates must be extremely low to accommodate acceptable magnitudes of the pressure differential across a core during a test, so adequate means of quantifying low flow rates at high pressure drops are needed. Because flow rates are so low, minuscule leaks in the test system can have dramatic effects on the measurement accuracy; hence, modifications that essentially eliminate all leaks are needed. Porosity of the rock is expected to be low, so modifications which allow for quantification of fluid saturation in the extremely small pore space are needed. In addition to the near-complete elimination of leaks, these modifications include minimization of "dead space" in the test system. For gas-liquid displacements, modifications are required to minimize permeation of gas through O-rings or other elastomeric seals, which may have significant effects on test results.

In addition to these modifications of experimental techniques, it is necessary to use a compatible brine or other non-reactive liquid. If a non-equilibrated brine or other reactive fluid is used, dissolution of the rock may lead to significant errors in flow measurements. Rock-fluid compatibility is an important, but often overlooked, concern in permeability measurements of

rock from hydrocarbon reservoirs, and it may be critical for anhydrite test samples, especially if there are substantial amounts of other minerals such as halite mixed in with the anhydrite.

This literature review is the end product of the first two tasks of a four-task project. Task 1 consisted of collecting literature on methods for measuring relative permeability. In Task 2, the collected literature was examined on two levels. First, the literature was reviewed and an overview of the literature conclusions, which comprises this report, was prepared. Second, a thorough evaluation of the methods was conducted to ascertain their suitability for measuring relative permeabilities of rock samples like the Salado anhydrite. If deemed necessary for completion of the evaluation, some of the important problems discovered in measuring the relative permeability of Salado anhydrite will be examined in scoping experiments under Task 3. The specific approach and deliverables of Task 3 will be decided as the evaluation matures. In Task 4, the knowledge gained through the efforts of Tasks 1, 2, and 3 will be summarized in a final report.

The remainder of this literature review is organized into six sections and five appendices. In Section 3, the nature of gas-brine flow in rocks is described in a conceptual fashion wherein complications caused by capillary effects are described in a semi-quantitative manner, providing a background for understanding the difficulties in measuring relative permeability of tight rocks. In Section 4, the categories of methods for measuring relative permeability are introduced, and the methods for processing data for the various methods are described. In Sections 5 and 6, detailed descriptions of steady-state methods and unsteady-state methods for measuring relative permeability are provided, and are supplemented by appendices, which contain an extensive tabulated summary of literature on relative permeability measurements and a collection of figures which depict the variety of methods used for measurement of relative permeability. Section 7 covers reports of methods used to measure relative permeability on analogous tight rocks. Finally, Section 8 contains a discussion of the merits of the various methods with respect to measurements with rock samples from the Salado anhydrite, and Section 9 contains a list of the reviewed literature.

3. NATURE OF GAS-BRINE FLOW IN ROCK

Quantitative description of multi-phase flow through rock requires measurement of porosity, absolute or intrinsic permeability, relative permeability and capillary pressure. Porosity is required for measurements of void space and is used to calculate the relative saturations of the pore fluids. Relative permeability combined with absolute or intrinsic permeability reflects the flow capacity for a fluid phase at a given pressure differential across a core. Capillary pressure refers to the differences in pressures between two stationary phases for equilibrium fluid saturations. In this section, a qualitative description of gas-brine flow through rock is presented to identify the key experimental considerations that must be taken into account when evaluating techniques for measuring relative permeability of tight geologic media. Within this report, the term "porous media" refers to "geologic media."

3.1 Two-Phase Flow in Porous Media

When a single-phase fluid (gas or liquid) flows through a porous medium, all of the pores and connections between pores are available for flow. When two or more phases are flowing through a porous medium, portions of the pores and connecting pathways are occluded by droplets, bubbles, or other such local accumulations of fluids in one phase suspended within fluids in the other phase, or attached to the surface of the rock grains, or both. Thus, the capacity for simultaneous flow of fluids in multiple phases is less than that of a single phase. Whereas intrinsic or absolute permeability is a measure of the ease with which a single-phase fluid will flow through a porous medium, relative permeability is a measure of the ease with which a fluid will flow through a porous medium when another fluid is present.

Because relative permeability and capillary pressure are closely coupled, this description of gas-brine flow begins with an overview of fundamental capillary pressure concepts. The following conceptual experiment illustrates the capillary pressure-relative permeability interrelationship for generic capillary pressure and relative permeability curves presented as Figure 1. Beginning with a cylindrical rock core sample completely saturated with brine, the sample is sealed on its cylindrical surface and exposed to gas on its upper face and to brine on its lower face. The core is mounted vertically in a test cell as shown in Figure 2. At the start of this experiment, the difference between pressures measured in the gas and brine phases is zero. Then, pressure in the gas phase is gradually increased with a positive displacement pump operating at a constant, low flow rate. Gas cannot enter the porous network in the rock until the pressure in the gas phase exceeds the pressure in the brine phase by an amount defined as the gas

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Figure 1. Generic gas-liquid capillary pressure and relative permeability curves.

threshold displacement pressure (also known as threshold pressure), P_{ct} . As shown in Figure 1, P_{ct} is the endpoint of the capillary pressure-vs-saturation curve corresponding to 100 percent brine saturation. Below this threshold pressure, the gas-brine interface at the inlet face of the rock sample is not deformed enough to penetrate even the largest pore throats. Dimpling of the interface increases with increasing gas-brine capillary pressure, P_c , which is defined in equation 1,

$$P_c = P_g - P_b \quad (1)$$

where

P_g = pressure in the gas phase at the gas-brine interface, and

P_b = pressure in the brine phase at the gas-brine interface.

At a gas-brine capillary pressure slightly greater than the threshold pressure, the dimples in the gas-brine interface will penetrate through the largest pore throats in the rock, displacing brine. If the gas-brine surface tension, σ , and the radius, R , of the largest pore throats were known, then P_{ct} could be estimated with a simplified version of the Laplace equation which describes the difference in pressure across the interface between immiscible fluids:

$$P_{ct} = \frac{2\sigma}{R} \quad (2)$$

Penetration of gas into a portion of the porous network does not necessarily mean there is a connected path of gas from the top face of the sample to the bottom face. More likely, much of the gas in the network resides just near the upper face of the rock. Further injection of gas by the pump is needed to develop a connected gas pathway. With continuing injection, pressure in the gas phase will increase, accompanied by increasing capillary pressure.

With continued injection of gas, a connected path will gradually develop, allowing gas to penetrate from inlet to outlet of the rock sample. The gas saturation at this point, where a connected gas flow path is formed, is defined as the critical gas saturation, S_{gc} , and is the end point saturation for the gas relative permeability relationship, as shown in Figure 1. At gas saturation values less than the critical gas saturation, relative permeability to gas is zero. The capillary pressure corresponding to the critical gas saturation is defined as the critical capillary pressure, P_{cc} . The difference between P_{ct} and P_{cc} is often small, the actual difference depending on the distribution of pore throat sizes in the rock sample. For performance assessment, P_{cc} is more important than P_{ct} because these activities are concerned with the potential for flow of waste-generated gas outward from the repository. As described by Davies (1991), this process will likely require that the outward-flowing gas establish a continuous network of gas flow paths corresponding to P_{cc} . However, because the difference between P_{ct} and P_{cc} is usually small, little

error may result from using P_{ct} in place of P_{cc} . Experimental measurement of P_{ct} and P_{cc} is needed to quantify this difference for any particular rock sample.

This conceptual experiment demonstrates one technique for measuring critical capillary pressure, gas threshold displacement pressure, and critical gas saturation. Other techniques, such as the centrifuge method or the porous plate methods, may be used for determining the entire capillary pressure relationship, but the simple experiment illustrated in Figure 2 is suitable for measuring P_{ct} , P_{cc} , and S_{gc} directly.

The effect of gravity in this conceptual experiment is generally negligible. For example, the earth's gravitational pull acting on a gas-brine density difference of approximately 1.0 g/cc in a 2.54-cm-long rock sample results in a capillary pressure at the top of the rock about 0.25 kPa greater than at the bottom of the rock. However, gas-brine P_{cc} is typically 5 to 10 kPa for a consolidated sandstone with permeability between $50 \times 10^{-15} \text{ m}^2$ and $500 \times 10^{-15} \text{ m}^2$.

3.2 Capillary End Effects

Threshold and critical capillary pressures and critical gas saturation all play an important role in producing capillary end effects which cause pore fluids to be non-uniformly distributed within a rock sample. Continuing the conceptual experiment to help define capillary end effects, consider the long cylindrical rock sample shown in Figure 3(a), mounted in a test cell in a manner similar to that shown in Figure 2. When gas breaks through at the lower face of the rock sample, the gas saturation will be as shown in Figure 3(b). For low rates of gas injection, the gas saturation at the lower face of the core will slightly exceed the critical gas saturation. Continued injection of gas at low flow rates will cause little change in the gas saturation profile in Figure 3(b).

Retention of brine near the outlet end of a rock sample, as shown in Figure 3(b), is called the capillary end effect. Whether the rock sample is mounted vertically or horizontally, a capillary end effect is generated when gas displaces brine from a rock sample. The amount of brine retained by the rock sample due to end effects depends on the nature of the gas-brine capillary pressure relationship, gas and brine relative permeabilities, absolute permeability, and the flow rate. A common and simple approach used to reduce the end effects is to increase flow rate.

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Figure 2. Schematic diagram for conceptual experiment.

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Figure 3. Capillary end effects in brine gravity drainage process.

3.3 Capillarity and Measurement of Relative Permeability

Capillarity and relative permeability are closely coupled. For low flow rates that typify most fluid movement in porous formations, capillary effects determine the distribution of fluid phases in the porous network. A phase which wets a mineral surface will occupy the small spaces in the network formed from that mineral, while the non-wetting phase will occupy the larger spaces.

Recognizing the strong coupling of capillarity and relative permeability, several research groups have proposed methods for estimating relative permeability from capillary pressure data. Rose and Bruce (1949), Burdine (1953), and Brooks and Corey (1966) all propose methods for estimating relative permeability from capillary pressure data. In the absence of measured relative permeabilities, such correlations can be useful. Capillary pressure data, particularly mercury injection data, is much more abundant than relative permeability data. However, extrapolating relative permeabilities from mercury data requires understanding wettability effects and the use of models such as Brooks and Corey. Such an extrapolation is used in the absence of relative permeability measurements.

It is important to recognize the coupling of capillarity and relative permeability in experiments aimed at measuring relative permeability. As explained in Section 3.2, gas-brine capillary effects produce non-uniform fluid saturation distributions in a homogeneous rock sample from which brine is displaced by gas. Non-uniform saturations lead to difficulties in measuring relative permeability, because it is necessary to determine which saturation in a non-uniformly saturated rock corresponds with which measured relative permeability.

An analytical perspective on the non-uniform fluid saturation caused by capillarity can be developed from a form of Darcy's law. Extending Darcy's law to two-phase flow through a porous medium, flow rates for gas and brine are written as shown in equations 3(a) and 3(b) which serve as a precise definition of relative permeability.

$$q_b = - \left(\frac{k_{rb} kA}{\mu_b} \right) \left(\frac{dP_b}{dx} \right) \quad (3a)$$

$$q_g = - \left(\frac{k_{rg} kA}{\mu_g} \right) \left(\frac{dP_g}{dx} \right) \quad (3b)$$

where

q_b, q_g	=	brine and gas flow rates
k_{rb}, k_{rg}	=	brine and gas relative permeability
k	=	absolute or intrinsic permeability
A	=	cross-sectional area available for flow
μ_b, μ_g	=	brine and gas viscosity
$dP_b/dx, dP_g/dx$	=	pressure gradients in the brine and gas phases along the length, x , of the rock sample

Equations 3a and 3b can be rearranged to express differential change of pressure in either fluid:

$$dP_b = - \left[\frac{\mu_b q_b}{k_{rb} k A} \right] dx \quad (4a)$$

$$dP_g = - \left[\frac{\mu_g q_g}{k_{rg} k A} \right] dx \quad (4b)$$

Because the differential change in capillary pressure is defined as shown in equation 5: then

$$dP = dP_g - dP_n \quad (5)$$

$$\frac{dP_c}{dx} = \left(\frac{1}{kA} \right) \left(\frac{\mu_b q_b}{k_{rb}} - \frac{\mu_g q_g}{k_{rg}} \right) \quad (6)$$

substituting

$$\frac{dP_c}{dx} = \left(\frac{dP_c}{dS_b} \right) \left(\frac{dS_b}{dx} \right) \quad (7)$$

then

$$\frac{dS_b}{dx} = \frac{\left(\frac{1}{kA}\right) \left(\frac{\mu_b q_b}{k_{rb}} - \frac{\mu_g q_g}{k_{rg}}\right)}{\left(\frac{dP_c}{dS_b}\right)} \quad (8)$$

For a steady-state experiment, the flow rates are independent of x and equation 8 can be integrated using a variety of procedures for initial-value problems including Runge-Kutta methods. Integration starts at the outflow end of the rock sample and proceeds toward the inflow end, with the outlet gas saturation just slightly greater than the critical gas saturation, as demonstrated by Richardson et al. (1952).

The results of integrating equation 8 for three total flow rates (with fractional flow rates of 20 percent brine, 80 percent gas) are shown in Figure 4. The input data for Figure 4 as listed in Table 1 were chosen to be representative of an experiment performed with an anhydrite sample from the Salado Formation. The saturation dependencies of relative permeabilities and capillary pressure used for calculating the saturation profiles in Figure 4 have the following forms:

$$k_{rb} = \left(\frac{S_b - S_{bi}}{1 - S_{bi}} \right)^{nb} \quad (9a)$$

$$k_{rg} = k_{rg,max} \left(\frac{S_g - S_{gc}}{1 - S_{gc} - S_{bi}} \right)^{ng} \quad (9b)$$

$$P_c = P_{ct} - P_{span} \ln \left(\frac{S_b - S_{bi}}{1 - S_{bi}} \right) \quad (9c)$$

where

- $k_{rb,max}$ = maximum brine relative permeability = 1.0
- $k_{rg,max}$ = maximum gas relative permeability
- S_{bi} = irreducible brine saturation
- S_{gc} = critical gas saturation
- nb, ng = exponents in equations 9a and 9b
- P_{ct} = threshold capillary pressure
- P_{span} = a parameter of equation 9c which gives a "span" of capillary pressures with changing brine saturation

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Figure 4. Flow rate and capillary end effects on Salado anhydrite simulation.

Table 1. Parameter values used in integration of equation 8 and to produce Figure 4. (Parameter values were chosen to be representative of experiments performed with anhydrite.)

PARAMETER	VALUE USED IN SIMULATION
Cross-Sectional Area, cm^2	50.27
Maximum brine relative permeability, $k_{rb,\text{max}}$	1
Maximum gas relative permeability, $k_{rg,\text{max}}$	1
Permeability, nanodarcies ($\sim 10^{-21} \text{ m}^2$), k	15
Brine Viscosity, cp ($=1 \text{ mPa} \cdot \text{s}$)	1
Gas Viscosity, cp ($=1 \text{ mPa} \cdot \text{s}$)	0.01
Irreducible Brine Saturation, S_{bi}	0.2
Critical Gas Saturation, S_{gc}	0.1
P_{span} , MPa	0.34
Exponents in equations 9a, b, and c: nb ng	1.7 1.5

The results shown in Figure 4 illustrate that in a steady-state experiment, the amount of brine retained at the outlet end of a rock sample due to end effects will decrease with increasing flow rate. Note that the volume of brine retained is relatively small for these calculations and that actual volume retained may differ from that shown in Figure 4, depending on the actual rock and fluid properties and the flow rates.

The evolution of procedures for measuring relative permeability, as evidenced by the summary of fifty years of literature in Sections 4, 5, and 6 and the associated appendices, illustrates the concerns regarding capillary end effects. Because end effects can cause dramatic variations in fluid saturation from the inlet to the outlet end of a rock sample, procedures for measuring relative permeability should not ignore them. A number of approaches are used to minimize the phenomenon. One technique is to use very long rock samples; however, because long samples are not always available, some experimentalists abut other rock samples to the inlet and outlet end of the test sample to simulate a long sample. In another approach, high flow rates and high pressure drops are used to swamp capillary end effects. Yet other techniques are

described in detail in later sections of this report. Each approach discussed for dealing with capillary end effects has inherent advantages and disadvantages and none are entirely satisfying.

4. RELATIVE PERMEABILITY METHODS AND DATA REDUCTION

Measuring relative permeability requires a strongly coupled effort of experimental techniques and data reduction skills. In this chapter, experimental approaches used to measure relative permeability are described with sufficient detail to allow for meaningful discussion of data reduction methods. Some of these experimental approaches are challenging to implement, but usually have simpler data reduction procedures, while those that are less challenging to perform often require detailed data reduction procedures. Following the description of experimental methods, data reduction techniques are explained, providing an outline for the in-depth discussions contained in Section 5 and 6.

4.1 Categories of Experimental Methods

Many different approaches for measuring relative permeability have been documented in the literature since the mid-1930's. During the 50-year history of relative permeability measurements, many comparative studies of the various approaches were written: e.g., Brownscombe et al. (1950), Osoba et al. (1951), Richardson et al. (1952), and Loomis and Crowell (1961). Additional summaries can also be found in texts and monographs (e.g., Scheidigger (1960); Amyx et al. (1960); and Honarpour et al. (1986)). Of these studies and summaries, that by Loomis and Crowell (1962) contains an impressive comprehensive analysis coupled with first-hand experience with many methods. Those of Brownscombe et al., Osoba et al., and Richardson et al. are also noteworthy.

In general, the approaches used to measure relative permeability can be categorized as steady-state or unsteady-state techniques, depending on whether fluid saturations are constant (steady-state) or changing (unsteady-state) during the measurement period.

4.1.1 Steady-State Methods

Steady-state methods all consist of a sequence of experiments with time-independent pressure drop and fluid saturations. In each experiment of a sequence, fluids are injected at a constant rate. Although pressure drops and fluid saturations change in the early part of the experiment, pressure drop and saturation are not recorded until they reach stable values. Once stable values are reached and recorded, flow conditions are then changed to obtain fluid saturations and the associated pressure drops for the next experiment in the sequence. Thus,

steady-state methods require a sequence of experiments performed over a range of discrete, steady flow conditions. Each step in the sequence may take a day to a week to complete, depending on the permeability and porosity of the rock and the corresponding time required to reach stable values of pressure drop and saturations.

Within the category of steady-state methods, four sub-categories can be used to classify methods according to the experimental approach for minimizing the influence of capillary end effects: (1) the multiple-core method, (2) the high-rate method, (3) the stationary-liquid method, and (4) the uniform capillary-pressure method. Although the names of the sub-categories of steady-state methods vary widely in the literature, the names used here describe of the approach used.

MULTIPLE-CORE METHOD

In this technique, frequently called the Penn State method, a rock sample is sandwiched between two other rock samples to build a longer sample. The upstream rock sample distributes flow of the multiple phases over the cross-section of the rock, and the downstream rock sample contains the capillary end effects. Typically, the two fluids are injected at high, constant flow rates.

HIGH-RATE METHOD

In the high-rate method, two fluid phases are injected into a single rock sample at high flow rate. The rate required depends on the length of the rock sample and its capillary pressure properties. By operating experiments at different total flow rates, the importance of the capillary end effect can be determined. The key difference between the multiple-core method and the high-rate method is the number of rock samples used in a test.

STATIONARY-LIQUID METHOD

In the stationary-liquid method, relative permeability of a fluid phase is measured in the presence of an essentially immobile second phase. Typically, the immobile phase is the wetting phase (brine), while the mobile (non-wetting) phase is usually gas. Because the interfacial tension between brine and gas is large, the capillary forces holding each fluid in place are strong. Thus, the brine phase is immobilized as long as the pressure gradient in the gas phase is small.

UNIFORM CAPILLARY-PRESSURE

In the uniform capillary-pressure method, often called the Hassler method, the capillary pressure between two flowing phases is kept uniform throughout a rock sample by keeping the pressure gradients equal in both phases. Because of the extraordinary challenges involved in implementing this method, reports of its use in the literature are limited.

4.1.2 Unsteady-State Methods

Unsteady-state methods consist of single experiments in which a fluid is injected into a rock sample and the transient behavior of pressure decay and fluid saturation is recorded. The time required to complete an experiment is significantly less than for steady-state experiments, taking an hour or less even for rocks with permeabilities of about 1 md ($1 \times 10^{-12} \text{ m}^2$). A larger number of variations on unsteady-state measurement methods is reported in the literature than for steady-state methods. Variations include injecting fluids at constant rate, constant pressure, or in a pulsed manner. In centrifugal experiments, fluid is drained from a rock sample at an exponentially declining rate, whereas in other experiments a pressure difference between the injected fluid and the displaced fluid is applied and then allowed to decrease toward an equilibrium value which is determined by capillary pressure properties. It is important to note that relative permeability and capillary pressure must be determined separately using most unsteady-state methods. Unsteady-state methods are further divided under four sub-categories: (1) high-rate methods, (2) low-rate methods, (3) centrifuge methods, and (4) stationary-liquid methods. All are briefly described below.

HIGH-RATE METHODS

The high-rate unsteady-state method is the most commonly reported in the literature. In this method, a fluid is injected at a high rate into a rock sample with a known initial saturation. By injecting fluid at a sufficiently high rate, the impact of capillary effects on the displacement process is minimized. Fluid saturation and pressure drop across the core are continually monitored and recorded throughout the displacement experiment.

LOW-RATE METHODS

In more recent literature (5 to 10 years), another unsteady-state method is discussed. In this method, fluid is injected at a low rate, and while the low injection rates may allow capillary effects to impact the displacement process, they better replicate in situ flow velocities. Data processing techniques, equivalent to the history matching techniques used in reservoir management and numerical modeling of reservoirs, have been developed to de-couple the capillary effects from the relative permeability effects. With these data processing techniques, it is possible to determine the capillary pressure and the relative permeability relationships simultaneously.

CENTRIFUGE METHODS

Centrifuge methods for measuring relative permeability evolved from centrifuge capillary pressure methods. To measure the capillary pressure relationship, a rock sample is mounted in a cup on a centrifuge rotor. As the rotor spins at a constant speed, fluid drains from the rock at an exponentially declining rate, eventually ceasing. By measuring the rate of fluid drainage at each of several centrifuge speeds, the capillary pressure relationship can be determined. The data processing required to obtain the relative permeability relationship is similar to that of the low-rate method, a history matching exercise.

STATIONARY-LIQUID METHOD

In a variation of the steady-state stationary-liquid methods, relative permeability of gas can be measured with pressure- or pulse-decay methods. The liquid saturation remains constant as it does in the steady-state stationary-liquid method, but the flow rate of the gas phase varies with time.

4.1.3 Trends in the Literature

In Figure 5, the cumulative numbers of references identified for each relative permeability measurement method are plotted as a function of the calendar year of publication, from 1930 to 2000. The high-rate unsteady-state method was the most reported. In spite of the comparative difficulties for data processing with this method (as explained in Section 4.2), its experimental simplicity and short test duration make it a very attractive technique. Among the steady-state

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Figure 5. Reported use of each relative permeability method.

methods, application of the high-rate method has been reported most often, followed by the multiple-core method, and the stationary-liquid method. The uniform capillary-pressure method was reported in only five papers.

A desire for relative permeabilities that are measured at reservoir conditions is influencing the trends in Figure 5. Measuring relative permeabilities at reservoir conditions often means operating at high pressures and high temperatures, with fluids sampled from the reservoir or blended to closely resemble reservoir fluids, and with confining or overburden pressures applied to the rock sample. Given these extra experimental complications, the simpler methods for measuring relative permeability are greatly favored. Thus, the steady-state high-rate method, and the unsteady-state high-rate method have been used more frequently for measurements at reservoir conditions.

4.2 Data Reduction

4.2.1 General

Data reduction and processing guide the design of an experimental method. In data processing, the measured or observed data from an experiment are converted into information of the desired form for interpretation or application. Depending upon the experimental method used, data from relative permeability tests may include length dimensions of the rock sample, pressure distributions, injection and production rates or cumulative volumes, elapsed time, and saturation distributions, and for centrifuge experiments, the rotation rate and the rotor dimensions. In all cases, the observed data must be processed to infer relative permeability relationships. Specific techniques for reduction of steady-state and unsteady-state experimental data are described in the remainder of Section 4.

4.2.2 Steady-State Methods

From the data reduction perspective, the steady-state methods are the simplest for determining relative permeability. Steady-state experimental methods are designed to ensure that pressure gradient and fluid saturations are uniform throughout the sample, and data reduction is correspondingly simplified. In steady-state methods, the observed parameters are rock sample length dimensions, flow rates for each injected fluid, pressure differential across the sample, and

the fluid saturations. Fluid saturations are indirectly determined by measuring the change of mass of the rock sample, by measuring the change of electrical resistance, and/or by measuring the change of absorption of x-ray or other radiation combined with initial pore volume measurements. Single-phase, or absolute permeability, effective porosity, and fluid viscosities data are also required for the calculation of relative permeability. Further, most of the techniques used to process steady-state data assume: 1) that the rock is homogeneous, and 2) that the saturation distribution is uniform throughout the rock sample.

Using these observed parameters and data, relative permeability for steady-state experiments can be calculated at each saturation state using integrated forms of Equations 3(a) and 3(b) rearranged as follows:

$$k_{rb} = - \frac{(\mu_b L q_b)}{(k A \Delta P_b)} \quad (10a)$$

$$k_{rg} = - \frac{(\mu_g L q_g)}{(k A \Delta P_g)} \quad (10b)$$

Although ΔP_b and ΔP_g can be measured separately, it is usually assumed that they are equal. The quality of this assumption improves with increasing flow rate. Because this method for processing of steady-state data is so straightforward, it is not specifically cited in the literature. However, data processing is described in much of the literature on experimental methods of steady-state measurements.

4.2.3 Unsteady-State Methods

Data processing for unsteady-state methods is more complicated than that for steady-state methods. Since the pressure gradient and the fluid saturations vary with position and time throughout the rock sample. Because the data reduction is complicated, there is technical literature devoted to development of methods for converting experimentally observed parameters into relative permeability relationships, beginning with Welge (1952) and Johnson et al. (1959).

Welge (1952) showed that the ratio of relative permeabilities (gas to brine, for example)

$$\frac{k_{rg}}{k_{rb}} = \frac{\mu_g}{\mu_b} \left(\frac{1-f_{bL}}{f_{bL}} \right) \quad (11)$$

can be calculated from production data (gas and brine volumes) in an unsteady-state experiment operated so that effects of capillary pressure can be neglected. As described in Collins (1961), Welge showed that the ratio of relative permeabilities can be calculated by differentiating the cumulative brine production, Q_{bp} , from a rock sample with respect to the cumulative gas volume injected, Q_{gi} , in which

$$f_{bL} = \frac{dQ_{bp}}{dQ_{gi}} \quad (12)$$

The ratio of relative permeabilities given by equation 8 is for the brine saturation at the outflow end of the rock sample at the time corresponding to the differentiation. This technique contains the implicit assumption that the rock is homogeneous and that capillary end effects are negligible. The brine saturation at the effluent end, $S_b(L)$, is calculated using equation 13 as demonstrated by Welge:

$$S_b(L) = \bar{S}_b + Q_{gi} f_{bL} \quad (13)$$

Here, $\bar{S}_b$ is the average brine saturation in the core.

The method presented by Johnson et al. (1959), commonly referred to as the JBN method, is used to calculate relative permeability for unsteady-state techniques in which both pressure and fluid production data are available. As is true for the Welge method, capillary end effects must be negligible for the JBN method to yield accurate results.

The JBN method was also discussed by a number of more recent authors. Jones and Roszelle (1978) demonstrated a graphical method based on the JBN method; this method is easier to use than the original JBN method, and it can give more accurate results. Odeh and Dotson (1985) suggested a modification of the Jones-Roszelle graphical technique that accounts for capillary end effects. Tao and Watson (1984a; 1984b) completed an extensive analysis of propagation of errors through the JBN method. Tao and Watson also suggested numerical routines for improving accuracy of the JBN method.

In the early 1980's, a history-matching approach for processing unsteady-state data evolved and its use became feasible as computers became more powerful. As this approach developed, new experimental methods evolved with reduced laboratory fluid injection rates which more closely replicate in situ flow rates. At low flow rates, many of the historical concerns about unsteady-state experiments became less important. For example, it was recognized that the time scales associated with wettability changes (typically, days) that may accompany the displacement

process are often much greater than the time scales of unsteady-state displacements (typically, minutes to hours). Accordingly, it was argued that the slower steady-state displacements provided a more representative measurement of in situ relative permeability. In addition, it was recognized that at low flow rates, fines migration, and emulsion generation could be minimized or maintained at magnitudes representative of reservoir processes (Batycky et al., 1981). On the downside, however, capillary effects become important and must be properly included in the history matching process at low flow rates.

Although most reservoir simulation numerical codes can be used for manual history matching as demonstrated by Archer and Wong (1973), a numerical code specifically developed for simulation of one-dimensional displacements can be much more time-efficient. Kerig and Watson (1987) described a powerful routine for matching production from unsteady-state experiments using cubic spline representations of relative permeability and capillary pressure. Civan and Donaldson (1989) and Ohen et al. (1991) describe other variations on this theme of history matching.

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5. DESCRIPTION OF STEADY-STATE METHODS

Literature on the steady-state methods dates from the 1930's, (Appendix A and Figure 5). Appendix A contains a concise summary of information presented in the cited literature on steady-state methods including the authors of the work, the type or variation of the method used or discussed, a summary of the information presented, a list of the observed parameters, and a list of the operating temperature and pressure conditions of the described experiment. Appendix B contains detailed diagrams of the experimental apparatus described in this section and cited in Appendix A. A literature review summary of each sub-category (multiple-core, high-rate, stationary-liquid, and uniform capillary-pressure) follows.

5.1 Multiple-Core Method

The multiple-core method was first reported in the literature by Morse et al. (1947) of Pennsylvania State University, and is often referred to as the Penn State method. In the multiple-core method, a sample of rock is mounted in an assembly between two other pieces of rock, one upstream and the other downstream to the direction of flow, as shown in Figure B-1. A variation on the rock mounting apparatus, by Henderson and Yuster (1948), along with a flow sheet of the flooding apparatus is shown in Figure B-2. In this variation, the abutted rock faces are machined flat to ensure close contact. Gas and brine are injected at constant flow rates at the inlet to the assembly, which includes a sand-filled mixing head where the gas and brine streams are mixed prior to flow through the test rock sample to ensure that both injected fluid phases are uniformly distributed.

For the most part, in the multiple-core method, capillary end effects are confined to the downstream rock. Geffen et al. (1951) reported conductivity measurements with 12 electrodes placed along the three rock samples in their multiple-core apparatus as shown in Figure B-3. Their measurements showed that saturations varied by 3 to 5 percent of the pore volume within the test section for displacements with oil and brine. These results suggest that rock heterogeneity could cause as much or more variation in saturation distribution as is caused by capillary end effects.

The evolution of the multiple-core method since its introduction by Morse et al. (1947) can be seen by comparing Figures B-1 through B-6. In the design of the rock mounting assembly, there is concern for uniform distribution of fluids, as evidenced by the teflon distributor in Figure B-4. The technology used in the flooding apparatus shows striking differences:

compare the differences among the apparatus of Henderson and Yuster (1948) in Figure B-2, Oak et al. (1988) in Figure B-5, MacAllister et al. (1990) in Figure B-6.

Parameters observed or measured in the multiple-core method are rock dimensions, pressure difference across the core, and gas and brine flow rates. In addition, brine saturation is inferred from change in mass of the rock sample, change of electrical conductivity, or change of absorption of x-rays or other radiation, as in other steady-state methods. To measure the change in mass, the rock sample is quickly removed from the assembly and weighed, and then returned to the assembly. This procedure may cause changes in saturation, so in situ techniques such as electrical conductivity or x-ray absorption are recommended. Porosity and permeability of the rock are assumed to be available from other experiments, and gas viscosity must also be measured or estimated. Gas and brine relative permeability are then calculated with equations 10a and 10b.

5.2 High-Rate Method

In high-rate experiments, gas and brine are injected at a constant fractional flow ratio into a rock sample. Injection of fluids is continued until the pressure drop across the sample is constant. At that point, fluid saturations in the rock sample are measured using the change of mass of the core, change of electrical conductivity, or change of absorption of x-rays or other radiation as described for the multiple-core method. Uniformity of saturation distribution from inlet to outlet is a strong criterion for determining whether steady-state has been obtained. Rock dimensions, absolute or intrinsic permeability, and fluid viscosities are used to calculate gas and brine relative permeability with equations 10a and 10b at the specific saturations. To generate a complete relative permeability curve, the procedure is repeated for a range of fractional flow ratios.

Examples of the apparatus used for the high-rate method are shown in Figures B-7 through B-14. The rock-holding assembly in Figure B-7 was designed for convenient removal and weighing of the rock sample. The apparatus in Figure B-8 illustrates the complexity of early apparatus designed by Wilson (1956) for studies performed at in situ conditions. Figure B-9 illustrates a design for the fluid distribution head by Sandberg et al. (1958).

Although weighing a rock is a simple means for determining saturation, other more refined approaches have also been applied. As shown in Figure B-10, fluid saturations were measured using nuclear magnetic resonance by Saraf and Fatt (1967). A volumetric balance was

used by Braun and Blackwell (1981) and Maini et al. (1989) as shown in Figures B-11 and B-13, respectively. Dria et al. (1990) used tracers to provide saturation data as illustrated in Figure B-14.

Capillary end effects are minimized by injection at high flow rates. The consequences of capillary end effects can be evaluated by performing a series of tests at the same fractional flow ratio, but with increasing flow rates. If capillary end effects are negligible, pressure drop should be linearly related to the flow rate.

The high-rate method is simple to understand, and data reduction is straightforward. However, the time required to reach steady state for each fractional flow is notoriously long, especially for rocks with low porosity and low intrinsic permeability. In addition, concerns have been raised regarding the differences in results between an actual displacement process and the step-wise variation of fractional flows used in the steady-state method.

5.3 Stationary-Liquid Method

In the stationary-liquid method, relative permeability of one fluid (usually gas) is measured in a rock sample with a known immobile fluid saturation (usually liquid). The relative permeability curve is developed by repeating the permeability test at different known saturations. In a demonstration of the technique, Osoba et al. (1951) reported that they reduced liquid saturation in a rock sample by blotting it with an absorbent tissue. By injecting gas at very low pressure gradients, production of liquid was negligible. When low pressure gradients are used, capillary pressure and saturation are effectively uniform throughout the rock specimen. The greatest disadvantage to this method is that only the mobile-phase relative permeability curve is generated.

In the earliest reference to the method, Leas et al. (1950) used a more complicated means for reducing liquid saturation. As shown in Figure B-15, the porous disks at each end of the rock sample are permeable only to the liquid phase which can be withdrawn in increments by a pump. Gas is injected directly to the sample through tubes which pass through the porous disks. Although their technique is cumbersome, it allows for simultaneous measurement of capillary pressure and relative permeability to gas.

Figure B-16 shows an early apparatus used by Loomis and Crowell (1962). In their implementation, liquid saturation was adjusted by blotting the rock sample with a tissue. The

apparatus depicted in Figure B-17 is a modern variation of the stationary-liquid method illustrated from a paper by Holditch and Ning (1990). However, in this variation, permeability is determined using pressure pulse decay. Therefore, this method is a hybrid; a combination of steady- and unsteady-state techniques as discussed in Section 6.4.

Observed parameters in the stationary-liquid method are rock dimensions, pressure drop across the core, gas flow rate, and brine saturation. As in most other steady-state methods, change in the brine saturation can be estimated from change in mass of the rock sample or one of the other methods mentioned previously. Again, porosity and intrinsic permeability of the rock are assumed to be available from other experiments, and gas viscosity must also be measured or estimated. Relative permeability for the gas phase can be calculated with equation 10b.

This method can be used for two immiscible liquids, such as for relative permeability measurements of oil in a rock with immobile brine saturation, or for relative permeability measurements of oil or brine with immobile gas saturation. These approaches are minor variations on the concept of the stationary-liquid method and depend on capillary forces to immobilize one phase.

5.4 Uniform Capillary-Pressure Method

The uniform capillary-pressure method developed by Hassler (1944) is probably the most difficult of the steady-state methods to implement, and use of the method has not been reported since 1952. Three diagrams of the rock-mounting assembly and accessory apparatus for the method are shown in Figures B-18 through B-20. Brine is injected and produced through porous disks located at each end of the rock sample. The wettability and the size of pores of the porous disks are selected to prevent gas penetration. Gas is injected directly to the rock face through a tube which penetrates the upstream porous disk; another tube, which penetrates the porous disk at the outlet end of the rock, allows gas production. A concern often mentioned in the literature is that the porous disks which separate flowing phases at the inlet and outlet end of the core may cause poor fluid distribution.

Because gas and brine are injected separately, the pressure drop across the core can be measured for each phase. Pressure drop in the gas phase is measured with pressure taps located close to the injection and production points. Hassler mounted a porous disk, in addition to the one used to separate fluids, against each end of the rock to measure pressure drop in the brine phase, connecting these small porous disks to a pressure sensing device. Because there is no flow

through these porous disks to the pressure sensing device, pressure drop in the brine phase can be accurately measured. In another version of the capillary-pressure method, Fatt and Dykstra (1951) developed calibration curves for pressure drop through the porous disks, and were able to overcome the difficulties involved in using separate disks for pressure sensing.

When using the uniform capillary-pressure method for measuring relative permeability, the brine injection rate is set at a specified constant value, and the gas flow rate is adjusted so that pressure drop in the gas phase is equal to pressure drop in the brine phase. Because the pressure gradients in the two phase are equal, capillary pressure and brine saturation are uniform throughout the rock sample.

Observed parameters in the uniform capillary pressure method are rock dimensions, gas and brine pressure drops, gas and brine flow rates, and brine saturation. Change in the brine saturation can be estimated from change in mass of the rock sample, or one of the other methods mentioned previously. Porosity and permeability of the rock are assumed to be available from other experiments, and gas viscosity must be measured or estimated. Relative permeability for the gas and brine can be calculated with equations 10a and 10b.

Although it is very refined, use of the uniform-capillary-pressure method has not been reported since 1952, probably because of the extraordinary complexity of the method compared to other methods.

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6. DESCRIPTION OF UNSTEADY-STATE METHODS

During a steady-state experiment, only the stabilized, time-independent data are used in calculating relative permeability. Conversely, in unsteady-state experiments, it is the transient data that are used for calculating relative permeability. In general, the unsteady-state methods consist of measuring pressure drop and average fluid saturation while a fluid is injected into a rock sample with a known initial saturation condition. Complex data reduction procedures are used to convert the time-dependent pressure and average saturation data into relative permeability relationships as described in section 4.2.3. Unsteady-state experiments can be completed very quickly; a single unsteady-state displacement test can provide the same relative permeability information as a series of time-consuming steady-state displacement tests. Thus, the speed with which relative permeability can be measured with unsteady-state methods offsets the complexity of data reduction procedures.

Development of unsteady-state methods began in the 1950's and continues today, as evidenced by Figure 5 and Appendices C and D. Appendix C presents a concise summary of information presented in the reviewed literature on unsteady-state methods, including the authors of the work, the type or variation of the method used or discussed, a summary of the information presented, a list of the observed parameters, and a list of the operating temperature and pressure conditions of the described experiment. Appendix D contains detailed diagrams of the experimental apparatus described in this section and cited in Appendix C. A discussion of the three sub-categories of unsteady-state methods, high-rate, low-rate, and centrifuge, follows.

6.1 High-Rate Method

The high-rate method described by Osoba et al. (1951) and Branson (1951) is very different from the high-rate method currently practiced. Osoba and Branson injected gas into a partially-liquid-saturated rock at a high rate for about five seconds. They would subsequently weigh the rock and determine the volume of fluid displaced by the injection process. They would then inject gas at a high rate for five seconds to displace more liquid. This process was repeated until the saturation range of interest was traversed. The pressure drop measured during the brief intervals of gas injection and saturation data were processed to calculate relative permeability using equations 10a and 10b.

With the introduction by Welge (1952) of a method for analyzing data from a displacement process, the high-rate method took on a new form. Rather than starting and

stopping injection at five second intervals, as practiced by Osoba et al. (1951), injection was continued at a constant rate, pressure drop was continually monitored, and cumulative production of the displacing fluid was measured as a function of time. Alternatively, for a constant pressure drop, the flow rate and cumulative production could be monitored as a function of time. The data from Welge's method were processed using equation 11, yielding a relative permeability ratio of the injected fluid to the displaced fluid (k_g/k_b , for example). With the advent of the JBN method (Johnson et al., 1959), the relative permeabilities of each phase could be calculated independently. Within ten years after the JBN method was first described, the high-rate method became the most commonly reported in the literature.

It is interesting to track the technological development of the high-rate method apparatus as it appeared in the literature over the past 37 years. Figure D-1 shows the apparatus used by Owens et al. in 1956. At the outlet end of the rock sample, a semi-permeable cloth barrier was mounted which trapped droplets of oil produced during the experiment. The remainder of the apparatus was quite simple, especially as compared to that shown in Figures D-2 and D-3. In the apparatus of Figure D-2, the levels of oil and water in the fluid separator are monitored using an optical device (Saraf et al., 1982). As shown in Figure D-3 by Islam and Bentsen (1986), fluid saturations are determined by microwave scanning of the rock sample, and multiple transducers are used to sense the pressure along the axis of flow.

The apparatus shown in Figure D-4, used by Gash (1991) for measuring gas-brine relative permeabilities in coal samples, is as simple in principle as that used by Owens et al. in 1956. Rather than measure produced liquids by visual observations of fluid levels, Gash weighed the produced liquids with an electronic balance, and he monitored the gas production with mass flow meters rather than by liquid displacement from a graduated cylinder.

6.2 Low-Rate Method

As documented in the literature, simultaneous measurement of capillary pressure and relative permeability is a new development in the area of two-phase flow measurements. As noted previously, the simultaneous measurement of both relationships requires a comprehensive data reduction process wherein the performance of a one-dimensional simulator is matched with non-linear regression techniques to the observed parameters from unsteady-state experiments. Perhaps the key feature of the simultaneous approach is that displacement rates of the unsteady-state experiments are maintained at or near reservoir displacement rates and, thus, better reflect in situ flow conditions.

The experimental techniques used for simultaneous measurement of relative permeability and capillary pressure are similar to those used for measurement of capillary pressure. As shown by Hyman et al. (1991a; 1991b) in Figure D-5, a rock sample is mounted in a core holder abutted to a liquid-permeable, gas-impermeable, disk at the effluent end. In this configuration, a liquid-saturated rock sample is injected with gas at a constant pressure. If the gas-injection pressure is less than the threshold pressure of the rock sample, gas cannot enter the rock. When the gas-injection pressure is increased and exceeds the threshold pressure, gas will penetrate into the core and the gas saturation will rise to the level dictated by capillary effects. Both the amount of liquid produced during the displacement and the difference in pressure between the injected gas and the produced liquid are measured as a function of time. When liquid production ceases, the gas injection pressure is increased to a new constant level, and the previous steps are repeated. The complete experiment may consist of five to ten injection pressure steps. This sequence, and apparatus used, is similar to that of Jennings et al. (1988), shown in Figure D-6, except for the semi-permeable barrier design.

To summarize, the differences between the high- and low-rate methods are that in the high-rate method, the tests are performed with a high pressure differential across the core and at rates high enough to overcome end effects. Conversely, the low-rate methods are performed with a constant pressure differential across the core sample and at constant rate, but the rates are low enough that capillary effects are important.

6.3 Centrifuge Method

In yet another variation of the simultaneous relative permeability/capillary pressure unsteady-state measurement method, a centrifuge is used to drive a fluid into rock at a pre-determined initial saturation condition. The amount of fluid produced from the rock is recorded as a function of time at a constant rotational speed. As fluid production slows or ceases, rotational speed is increased to a new and constant level, and the process is repeated. A complete centrifuge displacement experiment may consist of five to twenty rotational speed steps, and many of the cited researchers emphasize that production at each rotational speed need not entirely cease. Indeed, an advantage of the centrifuge method is that the experiment time is significantly shorter than a typical capillary pressure experiment, and yields both capillary pressure and relative permeability.

The centrifuge technology and apparatus which is described for measuring relative permeabilities is quite complex. As shown in Figure D-7, the volume of fluid produced at any

time is measured using a photodiode array, and lighting for the photodiode array is provided by a strobe light which must be synchronized with the spinning rotor. In another design shown in Figure D-8, Chardaire-Riviere et al. (1992) developed ultrasonic sensors for measuring fluid saturations along the core axis inside the rotating core holder to provide better saturation distribution information. It is important to note that there is no gas flow or pressure drop measured, so the gas-phase relative permeability must be calculated from liquid-phase relative permeability using Brooks and Corey (1966) or other similar equations.

6.4 Stationary-Liquid Method

In a variation of the stationary-liquid method described in Section 5.3, relative permeability of gas can be measured with pressure- or pulse-decay methods. In these techniques, the liquid saturation remains constant as it does in the steady-state stationary-liquid method, but the flow rate of the gas phase varies with time. These techniques are described in detail by Walls (1982), Walls et al. (1982), Bourbie and Walls (1982), and Holditch and Ning (1990). A diagram of the apparatus used by Holditch and Ning is shown in Figure B-17.

7. OTHER STUDIES WITH ANALOGOUS LOW PERMEABILITY ROCK

While reviewing technical publications on methods for measuring relative permeability of rock, some publications were identified which dealt with measurements of specific low permeability porous media. One set of publications focused on measurements for coal beds and the other set focused on low-permeability tight gas sand reservoirs.

7.1 Analogous Materials: Coal

The porosities and permeabilities of coal reported in the coalbed methane literature are of similar magnitude as preliminary (Appendix E) and documented (Davies et al., 1992) values for the Salado anhydrite. Specifically, coal porosities ranging from two to four percent, and coal permeabilities ranging from $7 \times 10^{-17} \text{ m}^2$ to $4 \times 10^{-15} \text{ m}^2$ are reported (Hyman et al., 1991a; Hyman et al., 1992; Gash, 1991; and Puri et al., 1991) compared to preliminary and reported Salado anhydrite porosities and permeabilities of 0.4 to 2.7 percent and $9.6 \times 10^{-21} \text{ m}^2$ to $5 \times 10^{-17} \text{ m}^2$, respectively.

Hyman et al. (1991a) measured relative permeabilities of coal with steady-state and unsteady-state methods. Although the relative permeability results from the different methods were comparable for the few coal samples tested, concern was expressed for the reliability of the steady-state methods because of plugging by fines migration during the extended testing period, sorption of sodium iodide by the coal matrix, and the long time requirements for completing measurements of low permeability material. Because x-ray absorption by brine doped with sodium iodide is the key means for measuring porosity and fluid saturation, loss of sodium iodide to the matrix would be very detrimental to tests results. Hyman et al. (1991a; 1991b; 1992) favored the use of a low-rate unsteady-state technique in which the transient production from a rock mounted on a porous plate is measured. From this measured response, relative permeabilities can be obtained by non-linear regression with a one-dimensional simulation of the displacement process.

Gash (1991) reported that unsteady-state measurements performed at Amoco Production Research compared well with steady-state measurements performed by Core Laboratories. Gash indicated that the x-ray absorption results from the steady-state studies show evidence of absorption of sodium iodide. Gash et al. (1993) reported minor modification to the apparatus and experimental methods previously used to improve measurement of produced fluids.

The apparatus described by Gash (1991) and Gash et al. (1993) uses a straight-forward approach for measuring fluid production. The produced brine is collected in a high-pressure separator which is mounted on a mass balance. The flow lines leading to and from the high-pressure separator are 1/16-inch diameter plastic lines configured to have minimal effect on the mass measurement. Produced gas is measured with mass-flow meters, which are well-suited for quantification of flow rates of gases with known and constant composition. By replacing the mass-flow meters with a device better suited for low flow rates, the Gash apparatus could be used for either low- or high-rate measurements of relative permeability with the unsteady-state method.

The apparatus used by Gash (1991) and Gash et al. (1993) holds promise in application to relative permeability measurements for Salado anhydrite for three reasons. First, the method has been used successfully for measuring relative permeability of coal which has similar porosity and intrinsic permeability to Salado anhydrite. Second, components for the experimental apparatus are readily available. Finally, the method can be adapted for either high-rate or low-rate studies.

7.2 Analogous Materials: Tight Gas Sand

Reported porosities and permeabilities of rock samples from tight gas sands are also of the same order of magnitude as the preliminary (Appendix E) and reported (Beauheim et al., 1991) values for the Salado anhydrite. Reported porosities for the tight gas sands range between four and ten percent, and reported permeabilities range from $4 \times 10^{-18} \text{ m}^2$ and $1 \times 10^{-15} \text{ m}^2$ (Holditch and Ning, 1990; Narahara and Holditch, 1988; and Narahara et al., 1988).

Holditch and Ning (1990) reported on efforts to develop a pulse technique for measuring relative permeabilities of gas in the presence of stationary brine. It is not clear whether capillary end effects were neglected or properly treated in their data processing methods. However, their pulse technique is a very simple method to implement, and may be well-suited for tight rock. In their apparatus, small pressure vessels are located on each end of a confined rock sample. Initially the vessels are at different pressures, but with flow through the rock, the pressure difference decreases to zero. The volumes of the two pressures can be adjusted as required for accurate measurement of relative permeability.

Chowdiah (1986) reported experimental data for gas relative permeabilities of tight sandstones measured with the steady-state stationary-liquid method. He obtained desired liquid saturations by two methods: 1) evaporation, and 2) drainage by gas injection. He reported critical

gas saturations between 30 and 50 percent for the samples that were prepared by the evaporation method and critical gas saturations of less than 15 percent for the samples prepared by the drainage method. In a later report, Chowdiah and Soeder (1990) concluded that both of the methods used to decrease liquid saturation led to very nonuniform distributions of liquid: the sides of the cylindrical samples were sealed during the evaporation process and sufficient time was not allowed for liquid to redistribute within the sample.

Ward and Morrow (1987) measured gas relative permeability using the steady-state stationary-liquid method for rock samples taken from the Mesa Verde Formation during the US DOE Multiwell Experiment. The rock samples were initially saturated with distilled water and desired saturations were obtained by evaporation. The authors found that relative permeability to gas was related to saturation according to equation 14.

$$k_{rg} = \left(1 - \frac{S_b}{0.7}\right)^{1.5} (1 - S_b^2) \quad (14)$$

Curiously, Ward and Morrow observed that maximum gas-relative permeability at low overburden pressures occurred in some samples at water saturations of about 15 percent. This observation, while not reflected in equation 14, should be viewed with caution, and the authors stated that relative permeability data "are insufficient for drawing general conclusions." Although Ward and Morrow did not measure water-relative permeabilities, they did suggest an expression for k_{rb} shown in equation 15.

$$k_{rb} = \left(\frac{S_b - S_{bi}}{1 - S_{bi}}\right)^4 \left(\frac{k_b}{k_{Klnbg}}\right) \quad (15)$$

where

- k_b = permeability to water at 100% saturation
- k_{Klnbg} = Klinkenberg permeability to gas
- S_{bi} = Irreducible brine saturation

The authors observed that permeability to water is usually much less than the Klinkenberg permeability to gas in tight sandstones. This expression includes this effect for empirical estimates of brine-relative permeability in tight sandstones.

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8. RECOMMENDATION OF METHODS FOR SALADO ANHYDRITE

The intent of this literature review was to identify methods for measuring relative permeability and make initial recommendations about which methods have the most potential for relative permeability measurements for the low porosity, low permeability Salado anhydrite. Most, if not all, of the methods described in this report could be used for the Salado anhydrite. However, each method offers a slightly different perspective on relative permeability and has inherent advantages and disadvantages.

While the steady-state methods are very straightforward to interpret, they are expected to be too time consuming, especially for tight anhydrite samples. This inherent time constraint could potentially limit the number of samples that could be measured or require the availability of redundant experimental apparatus.

Of the unsteady-state methods, the high-rate method is most frequently used in the petroleum industry today. The time needed to complete a relative permeability test with this method should be much less than that needed for any of the steady-state methods. However, interpretation of the data is much more complicated. The unsteady-state method can be implemented using a system composed of interchangeable off-the-shelf components as described by Gash (1991) and Gash et al. (1993).

With a few modifications, an apparatus designed for applying the high-rate method can also be used with the low-rate method. The low-rate method offers the possibility of simultaneous measurement of the capillary pressure and relative permeability relationships. Furthermore, in low-rate experiments, interstitial velocities can closely approximate those in situ and allow time for the complicated interactions between moving fluid interfaces to occur. Unfortunately, this method is still evolving and has not received the proportion of use as the high-rate method, and usually only yields liquid-phase relative permeability.

Like the low-rate method, the centrifuge method also offers the feature of simultaneous measurement of capillary pressure and relative permeability. The earliest applications of the centrifuge for relative permeability focused on measuring the relative permeability of the displaced phase, although in later applications relative permeability of both the displaced phase and the displacing phase can be measured.

For successful application to measurement of relative permeability of Salado anhydrite, considering all of the methods reviewed, the unsteady-state high-rate method offers the most

promise. In addition, using a technique such as the steady-state or unsteady-state stationary-liquid method to measure relative permeability of gas combined with the unsteady-state centrifuge method to measure the relative permeability of brine may also be considered. However, caution is advised because successful application of the centrifuge method for low permeability rock is unproven. Other methods should also be tested to provide additional perspective on relative permeability relationships. Regardless of the primary method(s) selected for Salado relative permeability tests, additional tests should be performed using alternative methods to confirm the accuracy of, and quantify the uncertainty of, the data.

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10. ACRONYM LIST

DOE	U.S. Department of Energy
IGT	Institute for Gas Technology; Chicago, Illinois
MB 139	Marker Bed 139
NAS	National Academy of Sciences
PA	Performance Assessment
PI	Principal Investigator
QA	Quality Assurance
SCA	Society of Core Analysts
SNL	Sandia National Laboratories
SPE	Society of Petroleum Engineers
WIPP	Waste Isolation Pilot Plant
WPIO	WIPP Project Integration Office
WPSO	WIPP Project Site Office

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APPENDIX A

Summary of Literature on the Steady-State Method for Measuring Relative Permeability

Authors (Date)	Unique Features	Observable Parameters	Operating Pressure, psi	Operating Temp., ° F
Multiple-Core Method				
Morse, Terwilliger, Yuster (1947)	Upstream fluid distributor is essential for mixing of multi-phase flow streams.	Rock dimensions, ΔP , electrical conductivity, oil and water flow rates, mass of rock with fluids	< 100	Ambient
Henderson, Yuster (1948)	Similar to Morse, Terwilliger, Yuster (1947), but rather than using gear pumps, liquids were pushed by regulated gas pressure.	Rock dimensions, ΔP , electrical conductivity, oil and water flow rates, mass of rock with fluids	< 100	Ambient
Geffen, Owens, Parrish, Morse (1951)	To minimize slug flow, the volume in the fluid inlet lines must be kept small. Used piston pumps. Used pressure transducer rather than manometer.	Rock dimensions, ΔP , electrical conductivity, oil and water and gas flow rates, mass of rock with fluids	< 100	Ambient
Caudle, Slobod, Brownscombe (1951)	Rock is confined by a rubber sleeve. Inlet and outlet ends of rock sample extend beyond pressure taps. Positive displacement pumps provide constant oil and water flow rate.	Rock dimensions, ΔP , oil and water flow rates, mass of rock with fluids	< 100	Ambient
Osoba, Richardson, Kerver, Hafford, Blair (1951)	Kerosene was degassed in order to get reproducible results. With unconsolidated samples, poor capillary contact at butted joints causes saturation gradients.	Rock dimensions, ΔP , kerosene and helium flow rates, mass of rock with fluids		
Jennings (1958)	Saturations were obtained with radioactive tracers (selenium-75).	Rock dimensions, ΔP , oil and brine flow rates, radioactivity of rock	< 100	Ambient
Odeh (1959)		Rock dimensions, ΔP , electrical conductivity, oil and water flow rates, mass of rock with fluids, temperature	< 100	Ambient

Authors (Date)	Unique Features	Observable Parameters	Operating Pressure, psi	Operating Temp., ° F
Schneider, Owens (1970)	Measured three-phase relative permeabilities. With radioactive doping of aqueous and oleic phases, gas saturation was monitored with x-ray absorption. Aqueous phase saturation was monitored with electrical conductivity probes.	Rock dimensions, ΔP , x-ray absorption, electrical conductivity, oil and water flow rates	< 100	Ambient
Owens, Archer (1971)	Used apparatus similar to Geffen, Owens, Parrish, Morse (1951). Studied effect of wettability on relative permeability.			
Lo (1973)	Studied effects of temperature on relative permeability in oil-wet and water-wet porous media. Rather than using three separate pieces of rock, one long sample was tested.	Rock dimensions, ΔP , electrical conductivity, oil and water flow rates, cumulative oil and water volumes produced and injected		75 - 300
McCaffery, Bennion (1974)	Considered effects of wettability on relative permeability of PTFE media. Time required per point was 2 to 6 hours.	Sample dimensions, ΔP , mass of sample with fluids, cumulative volume of produced and injected fluids, temperature	< 100	Ambient
Schneider, Owens (1976)	Tests with preserved rock samples. Used tissue paper to make capillary contact. Radioactive doping of aqueous and oleic phases as described by Schneider and Owens (1970).	Rock dimensions, ΔP , x-ray absorption, electrical conductivity, oil and water flow rates	200	Ambient
Schneider, Owens (1980)	Apparatus as described by Schneider and Owens (1970). Measured relative permeabilities for oil and polymer solutions.	Rock dimensions, ΔP , x-ray absorption, electrical conductivity, oil and water flow rates		

Authors (Date)	Unique Features	Observable Parameters	Operating Pressure, psi	Operating Temp., ° F
Heaviside, Black, Berry (1983)	Explored the validity of relative permeability concepts. Found that these concepts do not strictly apply to imbibition processes. Took up to 48 hours to obtain steady state.	Rock dimensions, ΔP , oil and water flow rates, mass of rock and fluids		
Monsalve, Schechter, Wade (1984)	Steam-water relative permeabilities with surfactants were measured. Saturation was measured with a tracer method.	Rock dimensions, ΔP , steam and water flow rates, tracer concentration	< 100	
Manjnath, Honarpour (1984)	Review of three-phase relative permeability prediction and measurement. Brine saturation determined by electrical resistivity, oil saturation by weighing.	Rock dimensions, ΔP , mass of rock and fluids, electrical conductivity, oil and water flow rates		
Delshad, Delshad, Pope, Lake (1987)	Measured relative permeabilities of micellar fluids at capillary numbers of about 0.01. Saturations by material balance and breakthrough analysis of radioactive tracers.	Rock dimensions, ΔP , tracer concentration, fluid injection rates, volumes of fluids produced		86
Oak, Ehrlich (1988)	Developed new method for x-ray absorption measurements of saturation. Show saturation histories for a displacement.			
Oak, Baker, Thomas (1988)	Saturations by x-ray absorption (oil and water were doped).	Rock dimensions, ΔP , x-ray absorption, gas-oil-water flow rates	800	70
MacAllister, Miller, Graham, Yang (1990)	Gas-water relative permeabilities. Used CT scanning to measure fluid saturations. One day required per relative permeability point.	Rock dimensions, ΔP , x-ray and absorption for CT, gas-water flow rates, volumes of produced fluids	500	Ambient
Oak (1990)	Apparatus as described by Oak, Baker, Thomas (1988).	Rock dimensions, ΔP , x-ray absorption, gas-oil-water flow rates	800	

Authors (Date)	Unique Features	Observable Parameters	Operating Pressure, psi	Operating Temp., ° F
Hyman, Brugler, Daneshjou, Ohen (1991)	Measured gas-brine relative permeability of coal cleats. Used x-ray absorption to measure saturations. Overburden pressure: 1000 psi. Injection of humidified gas.	Rock dimensions, ΔP , x-ray absorption, gas-water flow rates	300	ambient
Bennion, Sarioglu, Chan, Hirata, Courtnage, Wansleebe (1993)	Bitumen-water relative permeabilities at high temperatures. Unconsolidated rock mounted in lead sleeve. Electrically-traced flow lines to transducers to eliminate plugging by viscous oil. Overburden pressure = 600 psi.	Rock dimensions, ΔP , gas-water flow rates, volumes of produced fluids	290	400
High-Rate Method				
Wyckoff, Botset (1936)	Gas-water relative permeability in 10-foot-long sandpack. Saturations by electrical resistivity measurements. Nine pressure taps, with piezometer rings, connected to mercury manometers.	Sandpack dimensions, ΔP at taps, water and gas flow rates, electrical resistivities	< 100	Ambient
Osoba, Richardson, Kerver, Hafford, Blair (1951)		Rock dimensions, ΔP , kerosene and helium flow rates, mass of rock with fluids		
Richardson, Kerver, Hafford, Osoba (1952)	Oil is degassed prior to tests. Oil is fed to rock through an oil-wet porous disk. Pressure in the oil at the inlet is measured through an oil-wet disk. Measured capillary pressure at inlet. The authors termed this the "Hafford" method.	Rock dimensions, ΔP , P_c at inlet, oil and gas flow rates, mass of rock with fluids	< 100	Ambient
Wilson (1956)	Designed for high pressure, high temperature experiments with overburden pressure up to 10,000 psi.		< 5,000	< 160

Authors (Date)	Unique Features	Observable Parameters	Operating Pressure, psi	Operating Temp., ° F
Sandberg, Gournay, Sippel (1958)	A thin gasket with concentric patterns distributed phases at the inlet. Saturation was measured with radioactive tracers (cobalt-60, iodine-131, mercury-203). Ruska pumps displaced both phases through the rock.	Rock dimensions, ΔP , oil and brine flow rates, radioactivity of rock	<100	Ambient
Loomis, Crowell (1962)	Increased flow rate until relative permeabilities were independent of rate.	Rock dimensions, ΔP , oil and gas flow rates, mass of rock with fluids	<100	Ambient
Saraf, Fatt (1967)	Used NMR method to measure saturations for three-phase relative permeabilities. Aqueous phase was heavy water. Suggests that data reduction used by Sarem (1966) and Donaldson and Dean (1965) may be oversimplified.	Rock dimensions, ΔP , cumulative production of gas and oil and heavy water, NMR response,	< 100	Ambient
Ehrlich (1971)	A recirculating system for measuring relative permeabilities of large rock samples was built. Water-oil fractional flow was varied in a continuous and slow manner. Fractional flow leaving the rock was determined by weighing a 10-foot length of plastic tubing.	Rock dimensions, ΔP , recirculating flow rate, rate of addition of oil or water, accumulation of water and oil in separator		
Talash (1976)	Studied change in relative permeabilities with decreasing interfacial tension.			
Braun, Blackwell (1981)	Described device for measurements at reservoir conditions. Accumulation in a high pressure oil-water separator was monitored with a pressure transducer. Used in-line capillary viscometers.	Rock dimensions, ΔP , recirculating flow rate, viscosity, accumulation of water and oil in separator	4500	Room - 200

Authors (Date)	Unique Features	Observable Parameters	Operating Pressure, psi	Operating Temp., ° F
Amaefule, Handy (1981)	Correlated change in oil-water relative permeabilities with capillary number.	Rock dimensions, ΔP , oil and gas flow rates, mass of rock with fluids	100	77
Saraf, Batycky, Jackson, Fisher (1982)	Measured three-phase relative permeabilities. Optical sensing of interfaces in separator. Confined the rock with a rubber sleeve at overburden pressure of 1500 psi.	Rock dimensions, ΔP , oil and water flow rates, levels of gas-oil and oil-water interfaces in separator	370	75
Delshad, MacAllister, Pope, Rouse (1985)	Studied dispersion and relative permeability for microemulsion flooding processes. Used tracers to measure saturation.			86
Fulcher, Ertekin, Stahl (1985)	Varied capillary number in oil-water displacements.			77
Polikar, Ferracuti, DeCastro, Puttagunta, Farouq Ali (1986)	Measured end-point relative permeabilities of bitumen and water. Used copper sleeve to confine sandpack with overburden pressure of 2500 psi. In-line viscometer and pycnometer for bitumen measurements.	Sandpack dimensions, ΔP , bitumen and water flow rates, volumes of bitumen and water produced, volumes of bitumen and water in sandpack	1000	250 - 480
Polikar, Puttagunta, Decastro, Farouq Ali (1989)	Apparatus as described by Polikar, Ferracuti, Decastro, Puttagunta, Farouq Ali (1986).			
Wang (1988)	Apparatus similar to Braun and Blackwell (1981).	Rock dimensions, ΔP , recirculating flow rate, viscosity, accumulation of water and oil in separator		
Closmann, Vinegar (1988)	Steam-water relative permeabilities at residual oil saturation. Used CT scans to determine liquid saturation.		250 to 1500	300 to 500

Authors (Date)	Unique Features	Observable Parameters	Operating Pressure, psi	Operating Temp., ° F
Closmann, Waxman, Deeds (1988)	Tar-water relative permeabilities. Pressure taps extend into the ends of sample to avoid error due to fines movement or asphaltene plugging. Rock confined in rubber sleeve; overburden pressure = 1100 psi. Brine saturation by electrical resistivity.	Rock dimensions, ΔP , tar and water flow rates, accumulation of water and tar in separators, electrical resistivity		385
Maini, Kokal, Jha (1989)	Three-phase relative permeabilities at elevated pressure and temperature. Sandpack. Pressure taps within both ends of sandpack.	Rock dimensions, ΔP , oil /water/gas flow rates, accumulation of oil/water/gas in separator	500	212
Maini, Coskuner, Jha (1990)	Compared unsteady- and steady-state measurements of relative permeability for viscous oil and water. Sandpack. Pressure taps within both ends of sandpack. Similar to Maini, Kokal, Jha (1989).	Rock dimensions, ΔP , oil and water flow rates, accumulation of water and oil in separators		73 to 212
Shafer, Braun, Wood, Wooten (1990)	Apparatus may be a modified version of that described by Braun and Blackwell (1981). The apparatus was operated in both unsteady- and steady-state modes to obtain relative permeabilities at saturation extremes.			
Dria, Pope, Sepehrnoori (1990)	CO ₂ -oil-brine relative permeabilities at reservoir conditions. Rock confined with rubber sleeve; overburden pressure: 2400 psi. Four pressure taps.	Rock dimensions, ΔP and gradient, CO ₂ -oil-water injection rates, tracer concentrations and elapsed time, accumulation of fluids in separators	1400	160
Parmeswar, Maerefat, Brinkmeyer (1988)	Studied effect of viscosity on three-phase relative permeability. Apparatus as reported by Parmeswar, Maerefat, Brinkmeyer (1986).	Rock dimensions, ΔP , x-ray and microwave absorption, gas-oil-water flow rates		

Authors (Date)	Unique Features	Observable Parameters	Operating Pressure, psi	Operating Temp., ° F
Maloney, Mahmood, Honarpour (1989)	More on viscosity and three-phase relative permeability. Apparatus as reported by Parmeswar, Maerefat, Brinkmeyer (1986).			
Maloney, Honarpour, Brinkmeyer (1990)	Rock characteristics and three-phase relative permeability. Apparatus slightly improved from that reported by Parmeswar, Maerefat, Brinkmeyer (1986).			
Stationary-Fluid Method				
Leas, Jenks, Russell (1950)	Can measure capillary pressure as well as relative permeability of gas	Rock dimensions, ΔP in gas, P_c , volume of liquid withdrawn during P_c measurement, gas flow rate	< 100	Ambient
Fatt, Dykstra (1951)	Can measure capillary pressure as well as relative permeability of oil or brine; wettability of porous disks is altered with silicones. Constructed of glass, with nickel flow lines.	Rock dimensions, ΔP in brine or oil, P_c , volume of liquid withdrawn during P_c measurement, brine or oil flow rate	< 10	Ambient
Osoba, Richardson, Kerver, Hafford, Blair (1951)	Blotted a kerosene-saturated core with tissue paper to reduce liquid saturation. Other ways for reducing liquid saturation were tested, and gave equivalent relative permeabilities.	Rock dimensions, ΔP , mass of rock with fluids, gas flow rate	< 100	Ambient
Rapoport, Leas (1951)	Measured liquid relative permeability with stationary gas. Can measure capillary pressure. Rock confined with rubber sleeve. Liquid flow is driven by gas pressure. Porous disks are cemented to core with plaster of Paris.	Rock dimensions, ΔP , P_c , volume of liquid produced during P_c measurement, liquid flow rate	< 100	Ambient

Authors (Date)	Unique Features	Observable Parameters	Operating Pressure, psi	Operating Temp., ° F
Fatt (1953)	Technique similar to that of Osoba, Richardson, Hafford, Blair (1951), but with capability of overburden pressure up to 5000 psi.	Rock dimensions, ΔP , overburden pressure, mass of rock with fluids, gas flow rate	< 100	Ambient
Branson (1951)	Measured oil relative permeability with stationary gas. Can measure capillary pressure. Liquid flow is driven by gas pressure. Porous disks are cemented to core with plaster of Paris.	Rock dimensions, ΔP , P_c , volume of liquid produced during P_c measurement, liquid flow rate	< 100	Ambient
Loomis, Crowell (1962)	Measured relative permeabilities with stationary liquid and stationary gas. For stationary liquid, blotted the oil-saturated rock sample with tissue paper to reduce liquid saturation.	Rock dimensions, ΔP , mass of rock with fluids, gas flow rate	< 100	Ambient
Land (1971)	Removed liquid by blotting and by evaporation. Studied hysteresis in relative permeability to gas. Used technique of Loomis and Crowell (1962)	Rock dimensions, ΔP , mass of rock with fluids, gas flow rate	< 100	Ambient
Colonna, Brissaud, Millet (1972)	Used apparatus similar to Rapoport, Leas (1951). Though a schematic is reported, the operation is unclear.			
Reznik, Dabbous, Fulton, Taber (1974)	Measured air-water relative permeabilities of coal samples. Permeabilities: 0.01 to 50 md. Overburden pressure up to 1000 psi.		< 100	Ambient
Kanellopoulos, Petropoulos (1983)	Measured gas relative permeability of synthetic media with liquid absorbed from the vapor phase.			

Authors (Date)	Unique Features	Observable Parameters	Operating Pressure, psi	Operating Temp., ° F
Chowdiah (1986) and Chowdiah, Soeder (1990)	Measured gas relative permeability of tight sandstone with confining stress up to 5,000 psi. Water saturation was varied by evaporation, and by withdrawal through a tight membrane barriers.	Rock dimensions, ΔP , P_c , volume of water produced during P_c measurement, gas flow rate, mass of rock and fluids	1000	
Ward, Morrow (1987)	Gas relative permeabilities in low permeability sandstone. Overburden pressure: 500 to 5000 psi. Variability with overburden loading cycles.			
Narahara, Holditch (1988); Narahara, Holditch, Moore (1988); Holditch, Ning (1990)	Used transient pressure analysis to measure gas relative permeability and gas saturation simultaneously. Overburden stress: 20,000 psi. (The last reference is most descriptive of the apparatus.)	Rock dimensions, ΔP , P	1000	Up to 300
Uniform-Capillary-Pressure Method				
Hassler (1944)	Some of the techniques described in this patent are used in many laboratories for studies of rock properties. But the capillary pressure technique for measuring relative permeability is rarely used.			
Brownscombe, Slobod, Caudle (1950)	Alter wettability of ceramic plugs with silicones.	Rock dimensions, ΔP in gas and oil phases, flow rates	< 100	Ambient
Gates, Lietz (1950)	Gas-oil relative permeabilities.	Rock dimensions, ΔP in gas and oil phases, flow rates	< 100	Ambient

Authors (Date)	Unique Features	Observable Parameters	Operating Pressure, psi	Operating Temp., ° F
Osoba, Richardson, Kerver, Hafford, Blair (1951)	Grooves cut in the porous disks distribute gas flow. Tissue paper at butted joints ensures good capillary contact			
Josendal, Sandiford, Wilson (1952)	Oil saturation by radioactive tracer. Pressure taps on side of sample rather than ends.	Rock dimensions, ΔP in gas and oil phases, flow rates	< 100	Ambient

APPENDIX B

Schematic Diagrams of Experimental Apparatus Used for Measuring Relative Permeability with Steady-state Techniques

Figure B-1. Steady-state, multiple-core method. Rock holding assembly of Morse, Terwilliger, and Yuster (1947).

Figure B-2. Steady-state, multiple-core method. Rock holding assembly and Flooding apparatus of Henderson and Yuster (1948).

Figure B-3. Steady-state, multiple-core method. Rock holding assembly and Flooding apparatus of Geffen, Owens, Parrish, and Morse (1951).

Figure B-4. Steady-state, multiple-core method. Rock holding assembly and Flooding apparatus of McCaffery and Bennion (1974).

Figure B-5. Steady-state, multiple-core method. Flooding apparatus of Oak, Baker, and Thomas (1988).

Figure B-6. Steady-state, multiple-core method. Flooding apparatus of MacAllister, Miller, Graham, and Yang (1990).

Figure B-7. Steady-state, high-rate method. Rock holding assembly of Richardson, Kerver, Hafford, and Osoba (1952).

- A - BRINE INLET
- B - OIL INLET
- C - PRESSURE TAPS
- D - BRINE-OIL OUTLET
- E - CELL PRESSURING LINE
- F - "O" RING SEAL

Figure B-8. Steady-state, high-rate method. Rock holding assembly and flooding apparatus of Wilson (1956).

Figure B-9. Steady-state, high-rate method. Fluid distributing gasket of Sandberg, Gournay, and Sippel (1958).

1, 2, 3, 4, 5, 6 ARE 1/16" O.D. BRASS TUBING SOLDERED TO THE END PLUGS

1. UPSTREAM PRESSURE TUBE	5. DOWNSTREAM PRESSURE TUBE
2. WATER FLOW TUBE	6. OUT FLOW TUBE
3. OIL FLOW TUBE	
4. GAS FLOW TUBE	

Figure B-10. Steady-state, high-rate method. Rock holding assembly and flooding apparatus of Saraf and Fatt (1967).

Figure B-11. Steady-state, high-rate method. Fluid distributor and flooding apparatus of Braun and Blackwell (1981).

Figure B-12. Steady-state, high-rate method. Flooding apparatus of Wang (1988).

Figure B-13. Steady-state, high-rate method. Rock holding assembly and flooding apparatus of Maini, Kokal, and Jha (1989).

Figure B-14. Steady-state, high-rate method. Flooding apparatus of Dria, Pope, and Sepehrnoori (1990).

Figure B-15. Steady-state, stationary liquid method. Rock holding assembly of Leas, Jenks, and Russell (1950).

Figure B-16. Steady-state, stationary liquid method. Flooding apparatus of Loomis and Crowell (1962).

Figure B-17. Steady-state, stationary liquid method. Flooding apparatus of Ning and Holditch (1990).

Figure B-18. Steady-state, uniform-capillary-pressure method. Rock holding assembly and flooding apparatus of Hassler (1944).

A. Kleenex tissue capillary contact material.
 B. Pressure tap for wetting phase—porous ceramic material.
 C. Semipermeable membrane—porous ceramic material.
 D. Lucite butt pieces.
 E. Rubber sheath of Hassler-type core holder.
 F. Metal cylinder of Hassler-type core holder.
 G. Pressure applied to sheath to hold core and butts.

H. Metal face plate of Hassler-type core holder.
 1. Flow channel of nonwetting phase—through lucite and ceramic.
 2. Pressure tap for wetting phase.
 3. Flow channel for wetting phase—to under side of ceramic.
 4. Pressure tap for nonwetting phase—through lucite and ceramic.

Figure B-19. Steady-state, uniform-capillary-pressure method. Rock holding assembly and flooding apparatus of Brownscombe, Slobod, and Caudle (1950).

Figure B-20. Steady-state, uniform-capillary-pressure method. Rock holding assembly and flooding apparatus of Osoba, Richardson, Kerver, Hafford, and Blair (1951).

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APPENDIX C

Summary of Literature on the Unsteady-State Methods for Measuring Relative Permeability

Authors (Date)	Unique Features	Observable Parameters	Operating Pressure, psi	Operating Temp., ° F
High-Rate Method				
Osoba, Richardson, Kerver, Hafford, Blair (1951)	For high rate displacement of viscous liquid with gas, data reduction is simple - equivalent to that for steady-state methods. Termed the "gas drive" method.	Rock dimensions, ΔP , gas flow rate, mass of rock with fluids.		
Branson (1951)	Similar to "gas drive" of Osoba, Richardson, Kerver, Hafford, Blair (1951). Liquid saturation is taken as the average before and after gas injection.	Rock dimensions, ΔP , gas flow rate, mass of rock with fluids	< 100	Ambient
Owens, Parrish, Lamoreaux (1956)	Produced gas and oil are separated at the exit of the rock by an oil-wet, tight-weave fabric. Rock is carefully selected to ensure homogeneity. Measured k_r/k_r using Welge's method for processing data.	Rock dimensions, ΔP , cumulative gas and oil production vs. time, final mass of rock and fluids	< 100	Ambient
Loomis, Crowell (1962)	Used apparatus similar to Owens, Parrish, and Lamoreaux (1956). Used three methods for data processing: JBN, Higgins, and "alternate."	Rock dimensions, ΔP , cumulative gas and oil production vs. time, final mass of rock and fluids	< 100	Ambient
Donaldson, Lorenz, Thomas (1966)	To eliminate capillary end effects, high rates were used in some experiments, while porous plugs were butted against the outlet face of the rock in other experiments. Used JBN method for data processing.	Rock dimensions, ΔP , cumulative fluid injection and water/oil production vs. time		
Donaldson, Dean (1965)	Used Welge and JBN methods to process data for two- and three-phase experiments.		< 100	Ambient

Authors (Date)	Unique Features	Observable Parameters	Operating Pressure, psi	Operating Temp., ° F
Sarem (1966)	Measured three-phase relative permeabilities with unsteady-state method. Adapted methods of Welge and JBN to process data.			
Davidson (1969)	Studied sensitivity to temperature of water-oil and gas-oil relative permeability ratios in sandpack. Processed data with Welge method.	Rock dimensions, ΔP , cumulative fluid injection and production vs. time	< 100	75 - 540
Poston, Ysrael, Hossain, Montgomery, Ramey (1970)	Used JBN method to process data from water floods in a sandpack at temperatures from 75 deg F to 300 deg F. Also measured temperature dependence of interfacial tension and contact angle.	Sandpack dimensions, ΔP , T, cumulative fluid injection and production vs. time, sight-glass observations	150	75 - 300
Schneider, Owens (1970)	Used experimental procedures of Owens, Parrish, Lamoreaux (1956). Used Welge and JBN to process data.		< 100	Ambient
Owens, Archer (1971)	Used experimental procedures of Owens, Parrish, Lamoreaux (1956) to measure gas-oil relative permeability. Used Welge and JBN to process data.			
Mungan (1972)	Demonstrated difference between water-oil relative permeabilities measured with refined oil and reservoir oil. Used <i>Lvm</i> scaling parameter.		300	138
Lefebvre du Prey (1973)	Tested Teflon, stainless steel, and alumina porous media. Altered wettability.		< 100	Ambient

Authors (Date)	Unique Features	Observable Parameters	Operating Pressure, psi	Operating Temp., ° F
Mattax, McKinley, Clothier (1975)	Measured water-oil and gas-oil relative permeability ratios of unconsolidated sand. Core holder with rubber sleeve and rubber washers at ends to apply triaxial stress. Little detail of apparatus and methods.			
Weinbrandt, Ramey, Cassé (1975)	Cumulative volumes of produced fluids were sensed with a capacitance probe. Overburden pressure: 2000 psi. Used L_v scaling parameter. Used Welge and JBN to process data.			80 to 175
Talash (1976)	Studied change in relative permeabilities with decreasing interfacial tension.			
Sigmund, McCaffery (1979)	Used large samples (4 in. diam.) for studies of heterogeneous rock. Processed data with non-linear regression on 1-D simulator. Confined rock with rubber sleeve and overburden pressure.	Rock dimensions, ΔP , oil and water flow rates, level of oil-water interface in separator		Ambient
Bardon, Longeron (1980)	Measured relative permeabilities with very low interfacial tensions. Referred to Welge, JBN, and Jones and Roszelle for data processing.		6000	250
Labastie, Guy, Delclaud, Iffly (1980)	Processed data by history matching a numerical simulator to the experimental results. Measured capillary pressure at four locations along core, using semi-permeable pressure taps.	Rock dimensions, ΔP , P_c , x-ray absorption by doped oil, cumulative gas and oil production vs. time		150

Authors (Date)	Unique Features	Observable Parameters	Operating Pressure, psi	Operating Temp., ° F
Amaefule, Handy (1981)	Correlated change in oil-water relative permeabilities with capillary number. Collected produced fluids in automatic fraction collector. Used JBN to process data.	Rock dimensions, ΔP , cumulative gas and oil production vs. time	100	77
Saraf, Batycky, Jackson, Fisher (1982)	Measured three-phase relative permeabilities. Optical sensing of interfaces in separator. Confined the rock with a rubber sleeve at overburden pressure of 1500 psi.	Rock dimensions, ΔP , oil and water flow rates, levels of gas-oil and oil-water interfaces in separator	370	75
Sufi, Ramey, Brigham (1982)	Studied temperature effect on oil-water relative permeability in sandpack. Used photo-cell to monitor production of fluids. Overburden pressure: 2000 psi. Used Jones and Roszelle to interpret the data.	Sandpack dimensions, ΔP , oil and water flow rates, levels of gas-oil and oil-water interfaces in separator	200	75 - 250
Heaviside, Black, Berry (1983)	Explored the validity of relative permeability concepts. Found that these concepts do not strictly apply to imbibition processes. Used JBN and Welge.	Rock dimensions, ΔP , oil and water flow rates, produced fluids captured in fraction collector		
Bennion, Moore, Thomas (1985)	Rock confined with lead sleeve and overburden pressure: 1500 psi. Processed data with non-linear regression of a 1-D simulator similar to Sigmund and McCaffery (1979).	Rock dimensions, ΔP , oil and water flow rates	3000	570
Miller, Ramey (1985)	Data processed by Jones and Roszelle method. Used Rapoport and Leas scaling parameter Lvm .	Rock dimensions, ΔP , oil or water injection rates, produced fluids captured in separator, elapsed time	100	Room - 300

Authors (Date)	Unique Features	Observable Parameters	Operating Pressure, psi	Operating Temp., ° F
Maini, Batycky (1985)	Studied effect of temperature of oil-water relative permeabilities of heavy oils. Confined with lead sleeve; overburden pressure: 2500 psi. Used transient pressure decay test to measure oil permeability at connate water saturation. Processed data with non-linear regression of a 1-D simulator similar to Sigmund and McCaffery (1979).	Rock dimensions, ΔP , oil or water injection rates, produced fluids captured in high pressure separator, elapsed time	1000	520
Islam, Bentsen (1986)	Sandpack. Used microwave absorption to measure water saturation. Measured pressure gradient at seven taps.	Rock dimensions, ΔP and local gradient, microwave absorption, oil or water injection rates, volume of produced fluids, elapsed time		
Heaviside, Brown, Gamble (1987)	Measured relative permeabilities for intermediate wet rock. Saturations by gamma ray attenuation. Eight pressure taps along sample.	Rock dimensions, ΔP and local gradient, gamma ray attenuation, elapsed time	< 100	Ambient
Peters, Khataniar (1987)	Determined impact of instability on relative permeability. Sandpack. Data processing by Welge and JBN. One set of relative permeabilities was measured with steady-state method.	Rock dimensions, ΔP , water injection rate, volumes of fluids produced in fraction collector	< 100	Ambient
Maini, Okazawa (1987)	Temperature and relative permeabilities for heavy oil and water. Sandpack confined with lead sleeve. Capillary viscometer and pycnometer included in apparatus. Processed data with non-linear regression of a 1-D simulator similar to Sigmund and McCaffery (1979).	Rock dimensions, ΔP , water injection rate, volumes of fluids in high-pressure separator		Room to 400

Authors (Date)	Unique Features	Observable Parameters	Operating Pressure, psi	Operating Temp., ° F
Lai, Brandt (1988)	Tested a pressure-history-matching algorithm for determining relative permeabilities. Sand consolidated with epoxy. Compared results with Welge and JBN.	Pack dimensions, ΔP , gas injection rate, volumes of gas and water in separator		
Donaldson, Civan, Waqi Ul Alam (1988)	Relative permeabilities at reservoir conditions. Rock confined with Teflon sheet and rubber sleeve. Processed data with method of Civan and Donaldson which accounts for capillary end effects.	Rock dimensions, ΔP , water injection rate, volumes of fluids produced in fraction collector		Ambient to 150
Ruth, Adamson, de Freitas, Hriskevich, Kendall, Nikakhtar (1988)	Automated relative permeameter. Overburden pressure: 10,000 psi. Data processing by history matching.	Rock dimensions, ΔP , fractional flow at outlet, volumes of produced fluids	5000	Ambient to 480
Hawkins (1989)	Sample confined with up to 3400 psi overburden pressure. Data processed with JBN.	Rock dimensions, ΔP , volumes of produced fluids	300	230
Grader, O'Meara (1988)	Three-phase relative permeabilities for three immiscible liquids - chosen to eliminate capillary end effects. Glass-bead pack. Modified JBN. Pressure taps along pack.	Rock dimensions, ΔP and gradient, volumes of produced fluids in fraction collector, or volumes in separator	< 100	Ambient
Sarma, Bentsen (1989)	Proposed new method for analyzing unsteady-state data. Requires saturation and pressure profiles. Apparatus as described by Islam, Bentsen (1986).			
Narahara, Pozzi, Blackshear (1990)	Connate water and gas-oil relative permeability. Axial and radial stress: 2500 psi. Used JBN.		500	Ambient

Authors (Date)	Unique Features	Observable Parameters	Operating Pressure, psi	Operating Temp., ° F
Maini, Coskuner, Jha (1990)	Compared unsteady- and steady-state measurements of relative permeability for viscous oil and water. Apparatus essentially as described by Maini, Okazawa (1987). Processed data per Sigmund and McCaffery (1979).			73 to 212
Shafer, Braun, Wood, Wooten (1990)	Apparatus may be a modified version of that described by Braun and Blackwell (1981). The apparatus was operated in both unsteady- and steady-state modes to obtain relative permeabilities at saturation extremes. For unsteady-state, data processing by Welge and JBN.			
Puri, Evanoff, Brugler (1991); Hyman, Brugler, Daneshjou, Ohen (1991)	Measured porosity and gas-brine relative permeability of coal cleats. Used x-ray absorption to measure saturations. Processed data with Welge and JBN. Overburden pressure: 1000 psi. Injection of humidified gas.	Rock dimensions, ΔP , volumes of produced fluids in acoustic collector, mass of produced gas, x-ray absorption	300	
Gash (1991); Gash, Volz, Potter, Corgan (1993)	Amoco report on semi-cooperative effort with Puri, Evanoff, and Brugler (1991). Measured porosity with tracer tests. Used JBN. Overburden pressure: 1000 psi.	Rock dimensions, ΔP , mass of produced brine in separator, mass of produced gas, x-ray absorption	300	
Mohanty, Miller (1991)	Used CT-scanner to evaluate effect of flow rate on JBN relative permeabilities.			

Authors (Date)	Unique Features	Observable Parameters	Operating Pressure, psi	Operating Temp., ° F
Low-Rate Method				
Parmeswar, Maerefat, Brinkmeyer (1986); Parmeswar, Maerefat (1986)	Developing apparatus for measuring three-phase relative permeabilities. Non-linear regression on modified BOAST. Plan to measure oil saturation with x-ray absorption, water saturation with microwave absorption.	Rock dimensions, ΔP , oil /water/gas injection rates, x-ray and microwave absorption, wet-test meter for produced gas, produced oil and water fraction collector, elapsed time		
Amaefule, Ajufo, Peterson, Durst (1987)	Investigated the effect of fines migration on relative permeability measurements. Used high pressure pH probe in produced brine.	Rock dimensions, ΔP , oil or water injection rates, produced oil and water in separator acoustic sensing, elapsed time	<100	Ambient
Jennings, McGregor, Morse (1988)	Measured transient flow for the porous-plate method for capillary pressure measurements. Processed data with history matching of 1-D simulator.	Pc, liquid production, elapsed time	< 100	Ambient
Chardaire, Chavent, Jaffre, Liu, Bourbiaux (1989)	Description of experiments is very limited. Saturation profiles were measured probably by gamma ray attenuation.	Rock dimensions, ΔP , water injection rate, saturation profiles, cumulative produced oil, elapsed time		
Hyman, Ohen, Amaefule, Daneshjou (1991); Hyman, Brugler, Daneshjou, Ohen (1991)	Simultaneous measurement of capillary pressure and relative permeability of coal. Monitored time-dependent production from a porous-plate apparatus. Overburden pressure: 800 psi.	Rock dimensions, ΔP , brine production rate, elapsed time	ambient	ambient

Authors (Date)	Unique Features	Observable Parameters	Operating Pressure, psi	Operating Temp., ° F
Centrifuge Method				
Van Spronsen (1982)	Measured three-phase relative permeability. Data analysis similar to Hagoort (1978).	Rock and centrifuge rotor dimensions, rotational speed, volume of fluids collected vs. time	< 100	
O'Meara, Lease (1983)	Data collection was automated to improve the quality and the speed of collection. Data was processed by method of Hagoort (1978)	Rock and centrifuge rotor dimensions, rotational speed, volume of fluids collected vs. time	< 100	
O'Meara, Crump (1985)	Simultaneous measurement of capillary pressure and relative permeability. Processed data by history-matching with 1-D simulator.	Rock and centrifuge rotor dimensions, rotational speed, volume of fluids collected vs. time		
Firoozabadi, Soroosh, Hasanpoor (1988)	A pump maintains the oil-water interface at a fixed position during a spin; the pump is connected to the centrifuge bucket through a rotating seal; both imbibition and drainage processes can be studied.	Rock and centrifuge rotor dimensions, rotational speed, volume of fluids collected vs. time.	< 147	32 to 104
Narahara, Pozzi, Blackshear (1990)	Connate water and gas-oil relative permeability - just oil relative permeability was measured. Applied triaxial stress: 2500 psi. Used method of Hagoort(1980) to process data.	Rock and centrifuge rotor dimensions, rotational speed, volume of fluids collected vs. time.	ambient	ambient
Chardair-Riviere, Forbes, Zhang, Chavent, Lenormand (1992)	Demonstrated an ultrasonic method for measuring saturations in rock samples while spinning in a centrifuge. Centrifuge results for relative permeability were compared with results from an unsteady-state method.	Rock and centrifuge rotor dimensions, rotational speed, volume of fluids collected vs. time, saturations at three locations in the rock		

APPENDIX D

Schematic Diagram of Experimental Apparatus Used for Measuring Relative Permeability with Unsteady-State Techniques

Figure D-1. Unsteady-state, high-rate method. Rock holding assembly and flooding apparatus of Owens, Parrish, and Lamoreaux (1956).

Figure D-2. Unsteady-state, high-rate method. Flooding apparatus and Fluid-Level-Sensing assembly of Saraf, Batycky, Jackson, and Fisher (1982).

Figure D-3. Unsteady-state, high-rate method. Flooding apparatus of Islam and Bentsen (1986).

Figure D-4. Unsteady-state, high-rate method. Flooding apparatus of Gash (1991).

Figure D-5. Unsteady-state, low-rate method. Rock holding assembly and flooding apparatus of Hyman, Brugler, Daneshjou, and Ohen (1991).

Figure D-6. Unsteady-state, low-rate method. Rock holding assembly and flooding apparatus of Jennings, McGregor, and Morse (1988).

Figure D-7. Unsteady-state, centrifuge method. Apparatus of O Meara and Lease (1983).

Figure D-8. Unsteady-state, centrifuge method. Ultrasonic Sensing in rock holding assembly of Chardaire-Riviere, Forbes, Zhang, Chavent, and Lenormand (1992).

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APPENDIX E

Memorandum From Susan Howarth, 6119, to Martin Tierney, 6342: "Salado Anhydrite Porosity Data Marker Bed 139." Internal Memorandum, Sandia National Laboratories, Albuquerque, NM. June 1, 1993.

Sandia National Laboratories

Albuquerque, New Mexico 87185

to: Martin Tierney, 6342

from:
Susan Howarth, 6119

date: June 1, 1993

subject: Salado Anhydrite Porosity Data
Marker Bed 139

Attached are the preliminary (unpublished) results of 16 effective (interconnected) porosity tests performed on Marker Bed 139 rock core samples at TerraTek and RE/SPEC. These tests were performed this year on dry samples using a helium porosimeter. These data will be published later this year after other tests on these samples are concluded. The experiments were properly QA-ed and the data is useable for WIPP PA purposes. Please note that data from approximately 25 to 30 more tests should be available later in FY93.

As shown on the attached Table 1, porosity values range from 0.4 to 2.7% (0.004 to 0.027), with a mean of 1.369% (0.01369). The experimental uncertainty of this data is +/- 0.1% (+/- 0.001) as per personal communication with Dr. Joanne Frederick who ran the tests at TerraTek. I have also attached a histogram of the data grouping and a cumulative frequency curve which is based upon the histogram.

Please contact me at 844-0303 if you have any questions regarding this data or its application.

Copy to:

6119 E.D. Gorham
6115 R.L. Beauheim
6303 SWCF HYD/TPF 1.1.4.1.1 & 1.1.4.1.2

PRELIMINARY EFFECTIVE POROSITY DATA

Marker Bed 139 Anhydrite

PRELIMINARY EFFECTIVE POROSITY DATA

Marker Bed 139 Anhydrite

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