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Precision Methods for Testing the Integrity of Solution Mined Underground Storage Caverns

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ABSTRACT

Phillips Petroleum Company owns and operates (through its operating groups and subsidiaries) 57 solution mined storage cavern wells in the United States. These caverns are used to store a diverse variety of fluids in domal and bedded salt formations. Regulatory activity over the last ten years has generated the need to develop methods to "prove" the mechanical integrity of hydrocarbon storage cavern wells. The author, as a member of the company's Underground Storage Engineering Section for the last eleven years, has been active in developing the company's test program and analyzing the results of approximately 80 cavern mechanical integrity tests.

Phillips employs two basic methods for testing the integrity of caverns and cavern wells. The industry standard is the "interface observation" test and is based upon observation of the interface between a cap of immiscible test fluid (typically nitrogen gas) and the cavern fluid (typically brine or liquid hydrocarbon). Phillips developed an analytical tool (the "Brine Pressure Response" method) that greatly simplifies the determination of fluid volume injected during the calipering phase of an interface observation test. This analytical tool initially relied upon mechanical dead weight testers with resolutions (at best) of 0.7 kPa (0.1 psi). We now use precision, quartz crystal pressure transducers with resolutions of at least 0.07 kPa (0.01 psi), further improving the precision and simplicity of the Brine Pressure Response method.

Phillips tests the mechanical integrity of some caverns by what we term the "Precision Pressure Observation" method. Besides proving to be more economical and practical for some caverns than the interface observation test, precision pressure testing provides a more practical method of testing the integrity of the entire cavity (interface observation tests only the cased portion of the well and a small part of the cavern). Again, where we initially relied upon dead weight testers for pressure measurement, precision pressure transducers have improved and simplified data collection.

The objective of this paper is to describe the "Brine Pressure Response" and "Precision Pressure Observation" methods and provide specific advice on instrumentation, data collection, data analyses and presentation.

INTRODUCTION

Phillips Petroleum Company has a centralized Corporate Engineering group with an Underground Storage Section whose primary responsibilities include serving as internal consultants to the Company's operating groups for the design, operation, maintenance and trouble shooting of their underground hydrocarbon storage caverns. Phillips operates 57 storage (solution mined) cavern wells in the United States (44 in the state of Texas). These caverns have been used to store a variety of fluids as diverse as hydrogen and fuel gas to anhydrous ammonia and isopentane. The caverns are at depths as great as 1340 m (4400 ft) in domal salt and as shallow as 260 m (850 ft) in bedded salt.

The state of Texas requires a test of each cavern well for mechanical integrity at least once every five years. The Company's Underground Storage Section has the responsibility to design tests, assist in field execution and analyze and report the results. Because of our large variety of caverns, we have had to develop some innovative test procedures and tools.

Phillips developed and patented (Thiel, 1988) one analytical tool that we now call the "Brine Pressure Response" method. This tool greatly simplifies the determination of the volume of a section of cavern (a necessary step in the interface observation test method). Besides testing caverns by the interface observation method, Phillips has conducted several "Precision Pressure Observation" style tests with satisfactory results. Pressure tests have proven to be more economical and practical for some caverns than the interface observation test method.

Each cavern is unique in many ways and, thus, a test procedure must be tailored to the specific cavern to be tested at the specific facility. This paper is not intended as an instruction manual on how to perform cavern mechanical integrity tests. It (hopefully) will serve to introduce those already familiar with the basics of testing underground storage caverns to some precision testing tools and suggest an alternative to the standard interface observation test.

This paper describes the "Brine Pressure Response" tool, the "Precision Pressure Observation" test method and provides specific advice on instrumentation, data collection, data analyses and presentation.

IMPROVING THE STANDARD INTERFACE OBSERVATION TEST

Standard Interface Observation Test Method

The "Interface Observation" method of testing the integrity of storage caverns is the industry standard in the United States. There can be many variations in fluids and sequence, but the method normally involves injecting nitrogen into the annulus (between the production casing and the brine tubing) of a shut in, brine full, cavern that has been "prepressured" to near final test pressure. Cavern pressure rises as nitrogen is injected into the shut in cavern. Ideally, the gas/brine interface lowers to the desired depth (two or three meters below the deepest cemented casing in a narrow portion of the cavern "neck") just as cavern pressure reaches planned test pressure (test pressure at the interface is equal to or greater than the maximum allowed during normal storage operations).

The assumption is that if a cavern leaks, the leak path will be around the bottom of the casing, through the casing or from the wellhead. Assuming no significant pressure or temperature changes, a leak will be manifested by a loss of nitrogen and a subsequent rise in interface (after a suitable observation period, the length of which is dependent on desired test resolution and borehole configuration).

Depth to the interface is measured by a specialized density tool lowered by wire line inside the brine tubing. To correlate a rise in the interface to a volume (i.e., quantify an apparent leak rate), the volume profile of the well/cavern from the surface down to the final position of the interface must be determined. The standard technique requires "calipering" by determining the quantity of nitrogen injected (typically in terms of mass) and then calculating downhole volume. To optimize accuracy, the well is calipered in increments for the entire interval from the surface down to the final interface position. The standard analysis involves relatively complex calculations and accuracy is dependent to some extent on temperature assumptions.

Brine Pressure Response Method

The Brine Pressure Response method is an analytical tool that greatly simplifies the task of calculating the downhole volume of a test fluid (typically nitrogen) injected into a section of a well or cavern during the calipering phase of an interface observation style of integrity test.

The Brine Pressure Response method relies upon the fact that most storage caverns tend to pressurize linearly, particularly over a relatively small pressure interval; i.e., when a cavern is pressurized by injecting a fluid into its annulus, cavern pressure (as measured at the surface in the brine tubing) tends to rise linearly as a function of volume of fluid injected. This linear pressurization characteristic provides a method of measuring the volume of fluid injected into the annulus.

Figure 1 illustrates this linear characteristic. The cavern in this example was "pre" prepressured from static pressure to about 4.6 MPa (670 psia) the day before "final" prepressure to help stabilize the cavern and to reduce the amount of intensive data collection. During the final prepressure phase, we meter brine injected and correlate the volume data to tubing pressure at appropriate intervals. We normally inject into the annulus and measure pressure from the tubing to prevent inaccuracies that could result from slugs of hydrocarbon accumulating in the annulus, friction, or brine of varying specific gravities. However, if the well is thoroughly purged of hydrocarbon (or contains a blanket of liquid hydro-

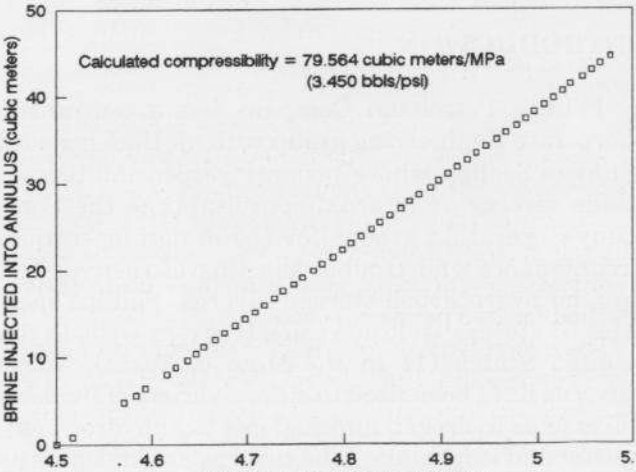

Fig. 1. Prepressure data from a domal cavern test (modified from Thiel, 1991a).

carbon down to the cavern proper), then brine injection into the tubing with pressure measurement from the annulus can also provide suitably accurate data.

We graph the pressurization data (to help note any anomalies) and calculate the cavern's "compressibility ratio" from the pressurization data. This ratio allows the easy calculation of the volume of any fluid injected into the annulus by measuring the pressure response in the tubing (hence the term, "Brine Pressure Response"). Table 1 lists the raw data and results of a cavern "caliper" using the Brine Pressure Response method. The compressibility ratio, 0.07955 m^3/kPa in this example (3.450 bbls/psi), was calculated from the prepressure data graphed in Fig. 1. As nitrogen is injected into the annulus, the interface moves progressively downward and the brine tubing pressure increases. The incremental increase in brine pressure is simply multiplied by the compressibility ratio to obtain the volume of test fluid injected into that interval; e.g., between interface levels 850.39 m (2790 ft) and 850.70 m (2791 ft), brine pressure increased 3.59 kPa (0.52 psi). This equates to 0.286 m^3 (1.79 bbls) of nitrogen (3.59 kPa × 0.07955 m^3/kPa) for an average effective diameter of 1.08 m (3.6 ft).

Anyone who has tried to caliper a well or portion of a cavern by converting nitrogen mass data into downhole volume (especially in the midst of a typically noisy and hectic test environment) should appreciate this much simpler method.

We compare the calculated volume of the cased portion of the well to the theoretical volume (from casing diameters) and, in effect, use the casing as a "prover" to verify the compressibility ratio. Normally, no adjustment in the compressibility ratio is necessary. In this example, measured cased volume agreed to within 3% of the theoretical volume.

PRECISION PRESSURE OBSERVATION METHOD

When developing a test method for our bedded salt caverns, we had to consider that some had relatively broad, flat, roofs immediately below the production casing (Thiel, 1990). This caused concerns about using the nitrogen interface observation method for two primary reasons.

The resolution of an interface observation style test is dependent upon the width of the cavern at the interface and the duration of the test. Using interface logging equipment capable of detecting a 15 cm (6 in.) rise in interface, a cavern with a 15.2 m (50 ft) diameter "borehole" immediately below the casing would require a two month test to obtain a 160 m^3/year (1000 bbl/year) test resolution (160 m^3/year test resolution has become somewhat of a standard). A two month test is not practical for most caverns. We also considered the impact of exposing the flat roof of a bedded salt cavern to the reduction in buoyant support resulting from injecting gas into the cavern.

TABLE 1

Cavern well caliper using the brine pressure response method (modified from Thiel, 1991a)

Interface depth (m)	Wellhead pressures (kPa)		Incremental volume (m^3)	Incremental effective diameter (m)
	Nitrogen	Brine		
0	5 022.76	4935.06		
152.40	6 467.35	5020.69	6.812	0.24
304.80	8 486.89	5101.22	6.406	0.23
457.20	10 111.51	5180.24	6.286	0.23
609.60	11 691.23	5257.60	6.154	0.23
762.00	13 220.90	5334.61	6.126	0.23
839.11	13 970.16	5374.33	3.160	0.23
Shutdown for 63 min to monitor interface				
839.11	13 955.95	5367.98		
849.48	14 056.82	5373.98	0.477	0.24
850.09	14 067.17	5379.36	0.428	0.95
Shutdown for 17 min to confirm location of interface (bottom of casing at 849.48 m)				
850.09	14 065.86	5378.53		
850.24	14 070.61	5381.01	0.197	1.29
850.39	14 074.75	5383.70	0.214	1.35
850.70	14 081.09	5387.29	0.286	1.08
850.85	14 086.75	5390.39	0.247	1.45
851.15	14 090.75	5393.49	0.247	1.02

The result was to develop a pressure test procedure that relies solely on the interpretation of pressure data (instead of interface position). The procedure also has the advantage that it tests the entire cavity (instead of just the area above the interface).

Hydrocarbon cap

As a general rule, a brine full pressure test is not considered valid. The theory is that at least the casing and casing shoe area (the top of the open hole) should be in contact with a fluid less viscous than brine — to more accurately simulate normal operating conditions. The casing and casing shoe areas are the most likely leak paths and it is conceivable that a cemented annulus that is relatively impermeable to brine could be considerably more permeable to a hydrocarbon liquid (or gas). Therefore, before initial

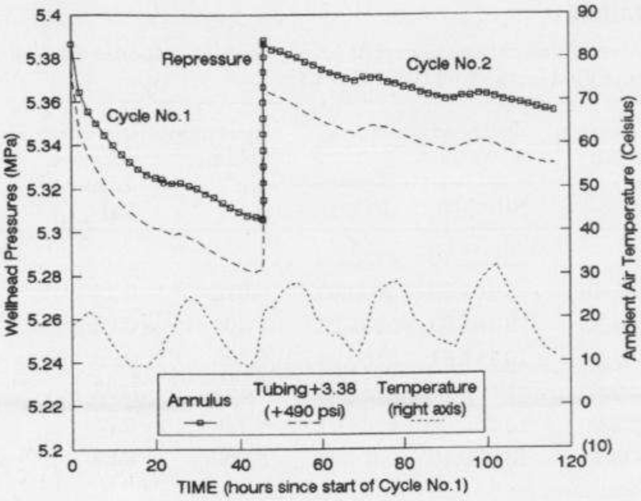

Fig. 2. Pressure observation data from bedded salt cavern tested by the Precision Pressure Observation method (modified from Thiel, 1991b).

pressurization, we establish a liquid hydrocarbon cap of sufficient quantity to insure the product/brine interface is below the bottom of the casing (typically using the product normally stored in the cavern, propane, butane, etc.).

Prepressure

After establishing the hydrocarbon cap in the cavern, we prepressure the cavern by injecting sufficient brine into the tubing to bring the cavern pressure up to about 90% of test pressure (as measured at the annulus). We do not collect detailed pressure data during "prepressure". We then isolate normal surface piping and install the test connections.

For our caverns, we have found the prepressure step is important to optimize cavern stability. We also believe that prepressure helps minimize destabilization during initial pressurization to test pressure. Depending on operational limitations, we prefer to prepressure two to four weeks before the actual test.

Initial pressurization to test pressure

We bring the cavern to test pressure (typically 110% of the normal maximum operating product pressure) by injecting brine into the tubing. Casing pressure (product), tubing pressure (brine) and brine injection quantities are recorded. As with the Brine Pressure Response method, we analyze the data and calculate a compressibility ratio (from the annular pressure data). The data are graphed as in Fig. 1, except that we normally graph both the annulus and tubing pressures.

Due to logistical or mechanical problems, we have had to collect the "pressurization" data at the end of the test by depressuring the cavern. This method is simpler in some respects, due to not having to operate a brine pump, and may be more accurate (since the cavern is presumably more stable at the end of the test than at the beginning). However, since the pressurization ratio must be known to analyze the test pressure observation data, it is preferable to have the ratio available before the test is terminated.

Observation cycles

After initial pressurization to test pressure, the cavern is shut in and pressures recorded at 2-h intervals for 24–72 h. Pressures normally decay exponentially at the beginning of the first cycle and then begin to linearize.

The cavern is repressured to test pressure — again by injecting brine into the tubing while recording brine quantity and wellhead pressures. The data are again graphed and analyzed to note any changes in compressibility.

A second cycle of 48–72 h is then started. The objective is to conduct as many observation cycles as necessary until pressure decay becomes essentially linear and relatively stable. This normally occurs after only two cycles. Figure 2 illustrates typical observation data.

Data analyses

We attempt to stabilize the cavern as far in advance of the test as feasible. However, the act of pressuring the cavern before and during the test is itself destabilizing (with respect to salinity, temperature and elastic response).

The purpose of conducting a cyclic test is twofold. One, it provides data to help determine if the cavern is essentially stable. Two, if the cavern is obviously not stable, then it provides data that allow mathematical prediction (through curve fitting) of what stable conditions would be if given enough time. (We have not yet encountered a test situation, with a liquid filled cavern, that requires this type of analysis.)

During initial pressurization to test pressure, the compressibility ratio is established. This ratio allows equating a pressure drop to a theoretical fluid loss.

If the cavern has essentially stabilized, then the pressure drop over the course of the last cycle (or over the most linear portion of that cycle) can be equated to a fluid loss rate using the compressibility ratio calculated during initial pressurization. Figure 3 illustrates this method. Hydrocarbon pressure decay over the last 48 h of the last cycle of this test was essentially linear at 0.3030 kPa/h (0.04395 psi/h). When multiplied by the compressibility ratio, 0.02424 m^3/kPa (1.051 bbls/psi) for this cavern (and with the proper unit conversions), the decay rate is equivalent to a theoretical fluid loss rate of 64 m^3/year (400 bbls/year). The theoretical fluid loss rate based on brine pressures correlated well at 70 m^3/year (440 bbls/year). It is important to analyze 24-h increments (i.e., the last 24 h, 48 h, 72 h, etc.) to neutralize diurnal temperature effects. From Fig. 3, it is obvious that the pressure decay rate would have been greater (and presumably less accurate) if only the last 15 h had been analyzed.

We do not expect to prove zero fluid loss rates with this type of test. Bedded salt formations contain anomalous layers that, though relatively impermeable, can have some permeability (greater than that of salt). Such "seep" losses would not be a mechanical failure, but merely the combined impact of several thin layers of shale or anhydrite with very low permeabilities.

If there are no obvious symptoms of mechanical failure (product appearing at the surface, etc.) and the fluid loss rate is of nominal magnitude, then it can be reasonably concluded that the loss is either a "seep" loss (where cavern fluid is slowly permeating horizontally into shale layers within the salt formation), the effect of various factors still stabilizing (cavern temperature, salinity, elasticity or some other unknown variable) or a combination of causes. We use 160 m^3/year (1000 bbls/year) maximum as minimum acceptable test resolution. In any event, the Precision Pressure Observation Method offers an alternative to the conventional nitrogen interface method of mechanical integrity test.

PRECISION PRESSURE MEASUREMENT

We originally developed the Brine Pressure Response and Precision Pressure Observation methods using dead weight testers of 0.35 kPa (0.5 psi) and later with 0.07 kPa (0.1 psi) resolution for pressure measurement. Precision, high resolution, transducers have further simplified and improved the accuracies of these methods. The transducers are superior in response, accuracy and resolution to even the 0.07 kPa resolution dead weight tester. Additionally, coupled with a recorder, the transducers collect data periodically throughout the test period without the manpower and consistency problems of a manual system. The increased quantity and quality of pressure data have further enhanced the overall quality of our testing program.

Two transducers are connected via small diameter hoses (filled with AAA tester oil) to the wellhead to measure annulus (nitrogen or hydrocarbon) and tubing (brine) pressures. A third transducer measures outside ambient air temperature (and is available as a spare if necessary). The transducers are housed a short distance from the wellhead in a portable building (the third transducer is mounted outside the building). The transducers are temperature compensated, but transducer temperature change can induce a residual error of five to ten parts per million of full scale per degree Celsius (Chinn, 1991). When long-term data accuracy is important (such as during Precision Pressure Observation tests), we air condition the test building to hold transducer temperatures relatively constant. The transducers are connected to a computer that applies the transducer specific calibration calculations (and calculates the temperature compensation) and outputs the data to a programmable printer.

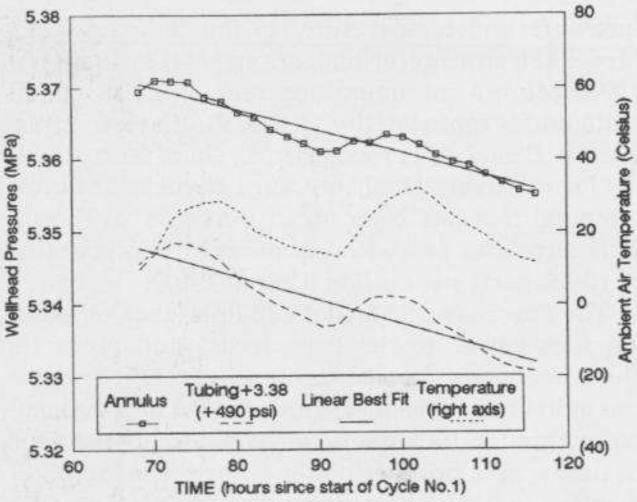

Fig. 3. Linear analysis of the last 48 h of a Precision Observation test (modified from Thiel, 1991b). Hydrocarbon pressure decay rate averaged 0.3030 kPa/h (0.4395 psi/h), which at a compressibility of 0.02424 m^3/kPa (1.051 bbls/psi), equated to a theoretical fluid loss rate of 64 m^3/year (400 bbls/year).

We have assembled three pressure measurement packages for testing the integrity of our caverns over the past six years (most recently in the spring of 1991). Each package varies slightly in the method of mounting and other minor details, but primarily consists of the following components. (Note that we are obviously very satisfied with the performance of our instrumentation, but I do not intend to imply that these components are necessarily unique or superior to similar instrumentation that may be available.):

- Three Paroscientific 42k Digiquartz Pressure Transducers
- One Paroscientific Model 702 Digiquartz Pressure Computer;
- 1 Fluke Model 2030A Programmable Printer

The transducers use a crystalline quartz resonator to detect pressure induced stress by measuring changes in the oscillating frequency (Busse, 1987). Each transducer provides dual frequency outputs (pressure and temperature) to the computer. The Model 42k transducer has a range of 0 to 13.8 MPa (2000 psia), a minimum accuracy of 0.02% of full scale and a repeatability of 0.005% (Paroscientific, 1986b). Based on our experience, short-term stability for relatively small pressure changes at stable temperatures has been about 0.14 kPa (0.02 psi). This correlates well with estimates by Paroscientific of 10–20 parts per million (Chinn, 1991).

The Paroscientific Model 702 Pressure Computer supplies power to the transducers and processes their frequency signals. Calibration coefficients for the individual transducers are entered into the computer through its numeric keypad and are retained in the event of primary power failure. The computer displays individual pressures and temperatures for up to four transducers and provides temperature compensation for the transducers. The display and digital output have a resolution of one part per million of full scale pressure (Paroscientific, 1986a). The computer is programmed to output in one of two resolution modes. The high resolution mode (which we use) averages the selected pressure channels for about 1.8 s each (temperature channels for about 1 s). Low resolution mode averages each channel for one tenth as long (Paroscientific, 1986c).

The Fluke Model 2030A Programmable Printer is a 20-character thermal line printer (Fluke, 1979) and receives pressure and temperature input from the RS232 serial digital output port of the pressure computer. The printer can be programmed to print out data, interval time (if applicable) and real time; on demand or at set intervals. The computer controls which data (pressures and/or temperatures from up to four transducers) are output to the printer.

During pressurization and nitrogen injection phases of tests, we collect data using the manual print function (to correlate to injection quantities or interface positions). During observation phases of the test, we program the printer to collect data at 2-h intervals.

We manually enter test data from the paper recordings into a personal computer for analysis and report writing. Paroscientific now manufactures "intelligent" transducers with independent signal processors that can output temperature compensated data directly to personal computers (or data loggers) for electronic storage of data. We have chosen to continue with our more "primitive" design for simplicity and compatibility of components between our three test packages.

The high resolution, precision, pressure measurement/recording packages have greatly simplified and improved the accuracy of our Brine Pressure Response method of calipering caverns during interface tests. Additionally, they have improved the quantity and quality of pressure data collected while testing caverns by the Precision Pressure Observation method.

RECOMMENDED DATA PRESENTATION

Interface Tests

For purposes of the final report, we provide some of the raw pressure data with the chronological summary of the test. But most pressure data for the final report is provided in graphic form. Prepressure data are illustrated essentially as in Fig. 1. Nitrogen injection data and analysis are provided as in Table 1. We also include a complete history of time and pressures from final nitrogen injection to the end of the test (similar to Fig. 2). Ambient temperature is not normally tracked closely during interface tests because pressure history is not the primary tool for determining the theoretical fluid loss rate. However, an accurate pressure history of the test is important for trouble-shooting anomalies.

Additionally, a careful analysis of differential wellhead pressures (nitrogen pressure minus brine pressure) can provide insight into temperature and interface stability during the test; e.g., a differential pressure increase could be an indication that either the interface was descending and/or the temperature of the nitrogen was increasing. The high resolution, stability and accuracy of the pressure transducers make such analyses feasible.

Precision Pressure Observation Tests

For the final report, most of the raw data are presented in three exhibits. The first exhibit is pressurization data similar to Fig. 1 (except that brine and hydrocarbon pressures are normally both included, and for all cycles). The second exhibit is a complete pressure and ambient air temperature history commencing at the start of the first cycle (similar to Fig. 2). The temperature trace aids in understanding pressure anomalies. The third exhibit (Fig. 3) is basically just an enlargement of the last 48 h (or so) from Fig. 2 with linear best fit curves added.

CONCLUSIONS

The Brine Pressure Response Method is an effective tool for measuring the volume of a fluid, such as nitrogen, injected into a cavern for mechanical integrity testing purposes. The method is relatively inexpensive and simple to implement. It is superior in simplicity and at least comparable in accuracy to the standard method of measuring the mass of nitrogen injected, estimating (or measuring) well temperatures and calculating the downhole volume based on the gas laws.

The Precision Pressure Observation Method offers an alternative to the conventional nitrogen interface test. The method is particularly attractive for testing those caverns that do not have a conveniently narrow borehole at the top of the cavern (and which, for normal resolution, would require an excessively long test period if tested by the interface observation method).

Precision, high resolution, pressure transducers are important tools that have significantly improved the quality and simplicity of the Brine Pressure Response and Precision Pressure Observation methods. Before the advent of such transducers, suitably precise pressure measurements could only be obtained by manually operated dead weight testers. Transducers are superior in response, accuracy, resolution and ease of operation. We now consider transducers essential to our cavern testing program.

REFERENCES

Busse, W.D., 1987. Quartz transducers for precision under pressure. Reprinted from Mechanical Engineering, 109 (5) (May).

Chinn, M., pers. commun., 1991. Paroscientific, Inc., Redmond, WA.

Fluke, 1979. 2030A Programmable Printer Instruction Manual. John Fluke Mfg. Co., Inc., Everett, WA, pp. 1:1.

Paroscientific, 1986a. Digiquartz pressure computers specifications sheet. Paroscientific Inc., Redmond, WA.

Paroscientific, 1986b. Digiquartz pressure transducers series 4000 specifications sheet. Paroscientific Inc., Redmond, WA.

Paroscientific, 1986c. Model 702/703 Operation and Maintenance Manual. Paroscientific Inc., Redmond, WA, pp. 2:16.

Thiel, W.R. (inv.), 1988. Method of determining the volume of a section of an underground cavity. US Patent Number 4,720,995 granted January 26, 1988, assignee Phillips Petroleum Co., 10 pp.

Thiel, W.R., 1990. Alternative methods for testing the integrity of underground storage caverns. Unpublished paper presented at the Spring, 1990, SMRI Technical Meeting, Austin, TX, 35 pp.

Thiel, W.R., 1991a. March 14. Final report, clemens cavern no. 16. Report prepared for and submitted to the Railroad Commission of Texas, Underground Injection Control, Austin, Texas. Phillips Petroleum Company. 16 pp.

Thiel, W.R., 1991b. April 9. Final report, borger cavern no. 23. Report prepared for and submitted to the Railroad Commission of Texas, Underground Injection Control, Austin, Texas. Phillips Petroleum Company. 16 pp.