PRESSURE CORING:
BETTER CORES FOR BETTER ANALYSES

Nick G. Eaton*, S.R. Radford*, C. Segrest**
*** Eastman Christensen, Bits & Coring Division**
**** Core Laboratories**

Abstract. In critical applications where reservoir engineers and geologists need to analyze samples in near in-situ conditions, *pressure coring* may be the only method of obtaining complete core analysis. The procedure can be used for any project in which success is dependent upon accurate calculation of reserves in place, or the reaction of reservoir rock to alternative recovery techniques.

The self-contained pressure coring system provides a means of capturing and maintaining the core at or near bottomhole pressure, preventing gas expansion and fluid loss. A flushing gel is used to displace drilling mud from the core barrel while keeping in-situ pressure constant. Still contained in the inner tube barrel, the cores are frozen for transport to the laboratory, where controlled thawing allows accurate fluid saturation measurements.

A case history is presented to illustrate operation and results of the pressure coring system, which is able to provide types of information unobtainable with conventional means. In addition to fluid saturation data, pressure coring provides wettability and relative permeability measurements, mechanical property data such as compressibility and shear strength, and measurements of methane content and deliverability. Thus, use of this system results in greater accuracy in core analysis, and affords greater precision in evaluation of hydrocarbon reserves.

INTRODUCTION

The ability to analyze core which has been retained at near in-situ conditions has become a strong reservoir engineering tool. In comparison with other methods, pressure retained core analysis is recognized as providing the most reliable measurement of vertical oil saturations, especially in formations that are highly saturated and contain frequent changes in lithology. The technique also is especially useful when the feasibility of secondary and tertiary recovery methods is being evaluated.

For ten years, the pressure core barrel has been, and continues to be, the only commercially available core barrel able to retrieve cores at true bottomhole pressure. With it, the fluids and gasses in the representative core typically are brought to the surface at very close to in-situ conditions.

When coupled with new low-invasion coring technology, pressure coring can have significant impact on reducing wettability changes that occur after a core has been cut.

Principle of Operation

The principle of the pressure coring system is to allow the cutting and recovery of core from a wellbore under true bottomhole pressures. To do so, a pressure regulator on the core barrel is surface-set to match and maintain the anticipated bottomhole pressure. Core is then cut in the conventional rotary manner, after which a ball is injected into the drill string from surface and pumped downhole to "trip" or activate the pressure core barrel. Once activated, the core barrel seals fully at top and bottom to maintain internal pressure as the barrel is removed to the surface.

At the surface, the core barrel is placed into a trailer-type service unit where the barrel is partially disassembled and flushed of drilling fluid while connected to a closed-loop pressure maintenance system.

When the flushing process is complete, the barrel is frozen in dry ice or liquid nitrogen to stabilize the core, then cut to length to be shipped for analysis.

Pressure Coring Apparatus

Pressure core barrels can capture and maintain pressurized cores within bounds set by the outside diameter (OD) of the barrel itself. Currently, pressure cores can be taken with a double-tube core barrel available in two sizes: 6.0" and 8.0" OD, which cut cores of 2.5" and 3.75" OD respectively. The maximum pressure rating currently is 10,000 PSI for the 6.0" barrel and 5,000 PSI for the 8.0" tool, while the average pressure retention for pressure coring operations is approximately 80%, a marked inprovement over earlier proto-type systems.

The pressure core barrel (Figure 1) is a double-tube core barrel, on which the outer barrel provides the mechanical connection to the core bit, transmitting both bit weight and torque. It also serves as the pressure vessel to contain the recovered pressures.

The inner barrel is a non-rotating thin-wall tube suspended on a mud-lubricated bearing. The inner barrel serves as transportation housing for the core. After processing and freezing, the inner barrel, with the recovered core inside, is cut into transportable lengths and capped.

Slip-jointed spline assembly

The upper section of the pressure core barrel is a telescoping, splined, slip joint containing a locking and releasing mechanism. This section allows axial movement of the inner and outer barrels relative to each other, which is necessary to seal the pressure within the tool.

The full-travel spline enables torque to be transmitted to the bit in any axial position. A locking mechanism is incorporated to lock the barrel in the coring position, and in the "tripped" or sealed position for retrieval. In the sealed position, the locking mechanism has adequate strength to allow weight to be applied to the tool without untripping the barrel.

Seal sub

Between the slip-jointed spline assembly and the outer tube is the seal sub. This portion contains a polished bore to receive the upper seals which form the main pressure containment above the core. It also contains a pressure tap arrangement to allow measurement of contained pressure once on surface.

Inner Barrel Assembly

The inner barrel assembly consists of a bearing assembly contained in the spline section, an inner tube connection section, the inner tube, and the core catcher assembly.

Pressure seal mechanism

While the ball valve assembly forms the lower pressure seal, the seal mandrel carries lip-type compression seals which form the upper seal. The double seal arrangement gives added protection to assure that the barrel seals properly.

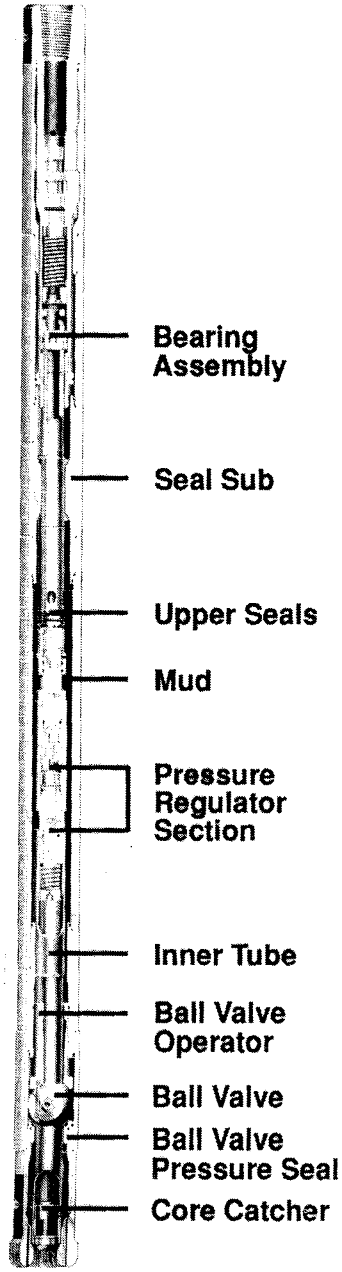

FIGURE 1. The double-tube pressure core barrel.

Pressure regulator

During retrieval, the pressure regulator section maintains pressure in the barrel, protecting it against effects of temperature- and differential pressure-induced volume changes. This assembly consists of a high pressure inert gas reservoir, a regulator with adjustable settings, and associated valving which supplies gas at a predetermined pressure to compensate for these effects.

The inner tube connector/tension section allows for connection of the inner tube to the lower end of the pressure regulator section.

The core catcher grips the core when breaking it from the formation after it has been cut. Various types of core catchers are available, with proper selection dependent upon formation characteristics.

Ball valve assembly

Below the outer tube is the ball valve assembly and the ball valve operator assembly, which are required to form the main pressure seal below the core. The operator assembly serves the purpose of closing the ball valve.

Temperature compensation

For special pressure coring operations such as those associated with "coal degassification" projects, the pressure regulator has been disabled, and internalized temperature thermocouples have been developed. These allow the core to be returned to bottomhole temperature, and thus pressure, while the pressure core barrel is being attended to in the service center.

Coring Operations

Pressure coring operations follow standard accepted coring practices but, due to the sophistication of the pressure coring equipment, should be performed only by fully trained personnel.

When the pressure core barrel has cut the core capacity of the inner tube, rotation of the barrel is stopped. The corebarrel is lifted off bottom to break the core in the normal manner. The kelly is removed and a steel drop ball is pumped down to the core barrel.

Once the ball is seated, it activates the core barrel closure mechanism and the barrel is effectively sealed at both top and bottom. The pressure core barrel is then retrieved to surface.

Non-invading gel

As an option, the inner tube can be pre-loaded with a non-invading gel which forms a protective barrier around the core as it enters the core barrel.

The gel is placed within the inner tube of the pressure core barrel before it is run into the hole. As the core enters the inner tube, the material is extruded around the core and forms a controlled-invasion filter cake which reduces the contact of mud with the core.

At present, a calcium bromide-based gel is used to provide particles to bridge the pore spaces in the core and reduce fluid invasion. The calcium carbonate particle size can be varied to the specific formation pore space requirements based upon two important rules:

(1) The median particle size of the bridging additive should be equal to or slightly greater than one-third the median pore size of the formation; and,

(2) the concentration of the bridging size solids must be at least 5% by volume of the solids in the final mud mix.[1] These rules would apply for any fluid used to reduce core invasion tendencies.

Advantages of using non-invading gel

The non-invading gel provides several advantages while pressure coring: (1) The gel, as it is extruded from the inner barrel, reduces mud flow near the core and lubricates the bit, helping reduce mud filtrate invasion during coring; (2) once the core enters the inner tube, any further invasion of the core by the mud filtrate is eliminated; and, (3) removal of the frozen non-invading gel from the core surface is much easier than is removal of frozen drilling mud.

In general, core can be processed much more rapidly in the core analysis laboratory, and the amount of core disturbance is reduced when non-invading gel is used, especially in cores which are friable to unconsolidated in nature.

When non-invading gel is used, the chloride content of the water produced during pressure depletion of the core must be corrected for contamination by the high concentration of bromide used in the formulation of the non-invading gel. This requires measurement of both chloride and bromide content of the produced water.

Service Unit Processing

Upon arrival in the service unit, the recovered pressure core barrel is placed in a vise for servicing. As the spline section is removed, a transducer is attached to the seal sub to measure and record the recovered pressure. The barrel pressure is constantly monitored, and can be recorded, throughout servicing and freezing.

Once the recovered pressure is noted and the spline assembly removed, the upper and lower flushing adapters are installed. A special regulator on the flushing equipment is available which can be set to match the recovered pressure prior to flushing.

Since the ball valve must be opened prior to flushing, the lower flushing cap is pressured to the recovered pressure using water in the back-pressure system. Once the pressure across the ball is equalized, the ball is opened.

The inner barrel is then pushed downward by the flushing ram in the upper adaptor until it seats in the lower flushing cup, isolating the core from hydrocarbon-based flushing fluid. The lower end of the barrel is elevated and flushing is begun.

The flushing system is a closed loop system which maintains back pressure equal to the recovered pressure throughout the process.

The pump on the flushing unit is started, injecting flushing fluid into the pressure core barrel through the lower adaptor. Displaced drilling fluid exits through the upper adaptor into the back pressure system.

The barrel is disconnected from the flushing system and an optional regulated nitrogen maintenance system may be attached to the flushing adaptor. The entire barrel, with the nitrogen maintenance and pressure monitoring systems attached, is placed in a trough for freezing, using dry ice or liquid nitrogen.

After the barrel has been frozen thoroughly, the pressure is bled off. The core barrel is removed from the freezing trough and placed in a vise. The lower adaptor is removed from the barrel and the inner barrel assembly is pulled out through the ball valve. The inner tube is cut to length, capped and marked for identification, and stored in a frozen environment for shipment.

Temperature Compensated Pressure Coring

This process is altered for coal degassification projects, since the pressure regulator is disabled and no flushing of the core barrel is required.

In these applications, the core barrel is placed into the service unit and hooked up to the pressure maintenance/monitoring system. In addition, heating tapes are wrapped around the pressure core barrel and plugged into a power source controlled by the output of the thermocouples within the corebarrel. As the internal temperature of the core barrel rises, pressure also returns to bottomhole levels.

Because the thermocouples are located in the center of the barrel, when they have reached designated temperature, the outer barrel is naturally much hotter. Caution must be exercised to avoid burns.

Standard practices exist for tapping the pressure and measuring the gas volumes removed from the pressure core barrel. When temperature equilibrium has been reached, the gas volume is extracted, measured and sampled according to these practices.

PRESSURE RETAINED CORE ANALYSIS

Advantages and Limitations

The primary objective of pressure retained core analysis is to provide fluid saturation data on cores that have not been subjected to fluid expulsion during pressure depletion as the core barrel is retrieved from bottom hole to surface. Pressure retained core analysis can provide information from any one or all of the following categories:

1. Air Permeability, md.
    a. Horizontal
    b. Vertical
2. Porosity, percent pore space
    a. Pore Volume
    b. Grain density, gm/cc
3. Stock Tank Fluid Saturations
    a. Oil Saturation
        1. From pressure depletion
        2. Total oil saturation
    b. Water Saturation
        1. From pressure depletion
        2. Total water saturation
4. Gas Analysis
    a. Composition, mol %
    b. Gas Volume, cc @ STP
    c. Gas Gravity

5. Water Analysis
    a. Chloride, mg/L
    b. Bromide, mg/L
6. Core Gamma Surface Log
    a. Total gamma
    b. Spectral Gamma
7. Filtrate Invasion Study
    a. Filtrate, percent pore space
    b. Filtrate, percent total water
    c. Tritium analysis
    d. Vertical permeability on plug samples
    e. Porosity on plug samples

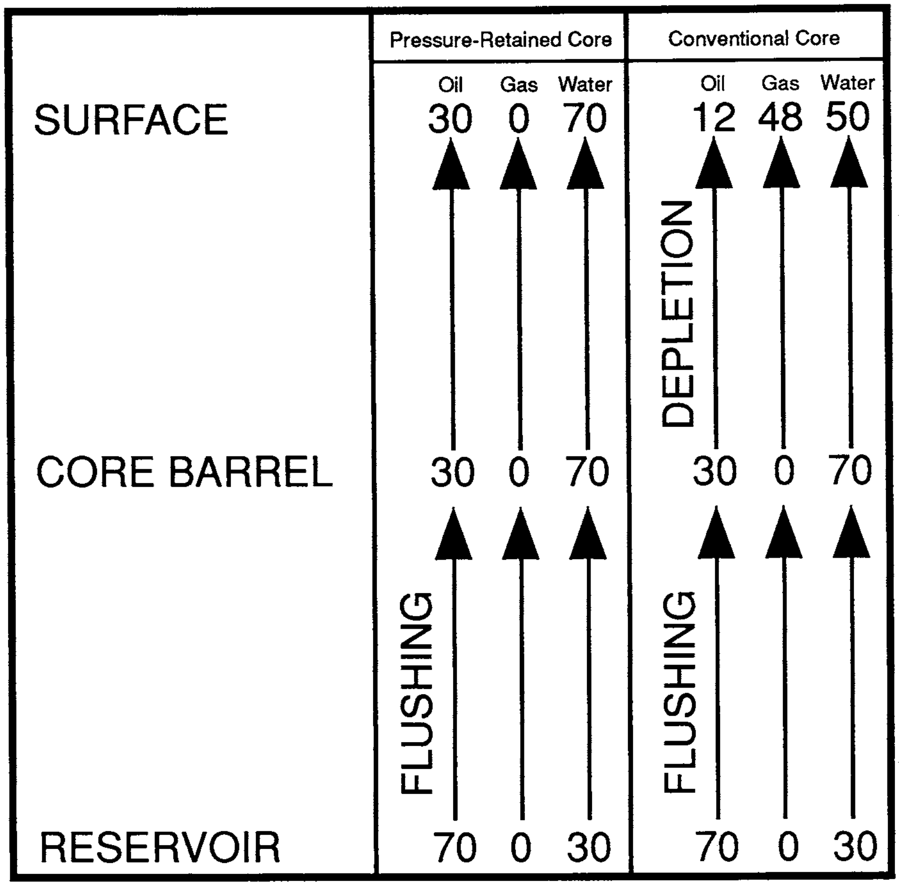

FIGURE 2. Percentage comparison of pore space saturation alterations.

8. Oil Analysis
    a. Composition, mol %
    b. Gravity, API

Pressure retained core provides fluid saturations more indicative of in-situ values than conventional cores, although this capability is controlled by several factors. For example, eliminating fluid expulsion during core retrieval, where pressure depletion occurs, prevents saturation alteration during this stage. Minimizing flushing of the pore spaces during coring also is necessary to obtain near in-situ saturations. Figure 2 shows how these factors affect core-measured fluid saturations, compared to in-situ values for badly flushed core.[2]

It is important to note that pressure coring is designed to prevent alteration from depletion but not from flushing. As a result, core saturations are indicative of in-situ values only if filtrate flushing is minimal. If significant flushing occurs, measured saturations may be more indicative of residual values after waterflooding. This can be important for the evaluation of tertiary recovery targets.

Minimizing fluid flushing

Flushing can be minimized by: (1) maintaining a minimal drilling fluid overbalance condition during coring; (2) having a low fluid loss mud system; and, (3) penetrating the formation as rapidly as possible while still assuring good core recovery.

Within the last few years, laboratory and field testing has shown that low invasion coring technology can significantly reduce problems related to fluid flushing of permeable formations.

In certain situations, such as depleted bottom hole pressures, a stabilized foam drilling fluid has been used successfully. However, caution must be exercised with mud weights above approximately 4 lb/gal as the foam has too high a water content to be considered stable. If the foam breaks down during coring, the core will be subject to a high fluid loss surfactant, and appreciable fluid saturation alteration may then occur.

Advantages of pressure coring

The ability to capture both oil and water phases in the core using pressure coring is a distinct advantage over conventional and sponge core analysis. By capturing all water which existed in the core at the completion of coring, it is possible to determine the percentage of filtrate which displaced either oil or water during coring.

Knowing the measured saturations and the percentage of filtrate, it is possible to qualitatively assess the saturation alteration during coring by use of the fractional flow characteristics of the formation.

In comparison, conventional and sponge coring only allow determination of the residual filtrate in the core after water is expelled during retrieval. Since most filtrate is located in the core's periphery, such a measurement of filtrate will be erroneously low. Oil saturation also is reduced during pressure depletion in a conventional core, although this oil may be captured in sponge core analysis.

Since gas is maintained in the pressure retained core, it is possible to measure gas volume as well as gas composition, which can be important when evaluating sweep efficiencies from miscible or non-miscible gas injection programs. In zones which indicate high sweep, residual saturations will allow assessment of various petrophysical properties of the rock after gas injection.

Gas-oil ratios, when averaged over an interval, have agreed favorably with assumed values.

Oil gravity can be determined on a foot-by-foot basis throughout a cored interval to assess gravity changes occurring with depth.

Note that the standard diameter of a pressure core is presently 2.5" or 3.75". The smaller diameter core decreases the volume-to-surface area of the sample, thereby increasing the degree of mud filtrate invasion and saturation alteration over that of a large diameter core. As in any core analysis measurement, the degree of accuracy is decreased as sample size is reduced. Small measurement errors will have less impact on large diameter pressure-retained cores.

Low Invasion Technology

Although low invasion technology is applicable to most types of coring equipment, it has been found especially applicable to pressure coring operations.

Low invasion technology combines advanced polycrystalline diamond compact (PDC) core bit technology and modified coring techniques to produce waterbase mud cores of high permeability sandstone with no mud filtrate invasion over two-thirds of the core's cross section.

Waterbase mud filtrate invasion while coring detrimentally affects water saturation and its distribution, residual oil saturation, and rock wettability, all of which are used to calculate total reserves and movable oil, among others. Most filtrate entering the core is generated by dynamic fluid loss from gage cutters in and near the throat of the core bit. Therefore, core invasion can be minimized by increased coring rate and reduced contact time with gage cutters.

Low invasion technology achieves this by: 1) reducing the number of cutters over the entire bit (increases depth of cut which can increase penetration rate); 2) using a parabolic bit design (reduces the dynamic filtration area); 3) using a low fluid loss mud (increases bridging solids); 4) reducing the number of gage cutters (reduces contact time of gage cutters); and 5) eliminating all throat diamonds (leaves mud cake intact).[3]

Field and laboratory testing has shown that filtrate invasion occurs in three principle areas during coring: 1) ahead of the bit; 2) in the bit throat, and 3) inside the core barrel. Patented low invasion technology has been shown to effectively reduce or eliminate all three of these influential factors.[4]

CASE HISTORIES

Introduction

In coring, particularly with relatively high-cost pressure coring, data is very closely held as proprietary to the customer. In general, companies are not willing to share "hard-earned" data with competitors. However, pressure coring has been successfully performed in most oilfield areas of the US, including offshore Gulf of Mexico, the Gulf Coast, and the Williston Basin of North Dakota, as well as in Southeast Asia, China and Canada.

"Traditionally a high cost operation with only marginal reliability, pressure coring remained a 'laboratory' tool until the late 1970s. As the need for such a service became apparent, the service side of the industry provided improvements and commercialization. However, the traditional views of pressure coring and a general lack of knowledge of current state-of-the-art continues to result in many potential users balking at adding this powerful tool to their operations."[5]

Even as long ago as 1983, when these comments were published, good results were being recorded. Since then, pressure coring has continued to enjoy approximately the same success rate. As of 1983, the pressure coring system had been used to cut 165 cores over a period of 4-1/2 years, representing more than 2000 feet of pressure core. Core recovery over this period averaged 83.6% although 55% -- more than half -- of the formations cored were considered soft to unconsolidated. Overall pressure recovery averaged 69% of bottom-hole hydrostatic pressure, or more than 75% of formation pressure.

During this time, pressure coring was used for determining residual saturation, locating oil-water contacts, and establishing correlations between current conditions and logs from early field development.

Successful cores were taken in very soft sands, sand/shale sequences, consolidated carbonates, and hard fractured carbonates. Pressures from several hundred to more than 6000 PSI were recovered on a routine basis, and pressure coring was successful using both oil- and water-based coring fluids, as well as air-foam systems, in both cased and open hole applications.

By 1983, reliability of the system had continued to improve with time and utilization, while the cost of using the system had decreased with utilization and development of improved equipment.[4]

Western Cretaceous Coal Seam Project

The following case history, described in detail in a recent CIM/SPE paper by M.J. Mavor, et.al.,[6] gives some indication of the value of pressure coring. Under the cooperative research efforts of the Western Cretaceous Coal Seam Project, funded by the Gas Research Institute, a number of wells were drilled in La Plata County, Colorado, with various coring operations conducted in the San Juan Basin Fruitland formation coal seams.

In addition to pressure coring, operations included conventional coring, sidewall coring, and drill cutting sample collection, after which standard gas collection was conducted, results were extrapolated, and comparisons made.

It was found that different coring or sample collection methods resulted in vastly different degrees of accuracy in prediction of well deliverability. This is due in part to the fact that, with the exception of pressure core samples, it is necessary to estimate the volume of gas lost while retrieving the samples.

Coal samples must be placed in desorption canisters immediately upon retrieval, and the volume of gas desorbed measured as a function of time, temperature and pressure. The "lost gas" volume is then added to the measured gas volume to improve accuracy of gas content estimates.

Two methods are commonly used for evaluating this "lost gas" volume: the Direct (Bureau of Mines) and the Smith & Williams methods, both of which make fairly broad assumptions which introduce varying degrees of error.[6]

In Table 1, the pressure core sample is accepted as the "baseline" and is judged most accurate since the sample is cored, sealed downhole, retrieved, and reheated to bottomhole temperature before the gas is tapped off and measured.

Unlike standard pressure coring, which employs a pressure regulator charged with inert gas to compensate for the effects of dropping temperature and contraction during retrieval, when pressure coring to determine methane gas volume, the pressure regulator is not used. Neither is gas of any type artificially added. Essentially, what enters the core barrel downhole is what's in it when it reaches the surface.

TABLE 1. Comparison of Gas Content Estimates

Sample Type	Lost Gas Analysis Method	Gas Content	Difference From Pressure Core	Difference From Pressure Core
		SCF/Ton	SCF/Ton	%
Pressure Core	None	601.4	0	0
Sidewall Core	None	635.4 + 52.7	34.0 + 52.7	5.6 + 8.8
Whole Core	Direct	557.4 + 15.6	-44.0 + 15.6	-7.3 _ 2.6
Whole Core	Smith & Williams	525.0 + 64.6	-76.4 _ 64.6	-12.7 + 10.7
Drill Cuttings	Direct	455.2 + 47.2	-146.2 + 47.2	-24.3 + 7.8
Drill Cuttings	Smith & Williams	433.2 + 60.8	-168.2 + 60.8	-28.0 + 10.1

To compensate for the drop in temperature in these applications, the barrel is reheated to bottomhole temperature, boosting pressure to appoximate bottomhole condition so that accurate measurement of gas volume can be made.

Results

The relative accuracy of the different methods of material collection can be evaluated by examining Table 1. From the gas collected from the various types of samples, to which generally accepted extrapolation methods were applied, the estimated coal gas content (SCF/ton) was calculated and compared to that found in core from the temperature compensated pressure core barrel.

An error of 5% was considered within the statistical error band, and therefore was taken to be in agreement with the pressure core.

Errors in determination of gas content varied from as low as 5.6% low for mechanically cut sidewall cores, to as much as 24-28% low for drill cuttings gas content estimates. Conventional core sample gas contents were low by 7-13%[6].

Of course, these results are for a specific reservoir with specific temperature and pressure conditions. In fact, since the outside temperature was a cold, minus 5°F, it was felt that the error was even less than would be expected at a warmer, more normal temperature.

Conclusions

The major problem associated with gas content determination is the need to estimate the volume of gas lost while retrieving the samples to surface. As a result of inaccuracies in the "lost gas" estimation procedures, significant errors exist in the determination of gas-in-place volume. Pressure core samples to do not suffer from this limitation, as the samples are sealed at reservoir pressure and retrieved to surface without gas desorption. It is clear that pressure coring is of critical importance to the coal-gas industry in determining field deliverability. Similarly, the oil industry has valued core analysis performed on pressure cores more highly than any other method.

REFERENCES

1. "Mud Design To Minimize Rock Impairment Due to Particle Invasion" A. Abrams, JPT (May 1977) 586-92.
2. "Pressure Retained Core Analysis" by C. Segrest, Core Laboratories (Midland, Tx.), produced January 1991.

3. "Development of a Method for Partially Uninvaded Coring in High-Permeability Sandstone" by J. Rathmell, G. Tibbitts, R. Gremley, H. Warner Jr. and E. White; SPE paper 20413.
4. "New Coring System Reduces Filtrate Invasion" G. Tibbitts, M. Reed, and M. McCarter. Advances in Core Evaluation, Reviewed in proceedings of the first "Society of Core Analysts" European Core Analysis Symposium London, UK 21-23 May 1990, pp. 55-77.
5. "Pressure Coring -- An Oilfield Tool," C.R. Hyland, SPE paper 12093.
6. "Formation Evaluation of Exploration Coalbed Methane Wells," M.J. Mevor, J.C. Close, R.A. McBane; paper CIM/SPE 90-101.