2013

A new in-situ method for measuring simultaneously coal seam gas content and permeability

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A NEW *IN-SITU* METHOD FOR MEASURING SIMULTANEOUSLY COAL SEAM GAS CONTENT AND PERMEABILITY

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ABSTRACT: This paper will describe a new method for measuring simultaneously coal seam gas content and permeability that can be performed on existing coal quality holes. The goal of the work was to provide an operational expedient and cost effective method for achieving these simultaneous measurements reliably and accurately. This reported method involves combining an established gas testing technique, based on downhole Raman spectroscopy, with an established permeability testing technique, based on open hole inflate straddle packer technology. This paper describes these two key enabling technology platforms and the means developed to facilitate simultaneous operations of both. A standard test program is also described, encompassing a review of test planning, test methods, and operational considerations required to successfully combine these measurement methods. In addition, the steps required to validate data integrity and ensure accuracy while optimising operational efficiencies are discussed. The conclusions of the work indicated that proper selection of equipment options and careful coordination of the test plans typically used for the two methods results in successful integration of the testing methods and simultaneous measurement of gas content and permeability in coal seams.

INTRODUCTION

Coal plays an important role as the primary source of energy for the generation of electricity worldwide. However, the coalification process that converts plant matter to fuel also produces methane and carbon dioxide gases. The release of coal gases during mining, can pose serious safety challenges through two mechanisms - outburst and explosive gas.

Generally, less permeable coals containing higher methane gas contents contain higher gas pressures and so pose a higher outburst risk. In addition, more permeable coals containing higher methane gas contents flow more gas, more quickly, into underground mine spaces and so pose a higher explosive gas risk.

Existing *ex situ* techniques (i.e. those conducted on fluid, gas or rock samples removed from coal seams) for measuring gas content and permeability require collection and laboratory analysis of core samples. In some cases, those samples do not reflect the complex, distributed characteristics of the coal seam being evaluated. In some cases, the analyses of those samples are complicated by changes to the samples that may occur during collection.

This paper describes a new technique for measuring concurrently gas content and permeability *in situ* and subsurface (i.e. conducted on the coal seams as they reside, without removing samples to surface). This technique integrates Reservoir Raman spectroscopy (RRS) with Drill Stem Testing (DST) technology and focuses on *in situ* measurement of fluids drawn from the coal cleats into a wellbore or tubing.

This integration provides some advantages in that it can be performed more quickly and at a greater density than typical *ex situ* methods. This *in situ* methodology is well suited to challenging downhole environments such as those containing friable coals, mixed carbon dioxide and methane gases, and trace amounts of gases. And it can be performed in existing coal quality holes (i.e. holes cored in order to obtain samples of coal for laboratory testing of quality and other metrics), obviating need for special cores or core holes for gas analysis.

Challenges of the new technique include the need to manage fluids wisely in order to insure representative data and to minimise operational time.

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ENABLING TECHNOLOGIES

Reservoir Raman Spectroscopy (RRS)

Raman spectroscopy is a well-established laboratory chemical analysis technique. It was invented after the discovery of the Raman Effect in 1928, for which Sir Chandasekhra Venkata won the Nobel Prize for Physics in 1930. Obtaining reliably measurements with Raman spectrometers in a borehole is not trivial. Most Raman spectrometers are bulky, difficult to operate, and require substantial electrical power - in many cases occupying entire benches in the laboratory. Over the past ten years, the RRS technology has undergone continuous improvement to reduce size, improve ruggedness, increase sensitivity and expand operating temperature range.

Several articles (Koval and Pope, 2006; Pope, 2006; Pope, 2009; Renouf and Pope, 2011) and technical papers (Pope, *et al.*, 2004; Lamarre and Pope, 2007; Pope, 2009a; Pope, 2009b) have been published on the measurement principle and disclosing case histories testifying to the system reliability, operational efficacy and accuracy of this technique compared to core-derived estimates of gas content.

In situ flow capacity testing from surface holes

Flow capacity (and thus bulk permeability), along with other reservoir parameters, can be determined from monitoring and analysis of pressure transients induced in a coal seam using DST technology, suitable for multi-zone open hole environments. This technique has been employed extensively by both coal mining and coal seam gas operators in order to avoid the challenges associated with *ex situ* analysis of permeability on coal core samples.

A variety of tubing and wireline deployed technology platforms have been developed to isolate target seams and induce pressure transients. Tubing deployed systems are commonly referred to as DST systems, while wireline deployed alternatives are referred to as pump-out systems. Both categories are further classified according to the type of packers employed, setting methods and the control system used to actuate the tester valve. Table 1 summarises capabilities of each type, with only one, the Tubing Pressure Actuated (TPA) system type, deemed suitable for facilitating simultaneous production and logging of formation fluids.

Table 1 - Comparison of alternative *in situ* flow capacity testing technology platforms

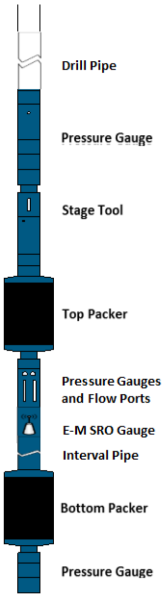
System Actuation Type	Conveyance Method		Application Types			RRS Wireline Access	Multi-Cycle Circulation
	Wireline	Tubing	Off Bottom	Single Trip MZ	Open Hole		
Annulus Pressure	✗	✓	✓	✗	✗	✓	✓
Compression Set	✗	✓	✗	✗	✓	✓	✗
Internal Control Line	✗	✓	✓	✓	✓	✗	✗
External Control Line	✗	✓	✓	✓	✓	✗	✓
Positive Pressure Pump-Out	✓	✗	✓	✓	✓	✗	N/A
Hydraulic Amplifier Pump-Out	✓	✓	✓	✓	✓	✗	N/A
Tubing Rotation Actuated	✗	✓	✓	✓	✓	✓	✗
Tubing Pressure Actuated	✗	✓	✓	✓	✓	✓	✓

Tubing pressure actuated DST technology

The TPA system, as depicted in Figure 1, features a fully integrated design, with all functions mechanically and hydraulically interlinked. These functions are accessed via a zero-displacement setting tool, which incorporates a balanced valve that is manipulated by altering height of the work string stickup. The zero-displacement feature minimises pressure perturbations during tool manipulation, thereby optimising pressure data quality. In the packer setting position, pressure is applied onto a full water column in the work string to actuate the inflate packers straddling the Zone Of Interest (ZOI), with setting pressure communicated from upper to lower packers via the interval pipe used to set test height.

While technical due-diligence is crucial in shaping test selection and test design, uncertainties in reservoir characteristics may require changes to the test design during execution in order to optimize validity of pressure transient analyses. Access to real-time formation pressures during the flow and shut-in periods is therefore crucial. A wireless surface readout formation pressure monitoring system is therefore included between the straddle packers.

The wireless system relays pressure data to surface using a low frequency electromagnetic (E-M) signal propagated through the surrounding overburden to one or more receivers staked in the ground at surface. This eliminates the need for complex inductive coupling systems or wet-mate connections and associated wireline equipment, thus saving costs and mitigating interruptions to rig operations.



Well Name:
Test Number:
Test Interval:
Interval Name:

Total Interval: -160.85 metres **Total Depth:** 705 metres
Ground Level: 138.11 metres **Rotary Table:** 138.91 metres

Description	Serial No:	ID	OD	Length	Depth
Stick Up					-1.36
Drill Rods Quantity	26 x 6m	4.000	4.500	156.00	-1.36
Pup Joint(s) Quantity	0	4.000	4.500	0.00	154.64
Cross Over Sub - 2 3/8IF X PQ			5.000	0.41	154.64
Cross Over Sub - IPI IF X 2 3/8 IF			3.385	0.00	155.05
Spacing			3.385	0.00	155.05
Cross Over Sub - IPI ACME x 2 3/8 IF			3.385	0.25	155.05
Fluid Gauge and Spacing	19629		3.385	1.50	155.30
Stage Tool			3.385	1.77	156.80
Circulating Sub			3.385	1.39	158.57
Top Packer Stick Up			3.385	1.24	159.96
Top Packer Seal Depth	Element #	11211			161.20
Top Packer Stick Down and Flow Sub			3.385	0.86	162.06
Outside Gauge Carrier	19934 & 19921		3.385	0.50	162.56
E-M SRO Gauge	48678		3.250	1.53	164.09
Spacing 5 x 2m, 1 x 1m, 1 x 0.5m			3.385	11.50	175.59
Bottom Packer Stick Up			3.385	0.35	175.94
Bottom Packer Seal Depth	Element #	19111		175.94	175.94
Bottom Packer Stick Down			3.386	1.38	177.32
					177.32
	19633				

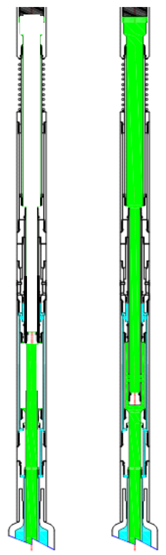


Figure 1 - Tubing pressure actuated DST system

Wireline entry guide system

To facilitate concurrent wireline operations and manipulation of the setting tool in the TPA DST system a unique load-bearing Wireline Entry Guide (WEG) system has been developed. A stack-up diagram of the integral Flow and Pressure Control Equipment (FPCE) system, which is connected to the work string, is shown in Figure 2. The design of the WEG (items 1-3), is shown in Figure 3.

Figure 3 reveals how the weight of the entire work string is supported by a cage, comprising a system of rods that connects the FPCE system to the top drive via flanged crossovers either end of the rods. This ensures that the wireline pack-off unit mounted in the top of the lower flange is not subjected to any loads, enabling a standard design to be used. The number, height and spacing of the rods, bolt design with the flanges and the geometry of the flanges ensures that loads will always be evenly distributed, and that the pack-off unit can be fully disassembled, and if need be replaced, without having to dissemble the cage.

To enable the RRS logging tool to be quickly and easily deployed the FPCE system also features specially designed load bearing quick union connections (items 7 and 8 in Figure 2). Together, the WEG and FPCE system design enables RSS logging operations to be conducted independently of changes to the TPA DST setting tool position.

As a result, it is possible to monitor real-time the solubilised methane concentration of produced fluid entering the work string during the main flow period, and/or log solubilised methane concentration profiles during the final shut-in period. In so doing, provided the produced fluid is not contaminated by filtrate or other extraneous sources, determination of coal seam gas content does not involve having to extend overall test duration beyond that required to determine flow capacity.

Another benefit of the WEG system is that any gas liberated from the fluid or coal prior to or during testing is contained within the sealed work string and can be readily flushed prior to further rig floor operations.

As a result, testing involves no additional risk - in fact, this type of surface pressure and gas control is improved over that available on a typical mineral rig.

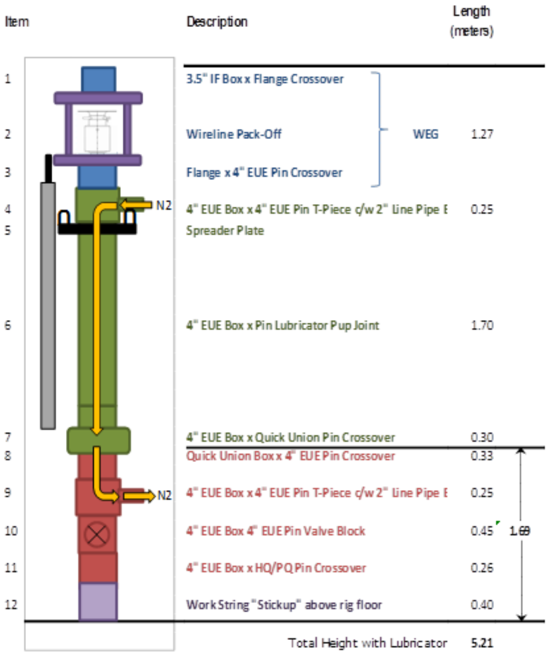


Figure 2 - WEG and FPCE stack-up configuration

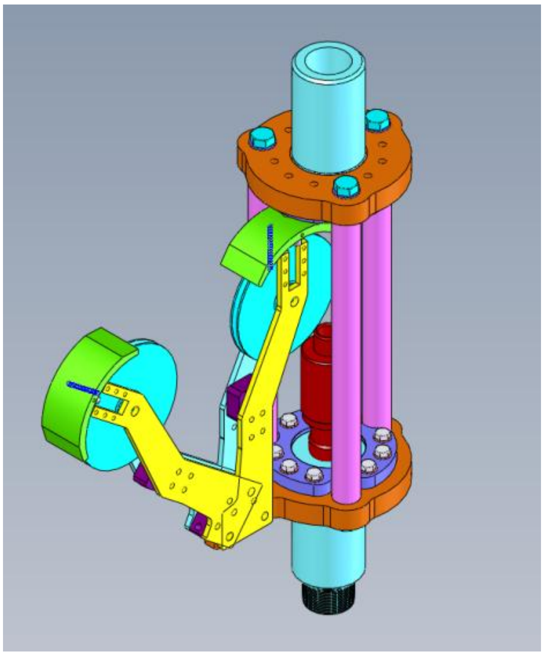


Figure 3 - Top drive wireline entry system

GENERIC TEST PROGRAM

In order to quantify permeability, skin and other coal seam reservoir parameters a variety of test types can be conducted, including Injection Fall Off Testing (IFOT), Diagnostic Fracture Injection Test (DFIT), tank tests and slug tests. All these test types however involve injection of fluids into the coal seam. In order to measure gas content using the RRS logging tool, native fluids need to be withdrawn from the coal seam. As a consequence, a conventional flowing/build-up DST is performed, comprising an initial pre-flow and build-up, followed by a main flow period and final build-up period, which must be of sufficient duration to establish pseudo radial flow conditions. Reservoir pressure is estimated from analysis of the initial build-up data, with analysis of final build-up used to derive flow capacity and other reservoir parameters.

This test type is widely used, with execution governed using well-established procedures and best practices. In the interest of brevity therefore, only innovations introduced to accommodate simultaneous measurement of coal seam gas content will be discussed.

Test design

A flow chart with appropriate evaluation criteria has been developed to guide decisions on whether to test for coal seam flow capacity and/or gas content, and if not gas content, whether to instead employ an IFOT test type. Furthermore, the evaluation criteria are chosen to enable decisions to be made prior to, or during, testing.

Fluid cushion

In order to limit potential for fines production a dynamic nitrogen cushion is employed in place of water that can be gradually bled off during the pre-flow to minimise reservoir shock and limit amount of gas liberated from solution in order to optimise the quality of pressure transient analysis. To limit nitrogen requirements, a hybrid nitrogen-over-water cushion is employed for deeper seams, using a bespoke formula to quantify volume ratios.

Fluid management

A number of innovations have also been developed to manage production and purging of produced fluid. Some of these are aimed at maximising fluid cleanliness, with others focusing on ways to displace produced fluid under pressure. This precaution is necessary in order to prevent solubilised methane from being liberated as free gas, which would compromise computation of gas content.

One such innovation involves partially displacing the produced fluid up the work string. This is achieved by applying nitrogen pressure down the work string until the total pressure at the bottom of the work string is equal to hydrostatic. The TPA DST setting tool is then moved to the circulating position, after which the nitrogen pressure in the work string is slowly bled off. The drop in work string pressure causes water to enter from the annulus, which is continuously topped up from surface - no pressure need be applied.

This procedure essentially reduces ambient temperature of the produced fluid column, and need only be adopted for applications where coal seam temperature exceeds the operating temperature range of the RRS logging tool.

Another innovation involves displacing the produced fluid under pressure all the way to surface, past a manifold shown in Figure 4, which incorporates an optically transparent sapphire window. This allows fluid properties to be interrogated by a surface RRS instrument, obviating need to log produce fluid *in-situ* on wireline. The choke manifold also features four sensor wells in the flow line to measure water rate, pressure, temperature and conductivity.

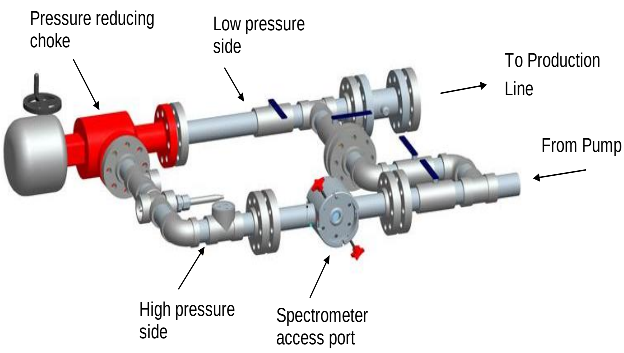


Figure 4 - RRS surface choke manifold

This procedure does extend overall test durations somewhat, however, as displacement of the produced fluid past a surface RRS instrument would need to be delayed until after the main shut-in period has been completed. However, this technique does enable applications of this integrated service to be extended into small hole sizes (HQ or less).

If RRS logs of fluid produced during the main flow period is not deemed sufficiently representative of reservoir conditions, it will be necessary to withdraw additional fluid from the coal seam. Two options are available for fluid removal, with choice dependent on two key factors; additional volume that needs to be withdrawn and available time:

- Move the TPA DST setting tool to the open position, allowing additional reservoir fluid to be introduced below the pre-existing column of produced fluid.
- Move the TPA DST setting tool to the circulate position to purge the work string contents and reset the cushion.

Purging produced fluid involves first filling the work string with clean water, and then circulating the entire contents up the annulus with additional clean water until conductivity of the annulus returns is the same as the clean water. Nitrogen pressure is then applied down the work string to reset the dynamic cushion, prior to moving the TPA DST setting tool to the open position.

A typical timeline for conducting tests using this new integrated gas content and flow capacity testing capability on a 24 h rig is shown in Figure 5, using an example of main shut-in period. In an actual test, the duration of the main shut-in period would be optimised to end once pseudo radial flow conditions have been established.

A typical test, therefore, would extend from 13 hr to 20 hr, depending on reservoir flow rate and residual mud and/or fines present in the wellbore. Tests have been regularly completed in the field over this range of operational times.

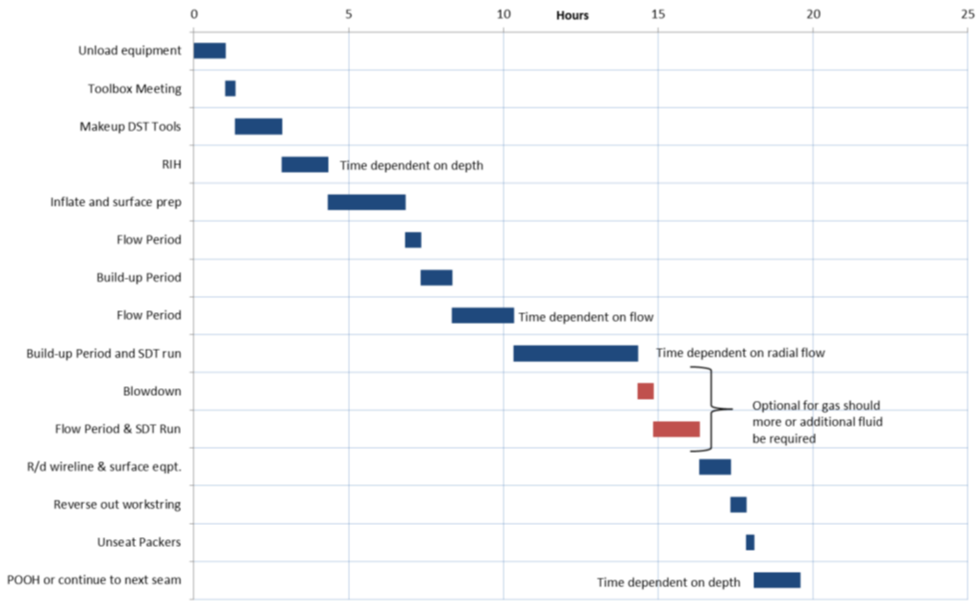


Figure 5 - Idealised RRS and TPA DST test program on a 24 hour Rig

DATA VALIDATION

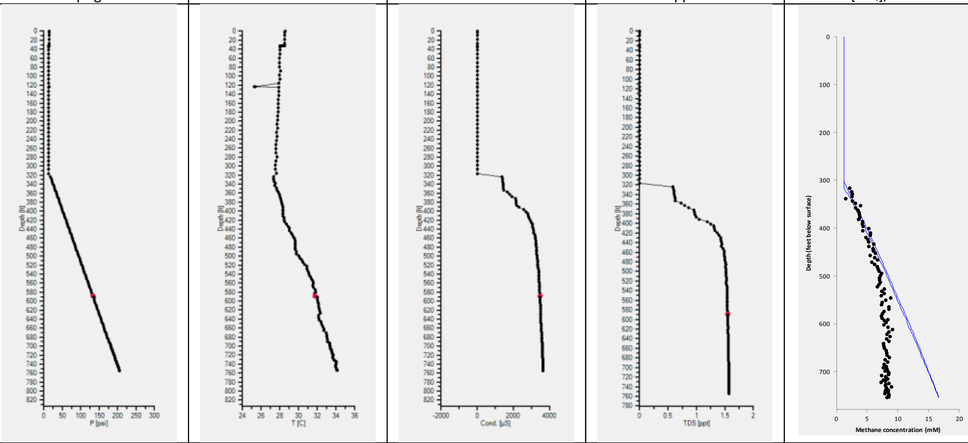
In addition to measuring solubilised gas concentrations, the RRS instrument also acquires measurements of solubilised pressure, temperature and conductivity on a continuous basis, as shown in example log in Figure 6. These parameters are needed to derive an appropriate constant for use with the solubility law, which in turn allows the measured methane and other gas concentrations to be equated to an effective partial pressure for each gas. These values are in turn used to determine the gas content for each species in the coal seam, using appropriate isotherms.

Determining partial pressure of solubilised (dissolved) gas in formation water can be achieved using a number of bubble point analysis techniques, such as head-space analysis of bottom hole samples or water-gas ratio measurements. However, these techniques can be affected by production perturbations from the surrounding coal, presence of residual solids, and fluid contributions from other completed zones. Thus, a single point measurement in a wellbore cannot be certain to represent the local reservoir. Definitive results can only be obtained by performing continuous measurements, in depth and/or time.

A distinctive feature of the RRS technology is its ability to obtain self-consistent data that simplifies the task of validating measurements prior to analysis. Firstly, the conductivity readings are used to distinguish between reservoir fluid, invasion fluid and completion fluid. Secondly, the pressure reading is used to confirm fluid column height, and is validated against measurements acquired by the various pressure gauges installed in the TPA DST test string.

Thirdly, the log of solubilised gas concentration shows the theoretical saturation curve (blue line, Figure 6, log at right) which closes matches measured values in the upper section of the fluid column. Lastly, the region of uniform measured concentration values (below about 550 m) represents under-saturated conditions. The concentrations measured in that region therefore represent the native concentration of gas in the coal seam and can be used to calculate the gas partial pressure in the coal seam.

Pressure	Temperature	Conductivity	TDS	Solution gas
psig	°C	uS	ppt	$[CH_4]$, mM



Pressure log (in psia) indicates fluid height and density.	Temperature log is shown in degrees Celsius.	Conductivity log is shown in micro Siemens.	Total dissolved solids log (shown in parts per thousand) is derived from conductivity log, temperature corrected.	Solution gas log shows gas concentration (in millimolar) at each depth measured. Blue line shows saturation concentration at each depth.

Figure 6 - Example RRS logs

SUMMARY

The integration of unique RRS technology with TPA DST technology has been successfully trialled for a number of large coal mine operators, with perceived advantages of the combined service encompassing the following:

- Provides a means for quantifying coal seam flow capacity and gas content at in-situ conditions using proven testing methods.
- The core-less measurement principle can be performed in existing coal quality holes, greatly reducing number of dedicated gas testing core holes required.
- The reduction in overall well count reduces mapping costs and time.
- The core-less measurements yields immediate results, further reducing time required to develop and implement pre-drainage strategies.
- Avoids data uncertainty associated with ex situ and rock-based measurement techniques.
- Widely accepted by coal seam gas auditors, enabling mine operators to book gas assets if desired.

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