SPE 167034

Surface Well Test Of Methane Gas Saturation In CSG Lateral Completions During Dewatering Using Raman Spectroscopy

S. Mazumder, M. Scott, Arrow Energy Pty Ltd., J. M. Pope, Q. Morgan, P. Ramsay, WellDog Pty Ltd.

This paper was prepared for presentation at the SPE Unconventional Resources Conference and Exhibition-Asia Pacific held in Brisbane, Australia, 11–13 November 2013.

Abstract

This paper describes application of an established coal seam gas (CSG) testing technology to the reservoir and production conditions prevalent in the Bowen basin, Queensland, Australia. The technology involves using Raman spectroscopy to measure gas partial pressure in single phase fluids produced under pressure from dewatering coal seam gas wells. The technique's efficacy has been described extensively in technical literature. Prior tests have been conducted on permeable coals that produce several hundred BWPD. Applying the technology to tight coals in the Bowen basin is not considered straightforward.

Introduction

Arrow Energy is a leading coal seam gas (CSG) company with five domestic gas supply operations, ownership of one gas-fired power station, interest in two others and plans to safely produce and export liquefied natural gas (LNG) through a world class plant on Curtis Island off Gladstone, Queensland, Australia. Arrow Energy is continuously striving to implement a number of core strategic business and technical initiatives, one being to evaluate and harness new innovative technologies, techniques and best practices directed at minimising field development costs. This drove Arrow Energy to commission a multi-well field trial of a spectroscopy-based technology, which provides a low cost, rapid option for establishing critical desorption pressure (CDP) across a CSG field, and important information regarding gas saturation change over time and gas drainage progress for CSG operators with tenements overlaying underground coal mine resource targets. In the absence of viable production logging tools for being able to back allocate production from individual coal seams, this could prove to be a game changer in terms of how CSG companies work in close association with overlapping tenure holders.

Background

Efficiently developing gas from coal seams can be a significant challenge for coal seam gas lease holders. This is because heterogeneity of gas pressures and gas content in coal seams can be extremely high, both laterally across a field and vertically between seams. Coal seam heterogeneities exist at essentially every level of resolution of inspection, ranging from microscopic changes in a coal's sorptivity for gas to "mesoscopic" variations in ash content, cleating and fracturing, and "macroscopic" changes in coal seam continuity, gas genesis and overburden burial history across a CSG field.

Existing *ex-situ* techniques for measuring gas content of coals require collection and laboratory analysis of numerous core samples, at sufficient density and spatial distribution, to capture the complex, distributed characteristics of the coal seam being evaluated. In some cases however, the sampling program is too sparse, culminating with inaccurate gas distribution models. In some cases, the analyses are complicated by changes to the samples that may occur during collection. Furthermore, gas content of coals is typically measured using the direct method analysis (DMA) on freshly cut cores, or more recently developed fast desorption techniques. A problem with these techniques is that overall results can be influenced by artifacts of the test apparatus and procedures used, by core sample type, by sample collection methodology and by the analysis conditions.

Even if all these factors are precisely controlled, the accuracy of derived *in-situ* gas content values obtained using either technique can still be compromised through significant errors in Q1 values, which can only be modeled, not measured. Compounding this inherent error is the fact that core desorption is a destructive testing method that cannot be completed twice on the same sample. This precludes methods for validating measurements, with no possibility therefore of assigning error bars to core desorption data.

Alternative fluid based measurement technique

While coal chemical and physical heterogeneity are "locked" into the coal structure, water and gas can and do migrate through the structure to "level out" variations in thermodynamic and chemical potential over geologic timeframes. Measuring the properties of fluids (such as gas partial pressure, solution gas concentration, hydrostatic pressure, etc.), and relating them via synthesized adsorption isotherms representing the drainage area of a well or field, therefore yields bulk averaged values applicable over the equilibrated region, enabling development of more accurate static gas content and gas saturation distribution models. It is possible to measure these properties at *in-situ* pre-desorption conditions, using field proven Reservoir Raman Spectroscopy (RRS) technology and proprietary analysis techniques.

Reservoir Raman Spectroscopy

RRS chemical-sensing technology takes advantage of a powerful realization that in gas-coal-water systems the effective partial pressure of methane in a particular unperturbed region of a CSG reservoir is equivalent throughout the local coal and in the trace levels of solution gas in the surrounding formation water. This partial pressure is in turn equivalent to the pressure at which methane will desorb directly from the coal, also known as the critical desorption pressure (CDP). This CDP can be directly related to coal gas content by cross referencing it with the measured methane adsorption isotherm for that particular coal.

Raman spectroscopy is a well-established laboratory chemical analysis technique (McCreery 2000). 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 reliable 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 2009c; Renouf and Pope 2011) and technical papers (Pope et al 2005; Lamarre and Pope 2007; Pope 2009a; Pope 2009b; Pope and Morgan 2013; Morgan et al 2013) 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.

The RRS instrument does not directly measure partial pressures, but instead performs laser based measurements of the amount of methane gas solubilized in the formation water. This can be achieved in the wellbore, with a continuous log profile constructed across all coal seams, or by displacing produced water in the wellbore under pressure past a surface well test RRS-equipped system. In either case, pressure, temperature and salinity of the fluid are also measured. These parameters are used to derive an appropriate constant for use with the solubility law, which in turn allows the measured methane concentrations to be converted into an effective partial pressure of methane.

When using the surface well test RRS instrument shown in Figure 1, it will be necessary to connect a choke manifold, illustrated in Figure 2, to the water flow line, as shown in Figure 3. The purpose of this choke manifold is to ensure that upstream pressure is maintained at above the bubble point pressure of solubilized gasses. An optically transparent sapphire window is also incorporated in the choke manifold to allow the surface well test RRS instrument to identify both composition (see Figure 4) and concentration (see Figure 5) of these solubilized gasses. If a fluid level gauge has not been installed in the well an echometer is provided to ensure that the hydrostatic head of the annulus water level is also maintained above the bubble point of the solubilized gasses.

Perceived benefits of this RRS technology, the associated measurement principles and data analysis methodology, include the following:

- Measurements of trace gas concentrations dissolved in formation water enables much quicker determination of gas content than is possible using conventional slow desorption tests on core samples.
- By avoiding Q1errors inherent in measured gas content values from core desorption tests the uncertainty in RRS-derived gas content values is both significantly reduced and precise.
- Measured values of reservoir pressure and CDP makes it possible to determine the pressure drawdown required in the natural fractures to initiate gas production, and thus help to validate extent of dewatering required.
- Testing of behind-casing coal seams can be achieved without need for additional drilling and coring by using plug/perforate strategies.
- Results are generated from a mature technology platform with a proven track record in hundreds of cased and open hole CSG wells (Pope 2009c).
- Surface well test RRS measurements of CDP can be performed on CSG production wells without retrieving the PCP or ESP completion.
- Surface well test RRS measurements of CDP can also be performed in the vertical production wellbore of CSG surface in seam (SIS) lateral wells without having to use well intervention systems such as wireline-deployed tractors or coiled tubing.
- By being able to identify areas of low gas saturation and/or requiring high water drawdowns the RRS technology can be used to optimise well placements and shape associated infrastructure installation, dewatering and gas production strategies.

The last three perceived benefits listed above were deemed of particular interest when determining the gas saturation of coal seams penetrated by existing SIS lateral wells at North Moranbah field in the Bowen Basin, Queensland, Australia, and the total drawdown in water level required to initiate gas production.

Field Trial Terms Of Reference

Arrow Energy has a mandate to deliver an economically viable world class CSG to LNG project in a responsible, sustainable and timely manner to meet global demand for clean energy. Success will depend on harnessing new innovative technologies, techniques and best practices directed at minimising field development costs. A multi-well field trial of the RRS technology, if successful, will provide Arrow Energy access to a new technical service that yields immediately actionable data, thereby alleviating bottlenecks through existing service channels. This availability enables real-time optimization of ongoing field development activities, in particular well spacing and location. Most significantly, this intervention-less service will facilitate concurrent operations, with gas testing having no impact on well completion and start-up timetable.

Objectives

The RRS technology has amassed an extensive track record, following its commercialisation in 2005, through multiple field trials and commercial services focused on determining gas saturation and content of coal seams (Pope 2009c). The principle objectives established for this field trial are as follows:

- Confirm the ability to effectively and safely operate the surface well test RRS system during well dewatering operations.
- Evaluate robustness of the test program, fluid management guidelines and decision tree criteria.
- Identify the best dewatering window in which to conduct RRS measurements on low permeability wells.
- Measure CDP to aid in determining pressure saturation and time to gas production.
- Assess the efficiencies achieved from concurrent testing and dewatering operations.
- A further aim of the field trial is to benchmark analyses of acquired data with results obtained from traditional desorption tests on core samples from offset wells.

Field trial deliverables

The surface well test RRS system incorporates a variety of different sensor types to continuously monitor coal seam fluid properties and behaviour during flowback operations. Additional sensors are included to monitor and diagnose test equipment hardware health, and to validate key measurements. The key deliverable specified for the field trial is a well report encompassing various treatments of measured data, data validation results, and the following RRS analyses:

- Critical desorption pressure.
- Gas content.
- Gas saturation.
- Required pressure drawdown.

An After Action Review (AAR) is also conducted aimed at identifying key technical and operational learnings, potential system improvements, projections of additional time savings based on key learnings and system improvements, and re-evaluation of the value proposition.

Field trial scope

To fully evaluate the capabilities of this new service it has been decided to test single coals seams in three separate SIS wells. RRS measurements are also to be captured from start-up of well dewatering operations, past the period when representative formation fluids reached surface (defined as being the period when all gasses have remained completely solubilised in the produced fluid), and until such time as supersaturated flowing conditions have been detected (defined as the point when measured partial pressure for solubilised gasses exceeds the submersible pump intake pressure).

Field trial evaluation criteria

To assess the merits of the new integrated service the success of the field trial is judged based on the following evaluation criteria:

- Accuracy of acquired data.
- Veracity of data analyses.
- Test expediency.
- Extent of operational support requirements.
- Comparison of testing and operational costs with alternative techniques.

.

Test Program Design

Appropriate test well candidates have been selected based on operational schedules and expected production and reservoir conditions One of the principal aims of the surface RRS well test program is to identify and manage the various flow regimes that can occur during the dewatering phase of CSG production wells. This focus is vital, as the RRS measurement technique is termed a pre-production gas content test method, necessitating that CSG wells be tested at an early stage of coal seam dewatering. Specifically, valid measurements can be most easily acquired before pressure in the bulk of the reservoir drops below CDP. In general, there are three main stages of dewatering that impact flow regime and chemistry:

1. **Stage 1: Cleanup** – produced fluid is filtrate and/or completion fluid, with no solution gas present.
2. **Stage 2: Single-phase (pre-desorption) water production** – submersible pump intake pressure is greater than CDP, with solution gas present at a partial pressure equal to reservoir CDP.
3. **Stage 3: Two-phase (post-desorption) gas and water production** – submersible pump intake pressure is less than reservoir CDP, with solution gas still present in the water phase, but at a partial pressure below CDP as at least some gas has broken out of solution. This is because the methane desorption pressure and the methane bubble point are equivalent.

Aside to ensuring measurements are captured during the second of these three stages, a number of other criteria must be met to ensure data validity. Firstly, surface pressure at the surface well test RRS system choke manifold must be maintained above CDP, and secondly it is important to ensure that the produced water is not contaminated by any completion fluid that may still be entering the submersible pump due to drop in annulus fluid level. These distinct dewatering stages and alternative flow regimes that can exist during each are summarized in Table 1, with only the conditions listed in the fourth row (highlighted in red) resulting in measurements representative of *in-situ* reservoir conditions.

Test window

In high rate wells (100+ BWPD), it is possible to observe all of three dewatering stages in just a few hours. In low rate wells (<50 BWPD), pre-test planning is required in order to limit the amount of time required at the well site, and thus control costs. In such cases, it is usually possible to predict the optimal time to test the well. That prediction involves identifying the following start and end points of a test window:

1. When Stage 1 fluid cleanup is complete.
2. When Stage 3 commences.

Estimating the times of these two points requires knowledge of expected well productivity, the drawdown programs to be implemented, etc. The times can then be adjusted/refined once the downhole pump is turned on and the actual well productivity is estimated from measured flow rate and bottom hole pressure (BHP) data. To assess the veracity of predicted test window start times and durations, it is typical that values be compared with RRS data acquired from one or two wells from initial startup until gas desorption occurs. The RRS data indicates exactly when cleanup (Stage 1) is over, establishing the early side of the ideal test window, and when gas desorption (Stage 3) commences, establishing the later side of the ideal test window. This full cycle test data will also be important when evaluating RRS test results, the context in which they were collected, and possible operational efficiencies that can be pursued.

It should be noted that the start point of the test window is not usually identifiable simply by reviewing produced water conductivity or turbidity, as a falling annulus fluid level can lead to a false interpretation. Also, the end point of the test window is not usually identifiable simply by reviewing gas production data only, as gas production volumes are relatively low until the pressure wave penetrates the coal seam substantially. Conversely, as the surface well test RRS system measures both fluid type (using the RRS and conductivity sensor) as well as solution gas level (using the RRS), identifying stage transitions is straightforward and definitive.

Reversing dewatering stage transitions

If RRS measurements have not been captured during the initial test window, it is feasible to reverse the CSG well dewatering process from Stage 3 back to Stage 2, by adjusting the pump rate. The same model used to predict test window start and end points is used to determine the time required to achieve this transition. The simulations, shown in Figure 6, enables the time required to increase BHP (and thus annulus fluid height) as a function of produced water flow rate, for a range of CDPs, expressed as a percentage of initial reservoir pressure. The family of curves is again derived based on knowledge of well productivity index (PI), with value of PI obtained by one of four methods:

1. Well owner provides PI value.
2. Derive PI if flow capacity (permeability thickness product k.h) is known.
3. Calculate PI from analysis of measured flow rates and bottom hole pressures during stage 1 dewatering, as shown in Figure 7.
4. Calculate PI from analysis of measured flow rates and annulus fluid level from echometer surveys during stage 1 dewatering.

Having modeled the time required to transition from Stage 3 back to Stage 2, another algorithm provides estimate of the time then required to displace the tubing contents as a function of produced water flow rate (see Figure 8). Only then, after

Stage 2 dewatering recommences and one full tubing contents has subsequently been produced, will the physical and chemical properties of the production water be representative of far reservoir conditions.

Field Trial Execution

Test execution forms part of an operation process management system (OPMS) to provide a common global system for planning and execution of well tests. This is achieved through strict adherence to test programs that are formalized under OPMS in the form of process maps. These maps constitute the topmost level of a multi-tiered structure that enable the user to drill down to more extensive written procedures governing each step in the process map, and which in turn link to very detailed work instructions and associated supporting documentation.

A detailed Test the Well On Paper (TWOP) exercise was conducted prior to mobilising personnel and equipment to familiarise field crew and company staff with the RRS well test program designed for the multi-well field trial. Through adherence to OPMS processes, procedures and work instructions the well tests were completed without incident, with the time breakdown for the entire test campaign on the two wells is presented in Figure 9. The primary uncertainty during test planning was related to the amount of time required to reach the RRS test window once dewatering operations on the SIS lateral wells commenced. As mentioned in the preceding section, the strategy for mitigating this uncertainty required that the surface well test RRS system be installed and commissioned prior to switching on the submersible pump. Unfortunately, adverse weather conditions spawned by a Cyclone led to significant delays in mobilising personnel and equipment, by which time dewatering of the SIS wells selected for the field trial had entered Stage 3. Reversing dewatering conditions back to Stage 2 then required additional appreciable time, due to the low flow capacity of the coal seam intersected by the SIS wells. Test durations for both wells were therefore greatly protracted, with overall chronology summarised below. The flow chart in Figure 10 also illustrates the key decisions enacted, and the prevailing production conditions at time of implementation of each, that drove changes to the original test program.

1. Wells commissioned on Day 1.
2. Estimated 5 days to clean-up completion fluid.
3. Mobilisation planned for Day 6.
4. Mobilisation delayed due to weather (Cyclone).
5. Wells remained on production.
6. Mobilisation on Day 14.
7. RRS Testing of Well A commenced Day 15 and ceased on Day 17.
8. RRS Testing of Well B commenced Day 18 and ceased on Day 21.
9. Equipment and personnel demobilized Day 22.

If mobilization had taken place as originally planned, analyses of pressure and rate data for both wells indicates that the test window would have been reached very quickly, with predicted versus actual RRS test durations disclosed in Table 2.

Field Trial Summary

Three SIS lateral CSG wells in the North Moranbah field, situated in the Bowen basin, Queensland, Australia, were selected for the surface well test RRS field trial. However, owing to problems with well tie-in operations and weather delays only two wells, Well A and WellB, were actually tested. A schematic of the under-reamed vertical well intersecting the toe of the WellA lateral is shown in Figure 11, with the PCP completion installed in the vertical well to dewater the coal seam shown in Figure 12. In keeping with best practice, the PCP is positioned below the coal seam, with a permanently installed pressure gauge positioned below the pump intake to monitor annulus fluid level. Burial depth of the particular seam intersected by the SIS wells varied between 300m to 400 across the region.

An overview plot of computed solubilised methane concentrations in the produced water during testing of Well A is plotted in Figure 13, with topside RRS meter measurements acquired during the second day of testing on Day 16 plotted in Figure 14. Similar plots of RRS data acquired from testing of Well B are plotted in Figure 15 and Figure 16. Estimates of gas content and other reservoir parameters derived from analyses of the measured data for Well A and Well B are included in Tables 3 and 4 respectively.

Key deliverables were met from the tests conducted on both SIS wells, with computed gas contents found to closely match measured values from fast desorption tests on cores in offset wells.

Detailed Discussion

The RRS technology measures concentration of solubilised gases in the water drawn from the cleat system. This is equated to a partial pressure for each gas, including methane, using an appropriate solubility law, such as Henry’s law. The partial pressure of methane in the cleats is the same as the partial pressure of methane occupying the micropores and coal matrix itself. It is also the same as the critical desorption pressure (CDP) of methane adsorbed to the coal structure. However, while partial pressure of solubilised methane in the water and CDP of methane adsorbed to the coal are the same, the concentrations, as determined by Henry’s law and an adsorption isotherm respectively, are different. It is thus necessary to reference a suitable sorption isotherm for the coal to compute a gas content.

Synthesis of bulk sorption isotherms

The advantage of the RRS measurement technique is that geological heterogeneity does not impact methane partial pressure in the reservoir. As a result, the RRS direct measurement of methane partial pressure represents the reservoir independent of that heterogeneity. Furthermore, by synthesizing an isotherm that accounts for short-distance geological heterogeneities (such as ash) in the coal seam, the RRS-measured partial pressure can then be used to calculate a gas content that likewise represents an entire coal seam accessed by the wellbore. In an optimised dewatering or pre-drainage strategy, this region would represent the accessible drainage volume for each well.

With the spectrometer exhibiting little sampling or measurement error (McCreery 2000), the uncertainty in computed gas content values is thus dominated by the errors accumulated in synthesizing a suitable bulk sorption isotherm. This isotherm must be representative of the coal sorptivity within the drainage volume of the well, i.e. not merely of the sorptivity of single or multiple coal cores collected from that drainage volume. At a minimum its construct is also corrected for differences between average near wellbore ash content and ash content in the individual samples used to determine Langmuir pressure and volume. If appropriate, the synthesised sorption isotherm can also be corrected for differences between coal seam temperature and bath temperature used to quantify coal sorptivity. The same approach can be applied to correct for differences between average seam moisture content, if known, and moisture content of the coal sample use to determine the sorption isotherm.

A statistical approach is used to analyse dry ash free Langmuir volumes and ash contents to separate variations in sorptivity from variations in ash content. The process developed to perform this analysis involves the following steps:

1. Evaluate available isotherm data of coal samples similar to the target seam being tested (i.e. similar depth, temperature, etc.) for variation in underlying sorptivity (reflecting variations in coalification or chemical/maceral content).
2. Investigate any outliers individually and identify a representative P(L) with a statistical measure of deviation.
3. Derive ash free adsorption isotherm values (i.e. correct Langmuir volume to ash-free basis), and check consistency of similar coals.
4. Establish density to ash correlation.
5. Determine average density of the target seam from evaluation of the density log, using appropriate cut-off values.
6. Customize V(L) for the target coal seam based on average ash content.
7. Identify and correct for temperature and moisture effects to derive representative P(L) and V(L).

If mean moisture content for the target seam is known then steps 2-6 above can be conducted on a dry, ash-free (DAF) basis. In addition, the results of these analyses can be rigorously evaluated for statistical variation, providing indication of how representative they are for the coal in question.

This process is applied to adsorption isotherm data for cores obtained from three offset wells C, D and E, with proximity to the test wells shown in Figure 17, and synthesized adsorption isotherm data for both test wells presented in Table 5.

Gas content comparisons

RRS-derived gas content values for the single seam intersected by the two test wells are compared to weighted average measured values from desorption tests on cores in three offset wells C, D and E in Figure 18. It is evident from this bar graph that there is good agreement between derived and measured values, other than well C-QA2. Figure 19 shows the much closer comparison achieved if well C-QA2 is considered as an outlier.

After Action Review

The aim of this review process is to analyze what happened compared to plan, why it happened, and how it can be done better, by the participants and those responsible for the project.

The AAR workshop is also intended as an opportunity to propose modifications or improvements to the topside RRS meter and manifold technologies aimed at:

- Improving reliability.
- Boost robustness.
- Expand system operations envelope.
- Compress test schedules.
- Simplify operation.

An internal AAR workshop has been conducted with the field crew following completion of the 2-well field trial, with main findings as follows:

- A low range flow meter and a bleed off line to monitor ultra-low flow rates using a graduated cylinder need to be retrofit to the choke manifold for testing of very tight coal seams.
- The passive cooling system incorporated in the design of the surface well test RRS instrument did not adequately dissipate heat generated by the laser and electronics during the very high daytime temperatures encountered during the trial. This caused a slight shift in computed values of methane concentration.

This led to two separate Opportunity For Improvement (OFI) forms being submitted to the Sustaining Engineering, who have since implemented modifications to both the choke manifold and surface well test RSS system to overcome these limitations.

Key Learnings

Following the AAR a separate review was conducted by WellDog and Arrow Energy to assess performance of the new in situ permeability and gas content measurement service. The evaluation criteria listed previously were used to assign Key Performance Indicators, with key findings as follows:

1. Use of the surface well test RSS system does facilitate concurrent gas testing and dewatering operations.
2. It is possible to reverse dewatering conditions from Stage 3 to Stage 2 even in very low permeability environments.
3. The surface well test RSS system can readily distinguish between representative reservoir and diluted/contaminated produced water.
4. The surface well test RSS system can be operated safely on a continuous 24 hr basis.
5. The surface well test RSS system has a wide dynamic range, with all seams tested to date having gas contents ranging from 1.5-13.3 m^3/t.
6. No revisions to either test program or SOPs are needed.

Conclusions

The RRS technical service is used to measure the methane partial pressure in fluids produced in two CSG wells completed as single zone lateral completions in the Bowen Basin of Queensland, Australia. Adsorption isotherms representative of the drainage volumes of each of the wellbores are synthesized by correcting offset isotherms for ash, moisture and temperature, and combining the results. Gas contents for the coals tested are calculated using the measured partial pressures and the synthesized isotherms. The results are compared to gas contents measured in offset wells and found to correlate closely.

Acknowledgements

The authors wish to thank their respective employers, Arrow Energy & WellDog, for supporting this work and giving permission to publish. The authors also thank the field personnel, including WellDog gas testing supervisors Art Toews and Mat Thomas, for their diligent and safe work in executing successful tests.

Abbreviations

AAR	After action review
BHP	Bottom hole pressure
BWPD	Barrels of water per day
CDP	Critical desorption pressure
CSG	Coal Seam Gas
DAF	Dry ash-free
ESP	Electrical submersible pump
HSE	Health, safety and environment
kh	Permeability.thickness product
LNG	Liquefied natural gas
OPMS	Operation process management system
PCP	Progressing cavity pump
PI	Productivity index
P(L)	Langmuir pressure
NPT	Non-productive time
OFI	Opportunity for improvement
RRS	Reservoir Raman spectroscopy
SIS	Seam to in-seam
SOP	Standard operating procedure
TWOP	Test well on paper
V(L)	Langmuir volume

References

1. McCreery, R.L. 2000. *Raman Spectroscopy for Chemical Analysis*. New York: John Wiley & Sons
2. Pope, J., Buttry, D., Lamarre, R., Noecker, B., MacDonald, S., LaReau, B., Malone, P., Van Lieu, N., Perosli, D., Accurso, M., Harak, D., Kutz, R., Luker, S. and Martin, R.: "Downhole geochemical analysis of gas content and critical desorption pressure for carbonaceous reservoirs", in Proceedings West Texas Geological Society Fall Symposium 2005, 26-28 October 2005
3. Pope, J.M.: "Get accurate, CBM reservoir data", *E&P*, September 2006
4. Koval, E, and Pope J.:, "Seeing a reservoir's character from solution gas", *World Oil,* November 2006, pp 144-146
5. Lamarre, R A, and Pope J.:, "Critical gas content technology provides coalbed-methane-reservoir data", SPE 103539, *Journal of Petroleum Technology*, 59(11):108-113, November 2007
6. Pope, J.M.: "Best Practices for multi-zone coalbed methane completions", 0933, International Coalbed & Shale Gas Symposium 2009, 18-22 May 2009
7. Pope, J.M.: "Retaining coalbed methane water discharge permits, 0934, International Coalbed & Shale Gas Symposium 2009, 18-22 May 2009
8. Pope, J.M.: "CBM Challenges", *World Coal*, December 2009, pp 51-54
9. Renouf, P. and Pope, J.: "Measuring gas content without cores, *CBM Review,* September 2011
10. Pope, J.M. and Morgan, Q.: "A new in situ method for measuring simultaneously coal seam gas content and permeability", Proceedings of the Coal Operator's Conference 2013, Wollongong, NSW, 14–15 February, paper 27
11. Morgan, Q., Pope, J. and Ramsay, P.: "Concurrent in-situ measurement of flow capacity, gas content and saturation", 121002-07 presented at APPEA Conference & Exhibition 2013, 26-29 May 2013

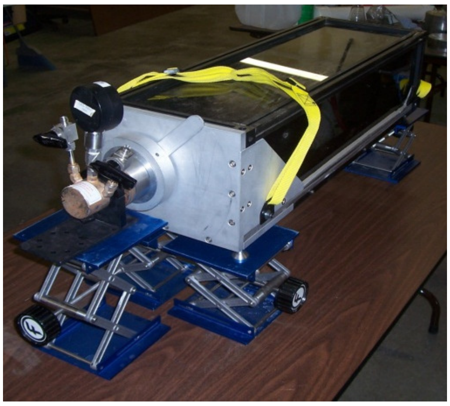


Figure 1: Topside RRS instrument

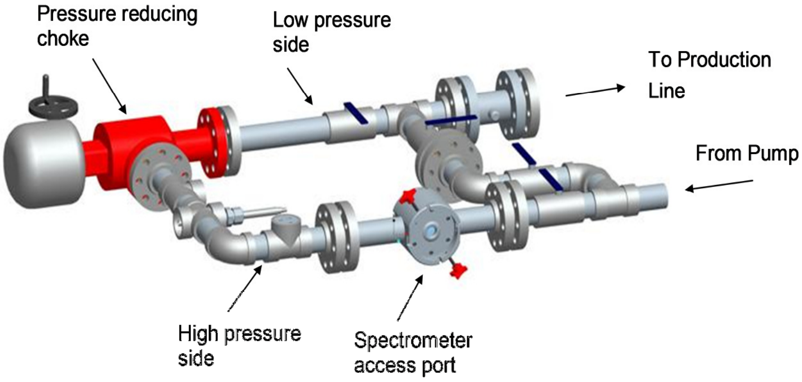


Figure 2: RRS surface choke manifold

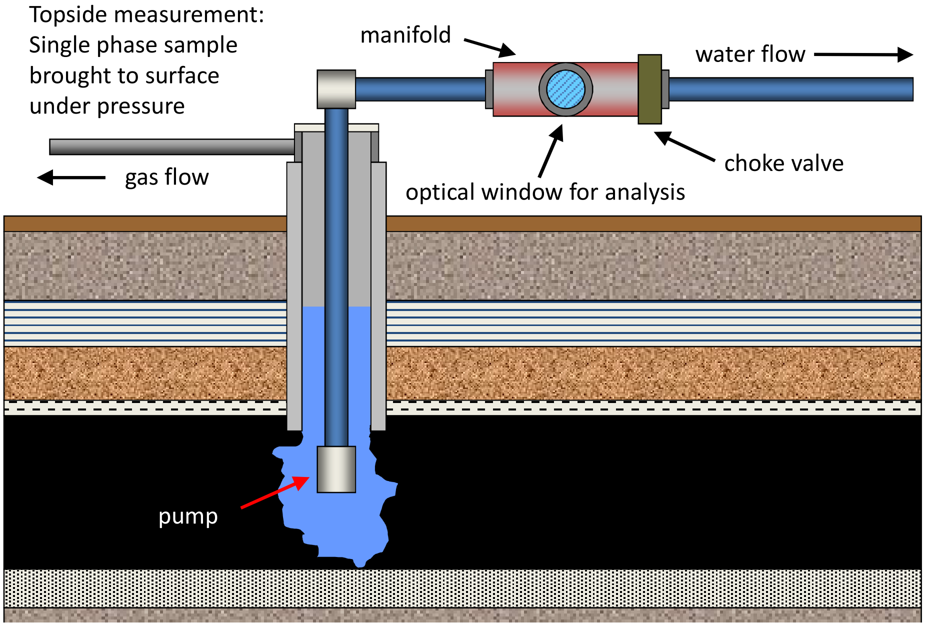


Figure 3: Topside RRS well testing configuration

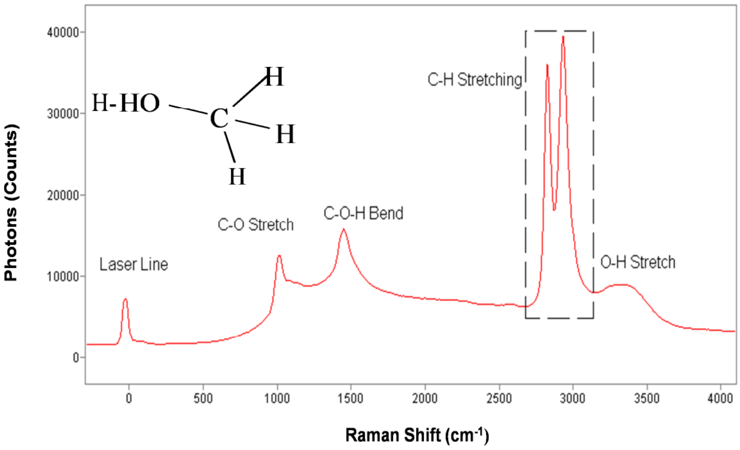


Figure 4: Methane and water Raman peaks

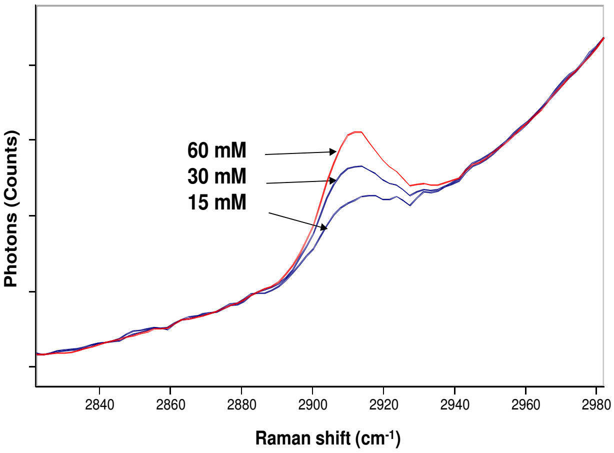


Figure 5: Methane Raman peak height vs. concentration

Dewatering Stage	Methane Concentration	Methane Partial Pressure	Annulus Fluid Level	Produced Water Salinity	Comments
Cleanup	None	N/A	Not relevant	Not relevant	Filtrate and/or completion fluid only
Single-Phase	Undersaturated	Above BHP	Not relevant	Not relevant	BHP < CDP
Single-Phase	Undersaturated	Below BHP	Falling	< Reservoir	BHP > CDP. Produced water is contaminated with completion fluid
Single-Phase	Undersaturated	Below BHP	Rising	= Reservoir	BHP > CDP. Produced water originates from the coal cleats only
Two-Phase	Saturated	Not relevant	Not relevant	Not relevant	WHP < CDP

Table 1: Flow conditions during dewatering of CSG producers

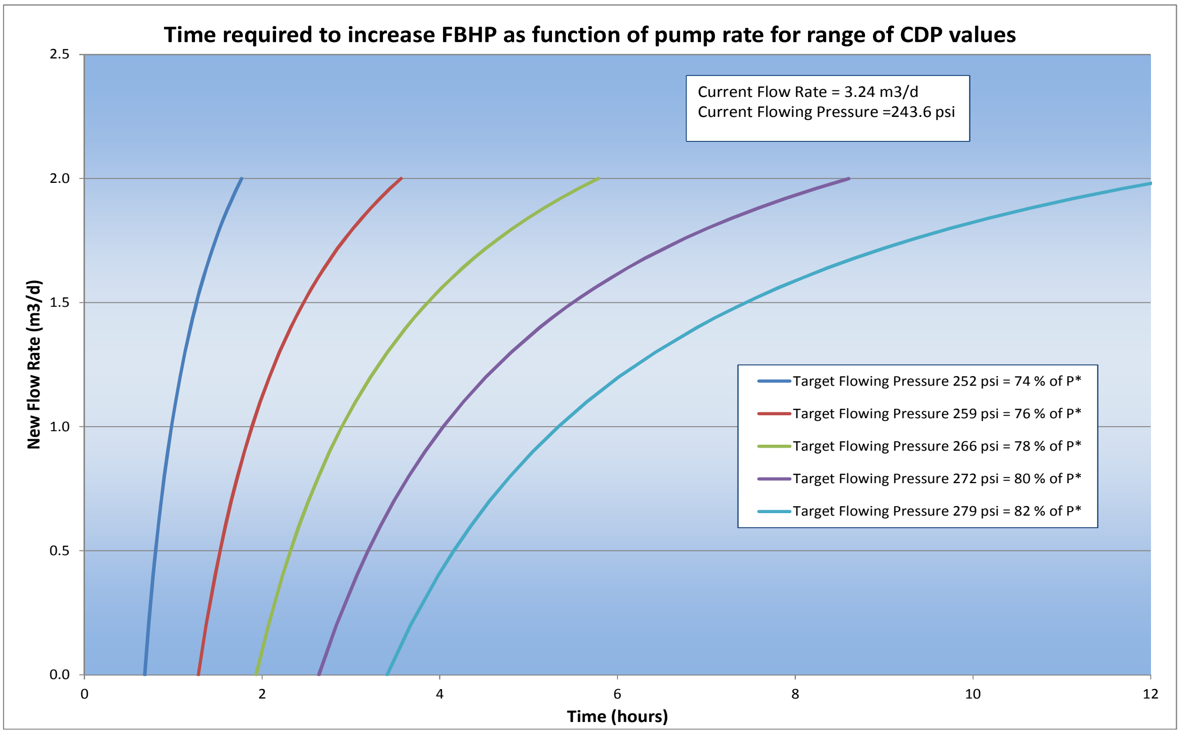


Figure 6: Simulations of time duration required to transition dewatering from Stage 3 to Stage 2

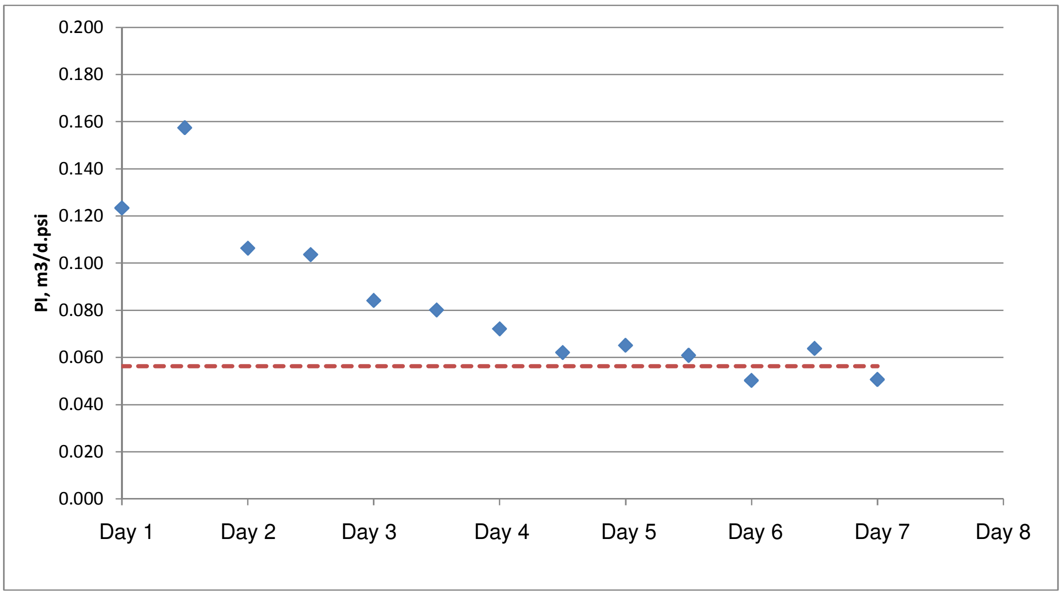


Figure 7: Well PI during Stage 1 dewatering

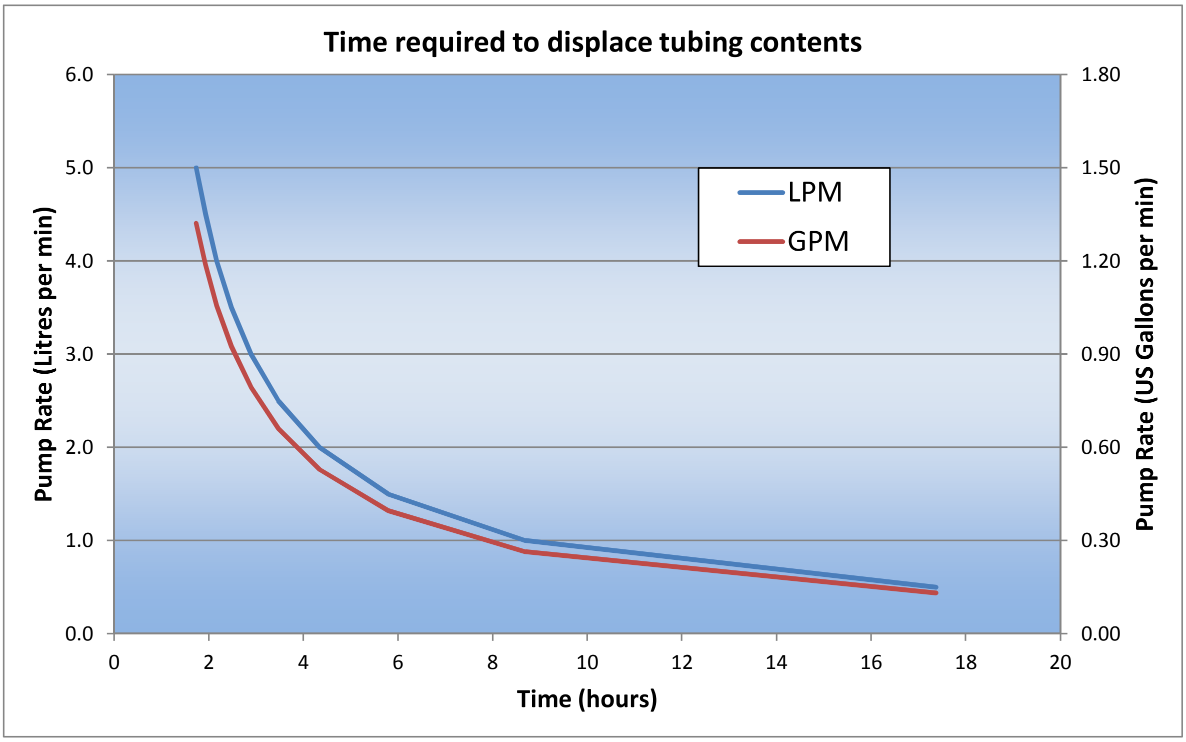


Figure 8: Time required to displace tubing contents

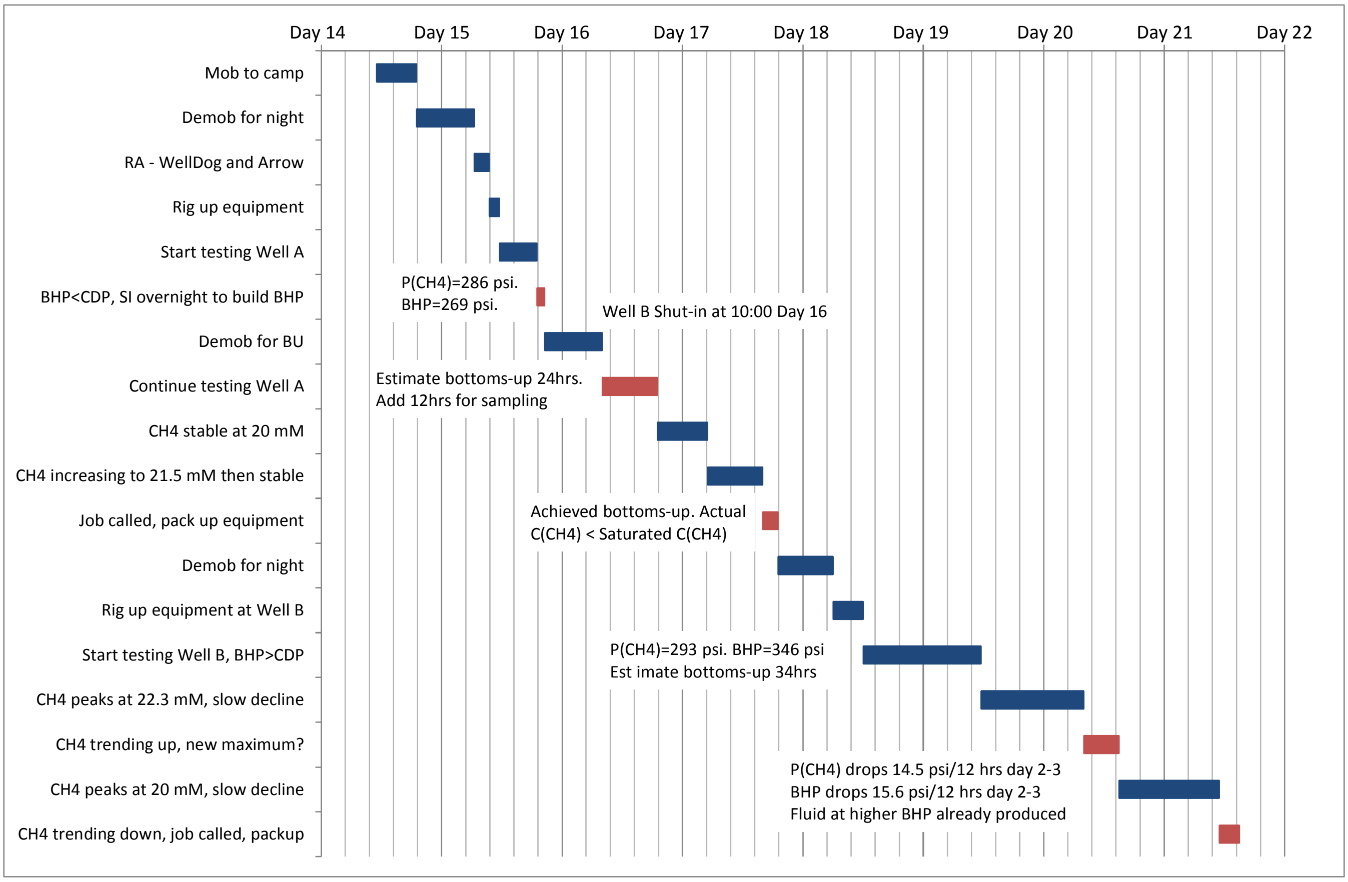


Figure 9: RRS Field trial operations breakdown Gantt chart

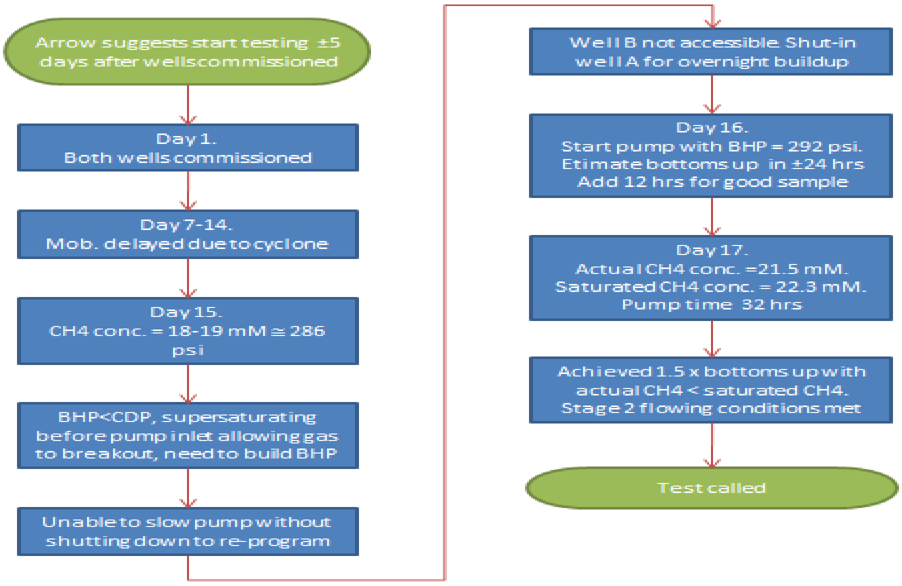


Figure 10: RRS field trial chronology and decision process

Well Number	Actual water rate during test (BPD)	Actual test time (Hours)	Water rate at proposed Test Window start (BPD)	Predicted test time if begun on time (Hours)
Well A	3.3	33.5	34.0	2.3
Well B	2.0	72.0	75.0	0.5

Table 2: Actual vs predicted RRS test times

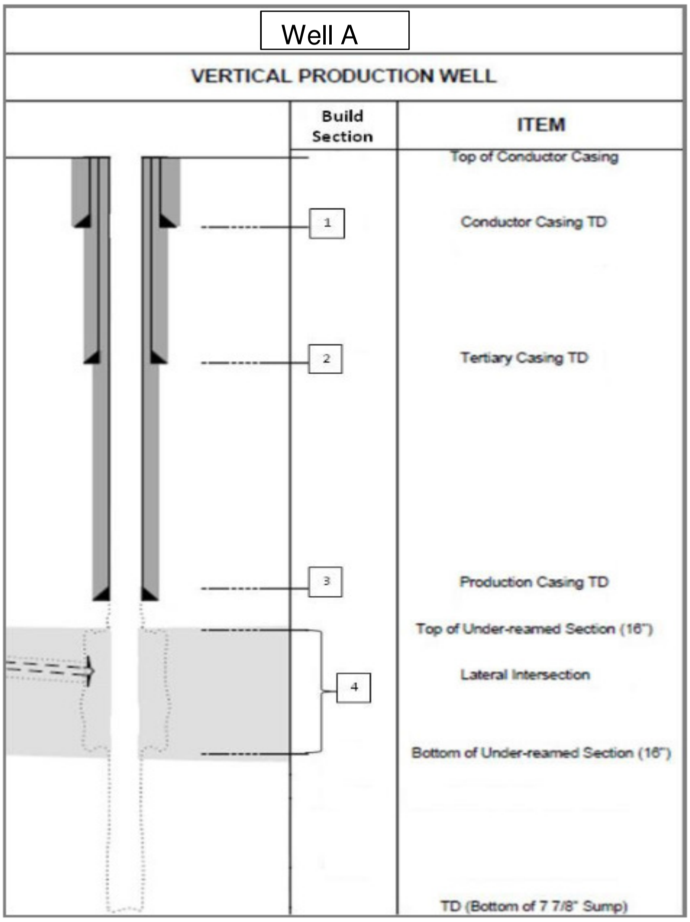


Figure 11: Well A Schematic

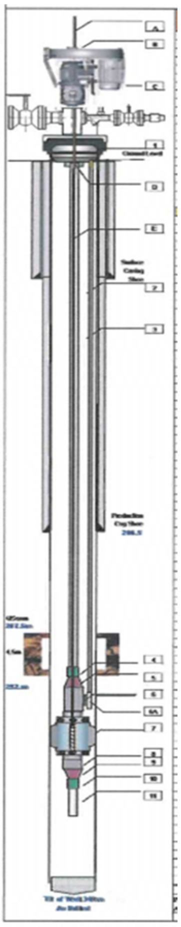


Figure 12: Well A Completion Schematic

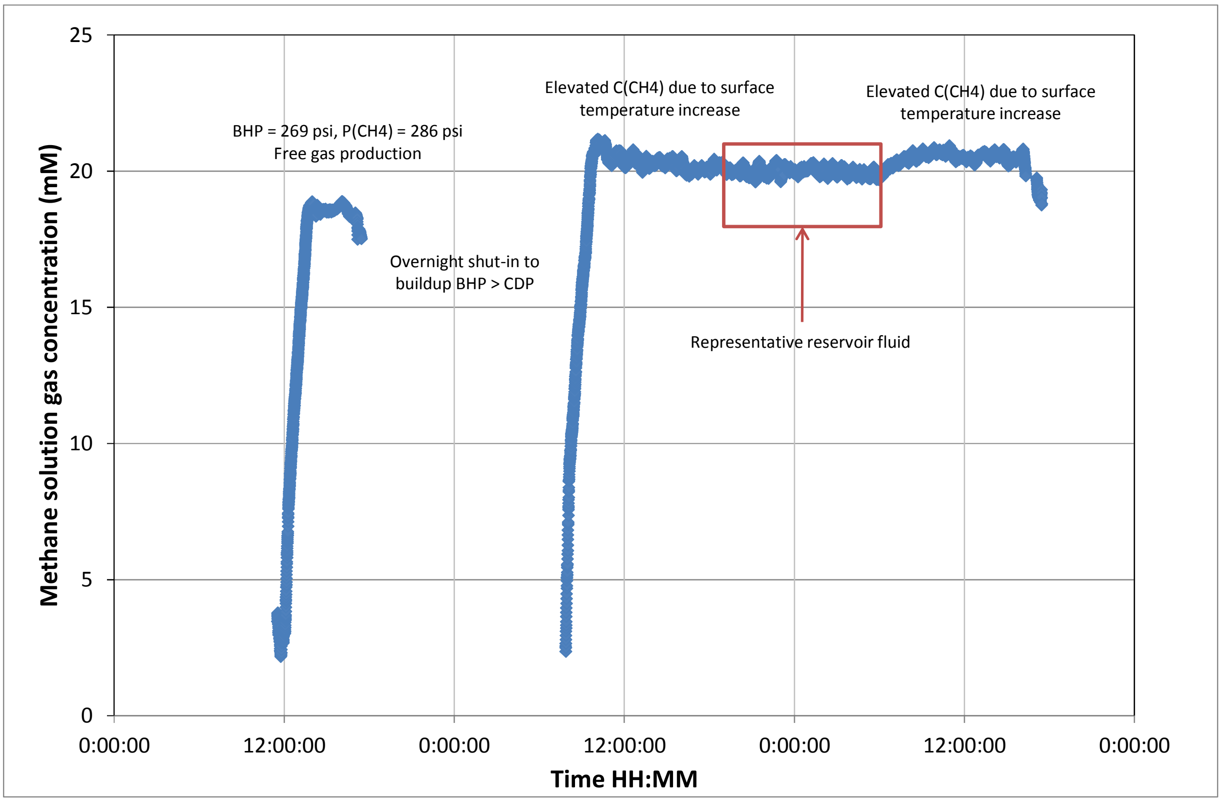
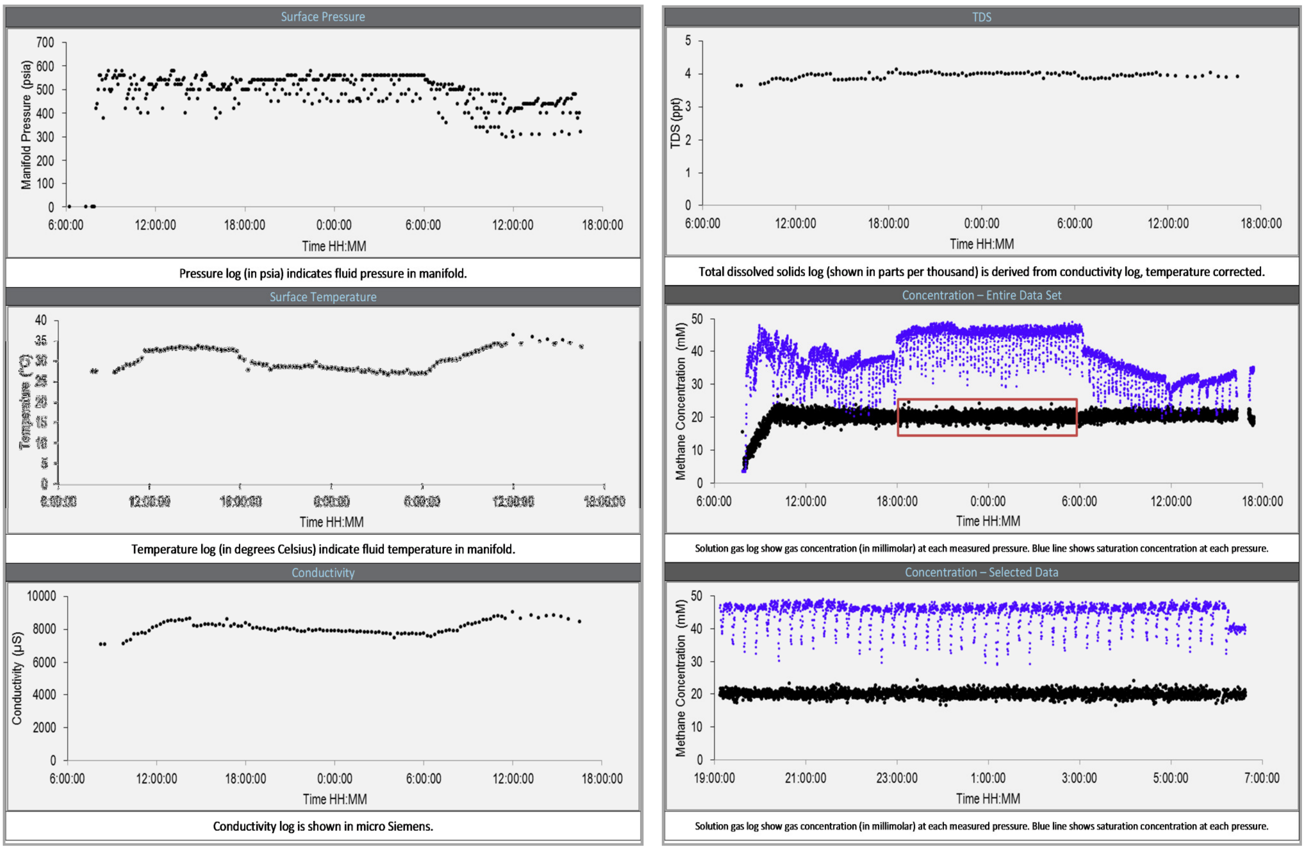


Figure 13: Overview of computed solubilised methane concentrations during testing of Well A



Pressure log (in psia) indicates fluid pressure in manifold.

Total dissolved solids log (shown in parts per thousand) is derived from conductivity log, temperature corrected.

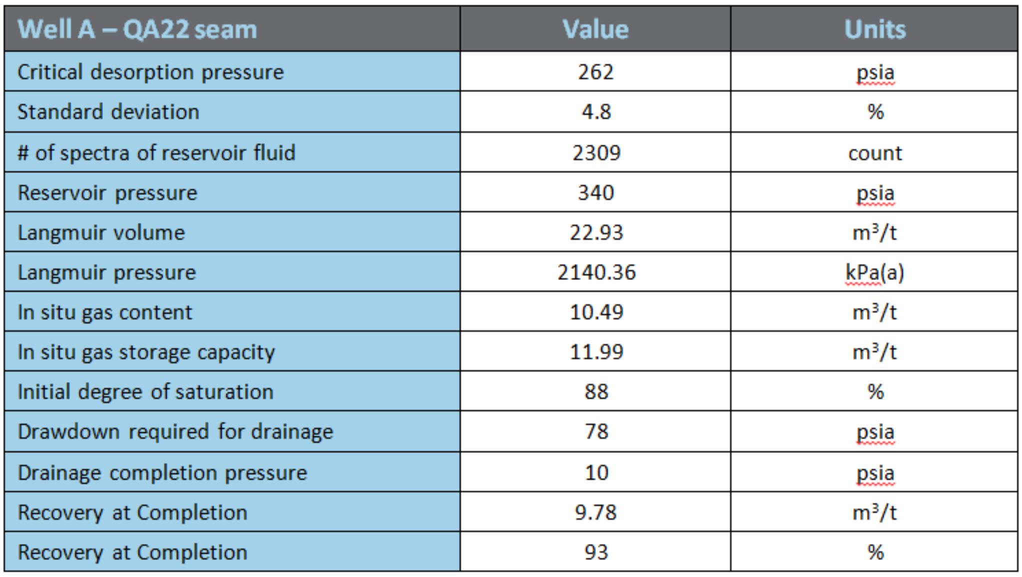
Temperature log (in degrees Celsius) indicate fluid temperature in manifold.

Solution gas log show gas concentration (in millimolar) at each measured pressure. Blue line shows saturation concentration at each pressure.

Conductivity log is shown in micro Siemens.

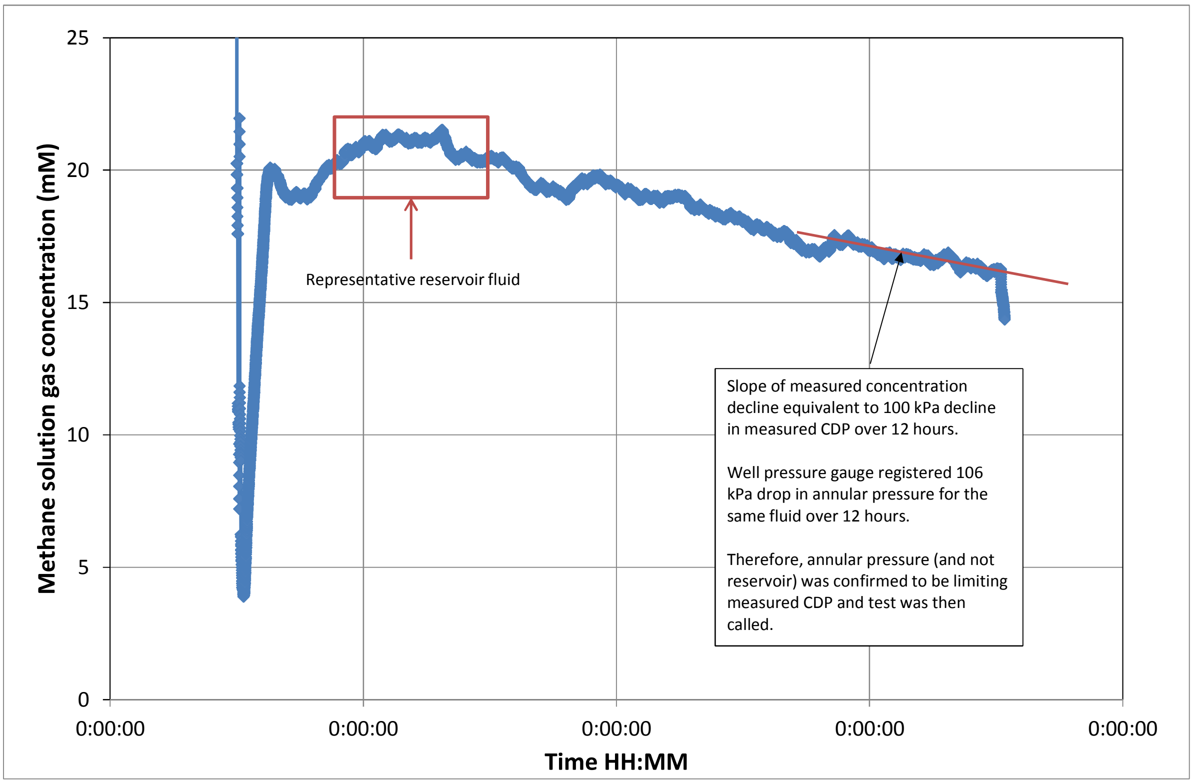
Solution gas log show gas concentration (in millimolar) at each measured pressure. Blue line shows saturation concentration at each pressure.

Figure 14: Topside RRS meter measurements during testing of Well A on Day 17



Well A – QA22 seam	Value	Units
Critical desorption pressure	262	psia
Standard deviation	4.8	%
# of spectra of reservoir fluid	2309	count
Reservoir pressure	340	psia
Langmuir volume	22.93	m³/t
Langmuir pressure	2140.36	kPa(a)
In situ gas content	10.49	m³/t
In situ gas storage capacity	11.99	m³/t
Initial degree of saturation	88	%
Drawdown required for drainage	78	psia
Drainage completion pressure	10	psia
Recovery at Completion	9.78	m³/t
Recovery at Completion	93	%

Table 3: Reservoir parameters computed from analyses of RRS data acquired from Well A



Slope of measured concentration decline equivalent to 100 kPa decline in measured CDP over 12 hours.

Well pressure gauge registered 106 kPa drop in annular pressure for the same fluid over 12 hours.

Therefore, annular pressure (and not reservoir) was confirmed to be limiting measured CDP and test was then called.

Figure 15: Overview of computed solubilised methane concentrations during testing of Well B

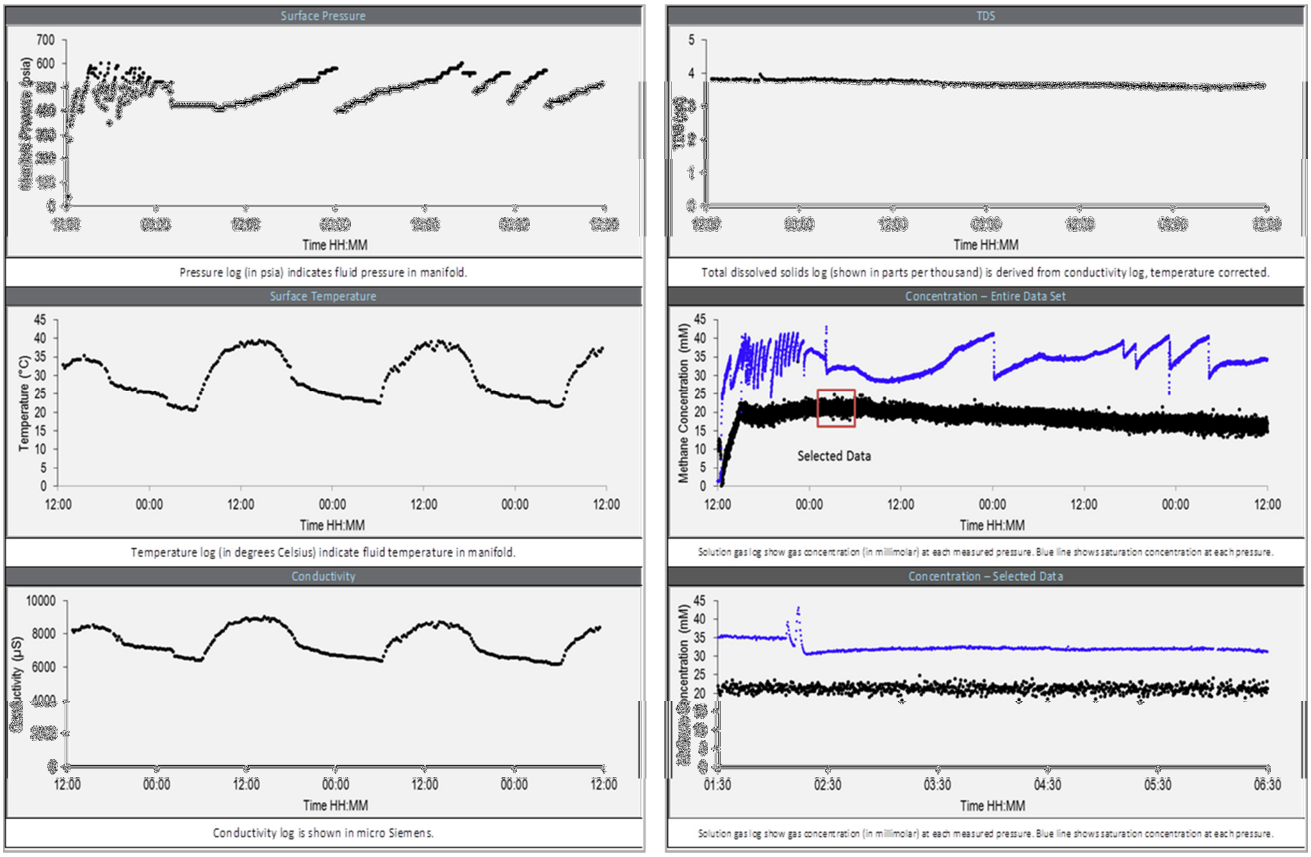
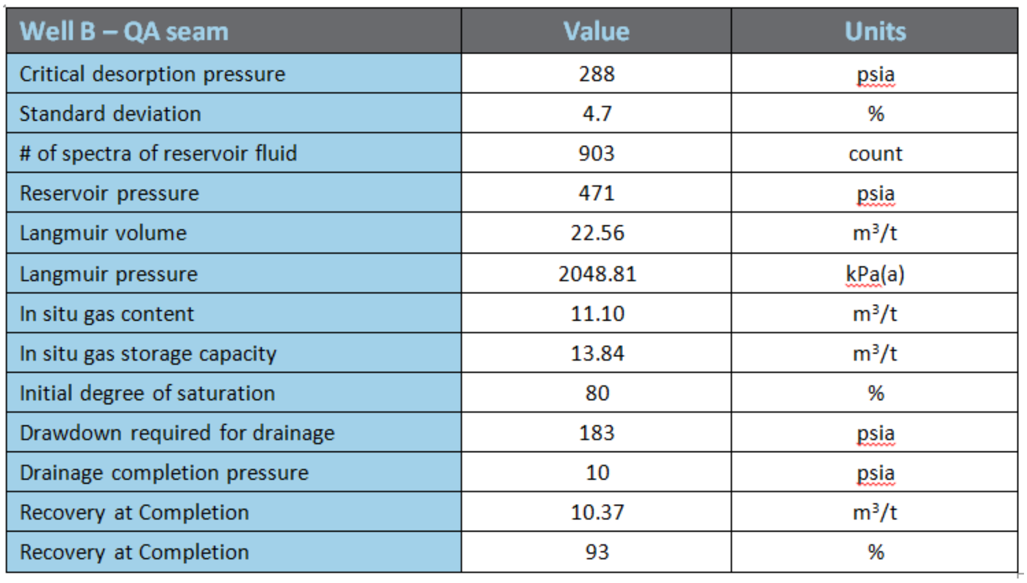


Figure 16: Topside RRS meter measurements during testing of Well B on Day 19



Well B – QA seam	Value	Units
Critical desorption pressure	288	psia
Standard deviation	4.7	%
# of spectra of reservoir fluid	903	count
Reservoir pressure	471	psia
Langmuir volume	22.56	m³/t
Langmuir pressure	2048.81	kPa(a)
In situ gas content	11.10	m³/t
In situ gas storage capacity	13.84	m³/t
Initial degree of saturation	80	%
Drawdown required for drainage	183	psia
Drainage completion pressure	10	psia
Recovery at Completion	10.37	m³/t
Recovery at Completion	93	%

Table 4: Reservoir parameters computed from analyses of RRS data acquired from Well B

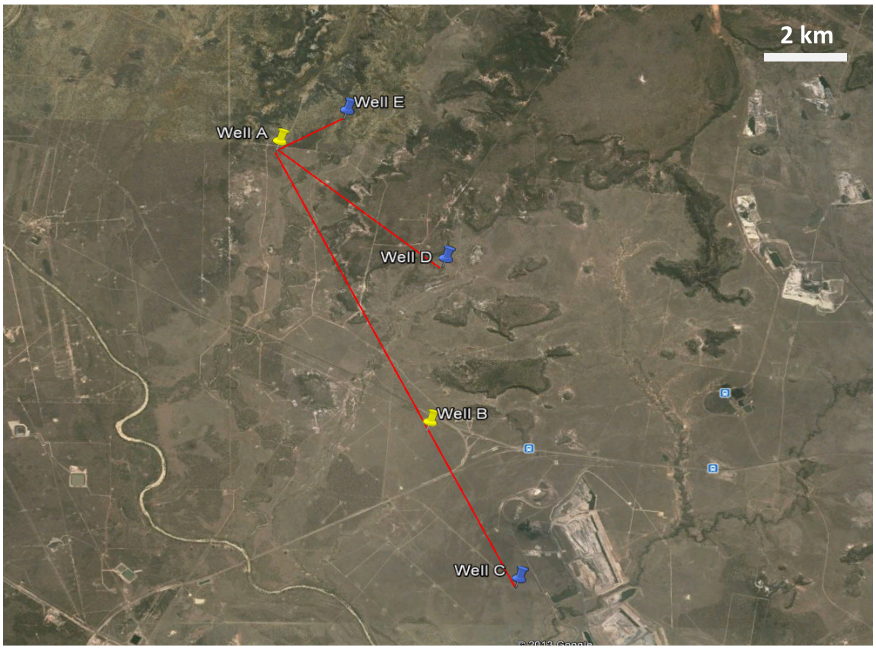


Figure 17: Location map for the two test wells and offset wells

Well A				
	As received temperature		Corrected to seam temperature (37^0C)	
	P(L) - synthetic, kPaa	V(L) - synthetic, m^3/t	P(L) - synthetic, kPaa	V(L) - synthetic, m^3/t
Average	2062.22	22.53	2140.36	22.93
Standard deviation	181.66	1.90	250.43	2.17
Standard deviation %	9%	8%	12%	9%

Well B				
	As received temperature		Corrected to seam temperature (40^0C)	
	P(L) - synthetic, kPaa	V(L) - synthetic, m^3/t	P(L) - synthetic, kPaa	V(L) - synthetic, m^3/t
Average	2062.22	22.53	2048.81	22.56
Standard deviation	181.66	1.90	178.84	1.92
Standard deviation %	9%	8%	9%	9%

Table 5: Synthesized adsorption isotherm data for Well A and Well B

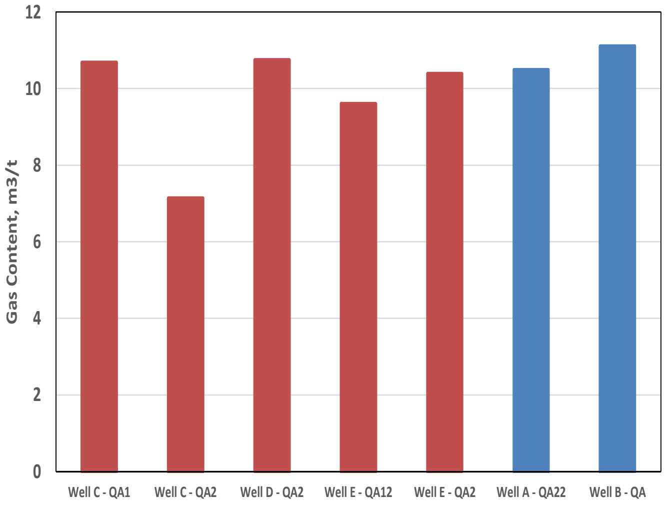


Figure 18: Comparison of derived vs measured gas content

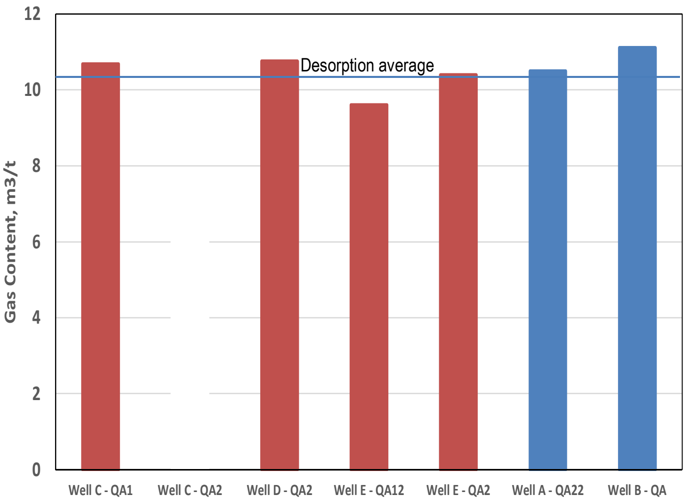


Figure 19: Comparison of derived vs measured gas content with outlier removed