Using mud gas components to quantify hydrocarbon liquid yields for gas zones in the Patchawarra Formation of the Western Flank, Cooper Basin

Christopher Webb  
Kite Exploration Ltd  
1A Winchester Drive, Maidenhead, Berkshire, U.K. SL6 3AH  
chris.webb@kitexploration.co.uk

Belinda Wong  
Beach Energy Ltd  
25 Coryngham Street, Glenside, Adelaide, SA 5065  
belinda.wong@beachenergy.com.au

Regie Estabillo  
Beach Energy Ltd  
25 Coryngham Street, Glenside, Adelaide, SA 5065  
regiebrando84@gmail.com

SUMMARY

The Patchawarra Formation is a Permian age fluvial sand and coal measure system deposited in the Cooper Basin of Central Australia. Fluvial sand channels up to 20 m thick form conventional gas reservoirs and are inter-bedded with seal and hydrocarbon source play components of overbank silts, clays and coal seams. This stacked play system presents a challenge to completion optimization and efficiency, which are critical components for achieving an economic well. A key driver to the success and economics of a well is the presence of liquid hydrocarbons (LPG; Propane and Butane and condensate; Pentane plus). As the liquid yields composition varies significantly throughout the Cooper Basin, estimating the liquid yield in new gas zones is vital to valuations of any potentially commercial development in this area.

This paper will present a new quantifiable method to forecast the liquid yields of specific gas zones utilizing mud gas logs. The method uses simple formulas applied to mud gas ratios to provide estimates of liquid yield per individual gas zone. Examples demonstrate the application of the method, calibration of fluid estimates to real PVT samples from corresponding gas zones and how the results have successfully optimized completion strategies in the Beach Energy operated Western Flank gas area. It is anticipated that with continued application, this simple method will become a useful tool in assessing the commerciality of gas wells and assist in identifying future exploration/appraisal and development targets.

Key words: mud gas ratios, hydrocarbon liquids yields, completion optimisation

INTRODUCTION

In the Beach Energy operated Western Flank gas permits (Figure 1), there is a rich legacy of gas wells that have been drilled in full evaluation mode, with logs, open-hole drill stem tests (DST), down-hole wireline sampling, and extended production tests (EPT). Recently, commercial pressure to reduce costs has resulted in increased requirements to estimate and quantify the potential yields and commercial value of gas zones with less evaluation data.

Mudlogs are fundamental industry standard formation evaluation tools that represent the first opportunity for evaluating the potential economic viability of a well or prospect. Recent internal studies have indicated that mud gas data could be analysed in a similar manner to laboratory-based PVT sample analysis. This has resulted in new quantitative methods that use the mud gas components and their ratios to derive quantifiable estimates of hydrocarbon liquids yield which can be used in commercial evaluation of potential gas pay zones.

The normal mud log records the total mud gas and chromatograph analysis of the methane (C1) to Pentane (C5) gas components as separate log curves. Haworth et al. (1985) in a seminal piece of work took these data to a qualitative level of assessment using ratios of the various gas components to establish bands of likely dry gas, light gas, medium gas/oil and oil. McCaffrey and Walker (2010) (Weatherford Laboratories) took this further and assigned the mud gas ratios labels including; Gas Wetness Ratio (GWR); Light-to-Heavy Ratio (LHR) and Oil Character Ratio (OCR) which can be used to help identify liquids in zones of interest (Figure 2).

In this paper, we extend the previous work to present a new qualitative ratio (the LPG to Sales Gas ratio) that is useful for log display visualization of a portion of the liquids in the mud gas. In addition, we define four new quantitative equations that use the mud gas components and their ratios to derive quantifiable estimates of 1) LPG (propane + butane) and 2) Condensate (pentane + heavier gases) yields within gas pay zones in units that are used in commercial evaluation. The quantitative liquid yields method has proven to be robust within the bands of liquid measurement uncertainties needed for current commercial requirements in the Western Flank. The ability to estimate the liquids contribution of individual zones has proven particularly valuable in Patchawarra producing wells that have multiple producing gas zones comingled into a single production manifold stream.

GEOLOGICAL SETTING

The geological setting for the Patchawarra gas play is summarised in this paper. Readers are referred to Webb (2015) and Soares and Webb (2018) for a detailed review of the geology and additional reading.

The Cooper Basin is a Carboniferous – Middle Triassic intra-cratonic basin located over the state boundary between northeast South Australia and southwest Queensland, Australia. The Patchawarra Formation is a widespread Permian aged fluvio-lacustrine inter-bedded sandstone, siltstone, shale and...
coal measure system, which was deposited close to the base of the Cooper Basin succession. Gas (sales gas – methane and ethane), LPG (propane plus butane) and condensate (pentane plus heavier hydrocarbons) are locally sourced from peat swamp beds (now coal) and migrate into stacked fluvial channel belts up to 20 m thick that form conventional sandstone reservoirs. In the study area, the Patchawarra Formation is at average depths of 2500 m subsea and has an average thickness of 300 m. Beach Energy’s operated gas permits are largely located on the Western Flank of the Patchawarra Trough within South Australia (Figure 1).

METHOD

Example wells

The three Patchawarra gas exploration wells, Brownlow 1, Lowry 1 and Canunda 3, were chosen to represent the range in liquid yields seen in the study area (Figure 1, Table 1). Each well has mud gas logs (chromatograph analysis of C1 to C5 components), standard open hole wireline logs and full stream PVT samples from gas bearing reservoirs.

Table 1. Example wells from the Western Flank and the range in liquid yields they represent. It is important to note that LPG yields increase as condensate yields increase.

<table>
<thead>
<tr>
<th>Liquid Hydrocarbon Yield</th>
<th>Condensate Yield (kbb/Lbf)</th>
<th>Example Well</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>&lt;20</td>
<td>Brownlow 1</td>
</tr>
<tr>
<td>Moderate</td>
<td>20 – 50</td>
<td>Lowry 1</td>
</tr>
<tr>
<td>High</td>
<td>&gt;50</td>
<td>Canunda 3</td>
</tr>
</tbody>
</table>

Mud gas logs and derived yield equations

The basis of the mud gas yield method uses equations derived by Beach reservoir engineers from first principles as described in Bradley (1987). The method uses the mud gas components, standard gas molecular weights and gas densities based on ideal gas behaviour at surface conditions (Silz, 2017). Similarly, third party PVT laboratory compositional analysis of individual gas zone samples uses the same formula to independently assess the liquid yields (PETROLAB, 2017). This PVT control set database provides the full stream PVT yield estimates of sales gas, LPG and condensate and inert gas (principally carbon dioxide and nitrogen).

Four liquid yield equations were derived through analysis of the mud gas components and recombined full stream PVT analysis. We informally designate these yield equations as:

**LPG Yield 1:** Regarded as a best estimate. Calculated yield from C3+C4 mud gas ratio yield.

**LPG Yield 2:** Regarded as a high side estimate. Calculated yield based on linear function fit to a cross plot of mudlog derived C3+C4 yields to PVT LPG full stream yields.

**Condensate Yield 1:** Regarded as a best estimate. Calculated yield based on power function fit to a cross plot of mudlog derived C5 yield to PVT LPG full stream yield.

**Condensate Yield 2:** Regarded as a low side estimate. Calculated yield based on linear function fit to a cross plot of mudlog derived C5 yields to PVT Condensate full stream yields.

The mud gas ratio for a particular zone is based on an interpreter selecting a representative portion of the mud gas logs and their drill depths compared to the wireline log depth. Care must be taken to ensure mud gas readings correspond to the wireline log depth zone of interest. In the Patchawarra Formation, coal gas peaks are generally distinctive and useful to delineate the wireline log depth shift relative to the mud gas peaks.

**MUD GAS RATIOS AND LIQUID YIELDS EQUATIONS**

The formulas, definitions, labels and coding are informal and specific to Beach Energy Ltd and are used in PETREL workflow software and calculator. Readers are encouraged to derive their own methods to suit their own software.

**Qualitative Mud Gas Ratios (Figure 2, Track 7)**

**LPG to Sales Gas** (Beach Energy Ltd derived)

LPG to Sales Gas (Beach Energy Ltd derived)

**Oil Character Ratio** (next 3 equations Haworth et al. (1995) and McCallfrey and Walker (2010) derived)

LPG to Sales Gas

**Liquid to Heavy**

GWR=(GAS_C2_ppm+GAS_C3_ppm+GAS_C4i_ppm+GAS_C4n_ppm+GAS_C5i_ppm+GAS_C5n_ppm)/(GAS_C3_ppm)

**Gas Wetness Ratio**

GWR=(GAS_C2_ppm+GAS_C3_ppm+GAS_C4i_ppm+GAS_C4n_ppm+GAS_C5i_ppm+GAS_C5n_ppm)/(GAS_C3_ppm)

**Quantitative Liquid Yields Formulas (Figure 2, Track 8)**

**Step 1: Mud gas ppm to decimal ratio**


**Step 2: Molecular mass of entire C1 to C5 stream**


**Step 3: Molecular mass of individual mud gas components**

C1mass_MUD_dec=(16.04276*C1_MUD_dec)/C1toC5_molemass

**Step 6: Qualitative Mud Gas Ratios (Figure 2, Track 7)**

**Step 7: Gravity/Density terms** (Modified for appropriate gas field units from Ref: Chapter 20 in Bradley 1987 – Ref: Silz 2017)

C1toC5_density=C1toC5_molemass/28.9660a

C1toC5_molemass=1.2250β*C1toC5_density

α The molecular weight standard air (gram/mole)

β The standard density of air (kg/m3)

**Step 5: Liquids yields**

YIELD C3_kT_Bcf=(C1toC5_density_standard*1000000/35.3147)*C3mass_MUD_dec/1000

YIELD C4in_kT_Bcf=(C1toC5_density_standard*1000000/35.3147)*C4inmass_MUD_dec/1000
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In order to maximise the value of information, it is important to understand the visual display of the qualitative ratio curves versus the quantitative yields curves. With reference to Figure 2 and Figure 3, there is a range of qualitative ratio responses in Track 7 compared to the calculated quantitative yield log curves for the pay zones in Track 8. Flags can be set up by the user with cut-offs appropriate to the basin to identify zones of increased light gas or wet gas relative to background levels. Within the study area, gas peaks associated with coals with a LHR ratio greater than 40 are marked by the grey blocked curve (Figure 2 and Figure 3). The coals exhibit a distinctly different character on the qualitative mud gas ratio compared to conventional gas zones marked by the red stars on the wells shown in Figure 3. The quantitative values estimated for coal zones have distinctly low LPG and condensate yields. The gas peaks associated with conventional gas sands have variable responses depending on the liquids content. The well Canundra 3 zone is an example of a liquids rich flag as shown by the OCR (Green), GWR (Orange) and LPG (yellow). The quantitative mud gas yields calculated for condensate for Canundra 3 are over 200 bc/mmcf. In comparison, the recombinated PVT sample analysis from production tests closely matches the mud gas yield at 214 bc/mmcf (Figure 3; PETROLAB, 2017). Brownlow 1 and Lowry 1 represent lower liquid yield wells which is supported by lower ratios and thinner flags over gas bearing zones. Despite this, these wells still show at strong correlation between mud gas and PVT yields (Table 2). Although the yield curves are calculated over the entire logged section, they are considered most relevant to those zones associated with gas peaks above background gas levels, and i.e. coals, carbonaceous shales and gas pay zones.

Interpreting mug gas yield calculations

The three examples presented in this paper demonstrate how the liquid yield calculation workflow has been applied to the individual wells and the resulting log curve display, however most importantly, the workflow demonstrates the positive correlation between the estimated yields to actual laboratory PVT results (Figure 3 and Table 2). Calibration of the workflow has given confidence to the mud gas method. Subsequently this has enabled us to apply the mud gas yield estimates to appraisal and development activities within the area without needing to obtain expensive test samples on every well. Since implementation of the method in 2017, the mud gas liquid yields workflow has been successfully used in the evaluation of all Beach gas wells drilled.

Sales gas yields have not been calculated from mud gas logs, as initial analysis did not show a strong correlation to the PVT data. This is likely due to variable amounts of inert gas (CO₂) and hydrocarbons. The inert content of mud gas is not routinely measured, and the data is not reliable, subsequently more work is required to understand the impact of inert gas on sales gas yields that could be estimated from mud gas calculations. In contrast, the LPG yield mud gas-based prediction to PVT shows a strong positive correlation likely because it is based on a simple ratio of LPG to sales gas. A similar ratio method of measurement also applies to the condensate yield calculation. In these cases, the inert gases may not affect the calculations.

To date, a full analysis of the variance, standard deviation and other statistical measures of the mud gas calculation results versus the separator and production yields has not been carried.
out. The full PVT composition data is based on recombined fluid samples from individual zone tests and it is noted that the compositional yields are close to but not identical to those from meters run at wellhead separators and production manifolds. This is likely due to differences in temperature and pressure that production and separator equipment run at compared to the samples recombined at laboratory conditions. In addition, uncertainty associated with the actual validity of test data should not be forgotten and the perils of obtaining representative reservoir fluid samples are well known (Schlumberger, 1998; De Oliveira e Melo, 2016). Uncertainty also exists in the actual liquids yield from DST, production separator and down-hole samples, influencing the functions derived through cross plotting. In cases with poor fluid sampling, mud gas data may have less uncertainty due to the amount of repetition and continuous sampling in-built in mud gas logging. Subsequently, it is not clear in every case if the PVT yield value taken represents the “true” value for a zone.

In this study, we have looked at the visual closeness of mud gas yields and PVT points as shown on logs as being the most useful for comparisons. The ranges from the mud gas calculations generally appear to be close to the PVT results. Results to date in over 50 wells suggest a reasonable confidence variance is ±40% (for example, a condensate yield estimate of 20 kbbl/Bcf has an uncertainty of ±8 kbbl/Bcf). This uncertainty range is valuable for reservoir engineering planning. LPG yield estimates are interpreted to have a better confidence variance of ±20%. Further work on the variability currently lies outside the scope of this project.

Economic evaluation and optimising completion strategy

Fracture stimulation is commonly used in the Cooper Basin to enable economic production of hydrocarbons from tighter reservoirs. Utilising the mud gas yield workflow presented in this paper assists in the identification of liquids rich zones and provides valuable information for completion engineers to optimise the commerciality of the completion. A conceptual case that presents the incremental economics of a completion stage is outlined in Figure 4 and demonstrates the economic value of understanding liquid yields per zone for completion design and planning.

In this example a single well is drilled intersecting 3 discrete zones with varying condensate yields of 5, 20 and 50 kbbl/Bcf respectively (Figure 4). Each zone is forecasted to produce 0.1 Bcf. The capital assumption for the economic modelling is based on a post-drill go forward scenario that has a fracture stimulation cost of $300,000 per zone. The results indicate that fracture-stimulation of zone 1 would yield a negative NPV of -$7,900. However, as the condensate yield increases to 20 kbbl/Bcf in zone 2 and 50 kbbl/Bcf in zone 3, the NPV increases and is positive in both cases. To understand the impact of the three zones on the commerciality of the well, consider two scenarios:

Scenario 1: The completion is designed without the benefit of the mud gas yield calculations and all three zones are fracture stimulated (as per historical practice). The cost of this scenario is $900,000 and the resulting total NPV is $328,000.

Scenario 2: The completion is designed with assistance from the mud gas yield equations to determine the potential condensate yields in each zone (i.e. zone 1 = 5 kbbl/Bcf, zone 2 = 20 kbbl/Bcf, zone 3 = 50 kbbl/Bcf). With this data, the completion engineer is able to conduct an economic analysis which identifies that zone 1 would yield a negative NPV, and subsequently decides to complete zone 2 and zone 3 only. The cost of this scenario is $600,000 and the resulting total NPV is $336,000.

In this example, scenario 2 yields a higher NPV. However, despite the difference in NPV between the scenarios being marginal at $10,000, the capital expenditure is $300,000 less in scenario 2 at $600,000 compared with $900,000 in scenario 1.

In the future as the method evolves, it is anticipated that the mud gas yields workflow will assist in field development and reservoir characterisation. The Cooper Basin is a stacked play system that presents a challenge to appraising and characterising individual intervals, as testing separate intervals is a cost prohibitive exercise. Therefore, being able to extract reliable yields from mud logs, that are run as standard in every well, is a cost effective and useful additional tool to assist in designing completions and achieving an optimal economic outcome.

CONCLUSIONS

1. The mud gas yield workflow provides reasonably reliable estimates of liquid content of potential pay zones.
2. Visualization of the mud gas yields as log curves is a useful technique to assess pay zones.
3. The additional information from the mud gas yield calculation is another useful QC tool for hydrocarbon sample validation and representativeness.
4. Calculating liquids yield estimates from standard mud gas logs appears to be a cost effective and useful tool to help assess commerciality.
5. Determining the liquids yields in each of the zones influences the completion design of the well, i.e. which intervals are worth completing and are of material economic value.
6. It is likely that with continued application of the mud gas yield method, improvements of the current and better
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Figure 2. Eight track log display, scales and legend used in Figure 3. Track 1: Gamma ray log curve blocked with lithology colour and total porosity flags. Lithologies labelled. Track 2, 3: Depth in metres: measured depth wireline log (track 2) and true vertical subssea depth (track 3). Track 4: Density and neutron logs with crossover shaded yellow as net sand indicator and density less than 1.95g/cm³ shaded grey. Track 5: Log scale mud log total gas curve (shaded pink) overlain on log scale deep and shallow resistivity with colour shading (blue/green=low to green/red=med/high resistivity) with resistivity over 100 ohm-m shaded grey. Track 6: Log scale mud gas components C1 to C5. Sales gas: C1 (Red)+C2 (pink). LPG: C3 (Orange)+C4i+C4n (Lighter Greens), Lightest Condensates: C5i+C5n (Darker greens). Track 7: Log scale mud gas ratios shaded above values that match with significant changes in gas ratios in the Patchawarra Formation in the study area. Yellow shading is values above 0.05 for the LPG ratio, orange for values above 0.02 for GWR, green for values above 0.75 for the OCR and grey for values above 40 on the LHR ratio. Track 8: Linear scale Liquids yields of Condensate (kbbl/Bcf) and LPG. (kT/Bcf). Condensate: Yield 1 (solid green), Condensate Yield 2 (dashed green), LPG Yield 1(solid orange), LPG Yield 2 (dashed orange). Points labelled with values are yields from zones tested and with full PVT analysis of laboratory recombined samples for condensate (green points), LPG (orange points).

Figure 3. Low to high liquid yields gas pay zone comparison. Track headers outlined in Figure 2. Red stars indicate the producing gas/condensate pay zones. Total gas curve in red in track 4 shows the gas peaks associated with both coal/carbonaceous shales and pay zones. The mud gas ratios (Haworth et al., 1987) in Track 7 give a qualitative indication of leaner and rich gas zones. Track 8 shows the four quantitative mud gas derived liquid yield curves. Gas zone PVT points are displayed and closely match the calculated yields derived from the mud gas workflow (Table 2). Using all eight tracks, the pay zone character can be differentiated from the coals/carbonaceous shales and water bearing sands. The mud gas yield curves in Track 8 give reliable and quantifiable values of the variable liquids content of the gas pay zones. This has been now applied to over 50 wells in the Western Flank area and has revealed a wide variation of liquids content confirmed by PVT.