Utilizing Pressurized Rotary Sidewall Cores for the Determination of Pore Fluid Total Material Balance and Characterization of Bulk Fluid Hydrocarbons*

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Search and Discovery Article #42364 (2019)**
Posted April 1, 2019

*Adapted from oral presentation given at 2019 AAPG Middle East Region GTW, Regional Variations in Charge Systems and the Impact on Hydrocarbon Fluid Properties in Exploration, Dubai, UAE, February 11-13, 2019
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Abstract

Once the general vertical location, quality, and character of a target reservoir are identified through mud gas analysis and subsequent petrophysical logging of the wellbore, pressurized rotary sidewall cores can be obtained from wireline deployable tools and evaluated within a relatively rapid timescale. Through depressurization and subsequent extraction (solvent and/or thermal methods), one can obtain pore fluid total material balance (stock tank) for oil-in-place and gas-in-place estimates, bulk hydrocarbon compositional and geochemical character, gas-oil or condensate-gas ratios, and equation-of-state thermodynamic models which allow for predictions of in-situ fluid phase behavior. Armed with these data an operator can rank stacked pay, make informed decisions about lateral well placement, and formulate reasonable estimates of EOR and well performance.

References Cited


Utilizing Pressurized Rotary Sidewall Cores for the Determination of Pore Fluid Total Material Balance and Characterization of Bulk Fluid Hydrocarbons

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Rated to 20k psi and 400 °F.

Holds 10 - 12 RSWCs which are in pressure communication with each other.

Can be configured with or without P & T gauges (down hole assembly and/or internal to the pressure vessel itself).

Can be configured with or without N₂ ballast to reduce pressure loss due to temperature effects.

Can be transported “live” for analysis and processing under controlled laboratory conditions.
• RSWCs are only as representative of the reservoir as is the skin of the wellbore.
  – Best in tight rocks (< 10 μd).
  – Active mud weight control is recommended to avoid filtrate invasion.

• Single pressurized vessel. Therefore all RSWCs are in pressure communication with one another.
  – Evaluate logs prior to selecting target zone.
  – Best to consider the tool to contain a single sample composed as 10 parts.

• Base fluid used for drilling mud can impact rock and data quality.
  – A small volume (~ 10 ml) of mud unavoidably gets trapped in the tool.
  – When targeting liquid hydrocarbons OBM can cause complications in data interpretation.

• Tool packing fluid (a perfluorocarbon) is compressible and possesses a temperature dependent density (1.88 g/cm³ at 60°F to 1.68 g/cm³ at 220°F).
  – Tool pressure under standard laboratory conditions is typically only a fraction of initial sealing pressure.
  – Once the bubble point or dew point is crossed the fluid phase transition is irreversible.
Tool Depressurization & Initial Core Processing

- The tool is systematically depressurized under controlled conditions.
- Gas volumes are quantitatively measured.
- Gas samples are periodically captured throughout the degassing process for compositional and isotope geochemical analysis.

- Once depleted of all measurable gas the RSWCs are extruded and all annular fluids are collected.
- Cores are quickly wiped clean, inventoried, weighed, labeled, and photographed.
- All collected fluids (fluid trap and internal annular space) are placed in a nonreactive air tight container (typically ~ 500 ml).
- Whole core tests such as benchtop NMR analysis are performed first followed by bulk volume determination. End trims are then taken to generate composite samples for all subsequent analyses.
Gas Phase Fluid Evaluation

\[ G_t = \left( 32.0369 \frac{V_g}{m_t^c} \right) + G_c \]

\[ GIP = 1359.7 A h \rho_b G_t \]

where:

- \( G_t \) total RSWC pressure core tool gas content, scf/ton
- \( V_g \) gas volume measured from the tool, cm\(^3\)
- \( m_t^c \) total sample mass of all RSWCs, g
- \( G_c \) crushed gas content, scf/ton
- \( GIP \) gas-in-place, scf
- \( A \) area, acres
- \( h \) reservoir thickness, ft
- \( \rho_b \) CRA bulk density determined from the composite RSWC sample, g/cm\(^3\)

- Both the molecular composition of the gas and isotopes of each component fractionate with depletion.
- Fractionation is driven by differences in diffusion rates, adsorption potential, and solubility in brine and/or liquid phase hydrocarbons.
Dean-Stark toluene extraction removes free water, bound water, and oil (including bitumen).

Water is measured. Oil is calculated by weight difference.

300°C thermal extraction. Volatilized compounds are condensed and captured (water and oil).

Fraction of oil recovery (relative to solvent based methods) is proportional to API° (i.e. MW).

\[ v_o = \frac{m_{pre} - (m_{post} + m_{water})}{\rho_o} \]

where:
- \( v_o \) volume oil, cm\(^3\)
- \( m_{pre} \) pre-test sample mass, g
- \( m_{post} \) post-test sample mass, g
- \( m_{water} \) extracted water mass, g
- \( \rho_o \) assumed oil density, g/cm\(^3\)
Programmed Pyrolysis Volumetrics

- S1 values are quantified – mg HC/g rock.
- Two reasonable assumptions can be made (or real values can be applied), unit conversions are made and then OIP values can be estimated.

\[
\rho_{\text{oil}} = \frac{0.886 \, \text{g}}{\text{cc}} \quad \rho_{\text{rock}} = \frac{2.5 \, \text{g}}{\text{cc}}
\]

\[
\frac{1 \times 10^{-3} \, \text{g HC}}{0.886 \, \text{g oil}} \cdot \frac{0.886 \, \text{g oil}}{\frac{1.13 \times 10^{-3} \, \text{cc oil}}{0.4 \, \text{cc shale}}} = 2.82 \times 10^{-3} \frac{\text{cc oil}}{\text{cc shale}}
\]

\[
2.82 \times 10^{-3} \frac{\text{cc oil}}{\text{cc shale}} \cdot \frac{6.29 \times 10^{-6} \, \text{bbl}}{8.11 \times 10^{-10} \, \text{acre-ft}} = 21.89 \frac{\text{bbl}}{\text{acre-ft}}
\]

\[
S1 \times 21.89 = \frac{\text{bbl}}{\text{acre-ft}}
\]
Cold Solvent – HRGC Volumetrics

• Composite RSWC pressure core sample
  – Sample aliquot is frozen and then crushed.

• Tool annular fluids and baseline mud sample
  – Fluids are centrifuged at 4000 rpm for 24 hrs.
  – Liquid phase is decanted into a separatory funnel and the FC-40, aqueous, and oil* phases are isolated from one another.
  – Solids are air dried and grain density is determined.

• Composite RSWC pressure core sample, all annular fluid and baseline mud components
  – The sample material is taken through a series of unheated extractions using cold CS₂ and the resulting extract is spiked with an internal standard (trans-2-heptene).
  – The extract is then subject to high resolution gas chromatography using the same standard conditions applied for whole oil/extracts.

*A real, free floating, measurable oil phase has yet to be observed.
Cold Solvent – HRGC Volumetrics

\[
C = \frac{m_{\text{ISTD}}}{A_{\text{ISTD}}} \quad \rightarrow \quad m^i_{\text{Ot}} = A^i_C \quad \downarrow
\]

\[
\frac{V^i_{\text{Ot}}}{\rho_o} = \frac{m^i_{\text{Ot}}}{m^i_{\text{Ot}}} \quad \leftarrow \quad m^i_{\text{Ot}} = \frac{m^i_{\text{Ot}}}{m^i_{\text{t}}}
\]

- \( C \): quantitative conversion constant, g ISTD/ISTD integrated peak area
- \( m_{\text{ISTD}} \): mass of internal standard, g
- \( A_{\text{ISTD}} \): integrated area of the internal standard peak, unitless
- \( m^i_{\text{Ot}} \): mass of oil in the \( i \)th component extract, g
- \( A^i_T \): total integrated area of all peaks in the \( i \)th component extract, unitless
- \( m^i_{\text{t}} \): total mass of oil in the \( i \)th component, g
- \( m^i_e \): mass of the extracted \( i \)th component aliquot, g
- \( m^i_i \): total mass of the \( i \)th component, g
- \( V^i_{\text{Ot}} \): total volume of oil in the total mass of the \( i \)th component, g
- \( \rho_o \): assumed oil density, g/cm³

\( i = \text{RSWC composite sample, aqueous phase, or solid phase samples from tool annular fluids and baseline mud.} \)
Cold Solvent – HRGC Volumetrics

\[ V_{OT} = V_{Ot}^c + V_{Ot}^a + V_{Ot}^s + V_{Ot}^f \]

- Annular fluid oil character is compared to baseline mud oil character for QC/QA and deconvolution of pore fluids from those hydrocarbons sourced from drilling mud.

\[ S_o = \frac{V_{OT}}{\left( \frac{m_t^c}{\rho_b} \right) \phi_t} \]

- \( V_{OT} \): Total volume of oil identified as sourced from the RSWCs, cm\(^3\)
- \( V_{Ot}^c \): Corrected total volume of oil extracted from the total mass of the RSWCs, cm\(^3\)
- \( V_{Ot}^a \): Corrected total volume of oil extracted from the total mass of the aqueous phase from the annular fluids in the tool, cm\(^3\)
- \( V_{Ot}^s \): Corrected total volume of oil extracted from the total mass of the solid phase from the annular fluids in the tool, cm\(^3\)
- \( V_{Ot}^f \): Corrected total volume of free phase oil obtained from the annular fluids in the tool, cm\(^3\)
- \( S_o \): Final oil/condensate saturation, pore vol frac
- \( m_t^c \): Total sample mass of all RSWCs, g
- \( \rho_b \): CRA or retort bulk density determined from the composite RSWC sample, g/cm\(^3\)
- \( \phi_t \): CRA or retort total porosity determined from the composite RSWC sample, bulk vol frac
• Our experience suggests there are permeability limits (no more than a few microdarcys) to the RSWC pressure core tool’s utility.
  – Care should be taken to ensure a fit-to-purpose mud system is applied to avoid mud filtrate invasion or HC expulsion from the skin of the wellbore.
  – Imbibition is still a possible problem under some circumstances.
• Tracing the mud system is always recommended.
• When the target interval is expected to contain liquid phase hydrocarbons drilling with OBM should be avoided.
  – In both WBM and OBM systems knowledge of the mud “recipe” is important. Regardless, if mud additives are identical to in-situ pore components, it can be difficult (or impossible) to delineate what volumes are from the pore matrix and which are from the mud.
• If at all possible, produced fluids (water and oil) from an offset well should also be evaluated.
• Even after evaluating 90+ RSWC pressure core runs we have yet to actually observe a true, free oil phase when analyzing the annular fluids trapped in the tool.
  – For that matter, out of all the runs we have evaluated only a small fraction of them have shown to have exuded quantifiable volumes of pore fluids out of cores and into the annular packing fluid in the tool. The majority of the time the liquid phase hydrocarbons characterized in the annular fluid components can be readily traced back to being sourced from trapped drilling mud.
Final Material Balance of Hydrocarbons – Gas

- If a post-mature gas play then:
  \[ G_t = G_f + G_a \]

- If a gas play the total material balance of hydrocarbons is completed subsequent to crushed gas analysis.

- If we are confident the measured gas volumes are reliable, and the adsorbed-gas corrected \( \phi S_g \) is well established, we can back calculate an accurate reservoir pressure (assuming reservoir temperature is known).

\[
G_f = 32.0368 \frac{\phi_i S_g - \phi_a}{\rho_b B_g}
\]

\[
B_g = \left[ \frac{p_{sc}}{z_{sc} (T_{sc} + 459.67)} \right] \left[ \frac{z(T_r + 459.67)}{p_r} \right]
\]

- total RSWC pressure core tool gas content, scf/ton
- gas volume measured from the tool, cm³
- total sample mass of all RSWCs, g
- crushed gas content, scf/ton
- free gas volume, scf/ton
- adsorbed gas volume, scf/ton
- CRA or retort total porosity, fraction of bulk volume
- CRA or retort gas saturation, fraction of porosity
- Adsorbed gas filled porosity, fraction of bulk volume
- CRA or Retort bulk density, g/cm³
- formation volume factor, res. vol./surf. vol.
- pressure, psia
- temperature, °F
- real gas deviation factor, dimensionless
- standard conditions
- reservoir conditions
Final Material Balance of Hydrocarbons – Oil

Example Only. Based on observed trends but not real data.

<table>
<thead>
<tr>
<th>Method*</th>
<th>Attributes</th>
<th>OIP</th>
<th>NOC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>bbl/acre-ft</td>
<td></td>
</tr>
<tr>
<td>Pyrolysis</td>
<td>300° Thermal extraction, mass/mass basis converted to volume/volume basis</td>
<td>96.41</td>
<td>103</td>
</tr>
<tr>
<td>Retort</td>
<td>300° thermal extraction, volume/volume basis (and mass/mass basis)</td>
<td>114.73</td>
<td>122.57</td>
</tr>
<tr>
<td>Cold Solvent Extraction - HRGC</td>
<td>Cold CS₂ solvent extraction, mass/mass basis converted to volume/volume basis</td>
<td>160.62</td>
<td>171.6</td>
</tr>
<tr>
<td>CRA</td>
<td>Toluene reflux solvent extraction, mass difference converted to volume/volume basis</td>
<td>191.6</td>
<td>204.69</td>
</tr>
</tbody>
</table>

\[
NOC = \frac{S1}{TOC} \times 100
\]

- \( NOC \) = normalized oil content, mg HC/g TOC
- \( S1 \) = pyrolysis S1 peak, mg HC/g Rock
- \( TOC \) = total organic carbon, wt. %

*Final OIP for all methods includes the oil volumes determined from CS₂ extraction of the annular fluids entrained within the pressure core tool.
Importance of Prolific Oil Saturation on OIP Producibility

- When NOC > 100, whenever tested, always flowed oil/gas.
- When NOC < 100, variable results but usually negative.
- Most economic unconventional oil plays have oil saturations greater than 100 mg of oil per gram of TOC and contain over 1 mg HC/g Rock.

Modified from Ruble, 2010, and Jarvie, 2010
Immature kerogen

Onset of thermogenic oil generation

Oil saturated kerogen: initiation of expulsion

Expelled* mobile oil

Predominantly unproducible oil

Producible oil

*Expulsion here refers to expulsion from kerogen and does not necessarily suggest primary expulsion and migration from the source rock.
Importance of Prolific Oil Saturation on OIP Producibility

Flagged Pay

- NOC > 100
- Oil > 1 mg Oil/g Rock
- $\phi S_o$ (frac BV) > 0.01

- 1 ft core interval.
- Carbonate lithology.
- Contains the same laminated facies on a much smaller scale.

Egenhoff et al, 2010
Characterization of OIP Volumetrics – Implications of Total vs. Producible OIP

- The produced oil from the Bakken, Eagleford, and Niobrara ranges from 35° and 60° API gravity. Molecular weight can be estimated from API gravity after Lasater, 1958*. The apparent range of oil gravity suggests the molar mass of the oils produced from these plays are approximately 100-200 lbmols.
- If we very simplistically assume these produced oils are composed of normal alkanes (CₙH₂ₙ₊₂) then they would contain hydrocarbons ranging from approximately C₇ to C₁₅.
- Considering the programmed pyrolysis S1 peak and the hydrocarbon distillates from retort are the result of the volatilization of hydrocarbons at an isothermal temperature of 300°C it is quite reasonable to consider that these two thermal methods provide a better measure of producible OIP (B.P. of C₁₇H₃₆ = 302°C).
- By evaluating the oil compositional character we can better understand OIP volumetrics in terms of reservoir quality and economic producibility.

\[ *MW = \left( \frac{7864.9}{API} \right)^{0.0386} \]
In a post-mature gas play total material balance of hydrocarbons is the total gas content determined subsequent to crushed gas analysis.

In a bubble point system the computed total oil volumes represent OIP. The associated measured gas volumes enable determination of GOR estimates. The GOR values here are consistently lower than production GORs due to our ability to ascertain complete material balance (i.e. RF = 100%).

In a dew point system the computed total oil volumes represent condensate volumes per unit volume of reservoir. The associated gas volumes enable determination of CGR estimates. The CGR values here are consistently higher that production CGRs due to our ability to ascertain complete material balance (i.e. RF = 100%).

Because we effectively obtain a volumetrically quantified profile of hydrocarbons from C1 to C40+ we can use these data, accurate estimates of reservoir P & T, and equation-of-state (EOS) modeling software, to obtain estimates of fluid phase behavior. This allows for first pass PVT evaluation prior to well completions and any subsequent production.
Thank You Very Much!

Questions?