Three-Phase Holdup Determination in Horizontal Wells Using a Pulsed-Neutron Source

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Abstract

In horizontal wells, it can be very difficult to interpret conventional production logging tools due to the fluid segregation in the borehole. This is even more a problem when there are more than two phases present in the borehole, i.e., oil, water, and gas. A pulsed-neutron tool measures many parameters which are differentially sensitive to all three possible borehole phases. Therefore, it is possible to combine the information available from a pulsed-neutron tool to determine the 3-phase holdup in horizontal wells.

One of the major difficulties in evaluating the response of a tool to 3-phase holdup is obtaining good data under realistic downhole conditions, i.e., realistic gas densities. Laboratory measurements cannot readily be made under these conditions; therefore, modeling techniques must be used to evaluate and characterize tool response. To validate a computer model, laboratory data are needed for benchmarking; therefore, for this study, over 400 laboratory formation measurements were performed using air to simulate gas. These formation conditions were also modeled using Monte Carlo techniques. The agreement between measured and modeled data proved to be enough that modeling can be used to confidently predict the tool response with air or realistic gas.

Once the ability to predict tool response under realistic downhole conditions exists, it is possible to combine information from a pulsed-neutron tool to quantitatively determine the holdup of all three phases. This is accomplished by combining the inelastic near/far ratio with the near and far carbon/oxygen (C/O) ratio. This approach to the holdup measurement has been demonstrated using a combination of laboratory data, Monte Carlo modeling, and field data. The results of this study have demonstrated that the RMS accuracy of this measurement is about 6% on each of the three phases.

Introduction

As horizontal wells have become more prevalent, the ability to reliably evaluate the production performance of these wells has become increasingly important. Existing production logging techniques, such as spinners, that have been successfully used in vertical wells cannot always be applied to horizontal wells with full confidence because of segregated flow in the borehole. For this reason, new techniques must be developed to evaluate oil and water flow rates in horizontal wells.

To determine the flow rates of the oil and water phases in a horizontal well, one must either 1) measure the individual oil and water flow rates directly, or 2) measure the individual oil and water velocities in addition to their holdups. (It should be noted, that for most production logging applications in horizontal wells, measuring only the holdup or only the velocity of the production fluids is usually insufficient to determine the source of production problems.) This paper will address part of the second approach, the measurement of individual oil, water, and gas holdups. Once determined, these holdups can be combined with velocity information, obtained from several possible approaches to obtain oil and water flow rates.

Background

Pulsed-neutron tools have previously been used to qualitatively determine the 3-phase holdup in horizontal wells. This approach uses the borehole sigma and the inelastic near/far ratio for this determination. The method is considered qualitative since tool calibration information is not available for the ratio measurement or the sigma of the gas.

Recent work reported by Peeters et al. has attempted to quantitatively determine the pulsed-neutron measurement for holdup in horizontal wells. Their approach utilizes three measurements from a single pulsed-neutron tool positioned in the borehole: C/O windows ratio, borehole sigma, and capture near/far ratio. The measurements are combined through a linear response matrix to produce the desired holdup measurements. The coefficients for the matrix are determined by regression of modeled or measured tool responses to known conditions.

A more quantitative approach has been employed with the RST Reservoir Saturation Tool. This tool was primarily

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designed to measure the oil saturation of the formation without depending on formation water salinity. This was accomplished by using a carbon/oxygen measurement. A large part of the problem of converting a C/O measurement into oil saturation is the effect of the borehole on the measurement. To properly determine the formation oil saturation, the borehole composition must be known reasonably well. In general, a 5% error on the borehole composition can cause a 15 s.u. error on the formation oil saturation. For this reason, the RST tool was designed with two detectors to compensate for the borehole effect. However, from previous statements, it is obvious that the RST tool can also measure the 2-phase borehole holdup in a well.

In addition to the obvious 2-phase holdup measurement, other data (in several forms), already available from the RST tool, are sensitive to the presence of gas in the borehole. Quantifying this information and combining it with the already available C/O measurement provides sufficient information to quantitatively determine the 3-phase holdup in the borehole.

To ensure the best quantitative answer, it is advantageous for the parameters measured by the tool to have approximately the same depth of investigation. In addition, these parameters need to be easily quantifiable. For this reason, the following tool measurements were chosen for this measurement: near carbon/oxygen ratio, far carbon/oxygen ratio, and the inelastic near/far ratio. Since all these measurements are inelastic measurements, their depth of investigations are about equal and do not vary with formation and borehole sigma. Other parameters sensitive to borehole holdup, such as borehole sigma and capture ratios, can be used, but their varying depth of investigation can complicate their quantitative use for this measurement. In addition, their use adds additional requirements in the form of assumptions about the borehole salinity.

One of the biggest problems in characterizing the tool response for a 3-phase holdup measurement is the acquisition of realistic data due to the difficulty and hazards of performing laboratory measurements with gas under realistic downhole conditions. Air is usually used to simulate the effects of gas for these measurements; however, real downhole gas has appreciable density and elemental constituents that cannot be ignored. Therefore, tool characterization depends heavily on tool response modeling. For this reason, this study uses a multistep process to develop the quantitative analysis required. These steps include:

1. Performing benchmarked laboratory measurements simulating 3-phase holdup conditions in horizontal wells using air to simulate gas.
2. Modeling the tool response using Monte Carlo techniques under the conditions measured in the laboratory to benchmark the model.
3. Develop interpretation procedures that quantitatively predict tool response using air to simulate gas.
4. Model the tool response to 3-phase holdup using realistic downhole gas characteristics.
5. Apply interpretation procedure to modeled data.
6. Apply interpretation procedure to acquired field data.

Finally, the issue of running the tool centralized or eccentricized in the borehole must be addressed. In a horizontal well, it can be difficult to centralize the tool in the borehole. An argument can be made that it is better to eccentric the tool and really be sure of its location in the borehole. However, eccentricing the tool can introduce some problems such as a nonlinearity of the borehole tool response. Therefore, this study has also tried to quantify the effects of tool position in the borehole.

Laboratory Measurements

Measurements to characterize the RST-A response under conditions simulating a horizontal well with 3-phase holdup were performed at the Schlumberger Environmental Effects Calibration Facility (EECF) in Houston, Texas. Since these formations are usually used to simulate vertical conditions, borehole liners were fabricated to divide the borehole fluid into three equal volumes. This simulated the effect of segregated fluids in the borehole. Different liners were designed for the centered and eccentric measurements to allow for the fluid displacement by the tool and the requirement of a rathole for the tool (Fig. 1).

Dividing the borehole into three equal volumes allows 10 possible borehole fluid combinations that simulate holdup in a horizontal well. These are shown in Table 1. Since it is not possible to have a realistic downhole gas present in the borehole for these laboratory measurements, air was used to simulate gas.

A series of measurements was performed using various formations at the EECF. The formations were selected to provide variations in lithology, porosity, borehole diameter, and formation oil saturation (see Table 2). Most of these formations were run with the tool both eccentered and centered in the borehole. All of the measurements used a 7-in., 23-lb/ft casing. Fresh water was used in the formation and borehole for all measurements. Some additional measurements were performed with 100 kppm brine in the borehole. Over 400 laboratory measurements were performed for this study.

Monte Carlo Model of RST-A Response

Since laboratory measurements with realistic gas conditions are not possible in the laboratory formations, characterization of the tool response depends heavily on tool response modeling. For this reason, a large part of the effort in this study has been to develop and test Monte Carlo models to predict tool response. To this end, a RST-A model for the inelastic measurement has been developed using the Monte Carlo modeling code MCBEND, which was developed by AEA Technology in Winfrith, UK. This model requires about 18 hours to run on a SUN Sparc 20 for each set of formation and borehole conditions. The outputs from the model are tallied such that the following tool responses are available: near and far carbon and oxygen yields, near and far carbon/oxygen ratio, near and far carbon/oxygen window ratio, and near/far inelastic countrate ratio.

To benchmark the RST-A model (as applied to 3-phase holdup problems), the laboratory measurements described above were modeled with MCBEND. The results from the modeling were then compared with the results obtained with
the measurements as shown in Fig. 2. These figures show that
the modeling can be used to predict tool response. Each figure
has a line fit to the data that can be used as a calibration to
convert from modeled results to measured results. Both
centered and eccentered data are shown on the plot.

Borehole Gas Holdup
The inelastic near/far countrate ratio can be used to detect and
quantify gas in the borehole. This is demonstrated in Fig. 3
for centered and eccentered tool positions with measured data
in which air was used to simulate the presence of gas. In this
figure, the lines on the plot show the data trends for various
fractions of air in the borehole.

The effect of porosity on the inelastic near/far ratio is small
when the air holdup is between 66 and 100% gas.

As far as sensitivity to 100% air in the borehole, the
inelastic near/far ratio changes by about the same amount
whether the tool is centered or eccentered. However, for air
holdups ranging from 0 to 33%, the centered tool has
substantially more sensitivity to the air because of its
proximity to the air region. For similar reasons, the
eccentered tool has more sensitivity than the centered tool
when the air holdup is between 66 and 100%.

Modeling was used to predict the RST-A inelastic near/far
ratio under the same measurement conditions as those in Fig.
3. This was used to benchmark the modeling, and a
correlation was developed so that modeled results could be
transformed into equivalent measured results (see Fig. 2). This
means that the calibrated modeled response gives the
same results as the measurements.

After the benchmarking of data of Fig. 3 via Fig. 2, the
formations were remodeled substituting realistic downhole gas
into the model. The gas was modeled as 0.3 g/ml methane
(CH₄). The modeled inelastic near/far ratio under these
conditions is shown in Fig. 4 for the tool centered and
eccentered. For this "realistic" gas, the dynamic range of the
inelastic near/far ratio is reduced by about 30 to 40% relative
to the air data for both tool positions. Like the air data, the gas
holdup lines drawn on the figure show the same general trend
in that the centered tool has its maximum sensitivity between
0 and 33% holdup while the eccentered tool has its maximum
sensitivity between 67 and 100% gas.

Two-Phase (Oil/Water) Holdup From C/O
As in the gas phase measurement discussed above, the
positioning of the tool in a segregated borehole impacts the
linearity and sensitivity of the holdup measurement. This
section will address this issue with respect to the 2-phase,
epitaxial, situation with a near/far C/O interpretation
approach.

For this section, the interpretation approach utilized will be
the standard RST approach in which carbon and oxygen
elemental yields can be expressed as sums of the contributions
due to the matrix, pore space, and borehole as:

\[ C_n = N_1 + N_2 \Phi S_o + N_3 Y_o \] ..................................(1)
\[ O_n = N_4 + N_5 \Phi (1 - S_o) + N_6 (1 - Y_o) \] ..................................(2)

where the N's are the near detector sensitivity factors of
carbon and oxygen to the matrix, pore space, and borehole.

(Similar equations can be written for the far detector where the
far detector sensitivity factors are designated by F's.) To
determine the sensitivity factors, four laboratory
measurements (or calculations) are performed where only the
formation or borehole fluids are changed (i.e., formation
porosity, lithology, borehole size, and casing size are fixed).

These measurements are usually referred to as the endpoint
definitions since they correspond to the endpoints of the
tool response. From these data, the near and far sensitivity
factors are determined using the four elemental yields from the
measurements with the above equations. This results in four
equations and three unknowns for both the carbon and oxygen
expressions, allowing the determination of the three sensitivity
factors for each elemental yield. To characterize the complete
tool response, this process is repeated varying porosity,
lithology, etc.

Once the tool response is known from the above
measurement, for every depth, the sensitivity factors are
defined on borehole size, lithology, porosity, etc. and the near and far C/O ratios are measured. Combining
these data results in the following two equations:

\[ R_n = \frac{C_n}{O_n} = \frac{N_1 + N_2 \Phi S_o + N_3 Y_o}{N_4 + N_5 \Phi (1 - S_o) + N_6 (1 - Y_o)} \] ..........(3)
\[ R_f = \frac{C_f}{O_f} = \frac{F_1 + F_2 \Phi S_o + F_3 Y_o}{F_4 + F_5 \Phi (1 - S_o) + F_6 (1 - Y_o)} \] ..........(4)

which have two unknowns. The solution to these equations
yields the borehole holdup and the volume of formation oil.

The above analysis assumes that the borehole fluid is a
homogenous mixture of oil and water as is the case with
vertical wells. However, in horizontal wells, the segregated
borehole fluid can introduce nonlinearity into the analysis.
The purpose of the following analysis is to characterize the
effect of this nonlinearity on the determination of holdup in a
horizontal well. The data used for this analysis will include
eight points per formation porosity, i.e., oil and water in the
formation with four different oil/water combinations in the
borehole depicting several holdups with segregated flow (see
Table 3). The data points shown will be from modeling (the
measured data show the same result.)

For this analysis, the coefficients for the interpretation
model are calculated from the four endpoint measurements of
the formation being considered as described above. These
coefficients are then applied to the other four data points of the
data set to look at the linearity effects with segregated
borehole fluid. (This approach solves for both the oil
saturation and holdup simultaneously). The results of this
analysis can be seen in Fig. 5 for a centered and eccentered
tool.

The top plot of Fig. 5 shows the reconstructed oil holdup
for data modeled in a 7-inch casing (8.5- and 10-inch
boreholes). The reconstructed holdup is extremely nonlinear if the tool is eccentered. In this case, it appears that the tool does not see the top third of the borehole due to the nonlinearity. If the tool is centered, then the tool response is fairly linear.

Since the effect being observed is a nonlinearity caused by the tool's limited depth of investigation, the effect should be reduced in a smaller casing size. The bottom plot of Fig. 5 shows modeled results for a 5.5-inch casing in a 8.5-inch borehole. As can be seen, the effect is reduced, but still a significant issue.

Table 4 summarizes the results of this 2-phase holdup analysis using C/O ratios. This table includes RMS accuracy estimates and 18-second precisions for this measurement. From these data, it is obvious that a centered tool always gives better accuracy and precision than an eccentered tool. However, if the tool must be run eccentered, accuracy can be improved by making corrections based on calibrations of tool response as shown in the plots of Fig. 5. The effect of this approach is reduced sensitivity to low oil holdups.

Another interesting result of this analysis is that for measurements using the RST-A tool, where the borehole fluid is unknown, a centralized tool will give better precision on formation oil saturation than an eccentered tool. However, if the tool must be run eccentered, accuracy can be improved by making corrections based on calibrations of tool response trends fairly straightforward. Also note that the inelastic near/far ratio response is quite orthogonal from the other responses, giving a clean gas signal. The near and far C/O ratios show a similar response; however, they are orthogonal enough to differentiate the borehole and formation signals.

3-Phase Holdup Determination

To determine the holdup of all three phases using the near and far C/O ratios and the inelastic near/far ratio, a two-step interpretation is currently used (these could be combined into a single step). The interpretation is based on the assumption that the three borehole holdups sum to unity and that formation gas is zero, i.e., $Y_o+Y_w+Y_f=1$ and $S_o+S_w=1$.

The first step is to obtain the gas holdup from the inelastic near/far (N/F) ratio. This is obtained from calibration data similar in form to those shown in Figs. 3 or 4 and can be expressed as:

$$Y_t = f(\%)$$

Once the gas holdup is determined, the water and oil holdups can be determined using a modified version of the normal RST C/O interpretation. The modifications made are to allow for the inclusion of gas holdup into the formulation as shown below:

$$R_n = \frac{N_1 + N_2 \Phi S_o + N_3 (Y_o + Y_f (\text{\%}))}{N_4 + N_3 \Phi (1-S_o) + N_5 (1-Y_o - Y_t)}$$

$$R_f = \frac{F_1 + F_2 \Phi S_o + F_3 (Y_o + Y_f (\text{\%}))}{F_4 + F_2 \Phi (1-S_o) + F_5 (1-Y_o - Y_f)}$$

where $\rho_g$ and $\rho_o$ are the downhole gas and oil densities. In these equations, the numerator and denominator have been modified from the original RST interpretation (Eqs. 3 and 4) to allow for the contribution of gas in the borehole. In the denominator, this results in a reduction of the amount of oxygen present in the borehole. In the numerator, it is assumed that gas will increase the carbon response by a factor approximated by the relative densities of gas and oil.

As with the normal C/O processing, the sensitivity factors are obtained from laboratory calibrations which use the borehole size, casing size and weight, lithology, and porosity as inputs. Once the C/O ratios are measured and the gas holdup is calculated from Eq. 5, Eqs. 6 and 7 reduce to two equations and two unknowns that can then be solved for the holdup and oil saturation.

In this formulation of the problem, it is assumed that the tool is equally sensitive to all sections of the borehole. As has been shown, this is a reasonable assumption if the tool is centered; however, if the tool is eccentered, this formulation will introduce some bias. Under many conditions, this bias can be reduced by providing a correction based on data similar to those in Fig. 5.

3-Phase Holdup Results - Centered Tool

The interpretation procedure outlined above has been applied to the measured and modeled 3-phase data obtained in this study to evaluate the expected performance of this measurement. This includes the measured data (with air) and the modeled data (with air and 0.3 g/ml gas).

An example of the measurement parameters for a 16-p.u. oil-saturated limestone formation with an 8.5-inch borehole and 7-inch, 23-lb/ft casing is shown in Fig. 6 in a three-dimensional plot. In this plot, the corners of the plots represent the conditions when only a single phase is present in the borehole, i.e., $Y_w=1$ is all water, $Y_o=1$ is all oil, and $Y_g=1$ is all gas (0.3 g/ml in this example). From one corner to another, the fraction of each phase changes linearly along that line. The point in the center of the plot has water, oil, and gas present in equal fractions. The 'z' axis of the plot shows the magnitude of the various parameters being displayed.

The data from Fig. 6 are obtained from modeling since a realistic gas was used (0.3 g/ml). As can be observed, the modeled data are dominated by the physics of the measurement, while the statistics of the Monte Carlo calculations are small by comparison. This makes identifying the tool response trends fairly straightforward. Also note that the inelastic near/far ratio response is quite orthogonal from the other responses, giving a clean gas signal. The near and far C/O ratios show a similar response; however, they are orthogonal enough to differentiate the borehole and formation signals.

When the holdup data of this study are analyzed through the above interpretation model, one can compare the predicted holdups to the known holdups to give an estimate of the accuracy of the approach. An example of these errors in reconstruction is shown in Fig. 7 for the input data of Fig. 6. These data show that the reconstruction is fairly good. The overall accuracy of this approach can be estimated by taking RMS errors of the data. This was calculated using data for several formations with different borehole size, porosity, and
saturation. This resulted in RMS errors of 6.3, 6.1, and 4.8% for the gas, oil, and water holdups, respectively.

While the holdup calculations are performed, it is possible to estimate the precision of the holdup measurement by propagating the measurement errors through the analysis. This was done assuming 18 seconds of data accumulation for the measurement, which is equivalent to logging at 500 ft/hr using a 5-level depth average. For these conditions, the 1-σ precisions were estimated to be 1, 1.5, and 15% for gas, oil, and water holdup, respectively. These precisions will vary depending on the formation porosity, borehole size, and casing size.

For an unambiguous interpretation, it is recommended that holdup measurements in horizontal wells be performed in conjunction with velocity measurements. Since the velocity measurements are stationary measurements, a holdup measurement could be performed at the same time as the velocity measurement, giving more than adequate precision to the measurement.

Centralization Error Effects on 3-Phase Holdup

As stated previously, one of the advantages of eccentralizing the tool is that its position is well known, while attempting to centralize the tool can introduce tool positioning uncertainty. To evaluate the effect of errors in tool centralization, a series of Monte Carlo calculations were performed in which tool position was varied from fully centralized to fully eccentralized. These calculations were performed for formations with an 8.5-inch borehole in both 16 and 33 p.u. sandstone formations. The calculations were performed with two different casing sizes: a 7-inch, 23-lb/ft and a 5.5-inch, 17-lb/ft casing.

The data were analyzed to show what would happen to the calculated borehole holdups if the tool was assumed to be centralized, even when it was not. This was accomplished by calculating the near and far detector sensitivity coefficients based on data with the tool centralized. In addition, the tool gas response (Eq. 5) was based solely on the centralized tool data. These coefficients were then used with the modeled tool data for all tool positions to predict the holdups one would calculate with this centralization error.

Figure 8 shows the RMS error on the borehole holdups as a function of centralization error for the two casing sizes modeled. The RMS error calculation includes data at both porosities and with both water and oil in the formation. In the figure, the RMS error at zero centralization error is a background error level due to the nonlinearity of the response and statistics of the modeling. For both casing sizes, it appears that there is no significant increase in the RMS error up to about 0.5 inches. Based on this analysis, as long as the tool is within 0.5 inches of being centered, there is negligible effect on holdup accuracy.

Field Example

Commissioned in 1993 as the first well in the offshore section of this reservoir (18 p.u. sandstone), the well has been on continuous production with interruptions only for workovers. The horizontal section was drilled with a 8.5-inch bit and completed with a 5.5-inch, 17-lb/ft casing and cement. The
response with gas under realistic downhole conditions.

The inelastic near/far ratio was shown to be an excellent stand-alone indicator of gas holdup. This measurement is more accurate with the tool centralized in the borehole than when it is eccentered due to nonlinearities caused by tool positioning.

The 2-phase holdup (oil/water) measurement was evaluated using the near and far carbon/oxygen ratios for the effects of tool positioning. This analysis was the normal dual detector C/O analysis but used to evaluate the nonlinearities in the measurement due to segregated flow. These results indicated that the tool response could be nonlinear if the tool was run eccentered with segregated flow, but that it could also be corrected over a large part of the dynamic range with proper calibration. It was also shown that running the tool centralized in segregated flow does not exhibit this nonlinear behavior.

A fully integrated 3-phase holdup analysis was evaluated using the inelastic near/far count rate and the near and far carbon/oxygen ratios. This analysis was performed using a RST analysis modified to take into account the gas contribution. The analysis used both measured and modeled data in combination for a centralized tool. For this analysis, the estimated accuracies are approximately 6 p.u. for each of the three phases. The estimated precisions (18 seconds of data) for this measurement are approximately 1, 15, and 15% for the gas, water, and oil holdups, respectively.

A field example indicated the accuracy and precision of the 3-phase holdup measurement are in line with the predictions from the modeling. Comparison of the holdups obtained with the RST tool compared quite favorably with holdup measurements performed by another totally independent technique, establishing the validity of both measurements. In addition, this field test example demonstrated that modeling results could be used to interpret log data accurately.

Finally, this field example reaffirmed the notion that velocity or holdup measurements by themselves will not always give a correct interpretation of production problems; but that holdup and velocity measurements together can.

Acknowledgments
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Nomenclature

Φ = Porosity

BOPD = Barrels Oil Per Day

BPD = Barrels Per Day

BWPD = Barrels Water Per Day

Cn = Near Carbon Yield

Ci = Far Carbon Yield

C/O = Ratio of Carbon to Oxygen

Fn = Near Detector Sensitivity Factors

Fi = Far Detector Sensitivity Factors

N/F = Inelastic Near to Far Ratio

\[ \begin{align*}
O_n &= \text{Near Oxygen Yield} \\
O_i &= \text{Far Oxygen Yield} \\
\text{OWC} &= \text{Oil Water Contact} \\
R_n &= \text{Near C/O Value} \\
R_i &= \text{Far C/O Value} \\
RMS &= \text{Root-Mean-Square} \\
S_n &= \text{Formation Oil Saturation} \\
S_w &= \text{Formation Water Saturation} \\
Y_a &= \text{Air Holdup} \\
Y_g &= \text{Gas Holdup} \\
Y_o &= \text{Oil Holdup} \\
Y_w &= \text{Water Holdup}
\end{align*} \]

SI Metric Conversion Factors

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References


### Table 1: Borehole fluid configurations used in 3-phase holdup measurements to simulate a horizontal well.

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### Table 2: Formations used for 3-phase holdup characterization.

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<td>10 Sand</td>
<td>33</td>
<td>Water &amp; Oil</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4: Accuracy and precision (18 second) of the RST-A oil holdup measurement, Y_O, for the tool eccentered and centered in the borehole with several casings and segregated borehole fluids. This analysis solves for φS_O and Y_O at the same time.

<table>
<thead>
<tr>
<th>Porosity (p.u.)</th>
<th>Case</th>
<th>Y_O Accuracy</th>
<th>Y_O Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>16-42</td>
<td>7</td>
<td>3.4</td>
<td>18</td>
</tr>
<tr>
<td>16-32</td>
<td>5.5</td>
<td>8.9</td>
<td>14-45</td>
</tr>
</tbody>
</table>

### Table 5: Accuracy and precision (18 second) of the RST-A volume of formation oil measurement, φS_O, for the tool eccentered and centered in the borehole with several casings and segregated borehole fluids. This analysis solves for φS_O and Y_O at the same time.

<table>
<thead>
<tr>
<th>Porosity (p.u.)</th>
<th>Case</th>
<th>φS_O Accuracy</th>
<th>φS_O Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>16-42</td>
<td>7</td>
<td>3.1</td>
<td>16</td>
</tr>
<tr>
<td>16-32</td>
<td>5.5</td>
<td>4.1</td>
<td>10-45</td>
</tr>
</tbody>
</table>

### Table 3: Fluid combinations used with the data for 2-phase holdup calculations from C/O. The holdup combinations used simulated segregated borehole holdup in a horizontal well. Those combinations used for calculation of interpretation coefficients are labeled as 'endpoints'.

<table>
<thead>
<tr>
<th>S_o</th>
<th>Y_o</th>
<th>Y_w</th>
<th>Endpoint</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>0.00</td>
<td>0.33</td>
<td>0.67</td>
</tr>
<tr>
<td>3</td>
<td>0.00</td>
<td>0.67</td>
<td>0.33</td>
</tr>
<tr>
<td>4</td>
<td>0.00</td>
<td>1.00</td>
<td>0.00</td>
</tr>
<tr>
<td>5</td>
<td>1.00</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>6</td>
<td>1.00</td>
<td>0.33</td>
<td>0.67</td>
</tr>
<tr>
<td>7</td>
<td>1.00</td>
<td>0.67</td>
<td>0.33</td>
</tr>
<tr>
<td>8</td>
<td>1.00</td>
<td>1.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

---

Fig. 1: Tool positioning in borehole with different liners allowing for centered and eccentered 3-phase holdup measurements.
Fig. 2: Near C/O ratio, far C/O ratio, and inelastic near/far ratio from measurements versus the MCBEND modeled results. The line shows a linear fit to both the eccentered and centered tool data.

Fig. 3: RST-A inelastic near/far count rate ratio as a function of porosity measured in IC logging mode. The tool was run eccentered and centered in a 7-inch, 23-lb/ft casing in both 8.5- and 10-inch boreholes. Air was used to simulate gas for these measurements. The lines are drawn to show the trends in the data for various air holdups in the borehole.
Fig. 4: RST-A inelastic near/far count rate ratios as a function of porosity modeled in IC logging mode. The tool was modeled eccentered and centered in a 7-inch, 23-lb/ft casing in both 8.5- and 10-inch boreholes. Gas was modeled with a density of 0.3 g/ml. The lines are drawn to show the trends in the data for various air holdups in the borehole.

Fig. 5: Reconstructed holdup from modeled data in which the interpretation coefficients were calculated from the endpoint measurements in 7- and 5.5-inch casing. These data include only oil and water in the borehole and formation. The interpretation solved for both $Y_0$ and $\phi S_o$ simultaneously. The line is drawn to indicate perfect reconstruction.
Fig. 6: Modeled response of the RST-A tool to changes in segregated borehole fluid composition for a 16-p.u. limestone formation with a 8.5-inch borehole and a 7-inch, 23-lb/ft casing. The data were modeled using gas with a density of 0.3 g/ml.

Fig. 7: Error in the reconstruction of borehole holdups using the modeled data of the RST-A tool. The formation used for this analysis was a 16-p.u. limestone formation with a 8.5-inch borehole and a 7-inch, 23-lb/ft casing. The data were modeled using gas with a density of 0.3 g/ml.
Fig. 8: Error on the 3-phase holdup estimate for a tool that is assumed to be centralized when it is really off-center. The RMS error calculation includes data for both 16 and 33 p.u. sandstone formations with both water and oil in the formation. In addition, the data include boreholes with 3-phase segregated fluids. For both casing sizes, it appears that there is no significant increase in the RMS error up to about 0.5 inches. Based on this analysis, as long as the tool is within 0.5 inches of being centered, then there is negligible effect on the holdup accuracy.

Fig. 9: Example of production logging measurements performed in a horizontal well drilled with an 8.5-inch bit and completed with a 5.5-inch, 17-lb/ft cemented casing. The measurements include PVL and WFL water velocity measurements, PVL oil velocity measurements, and RST and LIFT holdup measurements. The lines on the plot connecting the data have been added to help indicate the trends.