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A New Yield Power Law Analysis Tool Improves Insulating Annular Fluid Design

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Abstract

Engineering analysis can help avoid significant problems in deep offshore completions. Because yield-power-law fluids offer better convective heat-loss control, new algorithms have been developed that allow the modeling of convective heat transfer through such fluids. Special cases – Newtonian, Bingham Plastic, and power law – were also included in this model. This new software permits appropriate annular fluid design to avoid low-temperature-related problems such as hydrates, paraffin deposition, precipitation of salts at high pressure and casing collapse in un-vented annuli when multiple casing strings are used.

Yield-power-law fluids have viscosities that increase significantly as shear-strain rates diminish. As control over heat loss due to convection is developed, the shear-rate environment drops and viscosity of the yield-power-law fluid increases, reducing convective heat loss further. These fluids also tend to have relatively low high-shear-rate viscosity, making them easier to place and displace.

This paper explores the use of this novel engineering tool to show how changes in physical properties of the annular fluids, boundary conditions like bottomhole temperature (BHT), and fluids configurations in the wellbore result in changes in the temperature profiles in deep offshore wells – both “dry-tree” and sub-sea completions. These parametric analyses are then used to create practical general guidelines for the selection of annular fluids to meet the performance requirements in deep offshore wells and to avoid the physical and chemical problems that could arise.

Introduction

An engineering design tool, to be designated here as YPL-WTP, for “yield-power-law, wellbore-temperature-profile” program, was created to simulate wellbore temperatures during production, shut-in and injection. The program solves the energy equation for multiple casings.[1-7] The solutions depend on the physical properties of the annular fluids, sea floor, wellbore geometry, and geological boundary conditions, and the fluids’ configuration in the wellbore. The following parameters were studied:

- Bottomhole temperature (BHT),
- Rheological properties of both oil-based and water-based power-law (PL) and yield-power-law (YPL) fluids,
- Thermal conductivity,
- Well depth (TVD),
- Thickness of a gas-filled A annulus (with an insulating-fluid-filled B annulus) [the gas has been assumed throughout this study to be low-pressure nitrogen],
- Heat capacity,
- Location of the interface between gas [low-pressure nitrogen] and brine in a gas-filled A annulus,
- Thickness of an insulating-fluid-filled A annulus with no B annulus,
- Oil flow rate,
- Location below the mud line of the bottom of the insulating fluid,
- Seawater flow rate, and
- Coefficient of thermal expansion.

Many previously published algorithms for solving this type of problem[1-13] are based on mathematics that assumes that fluids involved have Newtonian or power law (PL) rheological properties. Key studies[8-13] on convective heat transfer for insulating fluids emphasize the use of non-Newtonian fluids with high yield stress. Algorithms used in developing YPL-WTP, are based on essentially the same mathematics[11,14,15]; however a significant distinction is that Herschel-Bulkley (or yield power law) fluids can also be simulated for non-Newtonian fluids with a high yield stress. Newtonian, Bingham plastic, and PL models were also included in YPL-WTP as special cases.

Benchmarking YPL-WTP against Other Calculations

In order to benchmark the YPL-WTP engineering tool, results were compared against the published literature, particularly the excellent recent publications by Vollmer, Fang, Wang, Javora, and their colleagues.[8,9] There was very little difficulty in matching their results (**Figure 1**); however, “reasonable” assumptions had to be made for some of the inputs to YPL-WTP.

The measured and predicted data of **Figure 1** and

Reference 8 (Figure 2) involve Newtonian or PL fluids and utilize mathematics detailed elsewhere.[8,10,11] As mentioned, Newtonian and PL models were included in YPL-WTP as special cases, and **Figure 1** indicates that the mathematics built into YPL-WTP is working as expected for Newtonian and PL fluids.

However, to include the broader case of YPL fluids, the generalized Metzner-Reed[16,17] approach was used to approximate rheological properties for these fluids. Results are shown in **Figures 2a** and **2b**, indicating that predicted flowing surface temperatures were 9 to 13°F higher when the insulating packer fluid is modeled as a YPL fluid rather than a PL fluid. The YPL-WTP predictions shown in **Figures 2a** and **2b** were performed with water-miscible fluids having the rheological properties given in **Table 1** along with PL rheological properties.

The 600 and 300 rpm dial readings, of course, are matched in **Table 1** for both YPL and PL fluids, while the PL model fitted-data do not match the 200, 100, 6, and 3 rpm dial readings. As a result, there was a temptation simply to utilize an approach as advocated in API RP 13D,[18] which fits the rheological data with two PL models, one that fits the 600 and 300 rpm dial readings and a second that fits the 100 and 3 rpm dial readings.

This approach does indeed do a much better job of fitting the rheological data of **Table 1**; however, when the YPL-WTP was used along with the API RP 13D[18] approach, the 9 to 13°F higher flowing surface temperature difference shown in **Figures 2a** and **2b** was only reduced to about 5 to 9°F. It is clear that the API RP 13D[18] approach is an improvement, but is insufficient to the task addressed here, which is much more than simply fitting the 600, 300, 100, and 3 rpm dial readings. The task here is that of modeling more realistically the convective heat transfer behavior of fluids in the shear rate range below 10 sec^{-1}, where the YPL model appears to more accurately address both the rheological and heat transfer behavior of real fluids.

YPL-WTP Engineering Tool

To reduce <u>conductive</u> heat loss, it is important that the annular insulating fluids have inherently low thermal conductivity, in the range of 0.07 to 0.30 BTU/hr·ft·°F. Thermal conductivity values discussed in this paper are derived from measurements[19,20,21] in the M-I SWACO laboratories. To reduce <u>convective</u> heat loss, it is important for the fluids to have a high yield stress (also referred to as τ_y), in the range of 10 to 105 $lb_f/100\ ft^2$. Including the yield-power-law model was considered critical to this engineering tool development because YPL fluids have the very rheological properties that are so important for an insulating fluid to perform well.

Yield-power-law fluids have viscosities that increase significantly as shear-strain rate diminishes. By imparting viscosity to the fluid, the engineer can gain partial control over heat loss due to convection, and the shear-rate environment will trend toward zero. The difference with a YPL fluid is that as the shear-rate trends toward zero, the viscosity of the YPL fluid increases significantly, further reducing convective heat loss. YPL fluids also tend to have relatively low high-shear-rate viscosity, making them easier to place initially, to bleed off pressure that may build up in annuli equipped with venting capability, and to displace in the event a well intervention is needed.

The YPL-WTP software permits the user to input the variables listed at the beginning of the paper to calculate the temperature profiles or the temperature and pressure at the mud line (ML). The software allows appropriate annular fluid design to assist in avoiding low-temperature-related problems such as hydrates, paraffin deposition,[9] precipitation of salts at high pressure and casing collapse[22,23] in un-vented annuli when multiple casing strings are used. **Figure 3** illustrates one of the complex wellbore configurations that can be modeled in the YPL-WTP software. Of particular note is the ability to model a fluid-filled B annulus (where the fluid is an insulating fluid or not) with a gas-filled or an insulating-fluid-filled A annulus.

It will be apparent from the studies described below that the performance demands on an insulating fluid are reduced significantly when a gas-filled A annulus is employed in conjunction with a B annulus filled with the insulating fluid. A further approach to reducing both the conductive and convective heat losses through the wellbore annuli is to employ vacuum insulated tubing (VIT).[24,25] A future revision of the engineering tool described here will include the option to employ VIT in the wellbore configuration. The new software in its current form approximates VIT as a gas-filled annulus.

YPL-WTP allows the user to output selected parts of the data to an EXCEL spreadsheet. The spreadsheet allows further subsequent graphing and processing of the temperature profile data. One example of such further processing is to input calculated temperature profiles into another program that calculates the pressure profile in a trapped annulus. Future development of YPL-WTP is planned that will have the capability within the program to calculate the pressure build-up in any un-vented or “trapped” annulus thus providing more accurate pressure projections.

Another approximation built into the present version of YPL-WTP is that the produced fluid column will always be single phase – *i. e.*, (1) the produced fluid is only oil that is enough above its bubble point and does not flash off solution gas as the oil rises in the wellbore to depths where pressures are lower than the bottomhole producing pressure (BHFP), and (2) the produced fluid is all gas not in the retrograde region, if any, of its phase diagram. Future development will incorporate a PVT package.

Temperature Profile

An example of the output from YPL-WTP is given in **Figure 4,** showing downhole temperature profile. On the left of the figure is a graph of depth (in thousands of feet) *versus* the temperature of three key areas – the oil column, the insulating fluid in the A annulus, and the "formation". The "formation" temperature plotted in this view is that of a "virtual cylinder" whose diameter is that of the outside of the outer-most wellbore annulus. The A annulus temperature plotted in this view is that of a "virtual cylinder" whose diameter is an average of the outside and inside of the A annulus. The oil column temperature plotted in this view is the temperature profile in the central axis of all of these "virtual cylinders".

In the case depicted, the simulation is that of a "dry tree" oil well completion, so the "formation" below the mud line is truly the formation, and above the mud line, it is sea water. The seawater temperature profile is that typical of deepwater Gulf of Mexico in the spring. Shallow-water-temperature profiles vary considerably from time to time, but this variation is not important for deepwater wells. The important aspects of deep seawater temperature profiles are (1) that the shallow water (less than several thousand feet) day-to-day and week-to-week variation is not critical to deep well thermal performance as long as the seasonal variation is captured in the simulation and (2) that the seasonal and year-to-year variation in deep water (greater than several thousand feet) is less than 1°F.

On the right in **Figure 4** is a simulation of the wellbore thermal environment, showing the color-coded temperature as a function of depth. The simulation shown in **Figure 4** is a for well that has been producing for 48 hr, during which time the wellbore thermal environment had warmed to a pseudo steady state, from an initial state of long-term shut-in.

Both deviated and vertical wells are represented in this view by their measured depth, making deviated wells appear vertical just for the convenience of depicting the well at an "informatively" large scale in a relatively compact section of the display.

Temperature and Pressure at the Mud Line

The simulation depicted in **Figure 5** is that of a "dry tree" completion producing oil in deep water in the Gulf of Mexico in spring. The well had been producing for 72 hr, during which time the wellbore thermal environment had warmed to a steady state, from an initial state of long-term shut-in. After reaching the warmed-up steady state, the well was shut in for an extended period, during which it cooled again to a second semi-steady state, similar to the initial conditions.

The output from YPL-WTP is given in **Figure 5**, showing a view of the temperature and pressure at the mud line. On the left is a graph of the temperature and pressure versus time for six key areas – the oil column, the insulating low pressure nitrogen in the A annulus, the insulating fluid in the B annulus, the cement in the C annulus, the cement in the D annulus, and the "formation".

In this example, the produced oil had a hydrate formation temperature of 68°F at bottomhole shut-in pressure (BHSP), so the user needed to know the shut-in time for the well to cool to 68°F in the producing stream, *i.e.,* the "Shut-in $\text{Time}_{\text{to 68°F}}$" ($SIT_{68}$) in order to schedule an intervention in the well. **Figure 5** shows that at temperatures above 68°F, about 16 hr of shut-in time is available (after the 72 hr production). If that intervention showed the potential to extend beyond 16 hr, it would be necessary to displace the well with some non-hydrate-forming fluid to at least about one-third-way between ML and TVD to avoid hydrate problems.

For clarity and comparison purposes, all of the calculation results reported henceforth are summarized in terms of the "SIT_{68}".

It has been established that YPL-WTP is at most incrementally different from previously published models and gives essentially similar results for Newtonian or PL fluids (**Figure 1**); but YPL-WTP provides important new insights (**Figure 2**) where the YPL model more accurately addresses the rheological behavior of the insulating annular fluid. With that basis established, to move forward we first had to introduce some of the characteristics of the software. Now we turn to a parametric analysis to investigate the effect of key variables on downhole temperature profiles.

Important YPL-WTP Parameters

To generate the data discussed in this paper, more than 150 simulations were run using the YPL-WTP, for various combinations of input parameters and wellbore configurations. In most cases, the study varied only one parameter at a time while artificially holding every other parameter constant. Data shown in **Table 2** indicate parameters that have the greatest impact on SIT_{68}. For simplicity and consistency, all of the wells compared in the remainder of the present study were assumed to have been completed at 15,000 ft TVD and are compared in terms of SIT_{68}.

The second column in **Table 2** presents values selected as "reasonable" variations in the parameters. Instead of performing calculations using YPL-WTP for large ranges such as BHT from 40°F to 400°F, the authors chose to focus on a range that was arbitrarily designated as more "reasonable" – BHT from 125°F to 350°F. Likewise, the coefficient of thermal expansion ranges from 1.18 to 4.56×10^{-4}/°F because the former value is that of a typical $CaCl_2$-based brine; and the latter, a typical synthetic-based drilling fluid.

To illustrate the importance of the various parameters and their distinct effects, the rows in **Table 2** are sorted in the order of decreasing span of the calculated values of SIT_{68} (difference between the minimum and maximum values). Parameters that have the greatest range of calculated SIT_{68} values were considered to have the highest impact, variability, or effect on fluid behavior. This analysis shows that relatively important parameters include the bottomhole temperature, the rheological properties of oil-based YPL fluids, the thermal conductivity, the well depth, and the thickness of a gas-filled A annulus (with an insulating-fluid-filled B annulus). These parameters will be discussed in further detail.

Because the rheological properties of oil-based YPL fluids came out as some of the more important parameters studied, it should be noted that rheology deals not with a single parameter, but with three. The yield power law equation (Herschel-Bulkley) is as follows:

$$\tau = \tau_y + k_m \gamma^{n_m} \quad (1)$$

where τ is the shear stress (lb_f/100 ft^2),

τ_y is the yield stress (lb_f/100 ft^2),

k_m is the consistency factor,

γ is the shear rate (s^{-1}), and

n_m is the flow behavior index,

Likewise, the power law equation is as follows:

$$\tau = k\ \gamma^n \quad (2)$$

It should be noted that the bottomhole temperature, the rheological properties, and the other parameters were studied individually; however the influence of boundary conditions on multiple parameters may couple in non-linear ways, thereby increasing the importance of "relatively minor" parameters and requiring a higher performance from the insulating fluid.

This paper also discusses a few of the less important parameters – for example, the rheological properties of water-based YPL and PL fluids because of their relationship to each other and to the rheological properties of oil-based YPL fluids.

Bottomhole Temperature and Water Depth

BHT and well depth (TVD) are uncontrollable parameters, but have very important implications for insulating fluid design and deployment. BHT emerged as the single most important parameter of all and water depth as the fourth. It is important to point out some important implications – namely, that the effects of the two parameters are strongly interdependent on each other. Since the BHT and water depth are important but uncontrollable parameters, the fluid and well must be engineered to deliver the necessary performance from the insulating fluid.

YPL-WTP simulations show that, for a well in deep water (WD 6,300 ft), and completed at around 15,000 ft TVD at a BHT around 175°F with a gas-filled A annulus and an insulating fluid-filled B annulus, there may be little difficulty in achieving 24-hr shut-in times with a relatively inexpensive water-based insulating fluid.

In contrast, YPL-WTP simulations show that for a well in deep water (WD 6,300 ft), and completed at around 15,000 ft TVD at a BHT below 175°F without a gas-filled annulus, the insulating fluid needs to be a high performance oil-based YPL fluid with a large τ_y, in the range of about 50 lb_f/100 ft^2 or higher. Similar fluid will also be needed for a well in moderately deep water, around 3,100 ft, and completed at around 15,000 ft TVD at a BHT below 150°F, also without a gas-filled annulus.

To achieve longer safe shut-in times, especially if the hydrate formation or wax appearance temperatures are higher, say, 77°F instead of 68°F, there may be a further need to engineer in additional features such as (1) a thick gas-filled A annulus with a high performance oil-based YPL fluid in the thick B annulus or (2) VIT to at least 1500 ft below ML, with at least a water-based YPL fluid in the annulus outside the VIT.

For more demanding situations, such as deeper water or when hydrate formation or wax appearance temperatures are higher, there may be a further need to engineer in additional features in the well design as well as the insulating fluid choice as indicated above. As broad as the present study has been, nevertheless there are clearly other parameters that could have been included, for example, TVD and hydrate formation temperature.

Rheological Properties

Rheological properties of both oil- and water-based fluids can be manipulated by appropriately selecting additives. For example, the addition of a mono-saccharide in various concentrations can be used to manipulate the viscosity of a water-based fluid, but the rheological properties are typically Newtonian. Similarly, the addition of a polysaccharide like HEC in various concentrations can be used to manipulate the viscosity of a water-based fluid, but the rheological properties are typically power law in character; and the addition of a biopolymer can be used to manipulate the viscosity of a water-based fluid, but the rheological properties are typically yield power law in character. To get a water-based PL fluid with n = 0.99 (nearly Newtonian), a fluid can be blended with a relatively large amount of a mono-saccharide and a small amount of a polysaccharide. To get a water-based YPL fluid with n_m = 0.99 (Bingham Plastic), a fluid can be blended with a relatively large amount of a mono-saccharide and a small amount of a biopolymer.

Likewise, it is not difficult to manipulate rheological properties of oil-based Newtonian and PL fluids. The difficulty until recently, has been to produce a low-thermal-conductivity oil-based YPL fluid. Oil-external emulsions that are YPL fluids have been known for some time; but unless the internal brine phase volume is only around 1 to 5%, the thermal conductivity of the oil-external emulsion is too high to make it a suitable oil-based YPL fluid. Therefore, oil-external emulsions have not been included in the present study.

Because of the previous difficulty with producing low-thermal-conductivity oil-based YPL fluids, the present study began with formulating three such oil-based fluids. When the rheological properties were measured at 70 and 180°F, the fluids proved to be YPL fluids, as shown in **Table 3** for Fluids 1-3 at 70°F and 180°F. Three other oil-based fluids were viscosified and their rheological properties at 70 and 180°F proved to be those of PL fluids, and shown in **Table 4**.

To make it less difficult to understand the role of specific rheological parameters, theoretical oil-based YPL Fluids 4-6 were simulated with similar high-shear-rate rheology as fluids 1-3, but with different low-shear-rate rheology. For the same reasons, theoretical oil-based YPL Fluids 7-9 were simulated with similar low-shear-rate rheology but different high-shear-rate rheology.

Because of the facility in manipulating the rheological properties of water-based fluids, as discussed earlier, it was decided that water-based fluids could also be viscosified in such a way as to match the values for Fluids 1-3 in **Table 3**. For simplicity and consistency, all of the YPL fluids of the present calculation series were endowed with the 70°F and 180°F values given for Fluids 1-3 in **Table 3** – both oil- and water-based.

Similar statements can be made for the rheological properties of water-based Newtonian and PL fluids; therefore, it was considered readily achievable that some mixture of water-based PL fluids and Newtonian fluids could be blended to realize the rheological properties presented for PL Fluids 1-3 in **Table 4**.

Again, to make it less difficult to understand the role of specific rheological parameters, water-based theoretical Fluids 4-9 were created. Fluids 4-6 were simulated with similar high-shear-rate rheology but with different low-shear-rate rheology; likewise Fluids 7-9 were simulated with similar low-shear-rate rheology but different high-shear-rate rheology. For simplicity and consistency, all of the PL fluids of the present calculation series were endowed with the 70°F and 180°F values given in **Table 4** – both oil- and water-based.

Rheological Properties of Yield Power Law Fluids

The values of SIT_{68} for water-based YPL Fluids 1-3 are plotted *versus* n_m at 70°F in **Figure 6**, *versus* k_m at 70°F in **Figure 7**, and *versus* τ_y at 70°F in **Figure 8**. The data for water-based YPL Fluids 1-3 are calculated using the same rheological properties as for oil-based YPL Fluids 1-3, although the SIT_{68} results ranged from 8.5 hr to 14.1 hr for water-based YPL Fluids 1-3 and from 21.8 hr to 43.7 hr for oil-based YPL Fluids 1-3 (**Table 3**). Except for having a smaller span of values (difference between the maximum and minimum values), trends of SIT_{68} *versus* the three parameters, n_m, k_m, and τ_y, seen for water-based YPL Fluids 1-3 correspond to those for oil-based YPL Fluids 1-3, respectively.

The difference between the values of SIT_{68} for water-based fluids and those for oil-based fluids seem to be primarily governed by the difference in thermal conductivity and secondarily by the difference in heat capacity. There is not a direct proportionality, however. The conjunction of these parameters – thermal conductivity, heat capacity, and rheological properties – seems to be both un-proportional and even non-linear.

If only the water-based YPL fluid data set is analyzed, and ignoring the oil-based fluids, it is very difficult to infer the relative importance of the three parameters, n_m, k_m, and τ_y, from **Figures 6-8** (water-based fluid data). A similar conclusion can be drawn if only oil-based YPL fluid data is analyzed while ignoring the water-based data set.

In response to this difficulty, six "theoretical" fluids were created based on the laboratory measured rheological properties for YPL Fluids 1-3. Theoretical though they may be, these rheological properties do reveal more clearly the relative importance of the three parameters, n_m, k_m, and τ_y. In the set of rheological values for YPL Fluids 1-3, both low shear rates and high shear rates are changing simultaneously, whereas n_m and k_m are more significantly affected at high shear rates and τ_y, at low shear rates. It was decided therefore to create theoretical YPL Fluids 4-6 wherein the high-shear-rate data are essentially constant while the low-shear-rate data vary, and theoretical YPL Fluids 7-9 wherein the low-shear-rate data are essentially constant while the high-shear-rate data vary.

It can be seen from a comparison of the data in **Table 3** that varying the low-end rheology while keeping the high-end rheology constant (Fluids 4-6) results in a systematic variation in SIT_{68}. Because the low-end rheology primarily affects the value of τ_y, **Figure 9** shows the dependence of SIT_{68} on the value of τ_y. The plot in **Figure 9** of SIT_{68} *versus* τ_y indicates that increasing τ_y results in a significant increase in the SIT_{68}.

The data in **Table 3** for these same fluids show very poor correlation of SIT_{68} with n_m and k_m. For the data for both water-based and oil-based YPL fluids when τ_y varies little, a series of 3-dimensional correlations of SIT_{68} *versus* n_m and k_m were made, ignoring the fourth dimension, τ_y. None of these several hundred correlations stand out as particularly good correlations; however, in all cases studied SIT_{68} increases with decreasing n_m and increasing k_m.

Clearly, SIT_{68} is strongly affected by τ_y, while data shown in **Table 3** indicate that for "theoretical" water-based YPL Fluids 7, 8, and 9, SIT_{68} values are essentially constant when τ_y is held constant even though n_m and k_m vary substantially.

As mentioned, a similar analysis was made of the oil-based YPL fluids and the same conclusion was reached that τ_y is the primary rheological parameter determining the SIT_{68}.

Rheological Properties of Power Law Fluids

The implications of the fact that YPL fluids with the smallest τ_y are also associated with the smallest SIT_{68} values continue. Likewise, as can be seen in **Table 4**, the water-based PL fluids studied here have SIT_{68} values that range from 3.7 to 8.6 hr, substantially smaller than the corresponding water-based YPL fluids. This observation only further underscores the statement made earlier that τ_y is the primary rheological parameter determining the SIT_{68}. The fact that τ_y with PL fluids has dropped to its minimum value (=0) continues to have implications, namely, that the PL fluids have yet smaller SIT_{68} values. Within this range of small SIT_{68} values, the values do become somewhat larger when n_m decreases and k_m increases, just as for YPL fluids.

Thermal Conductivity

After bottomhole temperature and rheological properties of oil-based YPL fluids, thermal conductivity is the next most important parameter in determining SIT_{68} values, as can be seen in **Table 2**. Oil-based fluids inherently have a lower thermal conductivity than water-based fluids.

In one part of the study, the thermal conductivity and heat capacity were allowed to vary at the same time as the rheological properties. The results were very complicated to interpret because the rheological property effects were difficult to understand; however, the influences of thermal conductivity and perhaps heat capacity were so strong that they seemed to over-ride much of the effects of the rheological properties, especially those of the secondary rheological properties, n_m and k_m.

Annulus Thickness

Annulus thickness appears in **Table 2** twice. First and most importantly in connection with a gas-filled A annulus when an insulating fluid is used in the B annulus. The second time is in connection with one of the parameters of lesser importance, the thickness of an insulating-fluid-filled A annulus with no B insulating annulus. Although the series is not included in the present study, it would seem reasonable to conclude that somewhat better SIT_{68} values would be obtained from the conjunction of a thick gas-filled A annulus when a highly insulating oil-based fluid is used in a thick B annulus. The expectation is that at some point on both A and B annulus thickness, and on insulating properties of the fluid in the B annulus, there would be reached a "point of diminishing returns". We have not approached that point in the present study.

Location of the Bottom of the Insulating Fluid

Table 2 includes two entries related to vertical location. The more important of the two is the location of the interface between gas and brine in a gas-filled A-annulus. This is mostly true because of the low thermal conductivity of low-pressure nitrogen. When the thermal conductivity parameter combines with the location parameter, the combined parameter becomes fairly significant.

The other parameter in **Table 2** related to vertical location is the location below the mud line of the bottom of the insulating fluid. Although the insulating fluid in this case had a low thermal conductivity, it was nevertheless higher than that of low-pressure nitrogen.

In both location-related parameters, what is being exploited is the extra heat from the deeper parts of the formation below the mud line. The formation at and just below the mud line has had periods of time on the geological scale to exchange heat with the very deep, cold seawater. Additionally, the heat transfer between the wellbore and the formation is typically more efficient than that between the riser and the cold seawater because the former is a solid-to-solid heat transfer, while the latter is solid-to-liquid. Therefore, often a higher overall heat transfer coefficients is seen below the mudline rather than in the deepest, coldest water. Moving the location of the interface between gas and brine in a gas-filled A annulus to a greater depth below the mud line means that the gas will be continuing to play its insulating role to a depth that by-passes some of the most efficiently heat-dissipating parts of the formation. The same is true of moving the location of an insulating-fluid-filled A annulus to a greater depth below the mud line of the bottom.

Seawater Flow Rate

It was surprising to see in **Table 2** that the seawater flow rate was only a minor parameter; however, it is conceivable that this parameter may become more important in wells with seawater flow environments higher than the 40 ft/min which was the highest rate included in this study.

Pressure Build-up in Trapped Annuli

A typical run of YPL-WTP with the temperature profile was exported into a spreadsheet. Subsequently, the data in the spreadsheet was input into a program that predicts annular pressure build-up that occurs when the temperature profile of the annulus changes, referred to in **Figure 10** as "post-processing". The post-processed data from YPL-WTP for an un-vented B Annulus show a rapid build-up of pressure early in the interval just after a well under long-term shut-in or pre-production conditions is switched to production. The objective here was not to show a systematic study, but simply to point out the capability and raise the issue. Further development of YPL WTP could bring the calculation inside the program and will not require the output to be post-processed by another program.

Subsea Completions

Subsea completions are simulated with an approximation that represents a subsea completion as a “dry tree” lying in water that is only 30 feet deep and has a surface and mudline temperature of 39.7°F. The resulting below-mudline temperature profiles were quite similar to those of “dry tree” completions with a mudline below 4700 feet of seawater. Clearly, the simulation misses a dimension of secondary influence, namely that the pressure environment is inaccurate. Fortunately, pressure is not a parameter of major influence, as is evident from the fact that the below-mudline temperature profiles were the same to three significant figures for both the simulated subsea and the “dry tree” completions with a mudline below 4700 feet of seawater even though the pressures in the two cases were considerably different in every respect. Nevertheless, future development of YPL WTP will improve this type of simulation by providing a more accurate pressure environment.

Conclusions

An important role for the new engineering tool is modeling the rheological and heat transfer properties of an insulating annular fluid where the YPL model is more accurate than previously modeled Newtonian or PL fluids. Under these circumstances, there are significant convective heat transfer consequences of the rheological behavior of the fluids, especially in the shear rate range below 10 sec^{-1}. Future work will focus on the shear rate range below 10, and even down to around 0.01 sec^{-1}, where the rheololgical and heat transfer differences between YPL and PL fluids are expected to be even greater.

The parametric analysis performed in this study led to the following order of importance:

1. Bottomhole temperature.
   Wells that deliver substantial amounts of heat from the bottom hole to the mudline will not make the heavy demands on the properties of the insulating fluid as will wells with low bottomhole temperatures.
2. Rheological properties of oil-based YPL fluids.
   Of the rheological properties, τ_y is the most important while n_m and k_m are secondary. When τ_y is constant or varying little, the Shut-in $Time_{to\ 68°F}$ (SIT_{68}) data generally increase with decreasing n_m and with increasing k_m.
3. Thermal conductivity of insulating fluids.
   One of the key ways that oil-based YPL fluids differ from water-based is in the much lower thermal conductivity of the oil-based fluids.
4. Water depth.
   Wells in deeper water will make greater demands on the performance of the insulating fluid.
5. Thickness of a gas-filled A annulus (with an insulating-fluid-filled B annulus).
   This configuration requires less insulating performance of the annular fluid than configurations without the gas-filled A annulus. Currently, vacuum insulated tubing (VIT) can be simulated as a gas-filled A annulus in YPL-WTP. Our expectation is that VIT[24,25] will perform better than the gas-filled A annulus, which might increase the impact of this factor and that, in turn, would make less demands on the performance of the insulating fluid. Because of this expected importance, future development of YPL-WTP will incorporate the VIT feature.
6. Heat capacity of insulating fluids.
   Unlike in other studies,[3] the heat capacity of the insulating fluid played a relatively minor role compared with the fluid properties listed above.
7. Rheological properties of water-based YPL fluids.
   Though the variation in the SIT_{68} is much smaller for water-based YPL fluids than for oil-based YPL fluids, the conclusion again is that τ_y is the most important while n_m and k_m are secondary. When τ_y is constant or varying little, the SIT_{68} data generally increase with decreasing n_m and with increasing k_m.
8. Location of the interface between gas and brine in a gas-filled A annulus.
   In a gas-filled A-annulus configuration, the extra heat from the deeper parts of the formation below the mud line is exploited to offset the less-insulating properties of the brine. A greater advantage of the more insulating properties of the gas can be achieved by increasing the depth of the interface between the gas and brine.
9. Thickness of an insulating-fluid-filled A-annulus when there is no B annulus.
   In the absence of a gas-filled A annulus, the best approach appears to be to increase the thickness of a fluid-filled A annulus. Within the range of the parameters studied, thicker fluid-filled annuli gave better insulation and less demand on the properties of the fluid. The expectation is that at some point, there would be a “point of diminishing returns” on the thickness of the insulating fluid, but we have not approached diminishing returns in the present study.

10. Rheological properties of water-based PL fluids.
    Because τ_y is constant (and equal to 0), n and k are the only rheological parameters in the power law equation. As above, the SIT_{68} data generally increase with decreasing n and with increasing k.
11. Oil flow rate.
    Prolific wells will place lesser demands on the performance of insulating fluids. As production drops over the life of a well, the same originally prolific well may require more performance from insulating fluids later in its production lifetime.
12. Location of the bottom of the insulating fluid.
    A greater advantage of the more insulating properties of the insulating fluid can be achieved by increasing the depth of the bottom of the insulating fluid in the A annulus.
13. Seawater flow rate.
    Seawater flow rates of <40 ft/min (which was the limit of our study) had only a minor effect.
14. Coefficient of thermal expansion of insulating fluids.
    Unlike in other studies,[3] the coefficient of thermal expansion of the insulating fluid plays a rather minor role compared with the fluid properties listed above.

To keep the scope of the study within reason, this study deliberately did not include some important parameters, including well depth and hydrate formation temperature. Future studies may include these or other important parameters.

The parameters studied are believed to very often be coupled with each other in highly non-linear ways. In most cases, the study varied only one parameter at a time while artificially holding every other parameter constant. As a result, the study was able to compare the rheological behavior of water-based and oil-based YPL fluids.

However, the authors anticipate that there will be field conditions with a confluence of boundary conditions that may couple non-linearly thereby increasing the importance of relatively minor parameters and requiring a higher insulating performance. In such cases, it may prove necessary to rely on both insulating fluid properties and the design of the well. Such a strategy, could include (1) a thick gas-filled A annulus (or VIT) extending well below the mud line, (2) a displacement of any brine in that A annulus to a depth well below the mud line, and/or (3) a thick B annulus filled with a premium hydrocarbon-based fluid viscosified to give it a relatively large yield stress, small n_m, and large k_m.

When the thermal conductivity and heat capacity were allowed to vary at the same time as the rheological properties, the influences of thermal conductivity and perhaps heat capacity were so strong that they seemed to over-ride the effects of the rheological properties, especially those of the secondary rheological properties, n_m and k_m.

Similar observations as those of the previous paragraph were made when the rheological behavior of water-based and oil-based power law fluids was compared.

It would seem that water-based fluids – both yield power law and power law – lie in a separate class than oil-based fluids. The water-based fluids are important because they offer a number of advantages, including low cost. Some hydrocarbon-based insulating fluids may be costly and would be difficult to deal with if there were a spill or accidental release from the annulus; but generally, hydrocarbon-based insulating fluids offer very low thermal conductivity, and as a result, high performance.

This study was intended as a first step in software development to help the understanding of the overall fluid-well configuration and to improve insulating annular fluid design. Optimization of the insulating annular fluid is not simply a lab exercise to explore the properties of the fluid, but an interactive process involving modeling the well geometry and other boundary conditions presented to the lab experimenter by the customer. The engineering tool described in this study should prove to be a valuable interface between laboratory and field.

Acknowledgments

The authors thank M-I SWACO for permission to publish this paper.

Nomenclature

BHFP	=	*bottomhole producing pressure*
BHFT	=	*bottomhole producing temperature*
BHSP	=	*bottomhole shut-in pressure*
BHST	=	*bottomhole shut-in temperature*
BHT	=	*bottomhole temperature*
FST	=	*Flowing Surface Temperature*
ML	=	*depth of the mud line*
PL fluid	=	*power-law fluid*
SIT_{68}	=	*shut-in time for a well to cool to 68°F in the producing stream*
TVD	=	*true vertical depth*
VIT	=	*vacuum insulated tubing*
YPL fluid	=	*yield-power-law fluid*
YPL-WTP	=	*yield-power-law, wellbore-temperature-profile program*
τ	=	*shear stress* ($lb_f/100\ ft^2$)
τ_y	=	*yield stress* ($lb_f/100\ ft^2$)
k_m	=	*consistency factor*
γ	=	*shear rate* (s^{-1})
n_m	=	*flow behavior index*

References

1. Marshall, D.W. and Bentsen, R.G.: "A Computer Model to Determine the Temperature Distributions in a Wellbore," *Journal of Canadian Petroleum Technology* (Jan-Feb 1982).
2. Corre, B., Eymard, R. and Guenot, A.: "Numerical Computation of Temperature Distribution in a Wellbore While Drilling," SPE 13208, SPE Annual Technical Conference, Houston, Sept 16-19, 1984.
3. Hallman, J.F. and Acor, L.G.: "New Environmentally Safe Heat Transfer Fluid Improves The Performance of Heaters in Gas Production and Transmission Systems," SPE 65616, 2000 SPE Eastern Regional Meeting, Morgantown, West Virginia, Oct 17-19, 2000.
4. Oster, C.A. and Scheffler, W.A.: "Temperature Profiles and Aquifer Mass Transfer in a Circulating Well," *Journal of Heat Transfer* (Feb 1982) Vol. 104.
5. Edwardson, M.J., Parkison, H.R., Williams, C.D. and Matthews, C.S.: "Calculation of Formation Temperature Disturbances Caused by Mud Circulation," *Journal of Petroleum Technology* (Apr 1962) 416.
6. Sagar, R., Doty, D.R. and Schmidt, Z.: "Predicting Temperature Profiles in a Flowing Well," *SPE Production Engineering* (Nov 1981) 441.
7. Keller, H.H., Couch, E.J. and Berry, P.M.: "Temperature Distributions in Circulating Mud Columns," *SPEJ* (Feb 1972) 23.
8. Vollmer, Daniel P., Fang, C.S., Ortego, A. M. and Lemoine, E. "Convective Heat Transfer in Turbulent Flow: Effect of Packer Fluids on Predicting Flowing Well Surface Temperatures," SPE 86546, SPE International Symposium on Formation Damage Control, Lafayette, Louisiana, Feb 18-20, 2004.
9. Wang, X., Javora, P., Qu, Q., Pearcy, R. and Starliper, A. "A New Thermal Insulating fluid and Its Application in Deepwater Riser Insulation in the Gulf of Mexico," SPE 84422, SPE Annual Technical Conference, Denver, Oct 5-8, 2003.
10. Incropera, F.P. and DeWitt, *Fundamentals of Heat and Mass Transfer*, Third Edition, John Wiley & Sons, Inc., New York, NY (1990).
11. Skelland, A.H.P., *Non-Newtonian Flow and Heat Transfer*, John Wiley & Sons, New York, NY (1966).
12. Willhite, G.P.: "Over-All Heat Transfer Coefficients in Steam and Hot Water Injection," *JPT* (May 1967) 607.
13. Ashford, J.D., Narcou, J.A., Ralph, J.M., Skaalure, E.W. "Annular Packer Fluids for Paraffin Control: Model Study and Successful Field Application," SPE 19730, SPE Annual Technical Conference, San Antonio, Oct 8-11, 1989 and *SPE Production Engineering* (1990) 351.
14. Prasad, V. and Kulacki, F.A.: "Free Convective Heat Transfer in a Liquid-Filled Vertical Annulus," *Transaction of the ASME* vol 107 (August 1985), 596-602.
15. Pak, B., Cho, Y.I. and Choi, S.U.S.: "A Study of Turbulent Heat Transfer in a Sudden-Expansion Pipe with Drag-Reducing Viscoelastic Fluid," *Int. J. Heat Mass Transfer* vol 34, no 4/5 (1991) 1195.
16. Metzner, A.B. and Reed, J.C.: "Flow of Non-Newtonian Fluids – Correlations of the Laminar, Transition, and Turbulent-flow Regions," *AIChE Journal* vol. 1, no. 4 (1955) 434-440.
17. Govier, G.W. and Aziz, K. *The Flow of Complex Mixtures in Pipes*; Krieger Publishing (1977) 203-206.
18. *API RP 13D – Recommended Practice on the Rheology and Hydraulics of Oil-Well Drilling Fluids*, 4th ed; API (May 2003).
19. Nagasaka, Y. and Nagashima, A.: "Simultaneous Measurement on the Thermal Conductivity and the Thermal Diffusivity of Liquids by Transient Hot-Wire Method," *Rev. Sci. Instrum*. vol. 52, no. 2 (Feb 1981) 229.
20. San, A.J., Dzialowski, A.K. and Loftin, R.E.: "Gelantinous Oil-Base Fluids as Insulators in Geothermal and Oil-Recovery Applications," SPE 11791, SPE International Symposium on Oilfield and Geothermal Chemistry, Denver, June 1-3, 1983.
21. Dzialowski, A., Ullmann, H., Sele, A. and Oosterkamp, L.D.: "The Development and Application of Environmentally Acceptable Thermal Insulation Fluids," SPE 79841, SPE/IADC Drilling Conference, Amsterdam, Feb 19-21, 2003.
22. Williamson, R., Sanders, W., Jakabosky, S. M. and Griffith, J.E.: "Control of Contained-Annulus Fluid Pressure Buildup," SPE/IADC 79875, SPE/IADC Drilling Conference, Amsterdam, Feb 19-21, 2003.
23. Halal, A.S. and Mitchell R.F.: "Casing Design for Trapped Annulus Pressure Buildup," SPE/IADC 25694, SPE/IADC Drilling Conference, Amsterdam, Feb 23-25, 1993.
24. Azzola, J.H., Pattillo, P.D., Richey, J.F. and Segreto, S.J.: "The Heat transfer Characteristics of Vacuum Insulated Tubing," SPE 90151, SPE Annual Technical Conference, Houston, Sept 26-29, 2004.
25. Azzola, J.H., Tselepidakis, D.P., Patillo, P.D., Richey, J.F., Tinker, S.J., Miller, R.A. and Segreto, S.J.: "Application of Vacuum Insulated Tubing to Mitigate Annular Pressure Buildup," SPE 90232, SPE Annual Technical Conference, Houston, Sept 26-29, 2004.

Table 1 – Rheological Properties of a Fluid Modeled as a Yield Power Law Fluid or as a Power Law Fluid

at 70°F			at 180°F		
	YPL Fluid #1	Modeled as PL Fluid		YPL Fluid #1	Modeled as PL Fluid
600 rpm Dial Reading	243	243	600 rpm Dial Reading	95	95
300 rpm Dial Reading	215	215	300 rpm Dial Reading	79	79
200 rpm Dial Reading	201	200	200 rpm Dial Reading	72	72
100 rpm Dial Reading	181	177	100 rpm Dial Reading	62	60
6 rpm Dial Reading	132	107	6 rpm Dial Reading	40	29
3 rpm Dial Reading	125	94	3 rpm Dial Reading	37	24
PV (cP)	28	28	PV (cP)	16	16
YP ($lb_f/100\,ft^2$)	186	186	YP ($lb_f/100\,ft^2$)	64	64
n_m	0.314	0.179	n_m	0.392	0.261
k_m ($lb_f\,sec^n/100\,ft^2$)	17.61	74.9	k_m ($lb_f\,sec^n/100\,ft^2$)	4.67	16.6
τ_y ($lb_f/100\,ft^2$)	104.5	0.0	τ_y ($lb_f/100\,ft^2$)	30.9	0.0

Table 2. The Effect of Various Parameters on Shut-in Time$_{to\ 68°F}$ (SIT_{68})

Parameter	"Reasonable" Range	Calculated SIT_{68} values (hr)
1. Bottomhole temperature	Varying from 125 to 350°F	9.8 – 32.9
2. Rheological properties of oil-based YPL fluids	Rheological properties are given in Table 3	21.8 – 43.7
3. Thermal conductivity of insulating fluids	Varying from 0.08 to 0.30 BTU/hr ft^2 °F	26.6 – 7.3
4. Water depth	Varying from 3100 to 4700 ft	44.4 – 26.4
5. Thickness of a gas-filled A-annulus (with an insulating-fluid-filled B-annulus)	Varying from 0.125 to 1.1375 in.	16.0 – 31.3
6. Heat capacity of insulating fluids	Varying from 0.70 to 1.0 BTU/lb °F	26.5 – 34.6
7. Rheological properties of water-based YPL fluids	Rheological properties are given in Table 4	8.5 – 14.1
8. Location of the interface between gas and brine in a gas-filled A-annulus	Varying from 0 to 300 ft below the mud line	26.2 – 32.1
9. Thickness of an insulating-fluid-filled A-annulus with no insulating B-annulus	Varying from 0.125 to 1.1375 in	4.0 – 9.8
10. Rheological properties of water-based PL fluids (*i. e.*, having $\tau_y = 0$)	See Table 4	3.7 – 8.6
11. Oil flow rate	Varying from 10,000 to 20,000 bopd	24.2 – 27.7
12. Location of the bottom of the insulating fluid	Varying from 0 to 1000 ft below the mud line	3.6 – 6.7
13. Seawater flow rate	Varying from 0 to 40 ft/min	25.9 – 26.6
14. Coefficient of thermal expansion of insulating fluids	Varying from 1.18E-4 to 4.56E-4/°F	24.3 – 23.9

Table 3 – SIT_{68} *vs.* Rheological Properties of Yield Power Law Fluids

Fluid	#1	#2	#3	#4	#5	#6	#7	#8	#9
at 70°F									
600 rpm Dial Reading	243	146	180	177	177	177	177	233	307
300 rpm Dial Reading	215	116	94	143	117	106	149	187	236
200 rpm Dial Reading	201	102	65	126	93	82	135	165	203
100 rpm Dial Reading	181	83	35	101	65	58	115	135	158
6 rpm Dial Reading	132	45	6	42	24	34	66	68	69
3 rpm Dial Reading	125	41	6	34	21	33	59	59	59
PV (cP)	28	30	86	35	60	71	28	46	72
YP ($lb_f/100\,ft^2$)	186	86	8	108	57	35	120	141	164
n_m	0.314	0.422	0.972	0.314	0.672	0.978	0.314	0.375	0.435
k_m ($lb_f\,sec^n/100\,ft^2$)	17.61	6.75	0.22	21.45	1.63	0.18	17.59	16.01	14.42
τ_y ($lb_f/100\,ft^2$)	104.5	29.9	4.8	0.2	17.5	34.7	34.1	33.9	34.1
SIT_{68} (hr) for Water-Based Fluids	14.1	9.4	8.5	7.8	9.3	14.6	8.3	8.2	8.3
SIT_{68} (hr) for Oil-Based Fluids	43.7	26.5	21.8	16.0	21.5	29.8	24.2	23.6	26.5
at 180°F									
600 rpm Dial Reading	95	84	82	76	76	76	75	105	136
300 rpm Dial Reading	79	60	42	58	50	43	59	79	98
200 rpm Dial Reading	72	50	29	49	39	32	52	66	81
100 rpm Dial Reading	62	37	15	38	27	21	42	51	59
6 rpm Dial Reading	40	14	2	13	8	10	20	20	21
3 rpm Dial Reading	37	12	1	10	6	9	17	17	17
PV (cP)	16	24	40	18	26	33	16	27	38
YP ($lb_f/100\,ft^2$)	64	36	3	40	24	11	44	52	60
n_m	0.392	0.542	0.970	0.392	0.642	0.965	0.392	0.469	0.515
k_m ($lb_f\,sec^n/100\,ft^2$)	4.67	1.90	0.10	5.34	0.90	0.09	4.67	3.98	3.82
τ_y ($lb_f/100\,ft^2$)	30.9	8.4	1.0	0.1	4.2	9.5	9.4	9.7	9.4

Table 4 – SIT_{68} *vs.* Rheological Properties of Power Law Fluids

Fluid	#1	#2	#3	#4	#5	#6	#7	#8	#9
at 70°F									
600 rpm Dial Reading	145	118	175	145	145	145	145	201	275
300 rpm Dial Reading	117	88	89	117	91	74	117	155	204
200 rpm Dial Reading	103	74	60	103	69	49	103	133	171
100 rpm Dial Reading	83	55	31	83	43	25	83	103	126
6 rpm Dial Reading	34	17	2	34	7	2	34	36	37
3 rpm Dial Reading	28	13	1	28	4	1	28	28	27
PV (cP)	28	30	86	28	54	71	28	46	72
YP ($lb_f/100\,ft^2$)	88	58	3	88	37	2	88	109	132
n_m	0.314	0.422	0.972	0.314	0.672	0.978	0.314	0.375	0.435
k_m ($lb_f\,sec^n/100\,ft^2$)	17.59	6.75	0.22	17.59	1.47	0.18	17.59	16.01	14.42
τ_y ($lb_f/100\,ft^2$)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SIT_{68} (hr) for Water-Based Fluids	8.0	5.8	3.7	8.6	1.5	1.3	1.9	1.5	1.3
at 180°F									
600 rpm Dial Reading	66	76	81	66	67	67	66	96	127
300 rpm Dial Reading	50	52	42	50	43	34	50	69	89
200 rpm Dial Reading	43	42	28	43	33	23	43	57	72
100 rpm Dial Reading	33	29	14	33	21	12	33	41	50
6 rpm Dial Reading	11	6	1	11	3	1	11	11	12
3 rpm Dial Reading	8	4	0	8	2	0	8	8	8
PV (cP)	16	24	40	16	24	33	16	27	38
YP ($lb_f/100\,ft^2$)	35	29	2	35	19	2	35	43	51
n_m	0.392	0.542	0.970	0.392	0.642	0.965	0.392	0.469	0.515
k_m ($lb_f\,sec^n/100\,ft^2$)	4.67	1.90	0.10	4.67	0.83	0.09	4.67	3.98	3.82
τ_y ($lb_f/100\,ft^2$)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

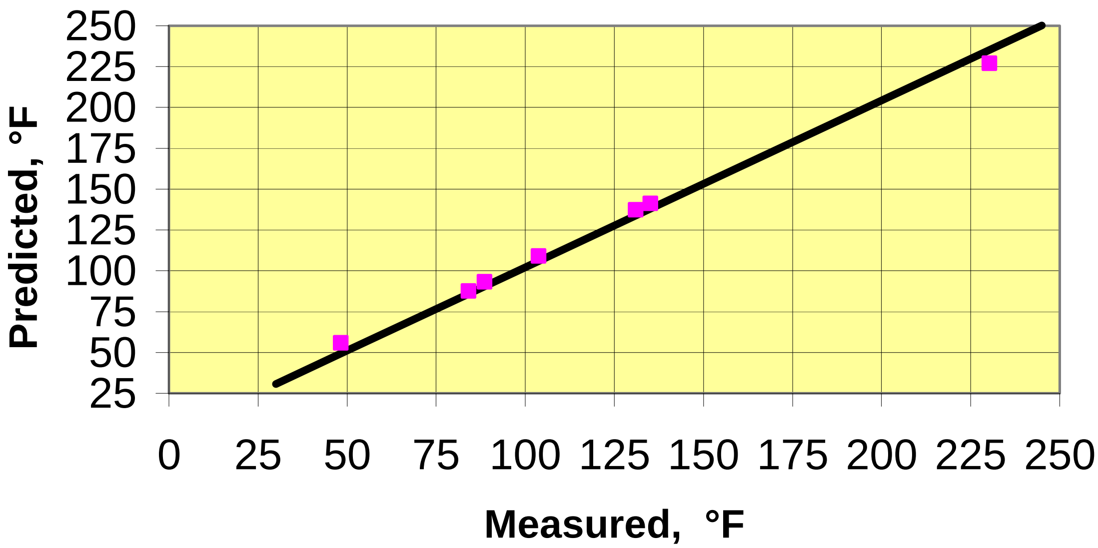

Figure 1 – Predicted *vs*. Measured Flowing Surface Temperature (FST). The predicted values are from YPL-WTP; the measured values are from Reference 8, Figure 2.

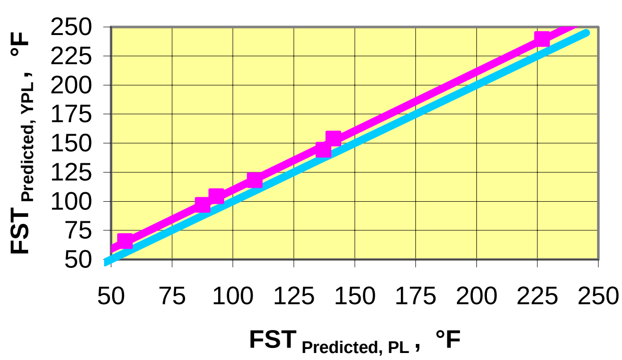

Figure 2a – The YPL-WTP-predicted flowing surface temperature ($FST_{Predicted,\ YPL}$) with a YPL insulating annular fluid *vs.* the YPL-WTP predictions when the fluid is modeled as a PL fluid ($FST_{Predicted,\ PL}$). The data show that the YPL fluid appears to provide better insulation and, as a result, a higher flowing surface temperature.

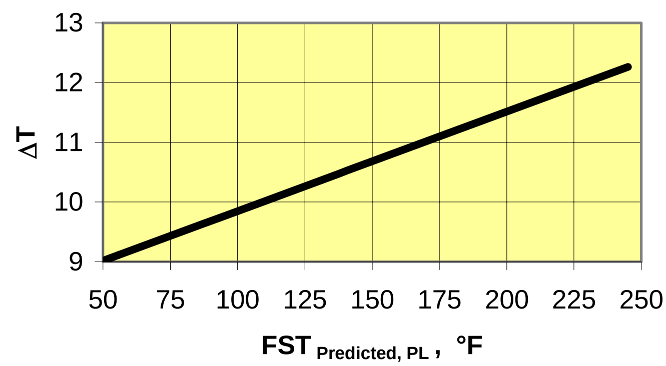

Figure 2b – The ΔT between $FST_{Predicted,\ YPL}$ and $FST_{Predicted,\ PL}$ *vs.* the same horizontal axis as in Figure 2a. This view of the data emphasizes that there is about a 9 to 13°F higher flowing surface temperature predicted with the YPL rheology inputs than with the PL inputs.

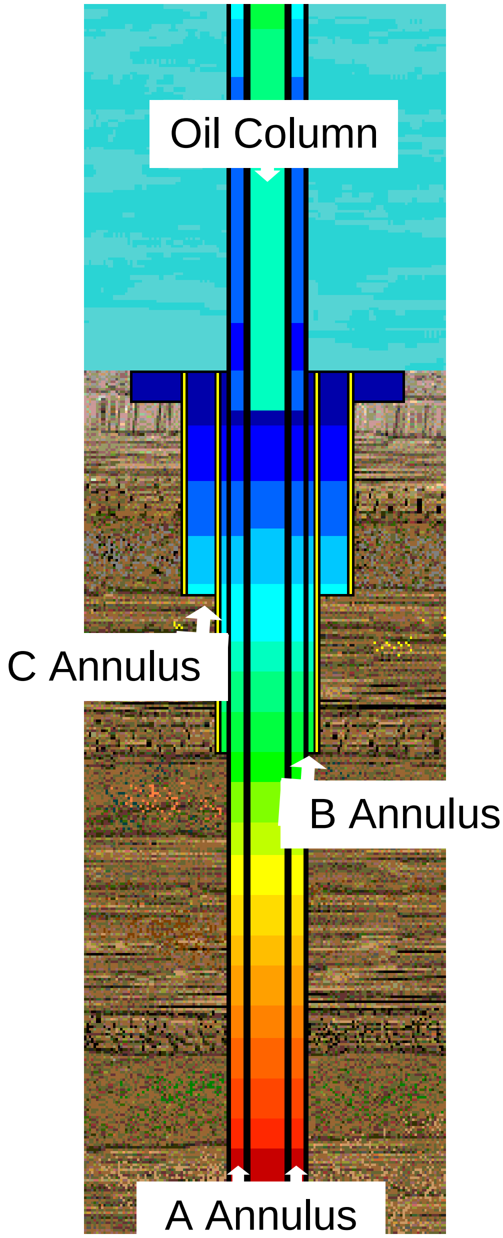

Figure 3 – A typical 'dry tree' completion in deep water, with four annuli. In this example, annuli C and D are cement-filled.

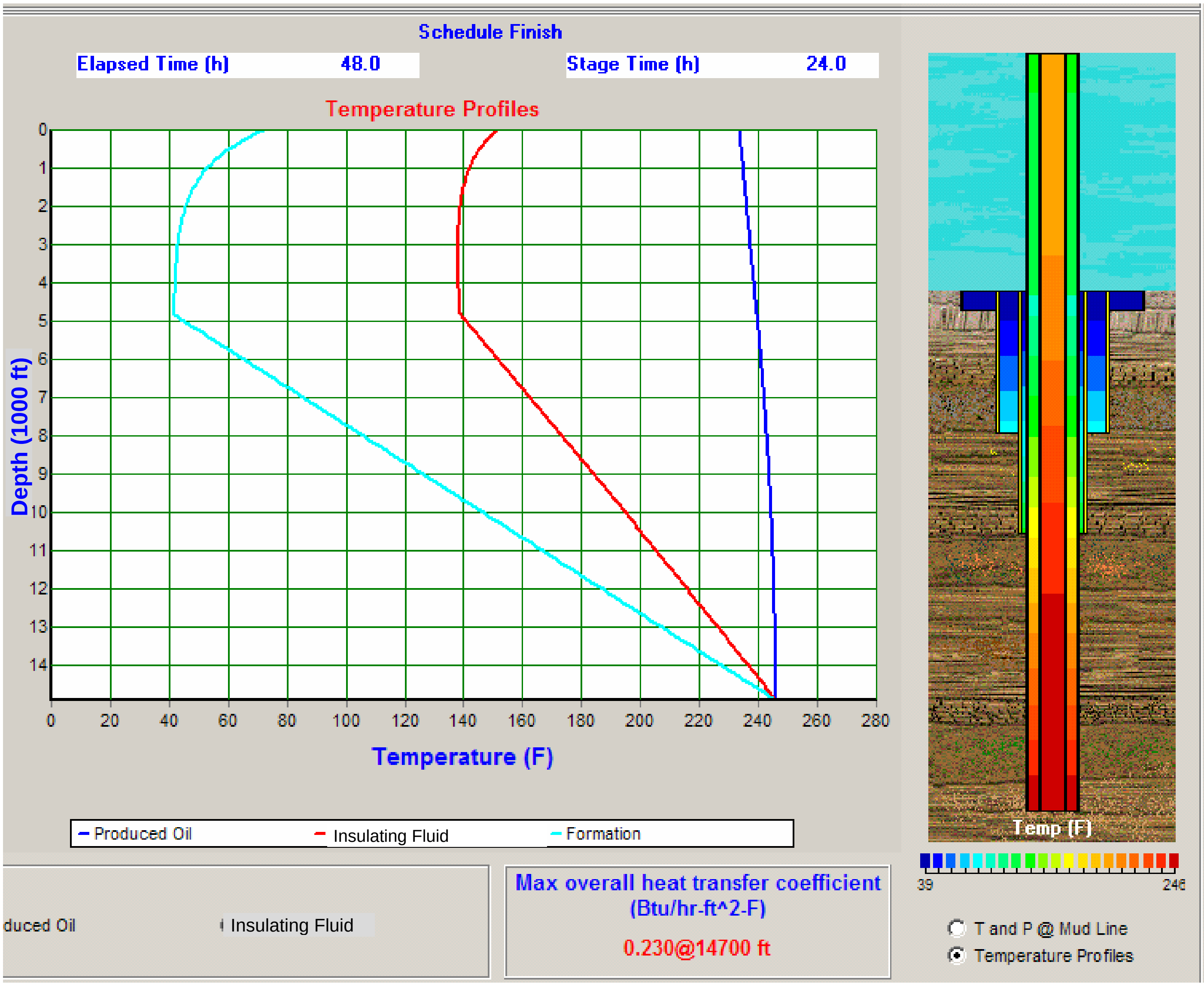

Figure 4 – An example of output from YPL-WTP – the temperature profile view.

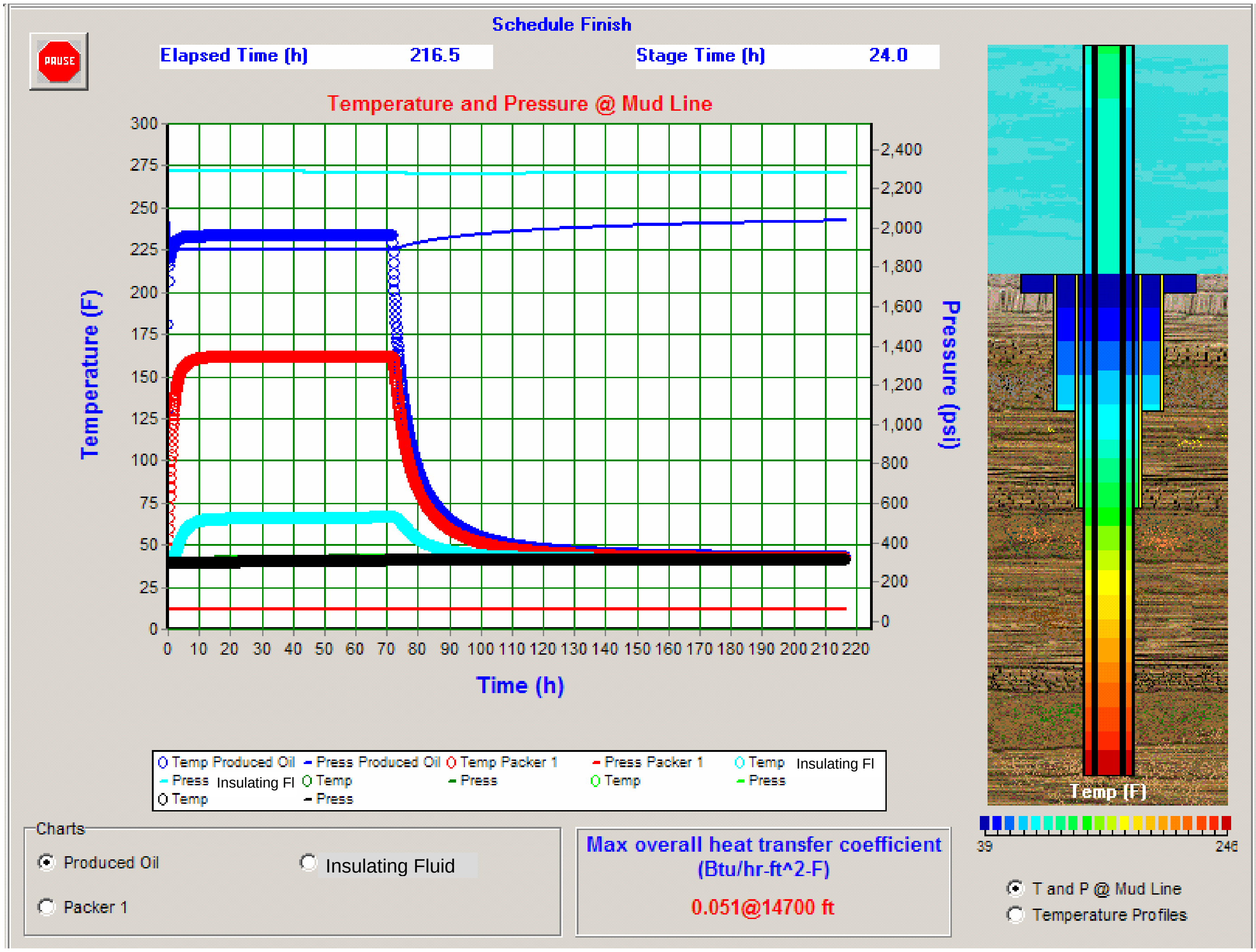

Figure 5 – Output from YPL-WTP – view of the temperature and pressure at ML.

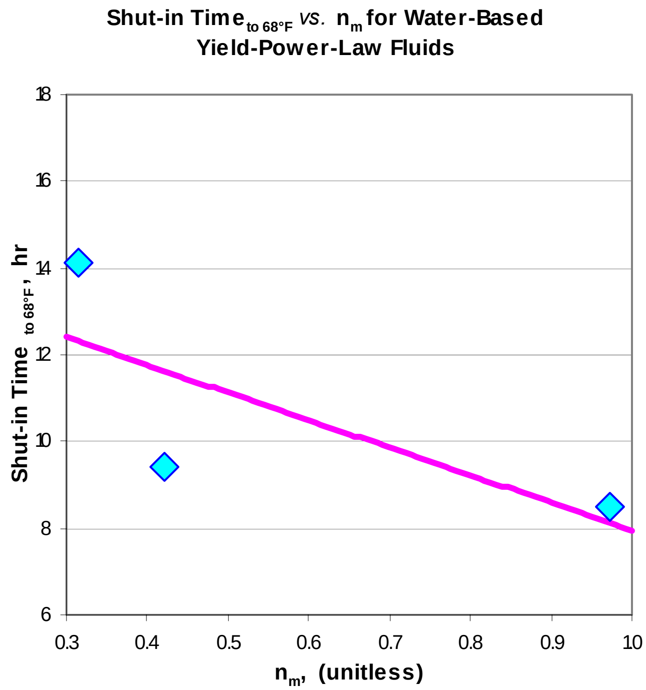

Figure 6 – Output from YPL-WTP for water-based yield-power-law (YPL) fluids – the "Shut-in Time$_{to\ 68°F}$" (SIT_{68}) *versus* n_m. The straight line is provided only to give an indication of the data trend.

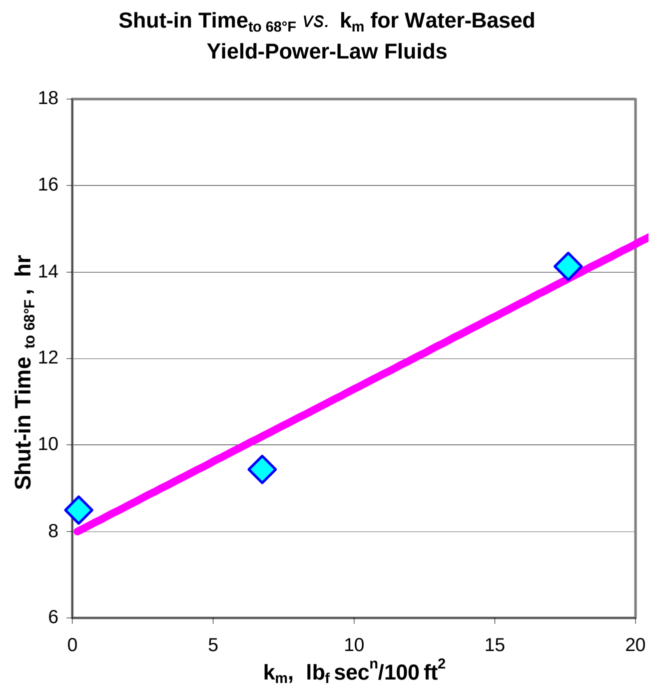

Figure 7 – Output from YPL-WTP for water-based YPL fluids – SIT_{68} *versus* k_m. The straight line is provided only to give an indication of the data trend.

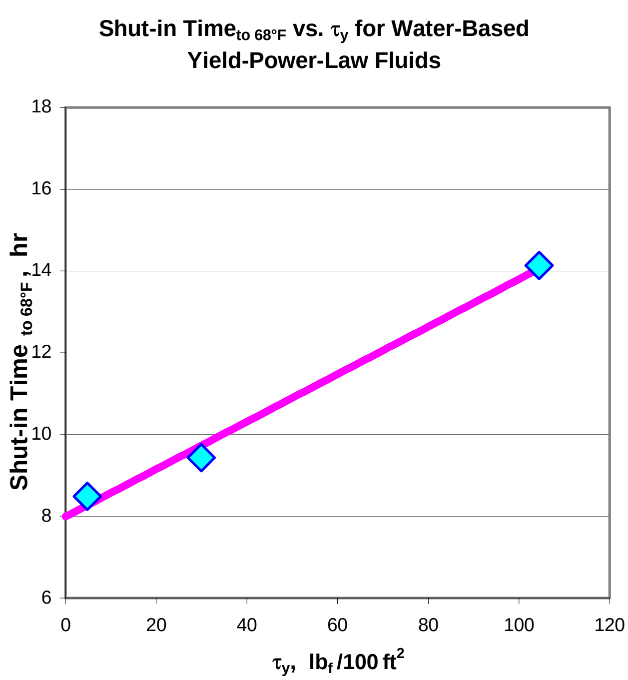

Figure 8 – Output from YPL-WTP for water-based YPL fluids – the "Shut-in Time$_{to\ 68°F}$" *versus* τ_y. The straight line is provided only to give an indication of the data trend.

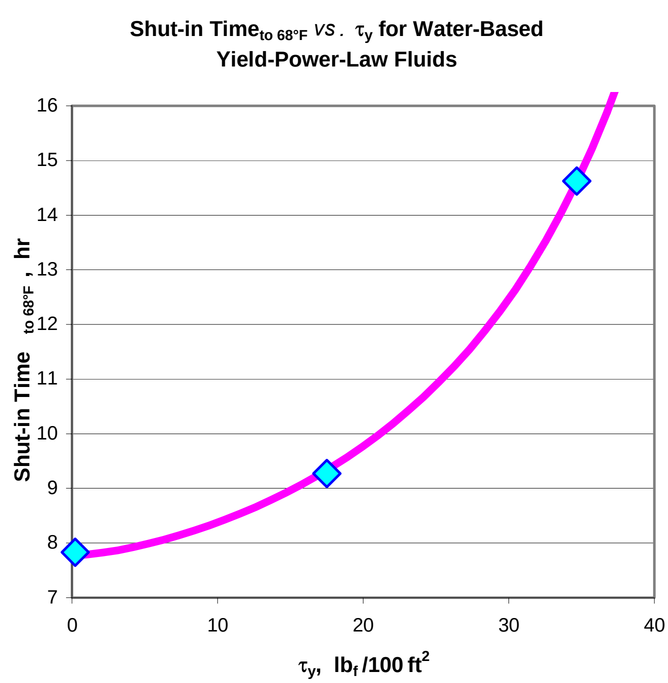

Figure 9 – Output from YPL-WTP for "theoretical" water-based yield power law (YPL) Fluids 4, 5, and 6 – the "Shut-in Time$_{to\ 68°F}$" *versus* τ_y. Note the data trend that increasing τ_y results in a significant increase in the Shut-in Time$_{to\ 68°F}$.

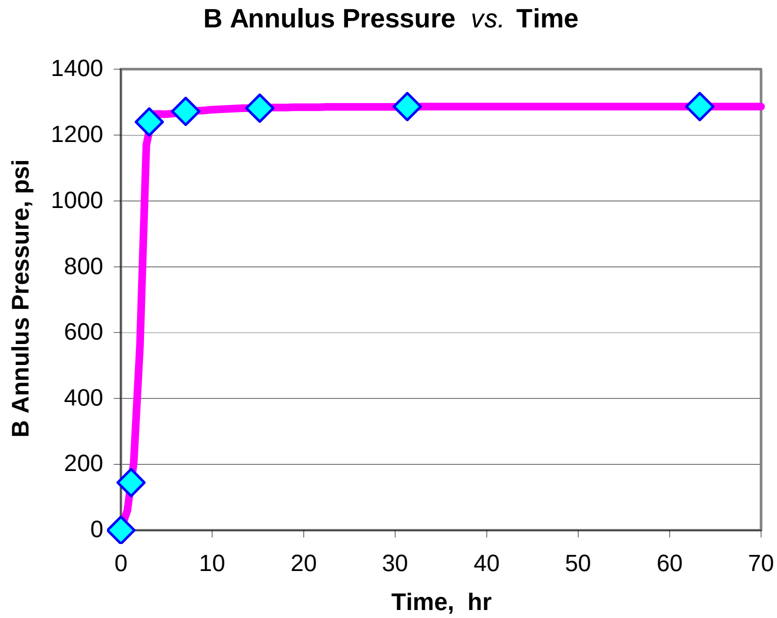

Figure 10 – Post-processed spreadsheet output from YPL-WTP for an un-vented B Annulus. The data show a rapid build-up of pressure early in the interval just after a well under long-term shut-in or pre-production conditions is switched to production.