A Systematic Approach for Wellbore Drilling and Placement of SAGD Well Pairs and Infill Wells

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Abstract

The initial drilling of a set of Steam Assisted Gravity Drainage (SAGD) well pairs (producer and injector) from a pad for heavy oil development is often accomplished using standard well creation techniques for the initial wells (in our case the producers) followed by the careful drilling of the parallel wells using advanced ranging techniques to accurately control the separation of the paired wells. In this paper we first demonstrate an improvement in the SAGD service by taking a more holistic approach to this creation; emphasizing maximum accuracy in the well creation at every step and yielding improved final results. This process also should result in improvements in the further field development and assessment of reserves.

When drilling the initial well, it is of critical importance that the position of the well be accurately known. To do this, we analyze the surveys using advanced techniques such as multi-station analysis to yield the most accurate definition of the well path. Careful control of the directional drilling process is also critical. During large azimuth adjustments, it is important that the tortuosity of the well be minimized. Accurate control of the inclination (and thus TVD) is equally important during the lateral section. This is achieved by at-bit determination of inclination. It should be noted that controlling as opposed to maintaining a uniform TVD may be required as the zone of interest may vary laterally.

Given this knowledge, the second well must also be carefully drilled and placed. Many of the above requirements are duplicated. During the build section, we often need to control azimuth in the presence of magnetic interference. This is accomplished using an alternate technique, Gravity MWD	extsuperscript{2}, which allows the accurate determination of the well azimuth. In addition, using passive ranging allows the continuous determination of the location of the drilling well and to anticipate changes in drilling parameters needed to maintain the required relative position of the paired wells.

Drilling infill wells presents other challenges. These are often attempted several years after the initial development and the knowledge of the position of the existing wells is less sure. In such cases, we find that the wells are best drilled with careful analysis to detect magnetic interference. We thus ascertain that the drilling well correctly maintains the desired separation from existing wells in place.

This paper demonstrates the improvements in initial and subsequent field development due to applying a systematic approach when drilling and correctly placing heavy oils wells for SAGD development in Alberta, Canada.

Introduction

Performance measures for drilling a Steam Assisted Gravity Drainage (SAGD) well pair (producer & injector) usually focus on maintaining an accurate relative separation between the two wells over their horizontal section. The relationship is normally presented as a bulls-eye with a target “box” with the producer in the center of a bulls-eye and the relative position of the drilling well displayed along with the desired relative location. (Figure 1). Our experience is that such a narrow focus is insufficient and leads to sub-optimal well placement. We need to look at more additional considerations to ensure accurate and correct well placement.

When considering the standard measures, we find that tortuosity of the entire well path tends to be ignored. Combining accurate surveys from the producer well with
accurate real-time surveys from the injector well allows us to reduce tortuosity.

When evaluating the pad as a whole, accurate surveys are important for achieving proper spacing of the well pairs (Figure 2). Accurate surveys are also important when drilling in-fill producers.

Ongoing field development is carried out by drilling additional pads (Figure 3). The goal is to minimize the productive formation that is skipped. This often involves landing the new wells in the vicinity of preexisting wells. For the optimum performance, we once again need to have accurate surveys and perhaps drill the producer with “nearby well detection” enabled.

A systematic approach being followed during the entire drilling process will address these concerns. Several techniques will be demonstrated in this paper. We have integrated the application of these methods into a consistent product - Real-time Analysis of Drilling and Advanced Ranging (RADAR™). This allows for rapid, real-time evaluation of data and fast steering decisions and accurate well placement.

### Borehole Tortuosity

Reducing the bending, twisting, and unwanted deviations of the wellbore (tortuosity) is critical in the processes of drilling, completing, and producing wellbores. The complex well plans (shallow depths and long horizontal sections) for SAGD well pairs highlight the need to minimize tortuosity in all areas of the wellbore. In depth pre-well planning reviews of the well plan/profile to include torque and drag calculations are a good start. Minimizing the torque and drag of the bottom hole assembly (BHA) along with accurate execution of the well creation leads to a reduction of tortuosity.

Selecting the proper drive system and BHA components to correctly drill a specific section of the wellbore can also effectively reduce the borehole tortuosity. The wellbore becoming washed out is also a contributor to tortuosity. Controlling washout can be achieved by selecting the proper bit for a given hole size and section that includes the correct total flow area (TFA) jets that will minimize fluid jetting but still provide good hole cleaning. If possible, monitor the effects of flow rate to downhole solids cleaning with an equivalent circulating density measurement (annular pressure sensor). Monitoring borehole washout with a caliper sensor is another method of understanding and potentially controlling tortuosity. Understanding what factors contribute to the borehole washing out will allow mitigation of this issue. In the horizontal section of these well pairs, implementing proper stabilization of the BHA to include per plan directional steering with any drive system will minimize the borehole spiraling effects, reduce borehole torque and drag and improve the project economics.

### SAGD Field Description

Cenovus Energy’s Foster Creek project began in 1996 and in 2001 became the industry’s first commercial SAGD project. Located in northeast Alberta, Foster Creek has over 160 SAGD well pairs with daily bitumen production in excess of 100,000 barrels and an estimated recoverable reserve of 1.4 billion barrels.

The bitumen at Foster Creek, located within the McMurray formation, exists at a True Vertical Depth (TVD) of between 470 and 550m from surface. This depth is considered too deep to make surface mining practical. As a consequence, in-situ methods are required. The primary technology used at Foster Creek is SAGD, a process which injects steam into the reservoir to reduce the viscosity of the bitumen so it can be pumped to the surface with high temperature electric submersible pumps.

The SAGD process has proven to be an effective method of in-situ production of bitumen from the McMurray oil sands of Alberta. This process requires an injector and producer horizontal pair to be installed within the target formation. The injector is positioned typically 5m TVD above the producer and is used for the injection of high pressure/high temperature steam at approximately 250°C. Reduced viscosity bitumen and condensed water is collected in the producer and pumped to surface. TVD lateral separation between the injector and producer are important for optimal efficiency of the SAGD process and to minimize potential steam breakthrough to the producer. A separation of 5m, +/- 1m TVD is critical for the process to work properly and ranging systems are required to ensure this optimal separation is maintained while drilling the injector. Efficiency of the SAGD process is measured by the amount of steam injected for an equivalent volume of bitumen produced or the steam to oil ratio (SOR). Foster Creek’s SOR, at less then 2.5, is considered one of the best in the industry.

The length of the horizontal section can vary depending on reservoir characteristics or surface constraints but is generally between 500 and 1000m. For proper production of the reservoir horizontal well pairs are positioned 100m laterally from one another. Multiple well pairs are drilled from a single pad to minimize surface disturbance and facility piping required. Pads typically have between four and twelve pairs.

The pad discussed in this paper, W01, is located in the western part of Foster Creek. W01 pad has a nine well pair configuration which, due to surface constraints, required the pad to be offset from the horizontal sections (Figure 2, 3). Each well consists of three separate sections, surface, intermediate, and horizontal.

The surface portion of the wells was drilled vertically with 444.5mm (17.5”) drill bits and cased with 339.7mm (13 3/8”) casing.

The intermediate section was directionally drilled from vertical to horizontal with 311.1mm (12 1/2”) drill bits and cased with 244.5mm (9 5/8”) casing. Build rates in the build/curve section of the intermediate hole were planned at 8 – 10’/30m.

The horizontal section was drilled with 222.2mm (8 3/4”) drill bits and completed with 177.8mm (7”) liners. Conventional adjustable bent housing motors were used to drill the intermediate and horizontal sections. Gamma and inclination at bit were also used to determine directional response and maintain the horizontal sections in the optimum portion of the reservoir.

Pads within the field are positioned according to location considerations, facility requirements, future well access, directional drilling capabilities, geological and reservoir characteristics.
Producer Wellbore

Accurate knowledge of the position of the producer well, both while drilling and after completion, is critical. First, at the completion of the build, the producer needs to be accurately placed in the proper geologic formation. Though the TVD may be modified based on the M/LWD sensors, any such variation does increase tortuosity and should be minimized. Thus, accurate measurement of the real-time TVD is quite important. The azimuth of the well is also important as it will strongly influence the heading of the horizontal though small modifications are possible during drilling.

The producer position controls the injector positioning. Various ranging methods will be used for final positioning of the injector relative to the existing producer. As ranging will only occur near the landing point, tortuosity will be reduced if we have accurate knowledge of the producer well path.

Similarly, accuracy of the producer lateral position aids in the accurate drilling of the injector horizontal. Additionally, field development also benefits from accurate knowledge of the producer position (and, by inference, the injector position) over the entire drilled length. Regular spacing of the well pairs is important for optimizing production. Therefore, the close tolerances of the entire suite of wells, over relatively long horizontal extents, amplify the need for accurate knowledge and control of the producer wells.

Producer Build

When drilling the producer build it is critical to reduce potential error to a minimum with regards to the well placement at the landing point. The three areas of concern are accurate measurement of the depth of the survey stations, misalignment of the directional sensor with regards to the long axis of the bore hole and interference from the BHA affecting the true azimuth of the well bore.

These effects, if not addressed, can lead to displacement errors not only in the direction of the well but also the TVD which is crucial in the reservoir section.

If there is a systematic error in the depth measurement this will create a TVD error as the well bore builds angle and will more than likely constitute the largest source of TVD uncertainty. Accurate calibration of the depth tracking system is essential and close monitoring of the depth tracking while drilling will substantially reduce this TVD uncertainty.

Any misalignment of the directional sensor with regards to the true well bore long axis due to BHA bending can be corrected for by performing a sag analysis of the BHA to be used. A misalignment of ±0.1° could create a ±1 m TVD error at the landing point of the build. Using two surveys tools in the BHA can further reduce the TVD uncertainty.

Removing the effect of the BHA interference and sensor biases is achieved using multi station analysis (MSA). MSA can be used in two modes.

MSA mode 1 assumes no knowledge of the earth’s magnetic field. It is used to find the biases, correct the surveys, and to determine the earth’s field strength and dip angle.

MSA mode 2 evaluates biases and corrects surveys assuming the earth’s magnetic field is known. The information comes from a variety of sources such as GSOC, BGGM, IGRF models etc. These tend to be an unreliable source as they fail to take into account local field variations.

Interpolated Infield Referencing takes an interpolated reading from nearby geomagnetic stations that is good for tracking the changes in the Earth’s field. However this also does not take into account local variations.

A site measurement of the Earth’s field is a good method and even better if it is monitored continuously. If a single site measurement is made then a check of the stability of the field at that time should be carried out to make sure there is not a magnetic storm or unusual activity in the field at that time. The single site measurement can then be used to compare the MSA derived field if both are closely aligned then it verifies the good workings of the MSA and the resultant corrected surveys should be accurate.

By applying the above procedures to the producer build surveys then the most accurate real time well bore can be drilled using current technology. The producer build is normally planned with an 8'/30m dls as a maximum with a tangential end of approximately 50 + m. Drilling is normally held between 40 and 60 m/hr. Depending on the profile of the well (outside of the pad or inside) 10 to 12 joints of magnetized 9 5/8” casing run at the toe of the intermediate casing string.

Finally, as the well is being landed, appropriate LWD sensor measurements are available while drilling. For these wells, real time gamma ray measurements were used. These formation sensor measurements are used to refine the landing TVD for the producers, accounting for variations in formation. The responsibility of modifying the target TVD may fall on the contraction company (as was the implementation in this well) or on any other drilling service company through application of geo-steering service.

Producer Horizontal

When drilling the horizontal section the same stringent QAQC procedures are adhered to for the directional surveys and the BHA includes the PZIG (payzone inclination and gamma ray) tool with at bit inclination and gamma to aid in the steering of the well (Figure 6). From historical data if MSA etc was not performed on the horizontal surveys then displacement errors in the grid location at the toe of the well of several meters could occur. This is crucial in the placement of the outside wells on a pad.

Injector Wellbore

The injector well focuses on maintaining a uniform separation from the previously drilled producer well under fairly tight tolerances. The initial portion of the injector is drilled with a separation such that there is no interference from the producer. Our goal is to land the injector smoothly above the producer, usually with a slight safety factor (in TVD). This goal calls for accurate drilling of the initial portion, smoothly transitioning into ranging.

Injector Build

With the producer build completed and the magnetized casing run in hole, the injector build well plan may be modified so that the approach to the producer well is a smooth transition from MWD surveys to the ranging section.
A similar if not identical BHA to that used during the producer build is utilized for the injector build.

The injector build is broken down into three sections as follows:

- Initial build and turn defined from MWD surveys.
- Transition zone defined from GMWD surveys.
- Ranging surveys at the end of the build section.

The Gravity MWD® (GMWD) System is used to provide an azimuth in areas of magnetic interference. It uses two sets of directional survey accelerometers to determine bending in the BHA. The alignment between the two sets of accelerometers must be known and can be measured on surface or derived down hole.6,7,8,9 The accelerometers also measure tool face so they can tell the orientation/direction of the bending. Hence the change in direction between the two sets. By chaining the sets you can get continuous changes in the direction of the well path, thus calculating an azimuth at every survey station.

The initial part of the well is drilled like a normal well. Full survey data from both directional survey systems is required along with their dynamic Z values. This is required to perform full QA checks and possible corrections on the surveys. Corrections required from MSA and sag analysis are applied real time.

During the initial build and turn section normal MWD surveys are used to define the well path. MSA and final calibration of the GMWD tool are also performed. In Figure 4 the graphical view of the GMWD tab section of the RADAR™ program is shown. The red line is a graphical representation of the gravity azimuth using the current calibration value and should lie on top of the green line which is the drilling well path. Normal survey course lengths are maintained until the landing point which is predetermined by the customer, usually based on the refined survey measurements made during the landing of the producer well.

There are actually 2 complementary passive ranging methods available during the landing of the injector well. Passive ranging makes use of the static magnetic field inherent in the metal. The metal in this case is casing that would normally have an unknown amount of magnetism imparted by Magnetic Particle Inspection at the ends of the casing joint. This magnetism is localised and does not come out from the casing very far. In order to increase the magnetism coming out from the casing to create a large magnetic target three things can be done. Firstly the casing should be subjected to a very strong magnetic field over its entire length (Figure 5), so the metal becomes magnetically (nearly) saturated. Secondly the poles in the casing should not be too far apart as they would tend to act like mono poles. Thirdly if opposing poles are used this tends to throw the magnetic flux further out from the casing. When these three things are done the effective passive range is more than adequate for SAGD work.12,13,14,15

The method can be validated by triangulation16,17. The magnetic field around the casing is axially symmetric and flux lines loop around like mug handles. If you now look down on top of the mug/casing you would not see loops but straight lines. These lines intersect in the middle of the casing determining its relative position as in Figure 4. Validation of the ranging method can be accomplished at any location where there is a divergence, convergence, or crossing between the 2 wells.

In Table 1 the difference between the two ranging methods, triangulation and RADAR™ ranging, are compared. The various well pairs were converging, diverging or crossing, in either their build or horizontal sections. Excellent comparison of this survey data showing very minimal radial error and strongly validates the RADAR™ ranging survey results.

<table>
<thead>
<tr>
<th>Well Section</th>
<th>Triangulation vs RADAR™ radial error (m)</th>
<th>Well Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Build A</td>
<td>0.08</td>
<td>Converge</td>
</tr>
<tr>
<td>Build B</td>
<td>0.09</td>
<td>Diverge</td>
</tr>
<tr>
<td>Horizontal C</td>
<td>0.08</td>
<td>Cross</td>
</tr>
<tr>
<td>Horizontal D</td>
<td>0.15</td>
<td>Cross</td>
</tr>
<tr>
<td>Horizontal E</td>
<td>0.10</td>
<td>Cross</td>
</tr>
</tbody>
</table>

**Injector Horizontal**

For the injector horizontal a target window is set by the customer. This is normally 1 m by 1.5 m (height and width) and can be to the left, above or to the right of the producer well. Applying an offset to the producer well surveys creates the well plan for the injector well as shown in Figure 7. Surveys stations for the injector horizontal are determined by the length of casing joints in the producer well with an optimal window preferred but not required. Survey course length for this pad was approximately 13.5 meters. By utilizing at bit inclination and gamma (Figure 6), TVD control between the two wells is maintained. The continuous Z wave information is graphically shown (Figure 8) and is the only real time radial distance information available in the industry today.

As there is no interaction required with any equipment in the target well drilling and surveying can continue as if drilling a normal well path. As with the injector build, triangulation can be used to verify the ranging data.

**Special Producer Wellbores - Crowded Fields, Infill Wellbores**

There are special circumstances where the prior procedures described need minor modifications. This occurs when there is a possibility of drilling close to preexisting wells. This is possible when wells from the existing pad are relatively close to the end of a previous pad and when drilling infill producer wells. The new wells are often drilled several years after the existing wells and there is concern as to the accuracy of the well position. The solution, in this case, is to drill the new producer with the injector build well BHA. This allows the early detection of interference from an existing well via the use of GMWD.

**RADAR™ - Real-time Analysis for Drilling and Advanced Ranging**

In the previous sections, we have presented a discussion of the various needs we address to accomplish our task of
delivering an optimal well pair for field development for SAGD. RADAR™ is the service brand and platform we have developed to enable the methods discussed and to accomplished this while drilling is progressing. The screen capture images (Figure 1, 4, 7, 8) of this application are of the actual system as used.

The emphasis on real-time, highly accurate, decision making has several consequences. The data must flow through the system with a minimal amount of user interaction. The specialized functions of M/LWD operator, ranging specialist, directional driller, and driller are performed in a cooperative manner; working together to reliably achieve an optimal result. As each specialist completes their tasks, the results are automatically passed to the next function in the processing chain. The topology to achieve this is shown in Figure 9. Note that there is also a satellite connection to a remote operations center to allow for consultation when needed along with continuous quality control.

Quality measures must be continuously available. It is not possible to spend days evaluating the data; time is critical. The results of the analysis, especially when variances are needed, must be clearly understood in order that consultation between stake holders, an important part of the decision process, is expeditiously carried out. Experience has shown that data analysis and decision making are usually best accomplished with a graphical display, especially when coupled with the backup ability to examine the values in detail in tabular form.

This systematic approach is achieved, allowing the methodologies used in the various drilling phases (as enumerated previously) to be provided via a consistent interface. This simplifies the application of the positioning methodologies.

For SAGD, the producer well focus is on highly accurate well location and a smooth well bore. The accuracy and flexibility requirements lead to the necessity of using unprocessed sensor values as opposed to inclination and azimuth values evaluated in the tool. Adherence to a well plan, which may be modified based on geologic parameters, needs to be closely monitored and the directional driller should minimize the excursions from the nominal path.

The injector well plan needs to be reassessed prior to the start of the build section and the well drilled as carefully as the producer. Our goal here is to minimize the corrections required during landing once the injector build section approaches the producer wellbore close enough for ranging to be performed.

The injector horizontal well plan is based on the actual producer surveys. The position of the injector is continuously updated and the directional driller is able to anticipate real-time changes as required.

Conclusion

This paper outlines a systematic approach to correctly placing SAGD well pairs and infill wells. This is achieved by first considering the entire development and accurate placement of the project field, well pad, well pairs and well(s). The case study area reviewed is in the heavy oil sands of the Foster Creek region of Northeastern Alberta, Canada.

Several techniques are implemented in this approach and are encompassed within the RADAR™ services. In well twinning, highly accurate well placement of the producer wellbore is followed by ranging, GMWD and at bit measurements to correctly place the injector wellbore per plan. The correct placement of infill wells in the field is also achieved by the same techniques.

Minimizing borehole tortuosity in these wells, coupled with rapid, accurate real-time evaluation while drilling, enables fast steering decisions to place these wellbore’s per plan and to improve the project drilling economics.

Acknowledgement

We would like to thank Cenovus Energy Limited for their continuous support and development of this SAGD well placement service. In addition, Leon Ceh, Ken Stenerson and all the field and support personnel who contributed many hours to ensure correct placement of every well pair that we have completed to date.

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Figure 1 - A RADAR display showing the spatial relationship between the lateral well pairs. The producer is in the centre of the plot and the well being drilled (injector) is depicted as a series of dots (surveys) within the target box (red).

Figure 2 - Plan view of the case study well pad that encompasses 9 completed well pairs (18 wells).
Figure 3 - Plan view of the well pad with adjacent well pad included. Direction control and anti-collision techniques were critical in the build sections due to the close wellbore proximities.

Figure 4 - Real-time RADAR QA/QC of the GMWD calculations prior to method implementation.
Figure 5 - The multi coil gaussing table. The wellbore casing is rolled in along the red rollers, the coils are energized (magnetizing the casing) then the casing is rolled out and stacked.
Figure 6 - M/LWD passive ranging BHA with @ bit sensors.
Figure 7 - Real-time RADAR well plan views of both the injector and producer well paths.

Figure 8 - A real-time RADAR view of the continuous Z wave measurement in a lateral section representing a near constant radial separation between the well pairs.
Figure 9 - The RADAR system is highly networked and focused on error free sharing of data and interpretations. The actual implementation is very configurable with tasks being carried out at the rig site and/or at a remote operation center.