ACCURATE LOAD & POSITION MEASUREMENT IS CRITICAL TO QUALITY DYNAMOMETER ANALYSIS

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ABSTRACT:

Analysis and control of reciprocating rod lifted (RRL) wells has changed drastically over the past 20 years. Advanced diagnostic tools first started appearing on desktop applications, and over time have shifted to the wellsite to provide more accurate control of an RRL system in real-time. All of these tools depend on a dynamometer card in order to properly analyze and control an RRL system. However, the inputs to the dynamometer card are often of questionable accuracy. A poor quality dynamometer card can lead to improper control of the RRL system and inaccurate results from the calculations that depend on the dynamometer data (i.e. rod stress, gearbox torque, structure loading, PIP, etc.). This paper will discuss the variety of instruments used to capture the inputs to a dynamometer card (polished rod load and position), their strengths and weaknesses, how to recognize errors in the input data, and how to correct it.

INTRODUCTION

Reciprocating rod lift is the dominant form of artificial lift used throughout the world, utilized by over 80% of the wells on artificial lift (Takács 2003). Consequently, rod lifted wells can consume the bulk of an operator's time allocated to field surveillance, analysis, and production optimization. Prior to the widespread adoption of dynamometer equipment, understanding a well's performance required piecing together multiple pieces of information such as well tests, fluid level shots, and on-site observations. Much of this information became dated very quickly and may not accurately portray what is happening as well conditions change.

Today's dynamometer equipment allows for measurement, remote transmission, and analysis of a well's performance in near real-time conditions. Though the widespread adoption of rod pump controllers, SCADA systems, and desktop analysis software has greatly increased the availability of this dynamometer data, the author has observed a general lack of quality in the data that is measured and presented to a user. This is not a problem that has recently developed; Kemler (1935) described early problems with damping and phase lag of the data collected by the dynamometers of his day.

This paper will discuss how polished rod load and position are combined to produce a dynamometer card, how these two quantities are measured, and review a number of cases that illustrate errors in the load and/or position measurement. These examples will show how control of the well and calculated values such as gearbox torque, structure loading, rod stress, and pump displacement are affected by these measurement errors.

WHAT IS A DYNAMOMETER CARD?

Simply put, a dynamometer card is one of the single most important pieces of data required for proper understanding of the operation of a reciprocating rod lift system. Merriam-Webster defines a dynamometer as "an instrument for measuring mechanical force" (Merriam-Webster.com 2015a). In the oilfield, we refer to the output of such an instrument as a dynamometer card, or simplified to dynamometer, dynagraph, dyno, or card. The force we are measuring is the force applied to the rod string throughout the pumping cycle of a surface pumping unit. To determine that force and plot a surface dynamometer card, the basic measurements that must be made are the load applied to polished rod vs. the position of the polished rod. Dynamometer cards can vary widely given the multitude of strokes per minute (SPM), depth, rod taper configuration, pump size, and fluid gravity conditions that may exist across different wells.

LOAD MEASUREMENT USING A BEAM-MOUNTED STRAIN GAUGE

The term strain gauge is a generic one referring to "an instrument for measuring minute deformations of test specimens caused by tension, compression, bending, or twisting" (Merriam-Webster.com 2015b). The early use of strain gauges for measuring the force applied to the rod string was described by Kemler (1936). These early strain gauges were installed on the polished rod and first used as part of a portable system for measuring well performance, not as part of a permanent control system. For the purposes of rod pump automation, the term "strain gauge" commonly refers to a sensor (Figure 1) that is mounted on the top flange of the walking beam as shown in Figure 2. The strain gauge measures changes in tension of the walking beam caused by changes in polished rod loading, and is typically used in conjunction with a permanently installed rod pump controller.

The beam-mounted strain gauge operates on a simple principle; as load on the polished rod changes, the tension present in the walking beam changes proportionally. Compared to a polished rod load cell, the use of strain gauges does not require the polished rod to be clamped off during installation or replacement and reduces the likelihood of damage to the load cell or cable during a workover. Strain gauges are also not subjected to the shock loading that occurs when the rods float on the downstroke, and for this reason are favored by some companies in heavy oil applications. Some vendors offer a strain gauge with an integrated inclinometer, which requires only a single sensor cable to be run to the rod pump controller at the time of installation.

However, the above benefits are quickly outweighed by the drawbacks present in utilizing a strain gauge sensor for load measurement. The most significant drawback is that it is not possible to establish a direct relationship between the output of the strain gauge and the pounds force applied to the polished rod. As a result, the user must "calibrate" each installation to the expected load range of the well. The user must input the minimum and maximum polished rod loads that correspond with the feedback observed from the strain gauge. If these loads are measured with a portable load cell at the time of installation, the resulting load readings will be the most accurate. However, a more common practice is to use the results of a design report. In this case the loads readings may have little resemblance to the well conditions at the time of installation.

The above problem is compounded by the simple assumption made in the original principle of operation: that the bending moment is the only force exerted on the beam by lifting the load of the rod string. On the contrary, there are many forces acting on the beam that cause changes in the observed tension. The most obvious is the effect temperature has on the measurement. As the temperature rises and falls, causing the material of the beam to expand and contract, the strain gauge's output will begin to drift and produce errors in the load measurement used to generate the dynamometer card. Changes in temperature may also affect the strain gauge itself if its design does not properly compensate for variations in temperature.

The other forces acting on the strain gauge that produce measurement errors are not obvious upon first glance. Again, the basic measurement assumption is that the rod load imparts a bending moment on the beam, and <u>only</u> a bending moment. However, when the beam is not horizontal, the pull from the polished rod has separate components that are perpendicular and parallel to the beam. The perpendicular component causes the beam to bend, but the parallel component may cause compression or tension of the top flange of the beam as the beam angle changes throughout the stroke. This parallel load component prevents the force measured by the strain gauge to be strictly analogous to the forces exerted on the polished rod, reducing the overall accuracy of the sensor (Gibbs 2012).

It is clear that the beam-mounted strain gauge is useful only as a qualitative representation of the load on the polished rod. For rod pump controllers that utilize only surface card control, this may be acceptable. However, any controllers utilizing a downhole card for control will require close attention and frequent adjustment of the load calibration in order to produce acceptable downhole cards. Additionally, the results of any calculations for gearbox torque, structure loading, rod stress, and inferred pump intake pressure will be suspect as these all require accurate load measurements to yield meaningful results.

LOAD MEASUREMENT USING A POLISHED ROD LOAD CELL

For permanently installed rod pump optimization systems, the most commonly used sensor for measurement of polished rod load is the polished rod load cell shown in Figure 3. The polished rod load cell is similar to the beam-mounted strain gauge in that both utilize a strain gauge as the base measurement element. However, the polished rod load cell differs in that it uses multiple strain gauges in a full-bridge circuit (Figure 4). The result of using this bridge circuit is that the output is directly proportional to the force applied to the polished rod, whereas the beam-mounted strain gauge is only approximately proportional to polished rod load (All About Circuits 2015). This gives the load cell a clearly defined linear relationship between the load cell output and pounds force applied

The full-bridge strain gauge configuration used by the load cell provides another important benefit over the beam-mounted strain gauge, and that is temperature compensation. As the temperature of the load cell changes, a temperature-induced change in strain will affect all elements of the bridge equally. In a full-bridge configuration, an equal change in resistance of all four elements does not change the ratio of their resistance, and produces no change in the sensor's output (National Instruments 2011). Load cell manufacturers typically include additional temperature compensation circuitry between the bridge and the cable connection to the rod pump controller to ensure the bridge is ideally balanced with respect to temperature changes. Discussion of this circuitry is outside the scope of this paper.

The polished rod load cell is installed in such a way that it can directly measure the force applied to the polished rod, and not infer it through measurement of some other component of the pumping unit. Figure 6 shows how the load cell is installed on the polished rod above the carrier bar, but beneath the polished rod clamps. This causes the full weight of the rod string to compress the load cell. An alignment bearing is typically used beneath the load cell to ensure the force of the rod string weight is evenly applied to the entire surface area of the load cell. One drawback of the load cell installation is that a crew equipped with extra polished rod clamps or a crane is required to secure the rods in place while the top coupling and polished rod clamps are removed. Additionally, the load cell and its cable must be removed and reinstalled during a workover, creating an opportunity for either of these components to be damaged. The cable is also more likely to be damaged on reverse geometry units such as a Mark II or air balance unit during normal operation.

Unlike the beam-mounted strain gauge, a load cell does not require the span to be calibrated per installation. However, the zero offset must be properly accounted for at the time of installation. Though a perfectly balanced bridge will provide a zero output with no load applied, the tolerances of the strain gauges and strain induced by the application of the gauges to the load cell element will typically result in a small offset voltage at zero load (National Instruments 2014). Most controllers have a simple offset calibration process where the load cell is connected with zero load applied, a command is executed, and the zero offset value is stored in the controller. Skipping this process will result in a dynamometer card with all points shifted up or down by the load value associated with that sensor's zero offset. This can result in erroneous results for the calculation of gearbox torque, structure loading, and rod stress.

The polished rod load cell is the predominant sensor for polished rod load measurement. The proportional output, direct measurement, and temperature compensation available with a polished rod load cell yield superior results when compared to beam-mounted strain gauges. If the user takes care to program the controller with the proper zero offset, the polished rod load cell provides the most accurate representation of polished rod load available.

INFERRING POLISHED ROD LOAD FROM MOTOR MEASUREMENTS

With the widespread use of variable frequency drives (VFD) to optimize pumping units, a new method of inferring polished rod load from data available in the VFD has become popular with some manufacturers. Modern VFDs are capable of independently determining the amount of current used to excite (magnetize) the motor and the amount of current that is producing torque. By determining the torque-producing current, the VFD can calculate the torque output of the motor. With knowledge of the sheave ratio between the motor and the gearbox, as well as the specific pumping unit geometry and dimensions as described in *API SPEC 11E* (2013), it is possible to infer a calculated polished rod load.

In order to accurately determine the torque-producing current, these VFDs require a motor tuning process to be completed at the time of installation. This allows the VFD to characterize the control outputs such as speed and torque as they relate to measurements of voltage and current. The most important variable determined during this process is the no-load current, which is key to distinguishing the excitation current vs. the torque-producing current. The best way to determine the no-load current is to operate the motor decoupled from the pumping unit. However, in many cases the motor will already be installed with the belts attached before the VFD is commissioned. Typically, VFDs offer the option of a non-rotational tune for such a situation. To complete a non-rotational tune the no-load current is either manually entered or calculated based on the measured stator resistance. Since the no-load current is not directly measured, this can lead to errors in calculating torque during operation, which in turn lead to errors in calculating polished rod load.

An additional source of error when using this method to infer polished rod load is the requirement to program the VFD with the pumping unit's API dimensions. If the API dimensions are not properly configured in the VFD, then the calculated polished rod load will not be correct. If the dimensions of a particular unit are not known it may be necessary to measure them in the field, which can be difficult on larger units.

The use of a VFD to infer polished rod load is viewed as advantageous as there is no additional sensor to install, and no cable to break. However, as detailed above there are many variables that affect the accuracy of that load calculation that make it less than ideal for control and analysis of rod lifted wells. There is no distinct element of operation of the pumping unit that can be directly measured and related to polished rod load without multiple interim calculations and inferences, leading to questionable accuracy of the resulting loads.

POSITION MEASUREMENT USING A POSITION SWITCH

When determining the position of the polished rod for a dynamometer, it is common practice to measure the movement of another part of the pumping unit and infer polished rod position from that measurement. The simplest methodology of determining polished rod position is with a position switch (Figure 7). A reed switch is embedded in a wand for ruggedness and ease of installation, and installed on the base of the pumping unit facing the crank arm. A magnet is attached to the inside of the crank arm or counterweight. As the magnet passes in front of the wand (Figure 8), the switch closes giving the rod pump controller a reference position value once per stroke. The position switch is an easily installed, low cost solution for position measurement.

With the reference point now measured, the controller must generate the additional position points that occur between switch closures. It is common to assume the motion of the polished rod is sinusoidal between switch closures, which will lead to measurement errors. This is caused by differences in the upstroke and downstroke velocities due to the geometry of the pumping units, belt slippage, or unit unbalance. This is especially true of improved geometry units such as the Weatherford Maximizer II or Lufkin Mark II. This can be easily observed in downhole cards calculated from surface data obtained with a position switch. Such cards will generally have a more jagged appearance or loops in the downhole card, especially at top and bottom of stroke.

At the time of installation, a technician must visually observe the movement of the pumping unit and execute a command on the controller at the moment the horsehead reaches its highest point. The controller uses the time measured between when the switch closure was detected and when the command was executed to know how to properly scale the internally generated position values. Any error in this calibration process will cause the entire surface card and resulting downhole card to be rotated either left or right. These erroneously rotated cards can give the indication of tubing movement that is not occurring and cause errors in the calculation of gearbox torque or inferred production.

POSITION MEASUREMENT USING HALL-EFFECT TRANSDUCERS

Instead of using a single position switch and calculating the additional required position points, a pair of Hall-effect transducers like those shown in Figure 9 can be implemented. A Hall-effect transducer is a solid state device with an analog output signal that increases in the presence of a magnetic field. The advantage to using a Hall-effect transducer is the ability to accurately detect the magnet in high-speed applications, such as when counting motor revolutions

(Honeywell Inc. n.d.). When used to determine polished rod position, one Hall-effect transducer is used to monitor the motion of the crank arm, and a second transducer is used to measure motor revolutions.

The addition of the second transducer for measuring motor revolutions allows this system to provide continuous position measurement throughout the stroke. The crank arm transducer provides a reference point (either bottom or top of stroke) once each stroke, and the controller uses the motor transducer signal to relate each revolution of the motor shaft to an incremental change in the rotation of the crank arm. After the rod pump controller is programmed with the API geometry and dimensions that describe the pumping unit, the crank rotation information can be used to calculate polished rod position.

The requirement to program the rod pump controller with the pumping unit's API dimensions is one of the potential sources of error in this method of position measurement. If the API dimensions are not properly configured in the controller, then the calculated polished rod position will not be correct. Even if the dimensions are available based on the manufacturer's published data, the A and C dimensions, and resulting stroke length, may vary in the field. This is due to the adjustment available in some units where the walking beam attaches to the saddle bearing, as well as manufacturing tolerances (*API SPEC 11E* 2013). If the dimensions of a particular unit are not known it may be necessary to measure them in the field, which can be difficult on larger units.

An additional source of error when using the Hall-effects transducers is the offset between when the crank arm transducer detects the magnet and when the reference point is actually reached. This is caused by the mounting position of the crank arm transducer to one side of the sub-base. This offset is normally referred to as the phase angle adjustment in controllers that support the Hall-effects transducers. If the phase angle adjustment is not properly configured, just like an incorrect top of stroke setting for a position switch, the resulting surface and downhole cards will be rotated left or right. This is the most common source of position error observed when using Hall-effects transducers.

POSITION MEASUREMENT USING AN INCLINOMETER

One aspect of the pumping unit that is frequently measured to determine polished rod position is the angle of the walking beam. There is a significant advantage to this approach as the movement of the beam is directly related to the movement of the polished rod. Measurement of the beam angle is typically done with an inclinometer such as the one shown in Figure 10.

The base measurement element used in an inclinometer is an accelerometer. In a stationary system such as a pumping unit, the accelerometer functions to detect the direction of pull from the Earth's gravity, making it an effective way of measuring angle of inclination. As the walking beam tilts throughout the stroke of the unit, the changing output voltage is used by the rod pump controller to determine polished rod position.

An inclinometer is calibrated for a specific orientation and angle range, typically ±45 degrees from vertical. During installation, the inclinometer is be mounted on the web of the walking beam, perpendicular to the beam, and near the pivot point. This means installing the inclinometer as close as possible to or directly on the Sampson post bearing, at the center of a rear-mounted geometry unit (Figure 11) or the rear of a front-mounted geometry unit (Figure 12). This will provide the maximum deflection of the inclinometer throughout the stroke, giving better resolution when the rod pump controller converts the output signal to polished rod position. This will also reduce the amount of vibration that may be transferred from the pumping unit to the inclinometer. Excessive vibration of the inclinometer will distort the position reading, reducing the data quality of the dynamometer card.

Proper installation of the inclinometer must also account for which side of the beam it is installed on. For example, an inclinometer configured to be installed on the right side of the pumping unit (wellhead to the right when facing the pumping unit as shown in Figure 11 or Figure 12) will output an increasing voltage as the polished rod is lifted. However, that same inclinometer installed on the left side, aka the “off” side, of the pumping unit will output a decreasing voltage as the polished rod is lifted. In order to account for this, most inclinometers use alternate wiring when installed on the "off" side of the pumping unit that reverses the signal output. Without this compensation, the dynamometer card would be plotted in reverse.

Despite following the best practices for installation detailed above, inclinometers will still be subjected to some amount of vibration from the pumping unit that will distort the position reading. Early inclinometers used a simple filter to reduce these distortions, with the side effect of creating a time delay in the response of the output. This time delay would cause the position signal to become skewed relative to the load signal, and rotate the resulting dynamometer card. Unlike an error in setting top of stroke for a position switch or Hall-effects transducer that can cause the card to lean left or right, the skewed inclinometer data will always produce a card that leans to the left. A de-skew adjustment in the rod pump controller can be used to correct this, similar to the phase angle adjustment used for the Hall-effects transducer. Newer microelectromechanical systems (MEMS) based inclinometers more effectively filter the distortions caused by vibration, producing a cleaner signal without requiring skew adjustment in the rod pump controller.

EXAMPLES OF LOAD AND POSITION MEASUREMENT ERRORS

The following examples are from actual wells exhibiting many of the measurement errors previously described for each sensor type. Both the dynamometers and analysis results will be discussed for each example, including the updated results after correction of the measurement error. Gearbox torque was calculated assuming the optimum amount of counterbalance was installed, since the exact counterbalance configuration was not known for each well.

It should be noted that due to a software limitation, all of the predicted cards shown in orange display the downhole card with buoyancy, while the field cards are shown with effective loads. This causes a slight difference in the position of the downhole card relative to zero, but does not affect the comparisons that will be presented.

Despite the use of diagnostic software to perform offline correction of some of the dynamometers shown as examples, the author strongly believes that the proper place to correct each of these measurement errors is at the wellsite controller. Several examples will show where the control of the well is affected due to the dynamometer shape, and correcting this offline will do nothing to improve the control and optimization of the well. The diagnostic software should be used to identify the source and severity of the measurement error, then the necessary calibration changes must be applied to the wellsite controller.

WELL A – BEAM-MOUNTED STRAIN GAUGE WITH IMPROPER LOAD CALIBRATION

Well A utilizes a beam-mounted strain gauge for measuring polished rod load. When compared with the orange predicted card in Figure 13, the measured surface card is shifted significantly lower, exhibits a narrower profile, and a portion of the downhole card is below the zero load line.

To correct the load calibration, the peak and minimum polished rod loads from the predictive program are programmed into the rod pump controller, and the load calibration process executed. This adjusts the span and zero offset to match the measured millivolt input range to the programmed calibration range. Figure 14 shows Well A after completing this load calibration process. There is a much closer match between the field and predicted surface cards, and the downhole card now lies on the zero load line. When using effective loads for the calculation of the downhole card, the minimum load on the downstroke should overlay the zero load line (assuming minimal downhole friction). This is an important reason to visualize downhole cards using effective loads as opposed to buoyant loads, as the zero load line becomes an important reference marker.

A comparison of the analysis results for Well A is shown in Table 1. Since the previous calibration was producing load values that were too low, the updated analysis results show significantly higher loading of the gearbox, structure, and rod string. The gearbox torque (102%) and peak rod stress (119%) are most concerning as both appear to be overloaded. If the pumping unit is not perfectly balanced, the gearbox torque could be significantly higher. Without taking corrective action, the life of both these critical components of the system will be greatly reduced.

WELL B – BEAM-MOUNTED STRAIN GAUGE DRIFT

Well B illustrates another problem that is common with beam-mounted strain gauges. Figure 15 shows a dynamometer card from Well B on day one. A positive load reading offset is clearly visible, as indicated by the red arrows, with the downhole card sitting above the zero load line. On day two, with no adjustment of the controller configuration, the card is observed in Figure 16 to lie on the zero load line.

Regardless of which card is more correct, this well clearly shows how strain gauge drift, either high or low, can yield inaccurate analysis results. This can result in possible false alarms for high gearbox torque, structure loading, or rod stress. The drift may also force an operator to set wider load alarm setpoints on the controller to prevent false alarms as the load signal drifts from day to day. Wider alarm setpoints may inadvertently allow the well to run in an overloaded condition, shortening the life of the pumping unit and downhole equipment.

Table 2 shows the analysis results for Well B. The peak polished rod load is 2,600 lbs. lower on day two after the strain gauge has drifted lower. This yields a 3% lower peak gearbox torque value, 7% lower structure rating, and 4% increase in peak rod stress.

WELL C – ZERO OFFSET ERROR WITH POLISHED ROD LOAD CELL

Well C utilizes a polished rod load cell for load measurement. In Figure 17, the downhole card is elevated 1,107 lbs. above zero, as indicated by the red arrows. This clearly indicates the presence of a zero offset error in the load measurement. When using effective loads for the calculation of the downhole card, the minimum load on the downstroke should overlay the zero load line as discussed above. While having a negative load on the downstroke may indicate either the presence of friction or a zero offset error, minimum loads above zero are always indicative of a zero offset error.

After software correction of the load offset, both the surface and downhole cards are shifted down until the downhole card sits on the zero load line. Figure 18 shows there is now a much better match for the surface loads of the field card compared with the orange predictive card.

The analysis results for Well C are shown in

Table 3. As would be expected, all results that are dependent on polished rod load are affected and reduced substantially as the zero offset is corrected. The calculated results with the corrected card show the gearbox torque to be 7% lower, structure loading to be 6% lower, and peak rod stress to be 13% lower. Compared with Well A that underreported the gearbox and structure loading, the uncorrected high rod stress values for Well C incorrectly indicate that the rod string is running close to capacity. This could serve as a false indication that the pumping unit needs to be slowed down, or that the system design needs to be modified.

WELL D – TOP OF STROKE ERROR WITH POSITION SWITCH

Well D uses a position switch for position measurement. Figure 19 illustrates that top of stroke for the field card in blue is severely off on this well. The first indication of this is the field card has a much more severe lean to the left as compared to the predicted card in orange (reference the dashed red and green lines, respectively). It should be noted the tubing anchor on this well is ~3,000 feet above the pump, so the slight tubing movement evident in the predicted card is expected (indicated by the dashed green line). Additionally, there is a 15 inch difference in the gross downhole stroke between the field and predicted cards, as indicated with the red arrow. This card gives the false impression that almost 25 inches of tubing movement is occurring, and possibly some incomplete pump fillage.

Figure 20 shows the field card after correcting the top of stroke setting in the controller. The top of stroke value in the controller was manually adjusted until the card rotation matched the predicted card. The surface cards overlay one another, and the slope and downhole stroke of the downhole card matches the predictive card. The jagged appearance of the field card at top and bottom of stroke is typical of calculating downhole cards from surface data obtained with a position switch. The pump is clearly full, with a slight amount of tubing movement.

Figure 21 shows Well D at pump-off before the top of stroke error is corrected. The net stroke is shorter than the actual net stroke, which can cause the controller to prematurely stop the well. Figure 22 shows another pump-off card for Well D after top of stroke was corrected. Notice that after top of stroke is corrected the downhole card no longer violates the pump-off setpoint (vertical line on the downhole card).

Table 4 shows the analysis results for Well D. Load and position correctly paired together is critical for calculating gearbox torque, as the torque factors for the pumping unit continuously change as the position changes. Due to the top of stroke error, there is a significant increase in gearbox torque after the position data is corrected In this case the gearbox is not overloaded, however this example shows how a unit with incorrect position data could be running in an overloaded condition, while the uncorrected analysis results show there is nothing to be concerned about. Unlike the following position error examples, Well D shows a 6-7% difference in the calculated peak rod stress attributed to the severity of the position data error.

The net stroke for both full and pump-off cards was greatly impacted, and indicated less fluid was being produced than actually observed. There was a 46-48% difference in daily displacement between the uncorrected and corrected cards. If inferred production from the rod pump controller is used to track production, this will cause a large error in the calculated production numbers.

WELL E – PHASE ANGLE ERROR WITH HALL-EFFECTS TRANSDUCER

This example shows a well without the proper phase angle adjustment setting stored for the Hall-effects transducer. Though the well has a tubing anchor, the dynamometer card in Figure 23 would indicate that the tubing is unanchored as indicated by the slope of the card on the upstroke (dashed red line). However, when the predictive card in orange is overlaid on the field card in blue, it becomes clear that there is a potential issue with the position data on this well. There is a slight difference in the slope of the surface and downhole cards at the beginning of the upstroke (indicated by the dashed green and red lines), and the gross downhole stroke is shorter than what is predicted (indicated by the red arrows). After the position data is software corrected in Figure 24, the predictive card and field card more closely overlay each other, and the gross stroke is a near perfect match.

Aside from the potential for improper diagnosis of tubing movement, there is a great impact on the control of the well. The pump-off card in Figure 25 is shown with the original position data. This card shows only 93.3 inches of net stroke, or 91.4% pump fillage. When the position data is corrected in Figure 26, it becomes clear this well is not pumped off per the current pump-off setpoint (solid dot is inside the surface dynamometer). The net stroke of the corrected card is 100.1 inches, or 95.2% pump fillage. This well illustrates the potential for under-pumping a well and lost production, and why position errors must be corrected in the controller and not solely in software.

Table 5 shows the results of several values from the analysis report for Well E. The two most impacted areas of analysis for these cards are gearbox torque and the downhole card stroke length. The uncorrected cards results in gearbox torque values that are 5-6% higher than the actual gearbox loading. This may result in false alarms for gearbox overloading or unnecessary corrective action being taken to try and reduce the gearbox loading.

The downhole card stroke length is also significantly impacted. The effect of this on control of the well was previously discussed, but this will also have an impact on inferred fluid production values based on the downhole net stroke. For this well, inferred production may be under-reported by 7-8%.

WELL F – SKEWED POSITION DATA WITH AN INCLINOMETER

In this example, filtering is increased on an older inclinometer, causing a time lag between when the position is sampled and when the output to the rod pump controller updates. The downhole card in Figure 27 appears to lean to the left (indicated by the dashed red line), a typical characteristic of a filtered inclinometer without properly de-skewing the position data in the rod pump controller. Though a card leaning to the right might be indicative of tubing movement, a card leaning to the left almost always indicates a position problem. The downhole stroke is longer than what is predicted (indicated by the red arrow), and the peak polished rod load point on the surface occurs earlier in the stroke than predicted (as indicated by the green arrow).

After applying the proper position de-skew in the rod pump controller, Figure 28, the downhole card has the typical rectangular shape expected for a full card with anchored tubing. However, there remains a difference in the gross downhole stroke when compared to the predicted card. This is likely due to a difference in the pump intake pressure when the field card was collected versus the pump intake pressure input for the predictive program.

The previous position error examples showed how a well may be potentially under-pumped when the card leans to the right, when the card leans to the left the well will be over-pumped. Figure 29 shows a pump-off card for Well F before correcting the skewed position data. After correcting the position data, Figure 30 shows the well is pumping harder than desired with the current setpoint (indicated by the red arrows)

Table 6 shows the analysis results for Well F. As with the previous position examples, the gearbox torque increases after the card rotation is corrected, especially for the pump-off card. The downhole stroke of the uncorrected card is longer than the corrected card, and shows a higher daily displacement. If inferred production is being used to track daily fluid production the production will be over-reported by 5-14%.

CONCLUSION

The dynamometer card has developed as the most important tool used for control and analysis of the performance of rod lifted wells. When deploying a rod lift optimization solution, it is important to understand the strengths and weaknesses of the sensor types available for measuring the dynamometer inputs. Regardless of the sensors selected, the user must take care that they are properly installed, calibrated, and configured in the rod pump controller. The example wells have shown that incorrect sensor data can result in poor well control, under- or over-reported production, and possible overloading of the gearbox, pumping unit structure, or rod string.

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TABLES & FIGURES

Table 1 – Analysis results for Well A

	Pump-off Card (Uncorrected)	**Pump-off Card (Corrected)**
Peak Polished Rod Load (lbs)	25,604	31,099
Minimum Polished Rod Load (lbs)	10,769	12,637
Gearbox Torque (in-lbs / %)	558,000 / 87	654,000 / 102

Structure Loading (%)	70	85
Peak Rod Stress (%)	93	119

Table 2 – Analysis results for Well B

	Day One (Zero Offset)	**Day Two (Strain Gauge Drift)**
Peak Polished Rod Load (lbs)	34,000	31,400
Gearbox Torque (in-lbs / %)	880,000 / 96	854,000 / 93
Structure Loading (%)	93	86
Peak Rod Stress (%)	60	64

Table 3 – Analysis results for Well C

	Full Card (Uncorrected)	Full Card (Corrected)
Peak Polished Rod Load (lbs)	19,471	17308
Minimum Polished Rod Load (lbs)	7,450	6268
Gearbox Torque (in-lbs / %)	494,000 / 77	449,000 / 70
Structure Loading (%)	53	47
Peak Rod Stress (%)	97	84

Table 4 – Analysis results for Well D

	Full Card (Uncorrected)	Full Card (Corrected)	Pump-off Card (Uncorrected)	Pump-off Card (Corrected)
Gearbox Torque (in-lbs / %)	181,000 / 56	265,000 / 82	147,000 / 45	175,000 / 54
Peak Rod Stress (%)	75	69	72	65
Gross Stroke (in)	89.3	104.1	87.9	103.0
Net Stroke (in)	62.4	92.6	35.7	52.1
Net Stroke Displacement (BPD)	68.5	101.8	39.2	57.3

Table 5 – Analysis results for Well E

	Full Card (Uncorrected)	Full Card (Corrected)	Pump-off Card (Uncorrected)	Pump-off Card (Corrected)
Gearbox Torque (in-lbs / %)	321,000 / 100	305,000 / 95	325,000 / 101	305,000 / 95
Peak Rod Stress (%)	78	77	83	82
Gross Stroke (in)	99.7	104.8	102.1	105.1
Net Stroke (in / %)	93.5	100.9	93.3	100.1
Net Stroke Displacement (BPD)	319.4	344.7	323.6	347.0

Table 6 – Analysis results for Well F

	Full Card (Uncorrected)	Full Card (Corrected)	Pump-off Card (Uncorrected)	Pump-off Card (Corrected)
Gearbox Torque (in-lbs / %)	419,000 / 65	436,000 / 68	410,000 / 64	471,000 / 73
Peak Rod Stress (%)	85	85	80	83
Gross Stroke (in)	151.0	137.0	138.6	132.2
Net Stroke (in)	145.3	127.6	108.9	103.7
Net Stroke Displacement (BPD)	472.8	415.3	354.3	337.4

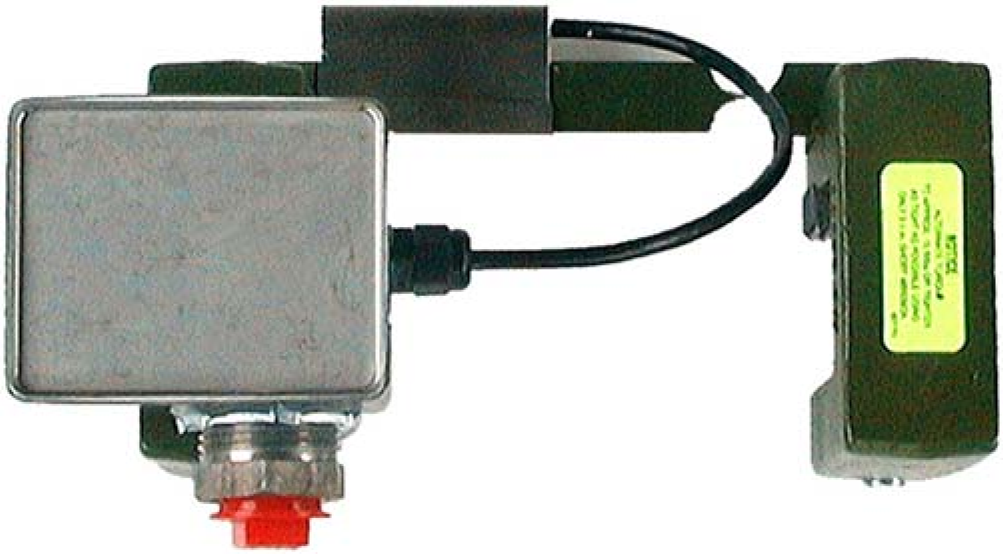

Figure 1 – Beam-mounted strain gauge

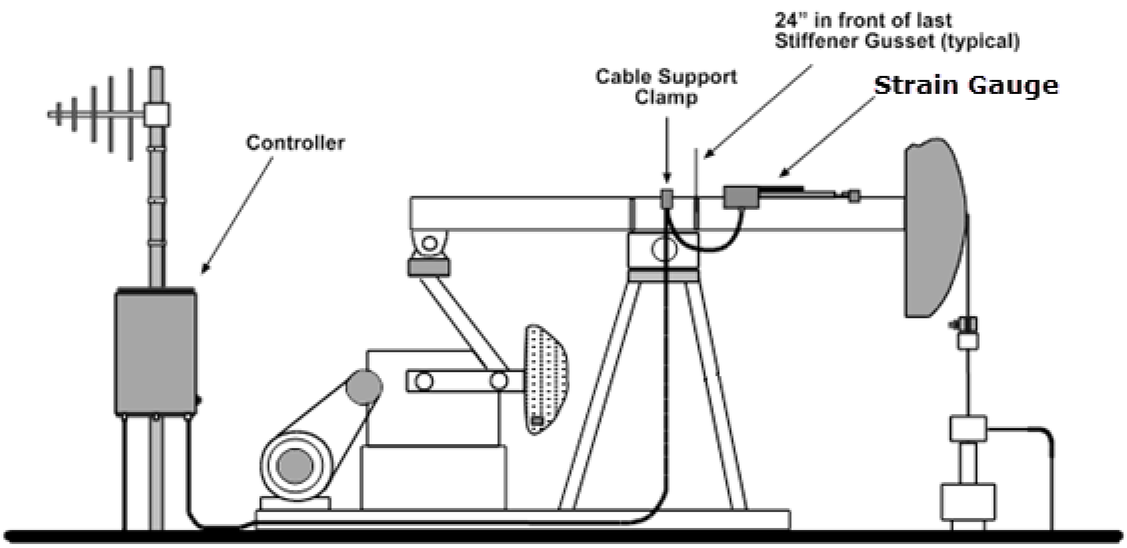

Figure 2 – Beam-mounted strain gauge installation

Figure 3 – Polished rod load cell

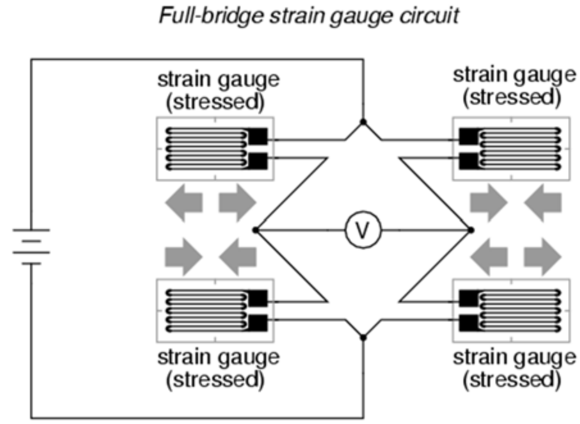

Figure 4 – Full-bridge strain gauge circuit
(All About Circuits 2015)

Figure 5 – Polished rod load cell rating

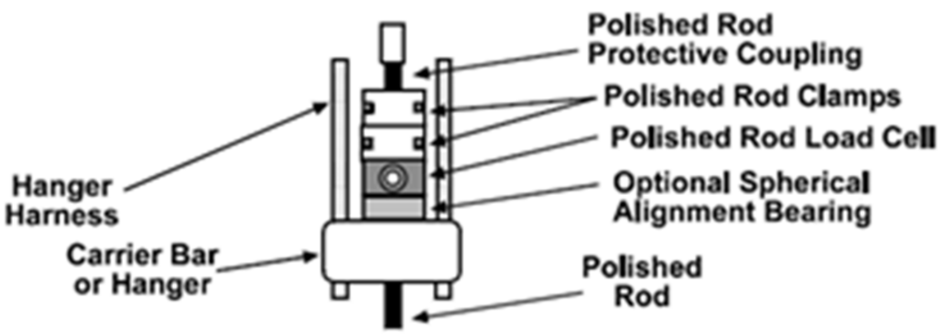

Figure 6 – Polished rod load cell installation

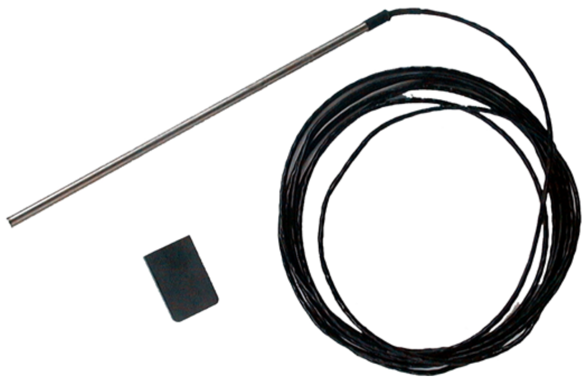

Figure 7 – Position switch with magnet

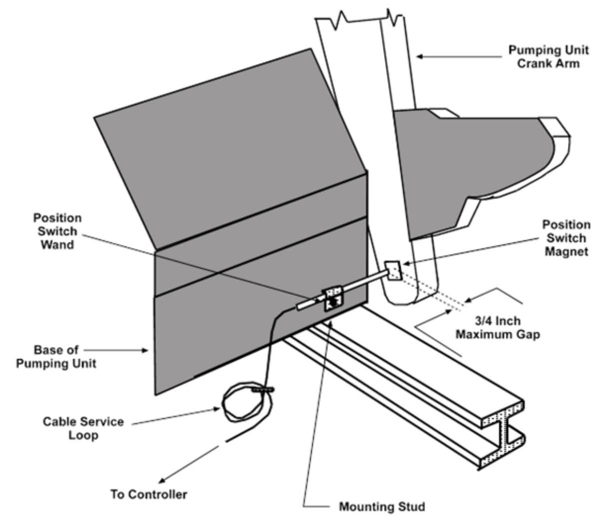

Figure 8 – Position switch installation

Figure 9 – Hall-effects transducer kit (Lufkin Industries, LLC 2013)

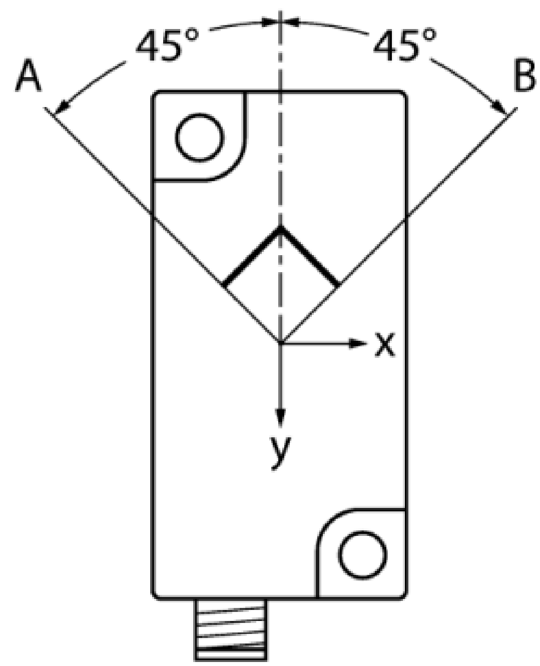

Figure 10 – Inclinometer

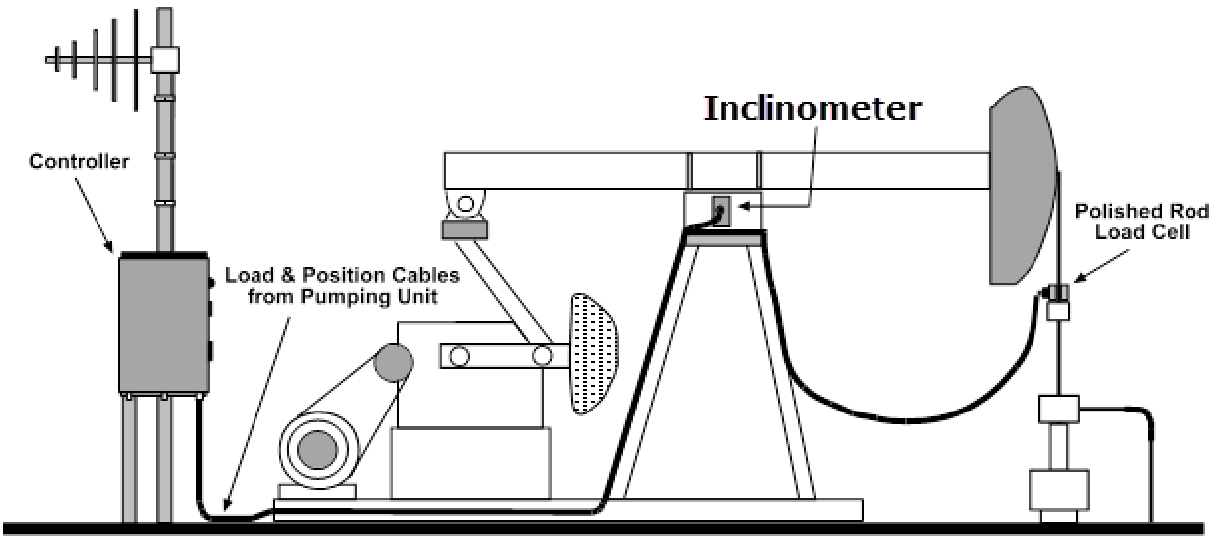

Figure 11 – Inclinometer installation for rear-mounted geometry pumping unit

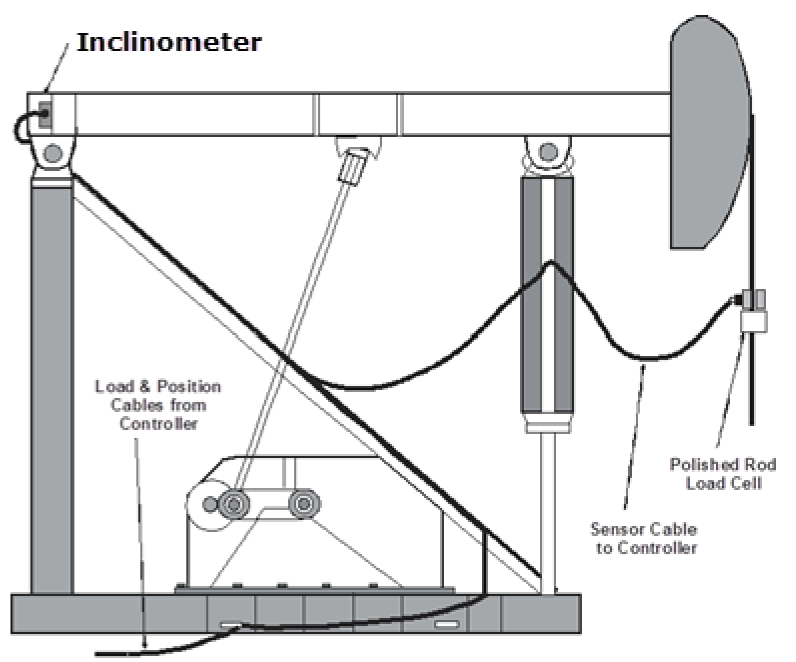

Figure 12 – Inclinometer installation for front-mounted geometry unit

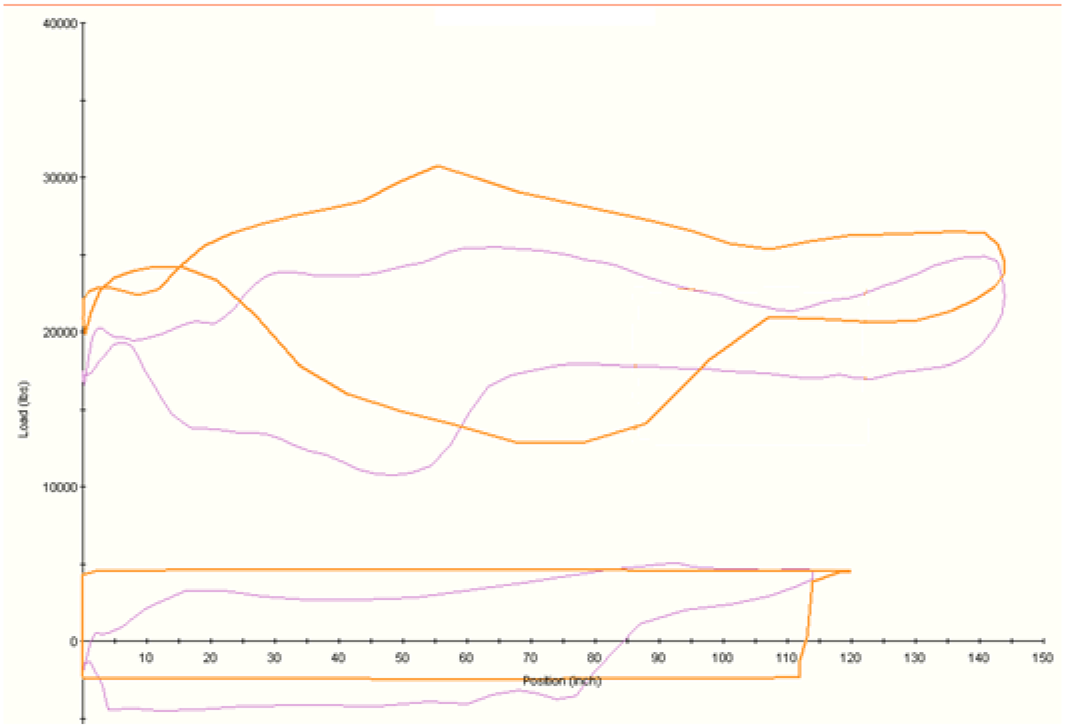

Figure 13 – Well A field card (magenta) from a beam-mounted strain gauge with improper load calibration compared to predicted card (orange)

Figure 14 – Well A field card (magenta) compared to predicted card (orange) after load calibration is corrected

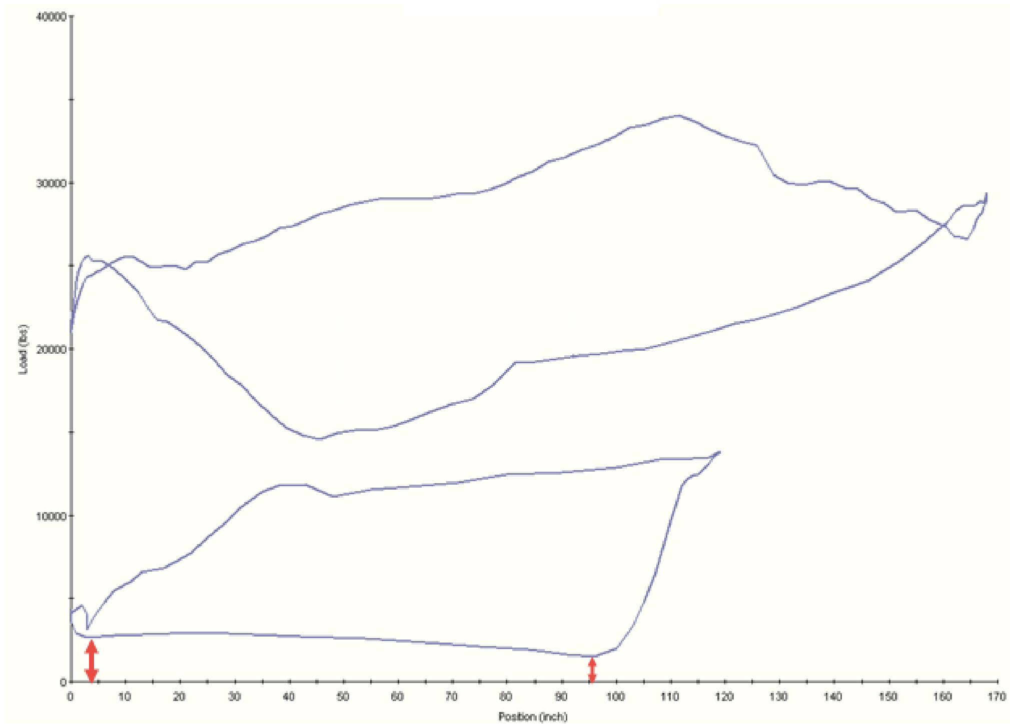

Figure 15 – Well B strain gauge offset observed on day one

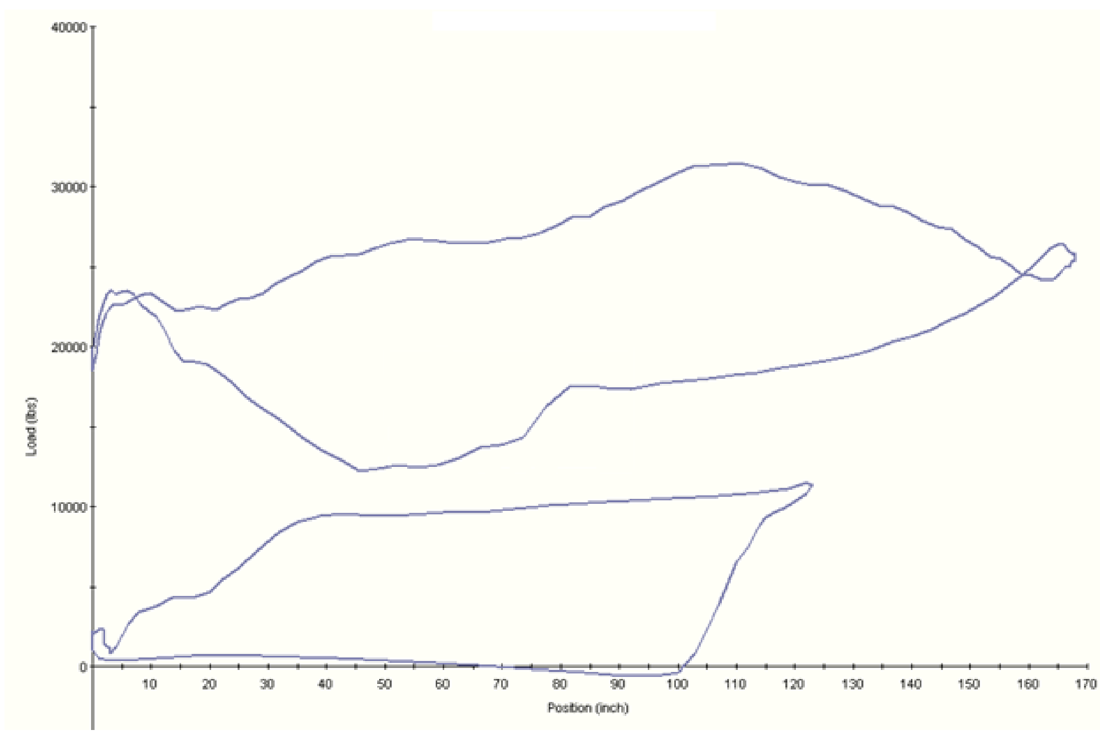

Figure 16 – Well B strain gauge drift observed on day two

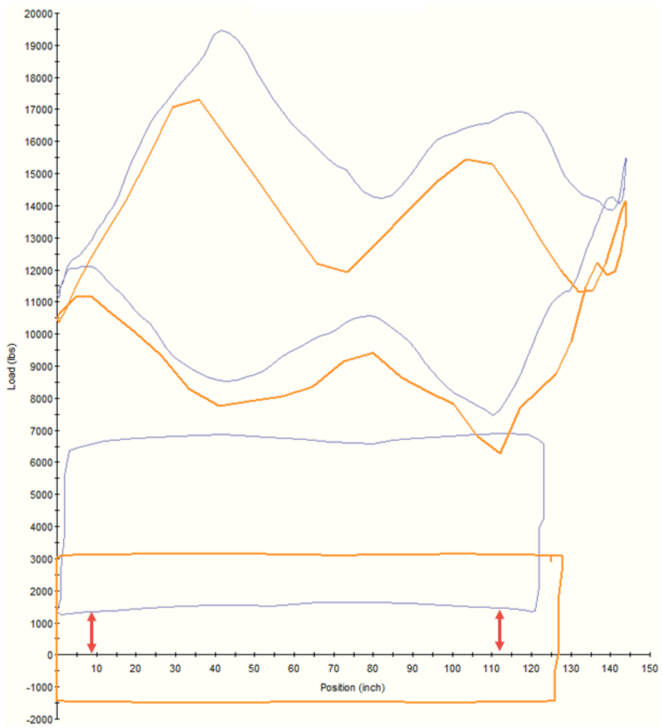

Figure 17 – Well C field card (blue) exhibiting zero offset error with polished rod load cell compared to predicted card (orange)

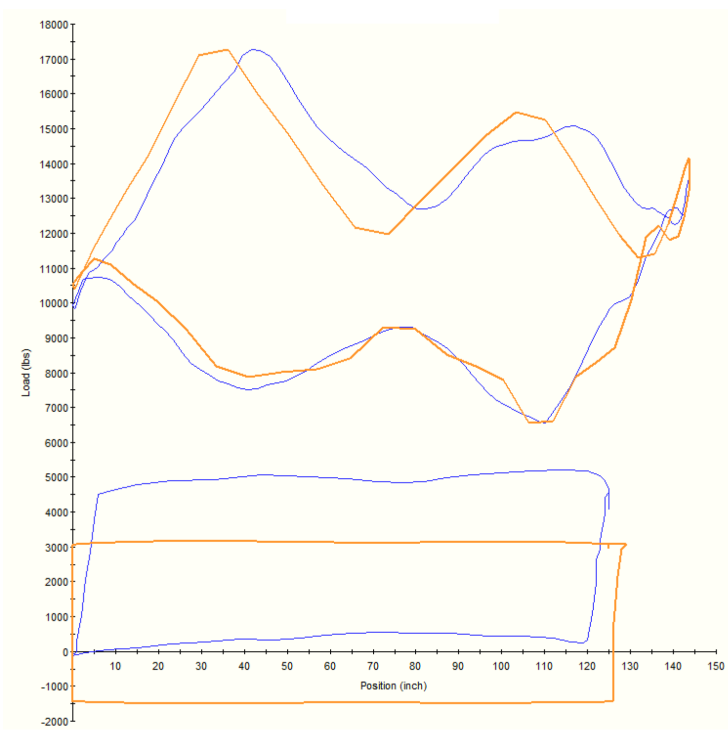

Figure 18 – Well C field card (blue) after correction of zero offset error

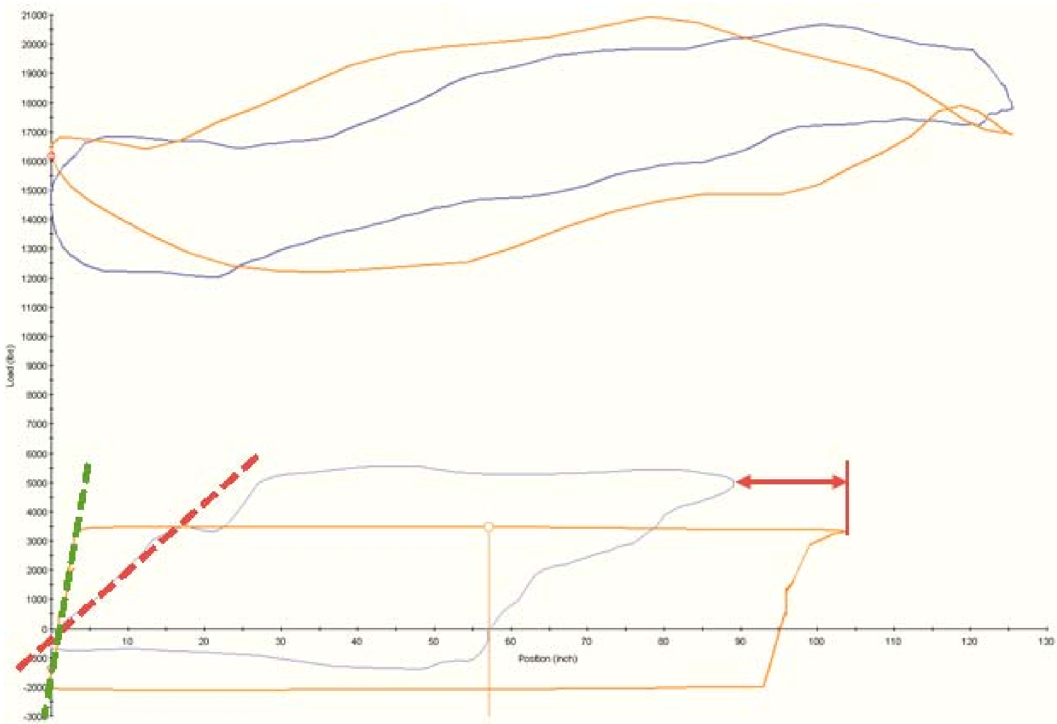

Figure 19 – Well D field card (blue) showing position switch top of stroke error compared to predictive card (orange). The dashed green light indicates the predicted amount of tubing movement, the dashed red line shows the tubing movement observed in the field card. The red arrow indicates the difference in downhole stroke length.

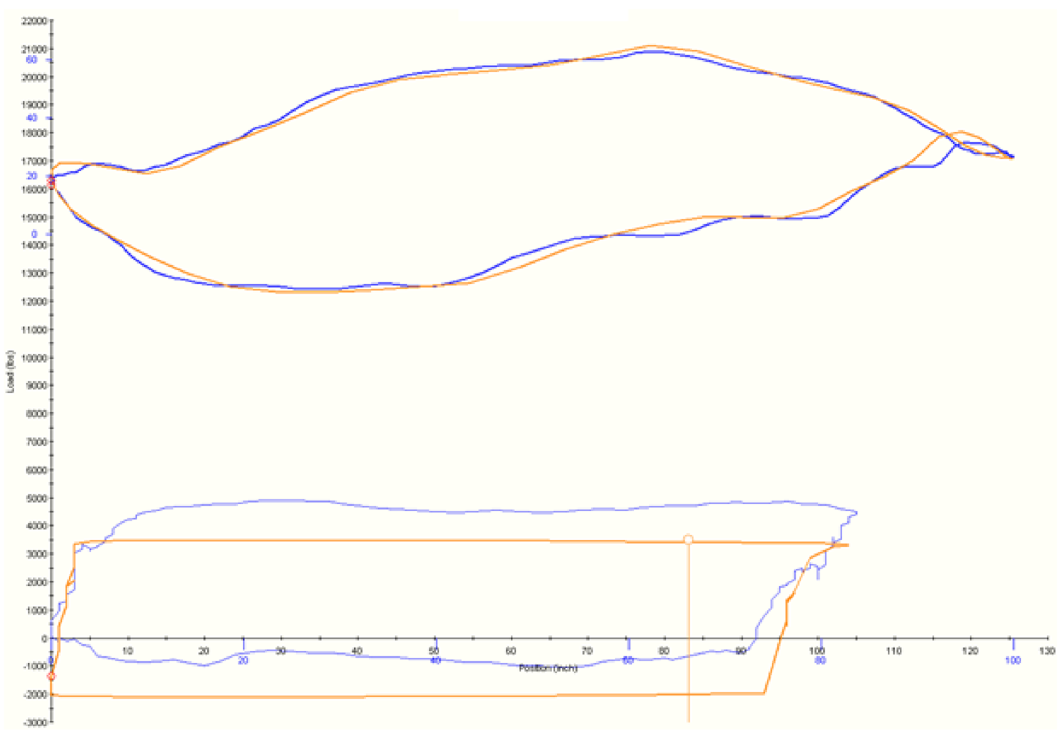

Figure 20 – Well D field card (blue) after position switch top of stroke correction

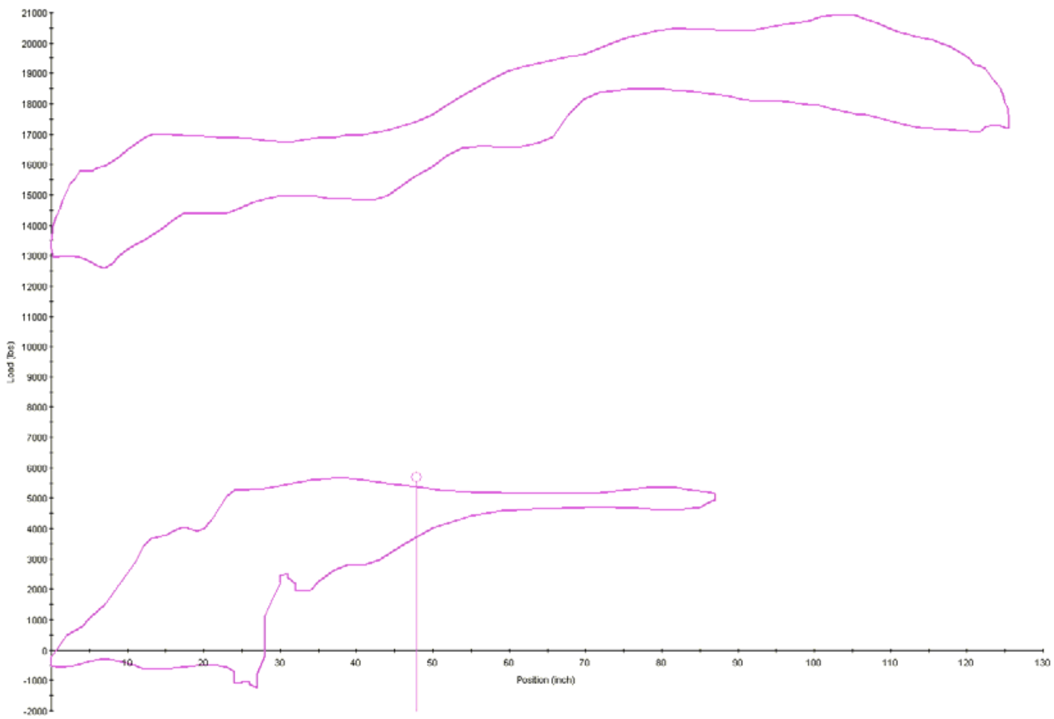

Figure 21 – Well D field card at pump-off showing position switch top of stroke error

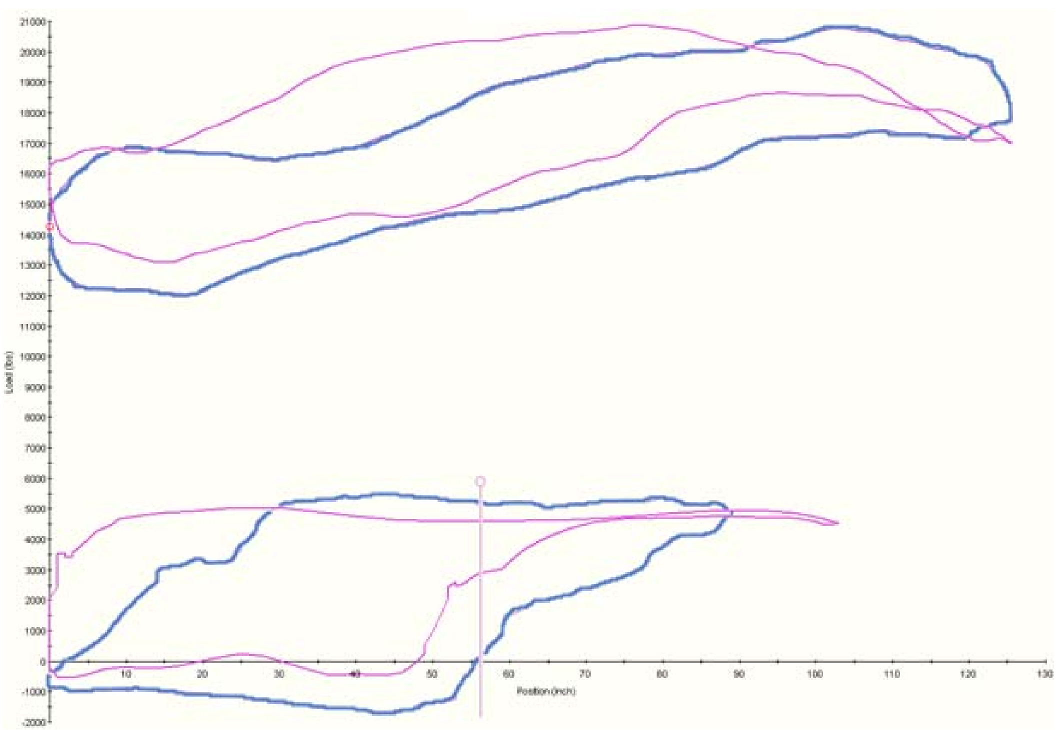

Figure 22 – Well D field card at pump-off after position switch top of stroke correction (magenta) compared to uncorrected card (blue). Notice the corrected card no longer violates the pump-off setpoint (vertical line on the downhole card).

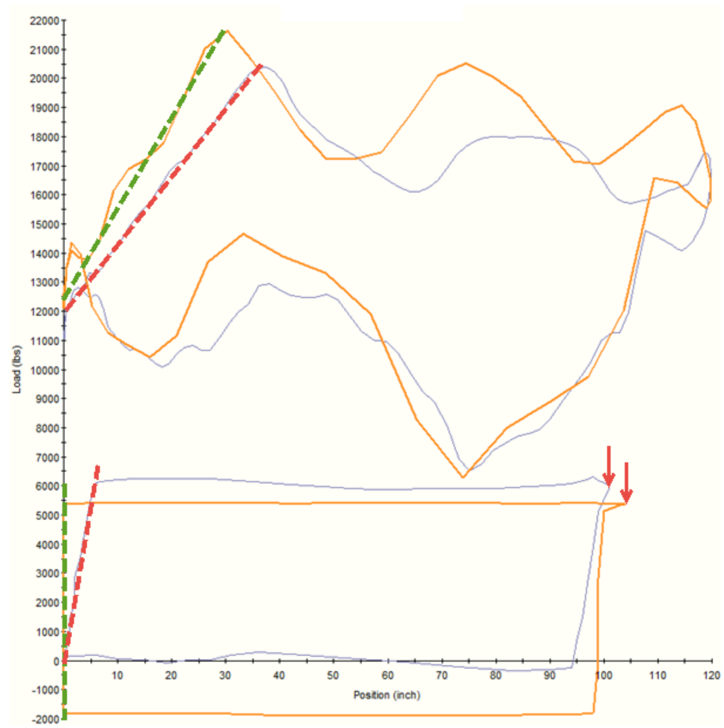

Figure 23 – Well E field card (blue) exhibiting phase angle error with Hall-effect transducer compared to predicted card (orange)

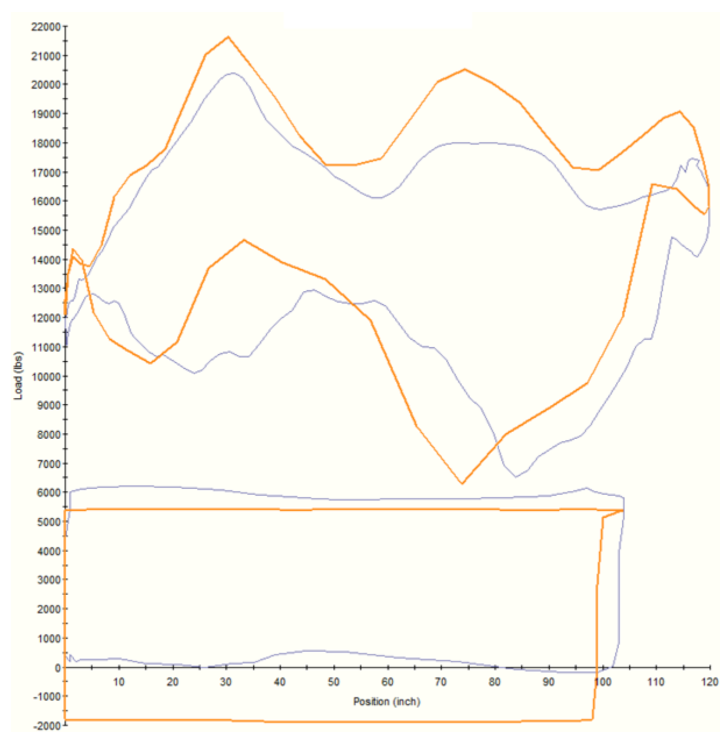

Figure 24 – Well E field card (blue) after Hall-effect phase angle correction

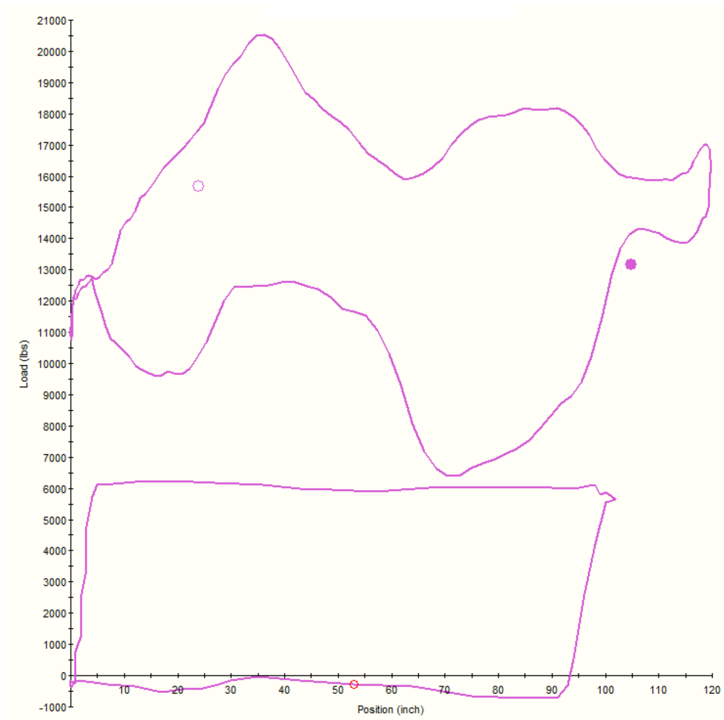

Figure 25 – Well E field card (magenta) of well at pump-off with Hall-effect phase angle error

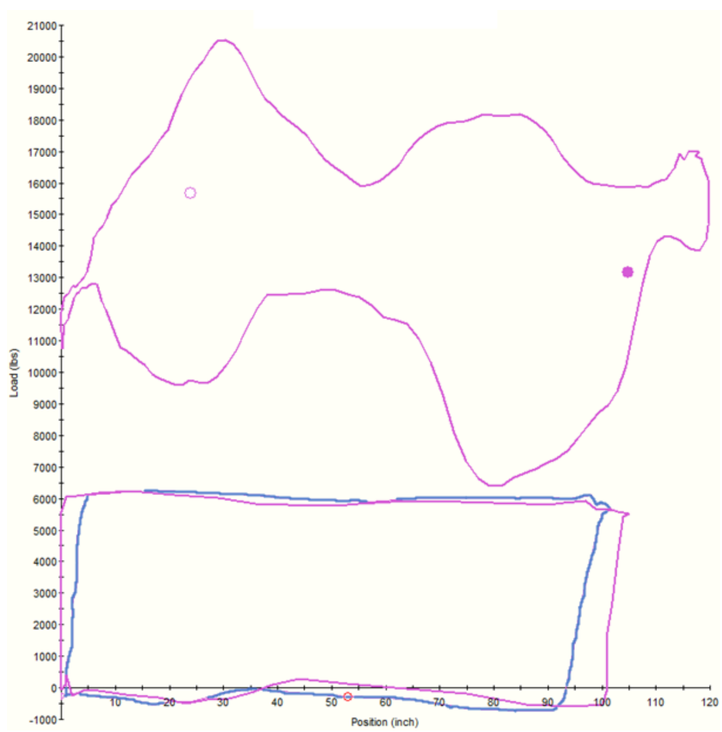

Figure 26 – Well E field card at pump-off after Hall-effect phase angle correction (magenta) compared with uncorrected downhole card (blue)

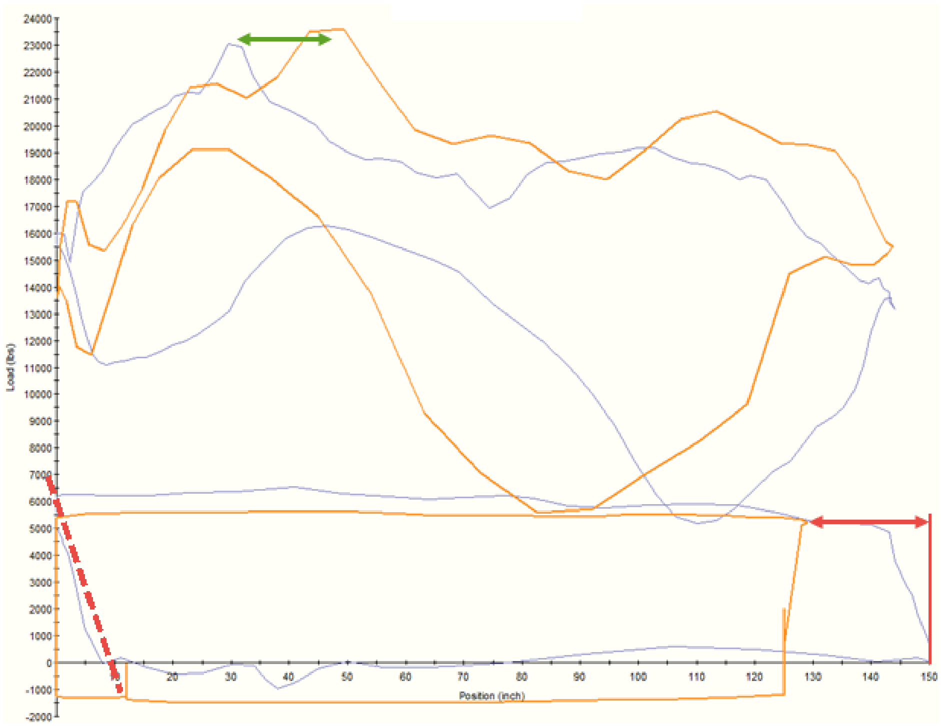

Figure 27 – Well F field card (blue) showing skewed position data due to inclinometer filter

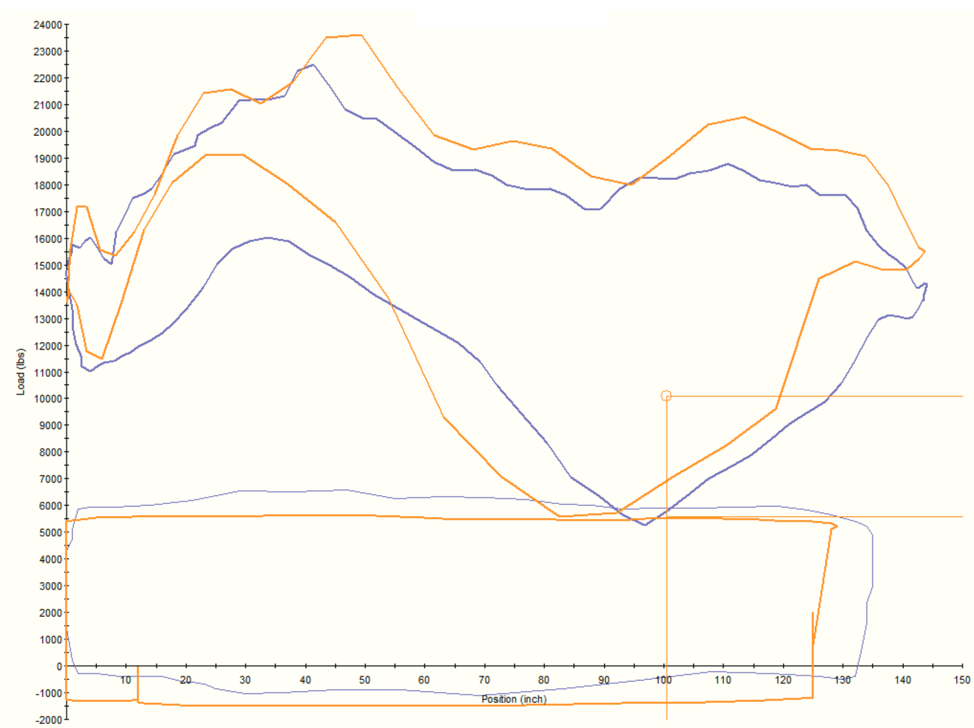

Figure 28 – Well F field card (blue) after de-skewing inclinometer position data

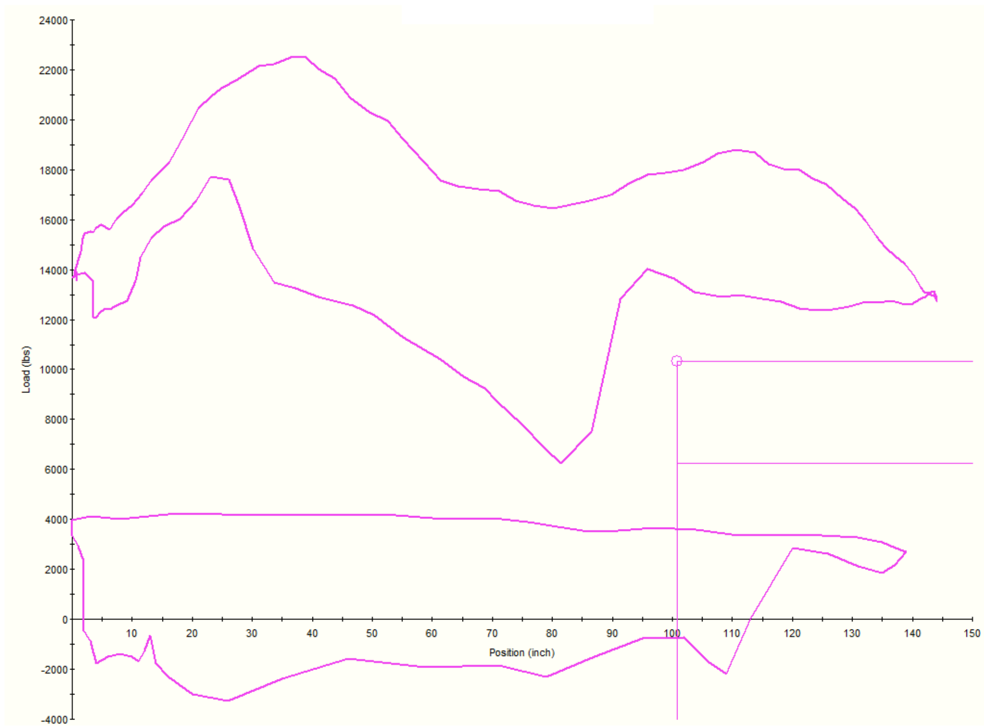

Figure 29 – Well F field card (magenta) of well at pump-off with skewed position data due to inclinometer filter

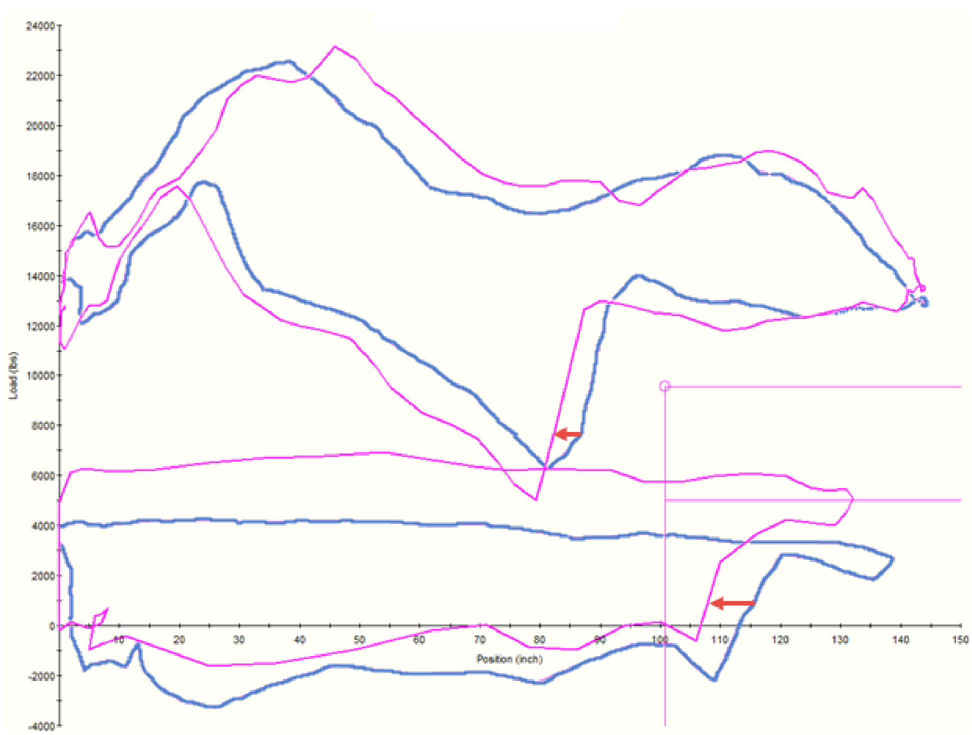

Figure 30 – Well F at pump-off with corrected field card (magenta) compared to uncorrected card (blue)