HIDDEN COMPLEXITIES OF ROD ROTATION: UNDERSTANDING TORQUE BUILDUP IN SUCKER ROD SYSTEMS

Walter Phillips, WANSCO
Nick Hooper, Continental Resources
Justin Bates, Echometer Company

Rod rotators are intended to distribute wear evenly around the circumference of sucker rods. However, in practice, rods, guides, and couplings frequently develop flat spots, indicating uneven rotation. The industry lacks comprehensive studies on how this affects the entire pumping system. Instead, solutions have focused on implementing higher torque rotators or positive engagement mechanisms to force rod rotation. These solutions are not driven by comprehensive data and outcomes, but by the assumption that; when the system is rotating at surface, everything must be fine downhole.

This paper applies to wells where:

- Rods, couplings, or guides wear flat on one or more sides
- Rotators appear functional at surface, but wear patterns on downhole rod sections indicate rotation is not evenly distributed through the rod-string
- Excessive torque is present on the rods (i.e., during a workover or re-spacing)

Rod rotators do work when properly used and maintained. This paper intends to explore what happens when rods are not freely rotating and the implications for the entire pumping system. The central premise is that forcing the rods to turn does not achieve the desired goal of even wear distribution. Further, forcing the rods to turn imparts a torque and that imparted torque is not thoroughly understood in the context of pumping dynamics.

Why are rod rotators so prevalent?

Rod rotators first appeared in a 1926 patent (US Patent No. 1,667,240) and were noted as problematic in early field applications (Weaver, 1937). Since then, rotator designs have improved, but subsequent literature only mentions them briefly as standard wear-distribution tools and accepts their application without question.

Rod rotators have two main functions. First, they aim to evenly distribute wear around the circumference of the rods to extend their service life. Second, rotation can help dislodge material buildup between the rods and tubing that linear stroking motion alone may not address. This rotation may also allow corrosion inhibitors or other chemical treatments to better reach the rod and tubing interface. Regarding solids addressed through rotation; paraffins can be managed with scrapers, and scale buildup can be reduced by rotationally moving the rods to expose different contact surfaces that stroking alone may not accomplish. Rods worn unevenly are not necessarily indicative of a problem if rotation is achieving the secondary goal of “clearing” or otherwise resetting the rod-to-tubing contact interface. Although ideally, rods would wear perfectly round as illustrated in Figure 1. Evenly worn rods are a clear indication of successful rotation. Uneven wear is not necessarily an indicator of a problem, but it should prompt an investigation.

While wear distribution alone tends to justify their use and discourages questioning rotator effectiveness or whether undiagnosed rotator failures contribute to larger, seemingly unrelated, well failures. Engineers face the simpler question "Why didn't you use a rotator?" rather than "Did the rotator improve performance, or extend runtime?" Or, more deeply, did a previous rotator failure (that was eventually repaired) contribute to a seemingly unrelated well failure?”

<u>Questioning rod rotation</u>

<u>*When rotators are correctly functioning, they are highly effective in their goal; even wear distribution*</u>. But when not applied correctly throughout the entire operation of the well, rod rotation can transition from beneficial (distributing wear) to possibly harmful (constant torque). If there is any appreciable torque on the rods, that means the downhole rotation is likely ineffective. Since rotator failures don't stop wells from pumping, failed rotators often remain undetected and unaddressed for extended periods, allowing uneven wear to develop unchecked. The most important takeaway from this paper should be; <u>*if you have a rod rotator on a well, make sure it is repaired immediately on failure*</u>. If a well fails with a seemingly working rotator, that does not indicate it was “*always*” working. A failed rotator may develop uneven downhole wear, which in turn may lead to other issues, long after the rotator is repaired. The damage stemming from a previously failed rotator (via the extended wear without rotation) can hide the root cause of failure.

Uneven wear commonly leads to high torque on the rods as the uneven wear creates a rotational restriction. Torque on the rods can then exacerbate compressive forces like buckling. The optimal approach may be to maintain rotation “*only*” while wear distribution benefits are achieved. Often this is a binary choice, either rotate or not. Ideally, rotation effectiveness would be continuously monitored. If rotator failures go undiagnosed for extended periods, the well should be assessed for effective rotation after the repair. This may mean returning at a later day to check the rotator arm for resistance or using new sensor technology to assess rotational effectiveness (US Patent No. 11,814,948, 2018). Torque on the rods is not necessarily bad. Rotating torqued rods may still achieve the secondary goal of dislodging material buildup between the rods and tubing (i.e., paraffins, scale, etc.)

Virtually all rod rotators in the market are based on the same fundamental design; a worm gear drive that actuates as the cable pulls the lever arm during the last few inches of the downstroke. The arm then falls under its own weight, to reset for the next stroke, in the first few inches of the upstroke. The torque that can be generated in this manner can be quite high and there is no way, short of shear pins, to precisely limit this torque. (see

Appendix, Extreme Torque Example). Smith introduced a completely different rotator design, replicated in Figure 4, that inherently limited torque by operating on the upstroke by a counterweight on the ratchet arm (Smith, 1988). By using such a novel rotator the torque could be limited simply by the arm weight, which would prevent forcing the rods to turn. Unfortunately, rotators such as this have not seen wide adoption in the modern oil field, nor has much effort been made to explore alternate approaches to rod rotation.

<u>"Flat spots"</u> – Uneven rod wear

Rod-pumped wells commonly develop flat spots on rods (Figure 2). In the context of rod guides, it was pointed out in 1995; "*different zones in the same well can each produce unique wear patterns*" (Ray, 1995). Although this was certainly common knowledge long before, surprisingly little information is available on this phenomenon and whether it is detrimental or not.

In short a "flat spot" is a section of rod, coupling, or guide, that is unevenly worn on one or more side. Both Figure 2 examples, particularly the "square" rod, show a form of distribution of wear, but this is not evenly distributed over the entire circumference. Figure 2 shows the rotator was clearly functioning, but something is causing the wear to be focused on specific "sides" of the rod. By "even rod wear" we intend to describe a wear pattern that leaves the rod, coupling, or guide substantially round (i.e. Figure 1).

Flat spots depicted in Figure 2 create a sort of lever-arm in the course of rotating that requires the rods to "lift" from the flat spot, which is closer to the center of rotational geometry, to the higher/further portion. The tubing wall bears the force of the leading edge as the torque builds. This geometry creates a situation where torque in the rod is what forces the rod to lift from one surface to the other in order to complete a rotation. If the rod was substantially round, there would be very little force required to rotate the rod. A flat tire is an appropriate analogy here.

How flat spots develop and how the rod-string reacts to rotating (or forcing rotation) "through" these flat spots is an area for much future investigation. What causes flat spots (rods worn excessively on the same side), in a well with a rod rotator, is also not adequately understood. Can flat spots develop on a rod with constant rotation? While this has not been studied, it is clear that flat spots are likely a result of a failed rod rotator and the continued wear on one side. Of important note, once a flat spot develops, it is irrecoverable short of pulling the well and replacing the worn section of rods and tubing. Repairing the rod rotator and forcing the rods to turn after a flat spot develops is unlikely to achieve the desired benefits of even wear distribution. It is important to prevent flat spots from developing in the first place.

<u>Worn Tubing</u>

Rotating rods alone does not address tubing wear. Producers with severely deviated wells have seen success rotating both the tubing and rods. Tubing rotation provides its own benefits and challenges and is outside the scope of this paper, see (Lacy, 1992). In the context of this paper, however, rotating tubing can help relieve torque on the rods by making it easier for the rods to rotate as both rods and tubing are moving together. An area for future investigation is the effect of forced rod rotation against the tubing wall. In some cases, a rotator (alone) may actually be more harmful to tubing wear as the torque of the rods is, by definition held by the rotational resistance created by a flat rod drawn into the tubing wall by a wellbore deviation. Rotating tubing both distributes wear on the internal tubing wall, and it serves to aid in rod rotation as both rods and tubing are both turning in the same direction (albeit at different rates).

Rod-string Unwinding

When faced with a downhole rotational resistance (typically in the form of "Flat spots", discussed above), the rod-string will act as a giant torsion spring. When torque in this spring is sufficient to overcome the rotational resistance, that release will allow a portion of the rotations stored to be dissipated down past the restriction. In other words, some of the rotations torqued in the upper rod section pass to the lower rod section as the rod-string plays catch-up to the surface rotations. In short, the rotational restriction temporarily stalls the downhole rotation, which in turn results in further uneven wear. The same total rotations are achieved, but not evenly/smoothly as intended.

Based on observed wells, it appears the common case of restricted rotation is limited; the rods do not fully unwind, but rather "flop-over" and only release part of the built-up torque. In other words, the rods overcome a rotational restriction but are subsequently, and quickly, caught by that same rotational restriction. What this means is that rotationally restricted rods almost always have some residual and persistent amount of torque. Of note, this residual torque is likely close to the torque required to overcome the rotational resistance, minus a rotation or 2. The effects of residual, ever-present torque has not been adequately studied, although it is often observed by the rig crew, or anyone "stacking out" the rods.

An extreme case of overcoming downhole rotational restriction is unwinding. "Backspin" is a term used to describe this but may be slightly misleading. The downhole rods are actually "catching up" with the surface rotations. In this scenario, several downhole rotations are released at once, sometimes with catastrophic effects. When "forcing" rods to rotate by using larger high torque or "no-slip" rotators, this condition should be closely monitored. It may be the root cause of several seemingly unrelated failure modes including rotator failures themselves and possibly rod failures such as unthreading or pin breaks. If this backspin phenomenon occurs in a well, it is not a singular or isolated occurrence. For context, a backspin event could easily occur several times per day, every day.

Friction vs. Wear – Sliding/stroking rod wear

In modern rod pumping, friction remains a primary challenge despite limited scientific data from operational wells. Tribology (the study of friction) provides important fundamentals worth noting:

- The opposing frictional force between contacting surfaces results from normal force and interface properties, not contact area size. This is a counterintuitive but well-documented principle. Theoretically, increased contact area from rod wear shouldn't increase tensile loads. However, practical rod-tubing interactions are far more complex.
- Standard friction calculations don't account for wear effects. As the frictional contact surface between rods and tubing wears, friction coefficients may change significantly. This is because the surface interface transitions from factory-finished, to worn states.
- Friction generally comprises one of 2 states; Static friction, or the force to start relative motion. And dynamic friction, or the force opposing motion while moving. Because the rods are moving linearly, static friction is easily overcome. A Torque Drag Analysis achieves a similar goal. In short, rotation (from a frictional sense) should only be concerned with dynamic friction.

Material contact interface (rod guides, coated rods, or tubing, tubing grade, coupling hardness, etc.) dictates much about frictional force but also wear patterns. Friction (and related wear) may not be constant as wear affects friction and vice versa. The fluid present in the tubing may contain solids which can migrate between the contact area and in-turn can “gouge” microscopic ridges in the steel. These ridges are sheared, causing the wear, which is different from friction in the strict sense, see Figure 3. All of this is to say; what we loosely refer to as “friction” can change with the changing contact surface properties and is far more complex, especially when an additional force, resulting from torsion, is applied at the point of contact.

Additional sources of mechanical friction may develop due to paraffin, scale, iron sulfides, corrosion, etc. In some wells, rotation serves to dislodge these, or provide an opportunity for solids to escape the rod-tubing contact interface which presents an interesting tradeoff. It might be beneficial to force the rods to turn in order to dislodge this buildup. This is not necessarily buildup in the tubing, but solids that have migrated into the rod-on-tubing contact interface.

<u>Rod-string Torque</u>

Downhole rotational resistance creates a complex normal force on the rod/tubing contact surface. There is a sideload from the wellbore deviation, but there is also a force acting on the leading edge of the flat spot. As the torque on the rods above the rotational resistance slowly builds up, the rods must lift away from the tubing wall (against the side-load force caused by the wellbore deviation) to move from the lower flat spot to a higher surface along the non-circular (rod, coupling, or guide) body. This increases the normal force against the tubing and, although the most significant forces are temporary, this cycle repeats constantly.

<u>The gear reduction in a rotator is ***not*** for generating torque</u>. Gear reduction is to slow the rotation to allow the linear stroking motion to ease the gradual rotation, like torque drag analysis operations in drilling, but in reverse. Linear motion breaks static friction, which

should ease rotation and on a perfectly round surface, this in turn would require minimum rotational force. Any modern rotator should have the structural capacity to turn the rods to a point of torsional damage. If the rods are not freely rotating, forcing them to rotate will not achieve the desired result of evenly distributed wear. There are, however, cases where forcing the rods to turn may achieve other goals, but this should be weighed carefully.

Torque imparted to the rod-string is limited by frictional contact applied at the polished rod clamp and base of the rotator. Smith points out the slip is internal to the rotator at the gear to table interface (Smith, 1988). This makes sense as the internal components of the rotator are lubricated. Some rotators use a positive engagement between the gear and table). This “holding force”, regardless which component slips, is a direct result of the polished rod load. Friction at the clamp or base (or internal shear pins, or internal friction) serves as the only safety from over-torque. Very little is understood about what an “acceptable” amount of torque on a rod-string means.

Smith enumerates the theoretical rod body torsion limit of several rods (Smith, 1988, pp. 153, Table 1). For D grade rods, this ranges from 262-1071 ft-lbs (5/8” – 1”). Smith further shows the “transferred” output torque of a rotator onto the polished rod can reach 240 ft-lbs. This was based on a test fixture simulating a polished rod load of 20,000 LBS and the friction interface between the polished rod clamp and rotator table. Considering the minimum polished rod loads rarely exceed 20,000 LBS, this is a reasonable torque value to consider, but real world conditions could alter this. How much torque on the sucker rods is too much and would it be wise to limit this imparted torque? Smith introduced a substantially different rotator design that inherently limits torque (Figure 4) Alternative rotator designs have not caught on in the intervening 27 years.

How much torque is too much?
If the potential torque output of a rod rotator is within an order of magnitude of the torque limit of the rod body and threaded connections, the question arises why don’t we see more failures? This is an open question and subject to further investigation. One possible explanation is as follows: excessive torque on the rod-string effectively “tightens” the couplings which would manifest as a pin break. Likewise, aggressive and repeated backspin events (see Rod-string Unwinding above) could serve to loosen the threads resulting in a loss-of-displacement failure or complete unthreading. Conventional logic would point to rod makeup and blame the rig crew or power tongs. While improper makeup is certainly a likely root cause, investigation of the rotator system would be prudent: were there severely flat-worn rods above or below the pin break? High tensile loads (i.e., high friction contact at the rotator/clamp interface)? Backspin or persistent rotator failures? Did the rig crew note the presence of torque.

Another possible explanation for not seeing obvious failures which could be attributed to high torque is that the rods change as they are being torqued. The overall rod length might shorten slightly, the rods may become less of an ideal slender bar and may take on properties of a coil (under torque). As with other aspects of rod rotation, these theories have not been adequately studied. If these behaviors alter the torque dynamics, this may aid in overcoming the rotational restriction (coiling the rod, for lack of a better description, helping to “lift” the rod off a flat spot). If the rods get slightly shorter as they are torqued, this can cause interesting side-effects regarding spacing. It should be noted all of these are speculation as very little literature exists on the topic. This is an area for much future investigation.

As discussed above, in some well conditions, “forced” rod rotation may serve a benefit of dislodging buildup on, around, or between the rods which would otherwise require a well intervention. In some wells it has been observed that peak polished rods increase after the rotator failed and then the loads quickly returned to normal once the rotator was repaired. This may indicate the rotator served to dislodge built-up material, substantially reducing rod loads, and that alone may be of more practical benefit than the distribution of wear on the rods. This may not require constant rotation.

Detrimental effects of rod-string torque

Torque is not necessarily detrimental to sucker rods; they are used in Progressing Cavity Pump (PCP) applications where torque is the fundamental driver of the pump. PC Pumps notably do not afford the opportunity to wear flat spots. The detrimental effects in the rod pumping application, however, are related to torques’ effect when combined with liner motion and wellbore friction. This creates complex side-loading that is in addition to, and compounded by, the geometric deviations of the wellbore path. If there are compressive forces present on the rod, the resulting effect is potentially magnified by that torque. “Buckling” is a term typically used to describe compressive forces. Compressive force, combined with substantial torque may be more detrimental than the industry currently understands.

Interestingly this torque, under lowered (or possibly compressive) longitudinal loads (in the direction of the rod-string) may also serve to overcome rotational resistance. It was observed in several wells that torque at surface, from some rotational resistance downhole, was reduced during the downstroke (above the point where the rotator arm actuated). In other words, the rod-string is slowly torqued up by the rotator. Tension alters the torque (higher tension with the same number of rotations will see an increase in torque), and the point where it overcomes the downhole rotational resistance is met on the downstroke. Where this occurs in the downstroke is interesting and is briefly discussed in Case Study #1 below.

Torque applied to the leading edge of a semi-flat rotating rod has not been adequately studied in the literature. This phenomenon could very well accelerate tubing wear as each “flop-over” event needs to overcome a higher normal force to lift the rod from the smaller diameter flat spot, onto the larger diameter body (rod, coupling, guide). This paper attempts to call attention to the transient increase in surface loads around a flop-over event as a possible indication of the detrimental effects (see Case Study #2).

Detecting Torque Buildup and Release

Freely rotating rods are ideal. It is nearly impossible to know from a visual observation at surface to determine if the rods are under torque. A rotator such as the one described by Smith, Figure 4 would provide a visual indication that torque has maxed out as the arm would not fall under its own weight. Unfortunately, the rotators currently used simply turn until something gives, and hopefully that is the rods turning smoothly downhole. A torque release, or an "unwinding" of one or more rotations downhole does not always have obvious indicators at surface.

In terms of observable phenomenon at surface, this may mean the bridle "twists" and relaxes by just a few degrees, which is barely perceivable. The more extreme case of "unwinding" or "backspin" can be apparent at surface either visually or audibly. A significant unwinding event may take several rotations before it occurs and may last just a second or two. It is impractical for a human to reliably observe either a small torque release or a larger unwinding/backspin, although, they have been observed on occasion. A visual example is provided in Case Study #1 and Figure 6 below.

An important fact to consider is that torque builds up slowly due to the gearing of the rotator, and releases suddenly. Detecting the slowly increasing deflection is difficult, but determining the abrupt change in deflection is evident. A corresponding change in polished rod loads, related to a change in bridle deflection, would indicate a change in some downhole condition, particularly a change in downhole friction, or in a change of downhole sideloading. This in turn may be evidence of some detrimental effects. For this, high quality dyno cards are desired. See Case Study #2 below.

Case Studies

Case studies are presented below. The first one describes observable phenomenon and shows how one may identify ineffective rotation. The second case study attempts to identify the dynamics, in terms of polished rod load, present on a well using high-quality sensing and monitoring tools.

Case Study #1 - Detecting torque release on the bridle:
The first well in which this was consistently and persistently observed, eventually failed due to a hole in tubing resulting from rod wear. Recall from above that rod rotation does not address tubing wear. While the torque release phenomenon is shown in this well, we cannot determine if it is detrimental or not (from this well alone). This well is a shallow big bore pump (approximately 3800 ft with a 2¾" pump). The worn section was near the bottom in a deviated section.

Figure 6 visually shows what was observed and correlated in sensor data (Figure 7). The bridle slowly deflects, or twists. Each pull of the rotator ratchet increased the torque on the rods and, because of a downhole rotational restriction, this increasing torque manifested in the bridle angle progressively deflecting more on each stroke. Once the downhole rotational restriction is overcome, the bridle substantially relaxes, or "un-twists".

The photos in Figure 6 are frames from a much longer video but represent the 2 adjacent strokes spanning a torque release (for “flop-over”). The strokes before, and after, resemble the ones pictured, and this cycle cyclically repeats.

The hole in tubing was near the bottom in a deviated section. Specifically, a tubing section was worn through by the rods and a corresponding flat section of rod couplings which are shown in Figure 8. While this failure was ultimately due to rod wear on the tubing, the well ran for over a year in this “torque and release” condition. Specifically, this was a year from when the condition was first observed using sensor data. It is likely the condition was present long before that. It should be further noted that a rotator failure was documented (and fixed) prior to the first observation of the “torque and release” on the bridle.

It is believed the failure mechanism progressed as follows:

- Rotator failure – caused the rod couplings to wear flat, as this condition went undiagnosed for some period.
- Rotator was repaired – Rotation resumed, but the “flat couplings” were not addressed.
  - Once a flat spot occurs, there is virtually nothing that can be done to “fix” this condition short of pulling the rods (and tubing).
- Subsequent rotations caused a periodic increase in side-load as the flat spot must be overcome during each rotation over the flat spot.
  - This portion of the failure mechanism is speculative. It is unknown if the runtime would have been better or worse had the rotator remained disabled after the flat spot had developed, or if immediately repairing the rotator would have prevented the flat spot from developing in the first place.
  - It is thought the persistent rotation against the flat spot may have accelerated tubing wear.

Given that a flat spot is unrepairable once developed, an urgency should be placed on detecting and repairing rotator failures to prevent flat spots from forming. Case Study #2 is an attempt to determine how long it takes for a flat spot to occur and to determine loads relative to rotational dynamics.

Case Study #2 - Monitoring loads with respect to rotation

To quantify rotational effects at surface, there are few options. The bridle deflection is a clear indicator of the occurrence, but this alone doesn’t necessarily indicate anything detrimental. Recall Case Study #1 ran for over a year and the failure was tubing, which the rod rotator would not have prevented. The desire here is to determine if rotational restrictions result in a change in dynamic rod loads. A corresponding tensile load increase could indicate a change in either frictional coefficient, side-loading, or both. Correlating a cyclic bridle deflection change, particularly one that occurs at the same radial orientation of the polished rod (i.e., compass direction), with a tensile load change might indicate a detrimental effect on the pumping system.

This is an incredibly challenging task as the “flop-over,” or unwinding event may only occur once in several hundred strokes. Furthermore, a tensile load change across this flop-over event may be trivial relative to the polished rod load, on the order of a few hundred pounds on a dyno card. Attributing such a small load change to a rotation related source is even more challenging to discern from other well dynamics. To identify this, a high quality loadcell, capable of acquiring high frequency data is required. The Echometer Horseshoe loadcell was selected to obtain high quality surface dynos.

Next, as the “flop-over” event to be captured is transient, occurring at an unknown interval of 15 minutes to several hours, a suitable data acquisition schedule was required. A well tech could be assigned to the well for this period, but that was impractical. The Remote Acquisition Monitor (RAM) was an ideal tool for this purpose as it could be left connected to the Horseshoe loadcell and remotely managed via cellular connection. This combination proved to be very insightful as a tagging event, or rather a skipped tag in this case, was identified and might otherwise be lost in the low-frequency, low resolution dynamometer data typically available via POC/SCADA.

An even more useful aspect of the RAM setup was the ability to concurrently determine fluid levels throughout the test. The proverbial needle in the haystack of a load fluctuation due to downhole rotational action could be easily masked by a fluctuating fluid level. This proved to be the case for this particular well, during the later phases of monitoring as the fluid level was drawn down and the well started gas lifting fluid through the tubing. But, as a wealth of data was acquired, the periods of stable fluid level were easily identified.

Figure 9 shows the core equipment used as well as the pertinent well details. The surface unit was a conventional LS-2660-500-320. Of note, a large portion of the rod-string was fiberglass. Rotating fiberglass presents challenges and, even more so than steel, has not been adequately studied.

The next significant challenge was to correlate the rotational deflection change to the load data. Unfortunately, the logged rotational data (from a separate sensing device) was not closely correlated to the Load & Position, or fluid level data. This correlation of independent data sources had to be done manually.

The plan for this test was to pump the well with the rotator initially disabled. This would accomplish 2 things:

1) Ensure there was no residual torque and,
2) Allow for observation as the rods torqued up.

The rotator was tied off such that it could be enabled while stroking. This is important because the act of stopping and starting the well may affect loads. The inertial effects on rod loading when starting and stopping or a change in fluid level might impact the rotational state, jarring the rods free (in the rotational sense). Fluid levels were monitored by the RAM, but to minimize variables, unnecessary starts and stops were avoided. After a period of about 2 weeks (which would be an optimistic timeframe for a failed rotator to be repaired), the rotator was enabled. In effect this was a simulated rotator failure and repair, but the pumping unit never stopped during this time.

Figure 10 shows dynos gathered during what is thought to be a flop-over event, following the start of rotation. These dynos were gathered during a period when the well was producing stability. This is important because load and/or stroke changes due to changing well conditions could easily be mistook for the rotational-related change we are looking for. In short, the theory is that a rotational event downhole, i.e. a “flop-over” would result in some change in polished rod loads as the mechanical friction, side-load, or some other phenomenon, alters the dynamics during that event. Figure 10, a) shows a sequence of 316 dynos overlaid and shows there was very little variation across this sequence.

To see the load variation, the dynos were exported so they could be plotted versus time and zoomed (Figure 10 b & c). What is particularly interesting in this well, during this period is there was a persistent “slight” tag. Originally it was thought this would corrupt the test (a tag could potentially “jar” the rotationally restricted rods loose). In other words, a pump tag might affect the rotation. In this dataset, however, the tag disappeared for one single stroke (Figure 10 d), corresponding to the peak of increased loads. The increased loads themselves may be attributable to some other source, but it is believed this corresponds to a flop-over event because the well was functioning in a particularly stable state during this sequence of dynos.

What could cause a load increase over approximately 10 strokes, wherein the peak load stroke also corresponds to a “skipped” tag is subject to discussion. It is believed, however that the act of releasing a downhole rotational restriction caused a change in loads. This could be an increasing side-load as the leading edge of the flat rod is forced against the tubing wall. This in turn would alter mechanical friction, which could alter the downhole pump stroke. Rods or pump stroke might have changed length slightly as the rotational restriction was overcome and the rods coiled (slightly) through the flop-over. Figure 10 shows progressively zoomed views of the polished rod load data to illustrate the specific stroke(s) of interest.

Figure 11 shows the same data explored by Figure 10, but in a more traditional dynamometer view. Note that the controller does not indicate a tag. The photo was of the POC screen, with a B/W image filter to remove reflection off the glass. Dynos are overlaid in TAM, but it is difficult to see the specific stroke that did not tag. The dyno events timeline is shown to better illustrate that stroke #246 (out of this sequence of 316) is the “skipped tag”.

Figure 12 shows the same bridle sensor from Case Study #1 which captured the magnetic field data at the bridle for approximately 8 hours. In this well, the field data was processed to show what amounts to a derivative of the bridle angle over time. Unlike Case Study #1, the raw field data did not immediately indicate the bridle deflection change. This is likely due to the substantially larger stroke length and possibly less bridle deflection because the rods did not have time to wear a significant flat spot. This data was taken after just a few weeks of pumping, following an RTP.

Rotations of the rod can be seen in the cyclic pattern of the fuchsia plot (Figure 12). 3 large and rapid changes on bridle angle can be seen in the plot and occur at the same orientation in the rotation. This is significant because a downhole restriction is likely to be a fixed location, and the amount of torque required to overcome that restriction is likely to be consistent. In other words, if the number of rotations stored in the rod-string is the same (i.e., torque), it should take the same number of additional rotations to subsequently overcome restriction. Under a stable tensile load, torque is directly related to the angle of change in the rotationally restricted rods (i.e. the torsion spring). Although the tensile load changes throughout the stroke, peak and minimum loads can be stable during periods where the well is consistently producing, which is why this period was selected.

Unlike Case Study #1 which occurred on every rotation, this well appears to be separated by 2 rotations. This is a fiberglass rod-string, which might explain the need for more rotational angle required between flop-over/unwinding events. These significant changes occur at the same rotational angle, which could indicate the same downhole restriction is rotationally catching the rod. The single rotation release seen in Case Study #1 is easy to explain; it is a shallow well with steel rods, which are considerably stiffer than fiberglass. A downhole rotation release was easily caught in one rotation, by the same restriction. In this relatively deep well with a substantial length of fiberglass, A single rotation might not be enough to overcome the downhole restriction. 2 or more rotations might unwind, or there might be a larger pattern that exceeds the 8-hour window of this sensor data.

We intend to continue monitoring this well for both loads and rotational deflection releases to see how (or if) the rotational restriction changes over time.

Conclusion:

Rod rotators remain an important component in artificial lift systems, effectively distributing wear when functioning properly. However, this paper has identified several key insights that challenge conventional industry practices:

1. **Rotator Failure Significance**: When a rotator fails, every stroke contributes to uneven rod wear. The development of flat spots can occur rapidly depending on well conditions, and once formed, these flat spots are irrecoverable without replacing the affected components. This emphasizes the critical importance of early detection and repair of rotator failures.
2. **Beyond Surface Observations**: A functioning surface rotator does not guarantee effective downhole rotation. Evidence suggests that even with an operational rotator, rods may spend extended periods in fixed rotational positions (downhole) before suddenly "catching up," particularly after flat spots have developed.
3. **Torque Considerations**: The industry's shift toward higher-torque rotators and positive locking (no-slip style) mechanisms may be counterproductive. Repeatedly forcing rotation against downhole restrictions can introduce significant torsional stress in the rod string, potentially exacerbating other problems like buckling or tubing wear.
4. **Detection and Monitoring**: Modern sensing technologies can detect the subtle signs of restricted rotation, such as bridle deflection and torque release events. Implementing these monitoring systems can provide early warning of developing issues before catastrophic failures occur (US Patent No. 11,814,948, 2018).

5. **Maintenance Priorities**: Rotator mechanism failures should be thoroughly analyzed rather than simply repaired. While lack of lubrication is often cited as a cause of failure, it may mask underlying issues with components or manufacturing processes. Likewise, the added costs of “overly” frequent lubrication may outweigh the cost of a rotator that needs less frequent attention. Cable attachments and the replacement of ratchet-pawls with one-way bearings represent areas of ongoing improvement.

Figures:

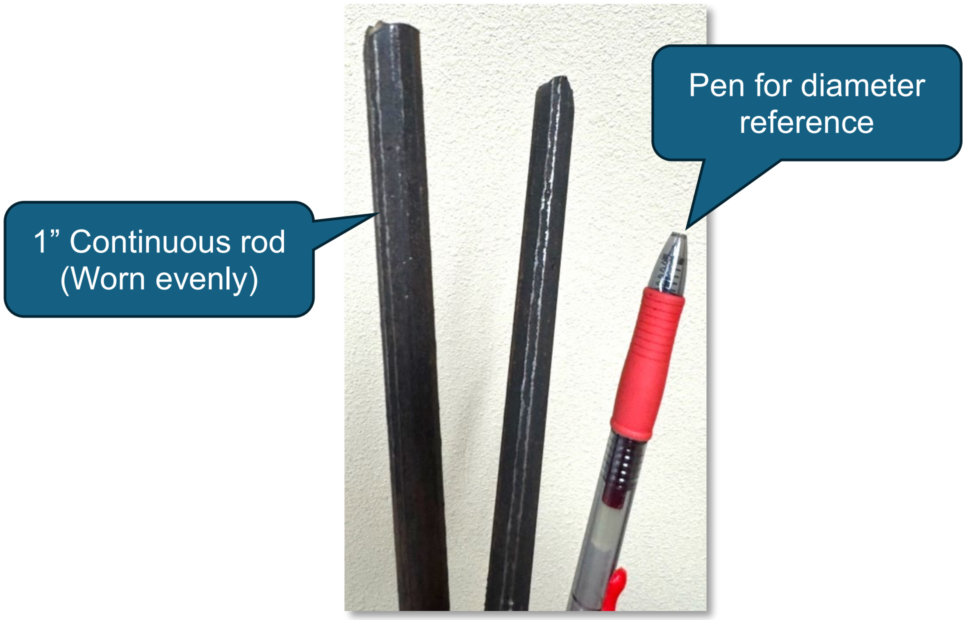


Figure 1 – The rod pictured was originally a 1” continuous rod (shallow well, big bore pump). This section of rod was worn down to approximately 3/8” and shown next to a pen for perspective. Even though this rod is worn “evenly,” clearly showing evenly distributed wear (i.e., effective rotation), there are indications that the rod has several wear “tracks” or lines which indicates a leading edge. This well failed due to a rod part.

Figure 2 – Rods may wear unevenly, resulting in interesting wear patterns The rotator was rotating the rods in both images, but that rotation was not “effective” or “evenly distributed.” While the wear pattern is not fully explained, there are likely other wear points in the same well that would alternatively catch and release the rotational motion of the rods. In both of these images, rotating the rod would require some appreciable amount of torque to overcome the “edges” to lift the rod off the flat spot and onto the higher adjacent portion. The rod would then fall into the next flat spot and the cycle repeats.

Figure 3 – Friction is a complicated phenomenon. Contact surfaces are not perfectly smooth and microscopic ridges may be present. The shearing of these ridges is the mechanism which creates wear (similar to the working theory of sand paper). We should see the result of the changing contact interface as a change in tensile load, but this is very tricky to determine apart from normal well load fluctuations. The reason tensile load may change is because the coefficient of friction is not perfectly fixed; it may change as the surface of the contact interface changes. Whether the resulting load is measurable or not is dependent on many factors.

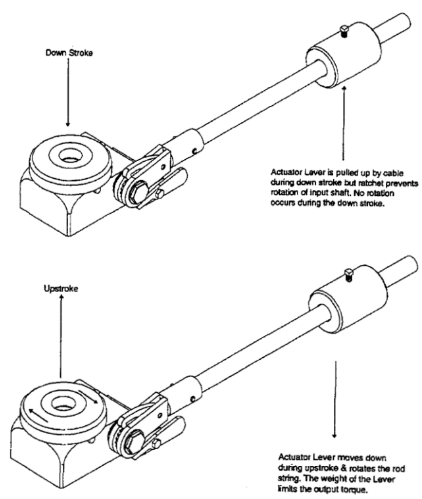


Figure 4 - M-300 Rod Rotator

SOUTHWESTERN PETROLEUM SHORT COURSE -98

Figure 4 – Smith introduced a radically different rotator design that inherently limited torque. In particular, it was described as applicable for fiberglass rods that may be more susceptible to torque on the rods themselves. The amount of rotational energy fiberglass rods may store when free rotation is resisted should also be considered. Figure reference: (Smith, 1988). Alternative rotator designs or application of existing rotator technology may be of interest.

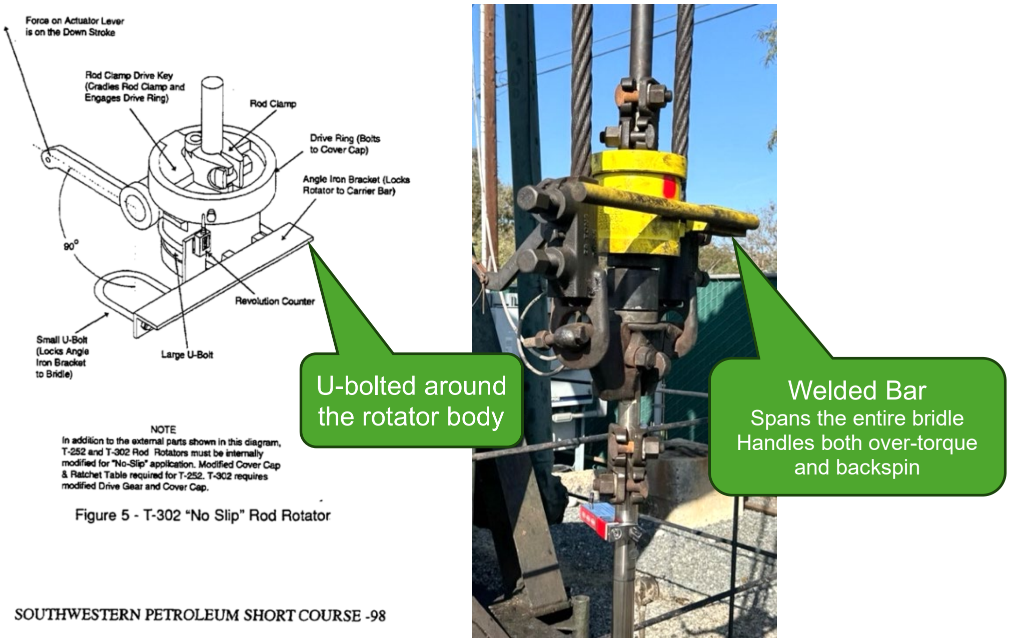


Figure 5 – Anti-rotation bars are a simple solution to keep the rotator aligned. Torque or “backspin” can move the entire rotator assembly which can cause subsequent failures of the ratchet and/or cable. The bar can be welded (suboptimal on a cast housing, but effective), or a large U-bolt can be used around the body of the rotator. Other methods are available to keep the rotator body stationary. Figure reference: (Smith, 1988). No-slip style rotators should include shear pins, especially when used in conjunction with an anti-rotation bar, to prevent excessive torque.

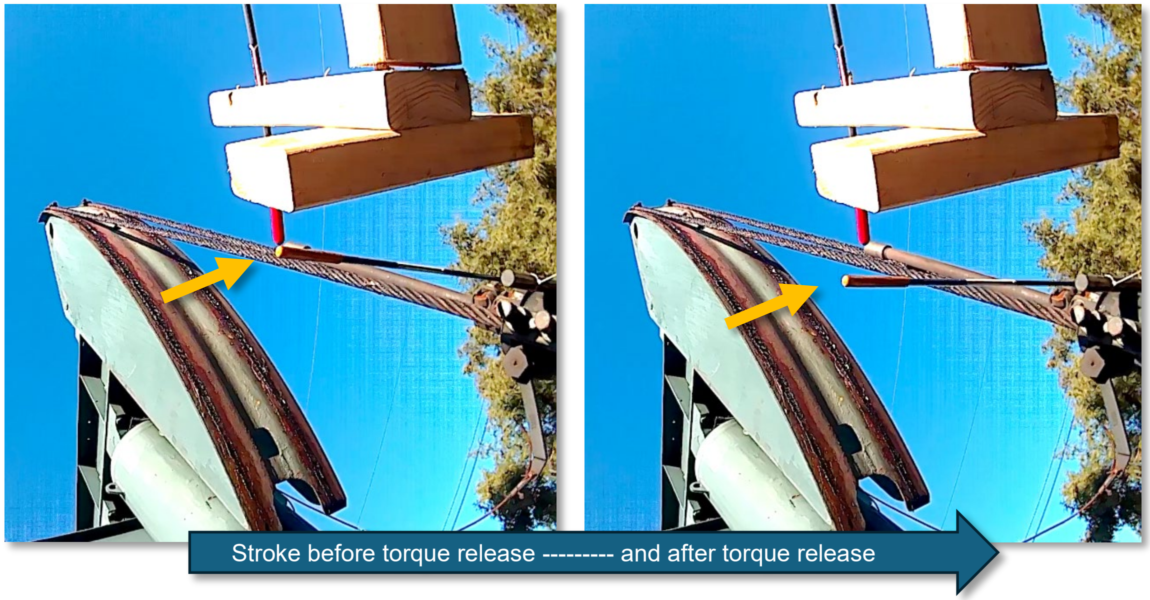


Figure 6 –Visual indication of bridle torque change. A probe was attached directly to the bridle (yellow cap) and moves up and down, but also rotates with any torque-induced deflection, which is what we intend to visualize. The stationary probe (red cap) was set near the path of the bridle to provide a fixed reference. These are selected frames from a video captured over several hours, and show 2 consecutive pump strokes. The yellow probe moved (rotated/twisted with the bridle) closer to the fixed red probe over many strokes. The picture on the left shows the stroke just before the torque release when the bridle was at maximum torque deflection. The rotating probe (yellow) was closest to the fixed probe (red). The picture on the right shows the very next stroke at (or following) the torque release. The yellow probe moves ever so slightly, but this is evident and measurable. A change in applied torque from a downhole “flop-over” event is the reason the bridle “relaxed.” In this well, a single rotation’s worth of torque was released downhole at each event.

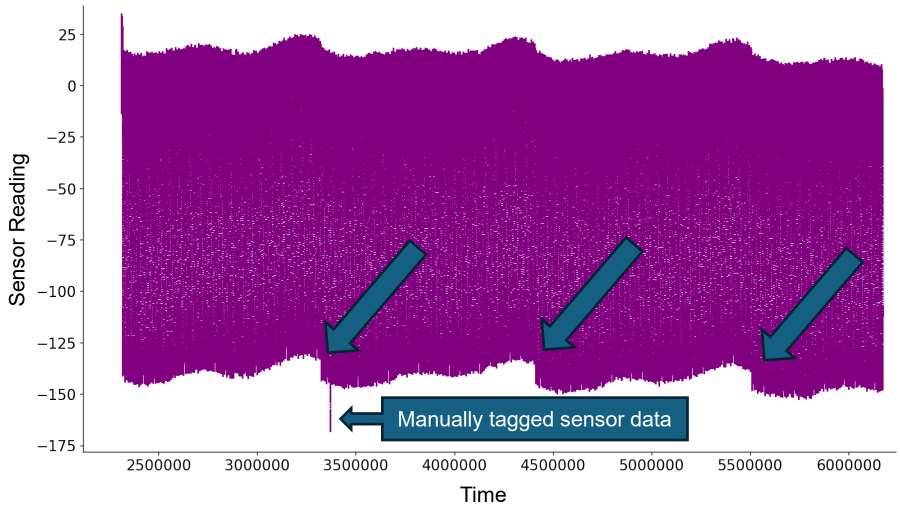


Figure 7 – Sensing torque release. The above visual example (Figure 6) was also caught in raw magnetic field sensor data. This plot illustrates sensor readings over approximately 600 strokes, or just over 3 complete rotations. The sharp change in sensor reading indicates a change in bridle deflection (highlighted by the 3 arrows). These events also occur at the same point in the overall rotation indicating the same downhole restriction is resisting the rotation and the same amount of torque (via the rotational angle) is required to overcome that restriction. While visually monitoring the well during the test, the physical change in bridle deflection was observed. A few strokes later it was realized that the sensor data could be tagged to correlate the visual observation with the logged sensor data for confirmation. Similar plots could be derived from accelerometer or gyroscope measurements (US Patent No. 11,814,948, 2018).

Figure 8 – Worn rod couplings are shown from Case Study #1. This is strongly believed to be the source of downhole rotational restriction observed a year earlier in Figure 6 and Figure 7. The tubing failed, but the rods themselves, even though the coupling wore flat, likely would have continued pumping. The rod-string was observed to torque and release, and the flat spot on the couplings shown above is likely the cause of the rotational restriction. It is unknown if forcing the rods to turn imparted an additional wearing force on the tubing, accelerating its wear.

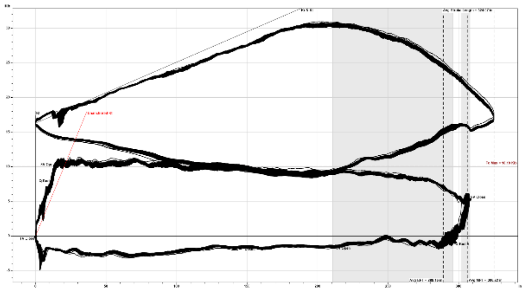
Tapers

		Taper 1	Taper 2	Taper 3	Taper 4	Taper 5	Taper 6	Total
Manufacturer		API	Other	Other	Other	NONE	NONE	
Rod Type		KD	FG	SB	SB	NONE	NONE	
Length	ft	130.00	7675.00	1300.00	955.00			10060.00
Diameter	in	1.000	1.250	1.000	1.500			
Weight	lb	376.0	9817.7	3737.3	6233.2			20164.2

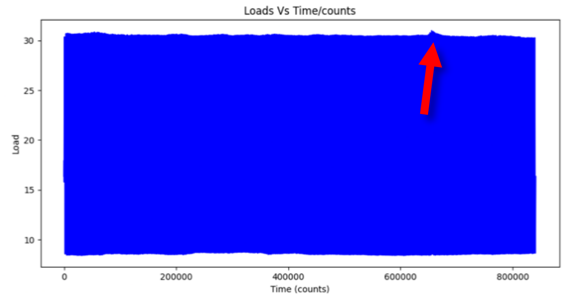
Pump

Intake Depth	10105.0 ft	Pump Length	40.0 ft	Pump Type	(●) R - Rod Insert Pump ( ) T - Tubing Pump
Pump Run Date	10/17/2024	Plunger Length	60.000 in		
API Pump Designation		Plunger Diameter	1.750 in	Location of Seating Assembly	( ) A - Top (●) B - Bottom ( ) T - Traveling Barrel
25-175 RHBM 40-5		Plunger Clearance	0.003 in		

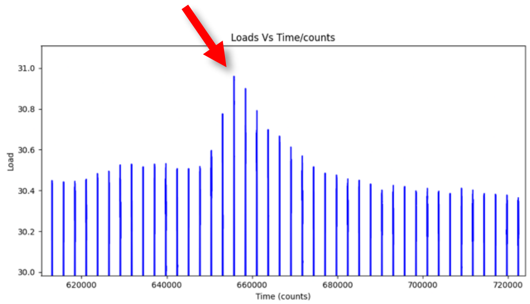
Figure 9 – The Horseshoe Loadcell, remote fired gas gun, and RAM combination was used to gather high quality dynamometer cards during the test. This allowed the test to continue without requiring onsite personnel. Dynos and further data analysis plots below were obtained from this equipment. Pertinent rod-string and pump details are shown.



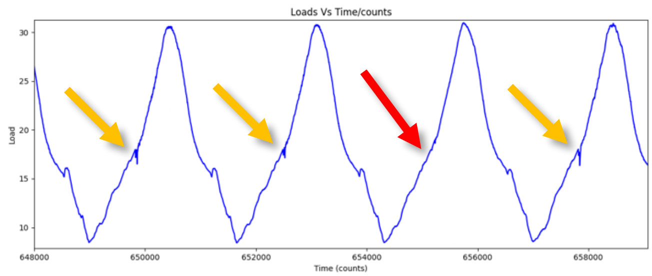
a) 316 dynos overlaid
Stable/consistent dynos



b) Load vs Time (from the 316 dynos)
Load anomaly identified

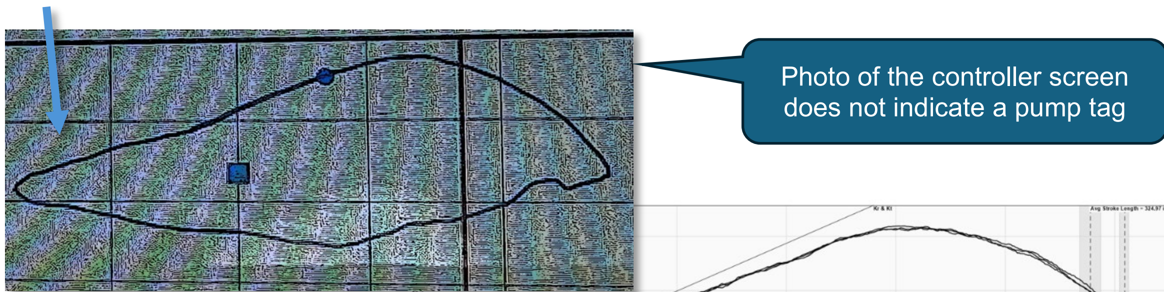


c) Zoomed load anomaly (spike)

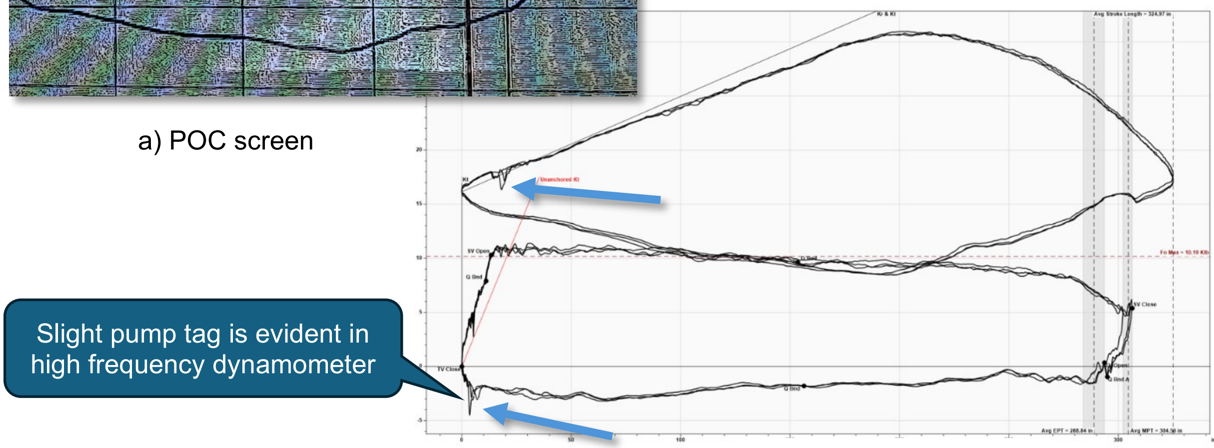


d) Tag identified, but missing
for the peak load stroke

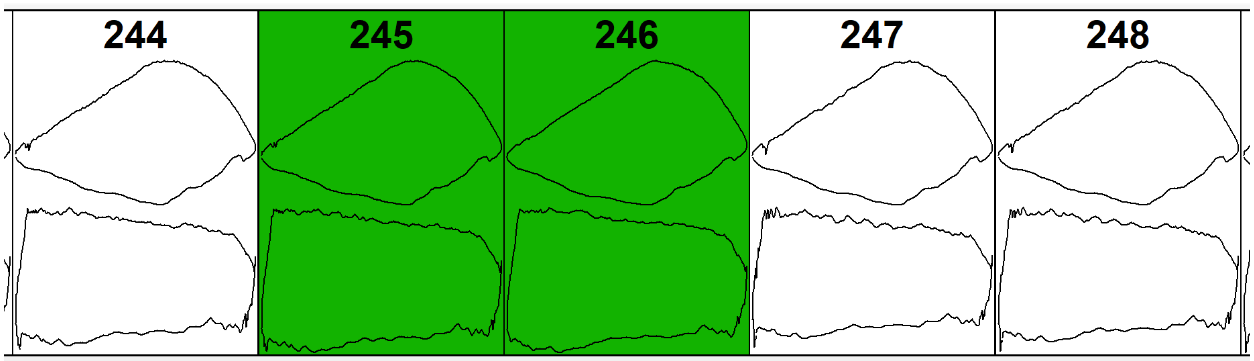
Figure 10 – A range of dynos were captured while the well was producing, in a stable state, during what is believed to be a flop-over event. Peak load variations are hard to determine from dynos (Fig. a), but they give a good view of how the well is behaving. Specifically, all dynos look roughly the same which means the well is behaving in a stable manner. The raw data was exported and plotted as load vs. time (Fig. b). A clear load increase is visible. When zoomed it can be seen this load anomaly took place over about 10 strokes (Fig. c). When further zoomed, it is clear a persistent "slight" tag disappeared for one stroke (Fig. d). The surface indicator of the pump tag, i.e. a sharp load variation is highlighted on each stroke. It is believed the stroke identified by the red arrow (Fig. d) is related to the rods flopping over. The load variations before and after this stroke may indicate the surrounding dynamics associated with that event.



a) POC screen



b) Overlaid TAM dynos



c) Individual cards. Stroke #246 (of 316) is believed to be related to a rotational event. Note: this is the only card in the series of 316 strokes that does not indicate a pump tag.

Figure 11 – The resolution on typical pump-off controllers obscures certain conditions such as a slight pump tag. A photo taken from the controller screen (Fig. a) does not indicate a tag. This is a factor of the sample rate of the controller on the surface card, as well as the method to calculate the pump card. When viewed through the Echometer tools (Fig. b) at a higher sample rate, a very slight tag is evident on all cards in the series except for one (Stroke #246, Fig. c). A random stroke that does *not* tag may seem innocuous, but referring to Figure 10, it can be seen there is a load variation surrounding this. In other words, something is happening that spans several strokes (approximately 10 strokes) but substantially affects one in the middle of the sequence.

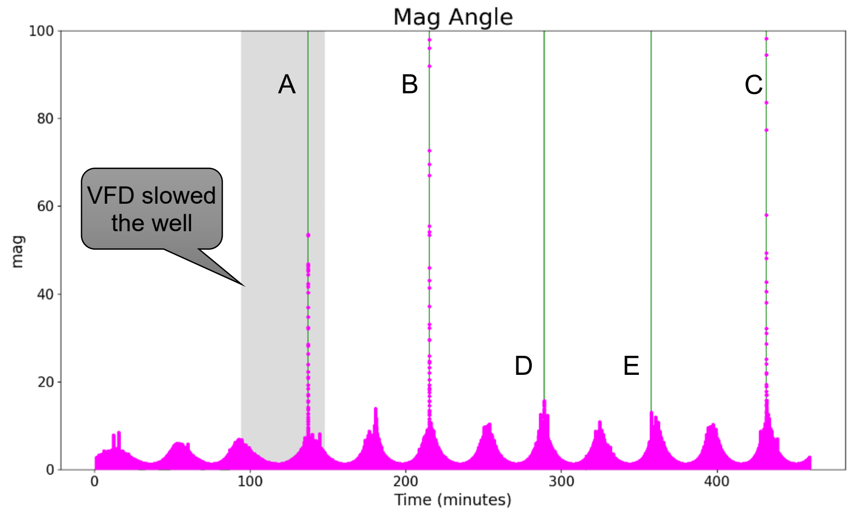


Figure 12 – Sensor data was gathered over approximately 8 hours and processed to illustrate a change in bridle angle. In this dataset, 3 significant events can be seen (labeled as A, B, C). These happen at the same point in the overall rotation (i.e. the polished rod is facing the same angle). Lesser events at D and E occur at the same rotational angle of the polished rod. These events may indicate a rotational event (possibly the rods downhole “releasing” or “flopping over”). The significance of every 2nd stroke may be related to the fiberglass rods being more flexible.

Appendix

Additional topics and discussion are provided below.

Anecdotes and observations

Because this topic has not been explored in the literature, it is useful to list some observations from informal discussions about this topic. The following is a collection of observations from several different sources. While these are not scientific observations, they do provide insightful questions and concepts to explore and may serve as a basis for further research.

- “We can tell when our rod rotators fail by watching peak polished rod loads”
    - The rod loads slowly increase over time. This is an interesting observation because it shows “friction” is not constant. Presuming all other factors are held constant, the loads should not change.
    - This implies that some friction-related change is occurring as the rods wear, but the exact mechanism is not thoroughly understood.
    - This could also indicate cyclic rotation has some “cleaning” effect, either by breaking buildup not touched by the linear stroking action, or by allowing chemical treatment to more fully contact the rods.
    - The simple flat 0.2 friction coefficient commonly used in design programs may be inadequate for modeling real-world dynamic conditions.

- “These wells don’t need a rotator because I drilled them right”
    - While this is a very subjective statement, it is common knowledge that geometry plays a significant role in rod wear.
- “We rotate elliptical rod”
    - The manufacturer discourages rotating elliptical rods, but at least one operator has seen success doing so.
    - This paper discusses the phenomenon of worn “Flat spots” in the rods due to wear. An elliptical rod is functionally equivalent (in the context of this paper) to a round rod with worn flat spots. Because elliptical rods are continuous, there may be different mechanics in the rotation compared to a rod coupling or guide which is a single point of focused contact with a larger moment arm than the rod body itself.
    - In other words, the elliptical rod may be easier to turn through a deviation simply because the leading edge of the “flat spot” runs the entire length of the deviation, or by creating a different rotational geometry not present in round rods.
- “We removed our rotators because rod wear was not a driving failure in this field, and they presented a safety concern due to imparted torque”
    - The safety concern alone was significant enough to make a field wide decision to eliminate rotators.
    - It is unclear if the rotators helped reduce rod failures or if other unrelated failures simply created an opportunity to address worn rods before they became a problem.
    - See “Rod-string Unwinding” above.
- “We can hear the rods spin when the torque is released.”
    - This pent-up torque is related to the safety concern above.
    - It is unknown how common this is in operational wells.
    - “Torque release” likely falls into 2 categories: significant with multiple rotations released at once, and single rotation or partial rotation releases. The mechanisms of torque release are not thoroughly understood and are a topic for further investigation.
- “This well has run for over a year with flat rods”
    - This observation is limited to a small number of wells because the ability to identify flat rods through a torque observation on the bridle assembly is relatively new. See Case Study #1 above.
- “Rotation, even if uneven, gives the rods an opportunity for lubrication”
    - Or “the lubrication or corrosion inhibitor gets wiped off.”
    - In continuous rods this may be a compelling argument, but in the case of stick rods, the coupling is a larger diameter, and the stroking action alone should be enough to migrate fluid into the contact interface.
    - Solids and grit may be a bigger detriment in such cases.
- “Stick-Slip” is a phenomenon that happens in PC pumps. While this may seem like a torque-release (flop-over) on a reciprocating rod string, Stick-Slip is a dynamic condition
    - “Stick-Slip” is almost exclusively governed by friction and torsional rod dynamics on a substantially round rod.

  - A “torque-release” in a rod pump is a product of friction related wear, which creates a non-circular rod body which must then be “lifted” away from the contact point to rotate.
- Torque Drag Analysis is common in drilling. While beyond the scope of this paper, the general idea is to use rotation to break static friction to better quantify linear friction
  - An ideally functioning rod rotator system works on the reverse principle: linear motion breaks the static friction and so any rotational torque present should be subject solely to dynamic friction. Further, the relative linear motion is substantial, while the rotational angle per stroke is relatively small. The rods have several strokes to work themselves over, rotationally, before torque increases appreciably.

<u>Why do rotators fail?</u>

Rod rotators are a common source of failure but rarely does a rotator failure result in an immediate stoppage of pumping. Typically, a rotator failure is a non-critical issue that is addressed as a matter of convenience, not as a matter of urgency. Rather than considering a rotator failure a nuisance issue, it may be better to say a “*functioning rod rotator is critical to prevent uneven wear*.” Distributing wear is the desired result, but when the rotator fails, one-sided downhole wear starts immediately and is irrecoverable once started. Rotators can fail for several reasons.

- Cable failures (broken, corroded, or exceeded tensile capacity)
  - Most common failure type, with breaks typically resulting from fatigue, poor connection installation, external forces, or rotator misalignment.
- Mechanical failure – Broken Ratchet
  - The old pawl-style ratchets were a common failure. One-way bearings have largely solved this, and field-installable retrofit kits are available from several different vendors.
  - This may be the most effective “upgrade” relative to cost and ease of implementing.
  - Old-style ratchet pawls can be identified by zerk-fittings on the large nuts on the lever arm and opposing backstop nut on the worm-gear body.
  - Newer one-way bearings are typically housed in a larger sealed nut.
- Mechanical failure – Main Gear
  - A failure of an internal component (i.e., gear or main bearing) may be an indication of substandard components or materials. A root cause failure analysis (RCFA) should always be performed on a mechanical failure of a rotator (beyond a cable or ratchet failure).
  - Manufacturers recommend frequent lubrication. How frequent should be weighed against labor costs. The reality is rotators are rarely lubricated in the field after the initial installation. Some materials and components perform better in this scenario. This should be evaluated as part of a RCFA.
  - The main gear does not experience high speeds or heat. Surprisingly, the main worm gear should not, under normal operation, see high forces.

Complete absence of grease is unacceptable, but higher quality gears may last longer between re-lubrication.
  - A gear failure can result from thrust bearing issues. Metal shavings from gear grinding, or other foreign material, may fall toward the thrust bearing, causing contamination. This contamination increases the load on the gear by creating rotational resistance within the bearing itself. This resistance is separate from the aforementioned downhole rotational restrictions.
- Mechanical failure – Main Thrust Bearing
  - The main thrust bearing is a roller style bearing. Frequent greasing serves more to prevent ingress of foreign material which can impede the smooth rolling. In the absence of foreign material, corrosion or uneven loading, the thrust bearing should function for quite some time. A quality assessment of the rotator body may uncover places where dirt, water, or other solids may enter the rotator body and migrate to either the main gear or to the thrust bearing.
  - Rotational rates vary greatly, but an “average” rotator may see 100 rotations per day (or 36500 / year). A typical wheel bearing, for example, would make this in about 60 miles. Loads are considerably different, as is component quality, so this is not an ideal comparison. It is only presented as an illustration.
- Rotational Slippage (polished rod clamp or entire rotator mechanism)
  - A slipping or grinding polished rod clamp is likely an indication of severe downhole sticking. It could also be insufficient loading (i.e., rod float, or impact from a severe pump tag reducing the normal force and thus the rotational friction force).
  - Uneven clamp installation or a non-level bridle may also result in a slipping clamp or rotator body. These conditions should be addressed before considering a positive engagement rotator or anti-rotation bar (Figure 5). The central premise of this paper is that forcing the rods to turn when they are not freely turning may be problematic with little benefit.
  - An exploration of the forces required to “slip” the polished rod coupling on the rotator table (i.e. the holding force on the frictional interface) can be found in (Smith, 1988).
  - Internal slippage may occur as a result of over greasing in some cases.
- Ineffective downhole rotation, despite functional surface appearance
  - This is the secondary premise of this paper. Just because the polished rod is rotating at surface, this does not mean the downhole rods are effectively rotating downhole.
  - In other words, the entire rod-string sees the same total rotations, on average. However, the downhole rods may be spending more time on one side, followed by a rapid rotation to “catch up” to surface rotation. See “Flat spots” and Rod-string Unwinding above.
  - This may not be detrimental in all cases. In the case of Case Study #1, the well ran for over a year (at least) in this condition.

Detailed trackable notes on these types of failure can be used to identify areas of improvement. Even a simple conversation with the personnel responsible for minor field repairs can be insightful. In other words, “we’re constantly replacing ratchet pawls” or “the cables are constantly breaking at the set-screw cable ends” might not rise to the level of trackable events as they are relatively minor repairs. These personnel may not be aware of one-way bearing upgrades or better cable attachments. If the rotator arm cannot be actuated by hand, something is almost certainly wrong with the rotator itself (see Rod-string Torque above). This is a quick and easy check for the pumper.

Anti-Rotation Bars

Anti-rotation bars are a simple, yet surprisingly uncommon, solution to keep the rotator body aligned with the ratchet/cable. Figure 5 shows some possible configurations. In one case it is a simple piece of angle iron U-bolted to the rotator body. Some operators have had success simply welding a bar to the rotator body. If the bar spans the bridle assembly it can help maintain rotator alignment during either a backspin event, or an over-torque condition.

Anti-rotation bars are effective when the relative rod load is low (i.e., shallow well, rod float, etc.). In some cases, a tagging well may dislodge the rotator body, allowing it to become misaligned with the cable, resulting in a cable failure due to misalignment.

Anti-rotation bars do not solve the underlying problem of high torque, or backspin; they might actually make it worse. They merely mitigate the resulting cable failure by ensuring the rotator body remains aligned with the cable. When installing an anti-rotation bar, one should understand that it may prevent the surface failure of the rotator mechanism (via the misaligned cable/ratchet), but it may in turn create the condition of increased torque. In short, if the rods are not freely rotating, the logic of forcing them to rotate should be considered.

Extreme Torque Example

How much torque can a rotator generate? It is a simple gear reduction problem; we can define the weak point for a theoretical example. Note, this example is not indicative of the torque that actually gets imparted to the rods, it is just a thought experiment provided to illustrate the mechanical components of a rod rotator have significant torque capacity. This example is intended to consider how easy it may be to impart a large amount of torque onto the rod-string. See (Smith, 1988) for a practical study on realistic torque values, using friction at the polished rod clamp interface as the weak link.

Consider defining the actuator cable as a weak link and assuming all other mechanical components could withstand the resulting forces. The tensile capacity of a ¼” steel braided cable is approximately 5000 LBS. On a 9” lever this is approximately 3750 ft-lbs on the input shaft of the rotator (the worm gear shaft or ratchet/bearings would likely fail at this torque). At a gear reduction of 38½ to 1 (154, 90° pulls, slow gear), that means

144,000 ft-lbs could conceivably be transferred to the polished rod. The actual torque imparted to the rods is several orders of magnitude lower. Rotators are only limited (practically) by the quality of their internal components, and the friction interface between the rotator and polished rod (via the clamp and bridle).

Assuming a practical transferred output torque of 240 ft-lbs at the polished rod clamp interface (per Smith), what is the required input torque? At 38½ to 1, that is just over 6 ft-lbs on the worm gear input shaft, which is tiny in comparison to the above example. On a 19¼ to 1 standard gear rotator, the input torque is about 12.5 ft-lbs. For reference this is around the torque you'd apply to a typical ¼ – 20 nut. Mechanical loss through the gear reducer may add a few ft-lbs but is still comparatively small. A rotator arm should be easily moved by hand. It may be difficult to discern downhole torque from such a high gear reduction, but a rotator arm that is difficult to move by hand is likely an indicator of an impending rotator failure.

<u>References</u>

Alexander, B. (1926). *US Patent No. 1,667,240.*

Lacy, R. (1992). The Rotating Tubing Hanger System: A Unique New System Designed To Extend the Run Time of Rod Pumped Wells. *SPE Permian Basin Oil and Gas Recovery Conference.* Midland: SPE.

Phillips, W. (2018). *US Patent No. 11,814,948.*

Ray, R. G. (1995). Determination of Rod Guide Erodible Wear Volume. *Southwestern Petroleum Short Course.* Lubbock.

Smith, D. (1988). Rod Rotator Torque in Rod Strings. *Southwestern Petroleum Short Course.* Lubbock.

Treiberg, T., & Justin, C. (2022). Wireless Sensor Technology To Monitor Rod Rotator Performance. *Southwestern Petroleum Short Course.* Lubbock.

Weaver, D. (1937). Pumping Slant Holes at Huntington Beach, California. *Drilling and Production Practice*, 138-147.