SUCKER ROD PUMP ROOT CAUSE FAILURE ANALYSIS

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ABSTRACT

Producers can spend a significant amount of money repairing a sucker rod pump (SRP) system without fully understanding the root cause of a failure. Incomplete, missing or incorrect data along with over reliance on a supplier to “fix the problem” can be ineffective. Following “best practices” developed in other fields or generic “rules of thumb” may lead to a higher than expected failure rate especially when artificially lifting fluid from an unconventional reservoir.

A “like for like” replacement may experience an early life failure resulting in another unplanned workover. As a result, increased lifting cost may contribute to unfavorable well and field economics.

This paper will discuss the results of a new root cause failure taxonomy and process which were developed for SRP systems installed in unconventional horizontal oil wells. Understanding common failure themes by using root cause failure analysis has supported the development of an effective failure mitigation strategy for new wells and corrective action for systems which require a workover.

BACKGROUND

Over 600 SRP systems have been installed and 523 downhole system failures were studied and documented to form the basis of the failure analysis strategy outlined in this paper.

All wells in this study are horizontal wells with a vertical depth from 6,500 to 11,500 ft. Most of the pumps are landed in the vertical section above the “kick off” point where the wellbore begins to build into the lateral section. A small number of wells were landed below the “kick off” point but do not represent any significance to the failure data or processes outlined in this paper.

Most wells were completed with 5.50 in. production casing. A smaller number of wells have 4.50 in. casing. A variety of common sucker rod grades have been installed dependent on load and fluid properties. Sucker rod guides are commonly installed to mitigate sucker rod coupling contact with the tubing. A majority of wells are deviated in the vertical section which may result in sucker rod side load of 300 to 400 lbs-f. Typically 20 to 150 lbs-f of side load is expected. All pumps are insert style with the most common plunger diameter being 1.50 in. with a two stage hollow valve rod configuration. A smaller number of 1.25 in. and 1.75 in. plungers have also been installed.

The produced fluid is gaseous and the crude oil gravity will range from 44 to 50 API. The fluid may also contain H_2S, CO_2 and paraffin at varying concentration. Bottomhole temperature at the pump landing depth will range from 260 to 285 F. Sand and water may be present as a result of a fracture stimulation. Additionally, sand and water may come from an offset well which has been fracture stimulated.

The focus of this paper will be on the systematic approach to data collection and failure analysis but will not go into the specific details of corrective action. Some examples of how data has been used to improve system reliability will be presented and several lessons learned will be shared.

INTRODUCTION

SRP systems were selected as a single artificial lift strategy for the life of the well. SRP systems have the ability to self-optimize using a variable speed drive and can be remote monitored through the SCADA network. The SRP surface equipment is robust and reliable. The bottomhole pump has well known operating characteristics and is suitable for a wide range of fluid properties. The SRP system has a wide turn down range to match the target production rate and decline curve of the unconventional reservoir.

A definition statement was developed for system optimization which defines a strategy of continuous improvement of system reliability. “Produce the maximum fluid rate within known constraints and unknown variability while minimizing risk and extending run life”.

Known constraints include casing and tubing size, depth, wellbore geometry and lateral direction. Unknown variability includes operating requirements, fluid properties, wellbore deviation, gas liquid ratio, H2S, CO2, paraffin and fracture stimulation which may introduce water and sand to the well.

Minimizing risk refers to the action of applying lessons learned from root cause failure analysis to make a change which will reduce the likelihood of a similar failure occurring and to extend run life.

To reduce life cycle cost and improve the reliability of the artificial lift system, a thorough investigation should be undertaken to identify the root cause of a failure. Unfortunately, “like for like” may be run back in the well if the root cause of failure is not identified and corrected. This may result in another workover in less number of days than the first production period as other components of the system may also be at risk for a premature failure.

One measure of system reliability is to analyze the number of production periods a well has experienced. A production period is defined as the “date start” to “date fail”. The first run of the SRP system is referred to as production period one (P-1). As subsequent production periods occur, they are numbered and tracked independently. This identifies exceptions in the data base bringing attention to wells with a larger number of production periods. A correlation can be made in which wells operating with higher number production periods are worthy of a more detailed analysis to help mitigate a repetitive failure.

Understanding the failure mechanism is important when developing an effective mitigation strategy. Simply stated, “we need to know why a rig is on the well”. It is important to make simple correlations of cause and effect. If cause and effect are not understood, then time and money spent mitigating failures may be wasted on ineffective solutions. A new set of failure modes may occur which add further complexity and possibly hide the original root cause of the problem.

Reliable, accurate data combined with detailed analysis can provide an understanding of the probability of a future failure given a range of conditions. This is different than the concept that it’s possible to determine the likely hood a particular failure will occur on any given day. Fundamentally, it’s about understanding probability and managing risk. It’s not good enough to simply track numbers of failures and create generalized plots. A less diligent process may result in an inappropriate correlation adding further cost to mitigate a problem which may not exist.

Suppliers of artificial lift products and service, work hard to try and mitigate failures, improve run life and provide alternate solutions to a problem. Unfortunately, the supplier is not usually in the best position to understand the full range of issues surrounding a failure. As an example, it’s difficult to ask a pump supplier to make a recommendation about reducing tubing and sucker rod wear or expect a sucker rod supplier to make a recommendation regarding the type of metallurgy of the pump components.

Each sub-system component is supplied from a different vendor. The advantage to this strategy is the likelihood more expertise and technical support will be available. The dis-advantage is there is not one supplier responsible for the overall performance of the system. Ultimately, the engineer is the owner of the results and in the best position to take responsibility for the system reliability as outlined in this paper.

Results have proven the process of real-time data collection and failure identification enables immediate corrective action to be conducted during the current workover. This approach is more cost effective than putting a rig back on the well after a short run and try to determine what went wrong and repair again.

The root cause failure analysis presented in this paper has reduced the sub-surface failure rate by 60% in 3 years. The total number of workovers has stayed relatively the same even with a rising well count.

FAILURE DATA BASE TAXONOMY

The creation of a taxonomy for a failure data base provides a meaningful structure as to how data and information will be documented. Without structure, data and information may appear to be conflicting, irrelevant or of no value. Data standards must be developed and followed. When documenting a failure, the description must be clearly understood and have relevant meaning. The use of comment sections has been minimized as they are considered to be unstructured data. Comments require interpretation and possible misinformation as conclusions and assumption written may be inaccurate or of now empirical value.

An artificial lift work flow (Figure 1) was developed to collect data at key points during various stages of the process. Information regarding installation, operation, diagnosis, workover, inspection and failure analysis is captured at the time work is conducted. This process has evolved over time and brought together from what would be traditionally considered as separate silos into one connected data gathering process.

Data collected during the artificial lift work flow is entered into different categories which correspond to the following:

1. Well primary information
2. ALS operating information
3. Sub-surface equipment
4. Tubing installation
5. Pump installation
6. Sucker rod and guides
7. Problem well report (PWR)
8. Workover inspection
9. Sucker rod and sucker rod guide inspection
10. Tubing inspection and scan
11. Pump shop inspection
12. Root cause failure analysis
13. Final technical review

CALCULATING RUN DAYS

The calculation of actual run days can be challenge. By default, many suppliers calculate run days as the date the equipment was installed or delivered to location, minus the date it was picked up for repair. This will over estimate run life and may provide misleading information about actual equipment run days or as it is sometimes referred to as “utility” of a system.

There is suggestion, counting equipment cycles is a more relevant measure of system and component reliability. This may have merit in applications where machines operate at constant speed and load or when operating conditions are similar amongst a group of machines. In the unconventional well, SRP systems will operate over a wide range of speed and load conditions throughout its life cycle.

Each well is unique and therefore the rate of wear, effect of fluid properties, operating speed and wellbore geometry are different. For the purpose of this paper the use of run days is the measure of run life. The table below outlines the complexity taken into account when calculating something as simple as average run days, failure rate and mean time between failure (MTBF)

1. Date start-pump began operation
2. Date shut in offset frac (SIOF)
3. Days lag-calculated number of days’ system was available but not operating
4. Date return to production (RTP), well successfully returned to normal operation after shut-in
5. Date fail-date of actual system failure not date failure identified
6. Days run-calculated number or actual days the system was operating
7. Date rig move in rig up (MIRU), actual day which rig moved to well to begin repair
8. Days mean time to repair (MTTR)-calculated based on (RDMO – date of fail)
9. Date rig down move out (RDMO)-Date in which rig leaves a well after repair

SRP DOWNHOLE SUB-SYSTEM

The downhole SRP system has been divided into three separate sub-systems. Each sub-system has been broken down further to the component level. The components contained in this particular list were identified as relative to a failure that caused a workover. Accessory components have been excluded from detailed tracking as they do not perform a critical function.

If a sucker rod or tubing sub-system fails due to a non-critical component it will be categorized as an accessory. For the pump, a non-critical component will be categorized as a connection or accessory. Tracking of the utility of components such as barrels, plungers and valves are excluded from the data base as relative to workover costs, they are not deemed to have any significance.

1. Sucker rod system
    - sucker rod
    - sucker rod coupling
    - polished rod
    - polished rod coupling
    - sucker rod guide
    - sinker bar

2. Tubing system
    - tubing
    - pup joint
    - tubing collar
    - anchor
    - sand screen
    - gas separator
    - pump seat nipple
    - chemical injection valve (CIV)
    - accessory

3. Pump system
    - barrel
    - plunger
    - cage travelling top
    - cage travelling bottom
    - cage standing top
    - cage standing bottom
    - valve rod
    - hold down
    - connection
    - accessory

ROOT CAUSE FAILURE ANALYSIS

Dezfuli (1) et al., presents a methodology which has been modeled to develop the hierarchal structure of root cause failure analysis. This methodology provides boundaries around critical components of the artificial lift system and standardization of terms and descriptions of a failure.

More than 50 different cause and effects have been identified and are used to describe the root cause of failure. Understanding cause and effects is important when analyzing clusters of failure types which can then be used to develop corrective actions.

In 2016, 92 SRP systems were installed and only 8 failed. None of the failures were due to holes in the tubing or pump configuration or sucker rod design.

The hierarchal structure used to categorize root cause failure analysis is as follows:

1. Sub-system
    - The sub-system which failed
2. Component
    - The specific component of the sub-system which failed
3. Part
    - The specific part of the component which failed
4. Failure
    - The loss of function of the component
5. Failure cause
    - The casual impact leading either directly or indirectly to the failure
6. Failure mode
    - The specific type of failure and manner in which failure occurred
7. Failure effect
    - The outcome which resulted due to the failure

SUB-SURFACE FAILURE RATE

Failure rate is the frequency at which a component or system will fail. The calculation is useful to measure the change of failure rate over time. A failure rate of 1.0 would indicate that when a failure happens the average time will be one year. This does not mean all wells will fail in one year, just the average time to a failure will be one year. Understanding the failure rate is an important measure of system reliability. It also highlights opportunities to improve weak points in the system.

Speaks (2) et. el., counts the total number of failures within a population, divided by the total time in which the component was in operation prior to the failure. Failure rate is the probability a failure will occur within a specified interval of time. This paper considers the time period to be one year hence failure rate is presented as a decimal value.

The sub-surface failure rate plot (Figure 2) highlights the reduction of failure rate during a three-year period from 2014 to 2016. The failure rate was reduced from .99 to .45. The plot presents two separate calculations of failure rate. The solid line includes failures which have occurred during the previous 12 months. The dashed line includes only failures from the previous quarter. Both are rolling average calculations.

The quarterly failure rate provides more sensitivity to variation of the failure rate and helps quickly spot undesirable trends which may warrant further investigation.

SUB-SYSTEM FAILURE RATE BY QUARTER

The plot (Figure 3) presents the failure rate for each sub-system. This includes the tubing, pump and sucker rod sub-systems. The plot provides a visualization of how each sub-system is performing relative to the total failure rate. The calculation uses the same methodology as the quarterly failure rate as stated in the sub-surface failure rate. The expectation is once a technical limit has been reached the failure rate will be constant within a range of expected outcomes as the system reaches later life.

MEAN TIME BETWEEN FAILURE

The plot (Figure 4) presents the MTBF broken down by field. This measure is a lagging indicator and has only gained value as the data quantity has increased. To be included in the calculation of MTBF, an observable event must occur, which is a failure. MTBF requires a large number of samples to validate assumptions and improve certainty about an outcome.

As more samples are collected, MTBF will begin to correlate with the failure rate. Mature fields which have operated over many years may have a significant number of documented failures which can be used as a measure of reliability. In the case of a new field development there is no data to analyze. During the rapid development phase, the goal is to not create a long list of samples (failures), but rather to work toward growing the average run days by keeping the workover rig off the well.

SCATTER PLOT

Scatter plots are useful to identify correlations between two variables. A series of scatter plots are presented in this paper which highlight a correlation between time and number of days to a failure. Each point on the plot is unique and represents one failure. This helps with understanding whether system reliability is improving and how much certainty there is about failure clusters on the plot. A cluster of failures may indicate something is consistently failing and worth further investigation. All three plots show a positive correlation and an increase in the number of days to a failure. This would indicate reliability is improving.

The scatter plot of pump failures (Figure 5) presents a positive linear correlation. The plot shows a high degree of certainty around pump failures which occurred from September 2014 to June of 2015. A cluster of failures is visible with less than 100 days of run time. A study identified the failures were due to installation of low temperature seat cups on the pump holddown. Two corrective actions were implemented because of the analysis. A change to a mechanical holddown is now standard and high temperature seat cups are installed when required. The strength of the correlation of pump failures related to seat cups was overwhelming and when compared to December of 2016, it is clear this type of failure has been eliminated.

The scatter plot of tubing failures (Figure 6) presents a positive linear correlation. Information from the data base documents 74% of tubing failures are due to contact with a sucker rod coupling on an unguided section of the sucker rod. This does not mean every unguided sucker rod will result in a failure, but when a failure does occur, its most likely to be in a section of tubing with no corresponding sucker rod guide. As a result, more attention is now placed on understanding wellbore geometry and placement, configuration and material of the sucker rod guide.

The scatter plot of sucker rod failures (Figure 7) presents a positive linear correlation. A high level of certainty exists regarding sucker rod failures. Through analysis of sucker rod body failures, corrosion has been identified as the root cause and is most likely to occur from 1,000 to 4,000 feet with an average of 250 days to fail. This does not mean all sucker rods will fail in 250 days but rather when they do, there is a high level of certainty about depth, time and root cause of the failure. Therefore, an investigation into the source of the corrosion can be conducted and effective mitigation strategy may be developed.

BATHTUB CURVE

The bathtub curve (Figure 8) is divided into 3 stages of the life cycle. When a failure occurs, the data point is plotted on the bathtub curve. It's important to understand which part of the life cycle the failure has occurred as this may help with the investigation.

Stage 1 is populated with early life failures and is associated with less than optimal design, operation or equipment integrity. 80% (431) failures have occurred in 400 days or less.

Stage 2 is the bottom of the bathtub curve. Equipment which fails is assumed to have performed as expected and may be considered as "normal operation" to a failure. A failure in stage 2 may represent an opportunity to implement corrective action to improve system run life. This is where many run life improvement initiatives stall out, specifically when root cause failure analysis is inconclusive or non-existent.

Stage 3 occurs when the slope of the bathtub curve begins to rise as the equipment reaches its technical limit. At this point, run life is more predictable and the idea of planned remediation prior to complete system failure may be possible.

The data in this paper represents a relatively young population of SRP systems which have were installed during a 3 to 4 year time period. The current distribution of the bathtub curve is skewed to early life failures.

CURRENT AVERAGE RUN DAYS

Although this paper is focused at root cause failure analysis, a plot of current average run days (Figure 9) is included. Current average run days is a lagging indicator which can be heavily influenced by the age of a given population rather than validate assumptions about reliability. The calculation sums the average of all run days which includes the current operating production period and all previous failed production periods for all wells on a monthly basis.

PIE CHARTS

A series of pie charts are presented which provide an overview not associated with time. Pie charts provide information which further break down the sub-system to the component level. It's easy to see which components and failure modes have the highest number of occurrences. This breakdown provides value for analysis, but generally does not present actionable information to be used for real-time corrective action.

The pie chart does provide a high level understanding of where attention should be focused in the sub-system and more importantly which component is having potential issues.

For purposes of this paper, the information contained in the pie charts does not follow the exact hierarchal structure used for failure analysis but is used for illustration purposes to represent factual information drawn from the data base.

The pie chart (Figure 10) represents the total number and percentage each sub-system has failed. The sub-system with the highest risk for a failure is the pump at 50%. Second highest sub-system at risk is the sucker rods at 29% and lastly the tubing at 21%.

The pie chart (Figure 11) summarizes pump system failures. Note the wide range of failure modes in this data set. It's apparent the operating environment which the pump is being exposed to is hostile. As well, issues with the original pump configuration using low temperature seat cups account for 39% of failures of the pump system.

The pie chart (Figure12) summarizes tubing system failures. From the pie chart it can be observed when a failure of the tubing system occurs, 74% of the time, it is related to a hole in the tubing. The second most common failure of the tubing system is corrosion of the pump seating nipple at 10%. Initially a carbon steel pump seat nipple was installed which was proven to be susceptible to corrosion. A stainless steel pump seat nipple is now installed and has eliminated this type of failure.

The pie chart (Figure 13) summarizes sucker rod failures. The sucker rod itself, contributes to 62% of all failures. Sucker rod couplings are 27% of the failures. For sucker rod couplings, the primary failure mode is wear due to contact with the tubing.

CONTINUOS IMPROVEMENT AND RESULTS

Data collected from the process outlined in this paper has supported the development of standards and recommended practice for new system design and repair. More robust sub-surface equipment is being installed and improvements to system reliability is being measured.

Failure modes are now better understood and corrective action can be implemented quickly. A significant lesson learned from owning the failure data is the concept of "don't mitigate what you don't know". Many products or service in the market have great features and claimed benefits but unless you know the root cause of failure it may be difficult to understand which of these products or service offer the best solution to a specific problem.

The engineer is in the best position to decide if a proposed solution has merit or not when there is a high level of certainty as to why the workover rig is on a well.

The continuous improvement of the SRP system has been a result of a focused effort to study the details and mitigate known problems. Generalizing failures facilitates generalized solutions, which in itself can further contribute to reduced well and field profitability.

The following are examples of corrective actions which have been implemented as a result of the process of root cause failure analysis. These corrective actions were critical to improving system reliability, reducing operating expense and production deferral due to downtime.

Pumps (Failure Rate 0.15)

1. Replace top cage with hard lined
2. Replace standard travelling valve and standing valve cages with insert guided
3. Change from silicon nitrate balls to titanium
4. Add double standing valve cage
5. Change from cup type to mechanical holddown

Tubing (Failure Rate (0.06)

1. Implement multi-directional tubing scans
2. Identify technical limit of sucker rod guide material
3. Identify 80% of tubing failures were a result of slick sucker rods with no sucker rod guides installed
4. Identify limitation of drilling deviation survey and design software for sucker rod guide placement
5. Implement gyro survey where required for enhanced measurement of wellbore deviation

Sucker Rods (Failure Rate 0.16)

1. Eliminate sinker bars and install 1" rods for stiffness rather than weight
2. Design the sucker rod string to operate with less load where practical
3. Identify corrosion failure modes for variety of sucker rod grades and material
4. Identify corrosion as primary failure cause of sucker rod failures from 1,000 to 4,000 ft.
5. Identify metallurgy issues with sucker rod coupling

CONCLUSION

Competency using root cause failure analysis is critical to managing cost in an asset being produced with any form of artificial lift. It's possible to monetize failure data to prioritize the largest opportunities to reduce downtime and cost associated with workovers.

Failures present an opportunity to improve system performance only if a process exists to capture the root cause of failure and document the lessons learned.

Too often, only the cost to repair the artificial lift system is taken into consideration. This may undervalue the return on investment possible by making a formal effort to document the root cause of failure and the corrective actions which can be undertaken based on knowledge rather than assumptions

During times of high commodity prices, the hidden cost of production deferral may equal the cost of the workover. In times of low commodity prices, failures may make a well, field or asset uneconomic.

Regardless of commodity pricing, there is strong economic justification to eliminate sub-surface failures wherever practical. Recommended practices developed from knowledge gained conducting root cause failure analysis as outlined in this paper will support reduced lifting cost and maximize production.

REFERENCES

1. Dr. Homayoon Dezfuli, Dana Kelly, Dr. Curtis Smith, Kurt Vedros, William Galyean, Bayesian Inference for NASA Probabilistic Risk and Reliability Analysis, June 2009
2. Scott Speaks, "Reliability and MTBF Overview", White Paper

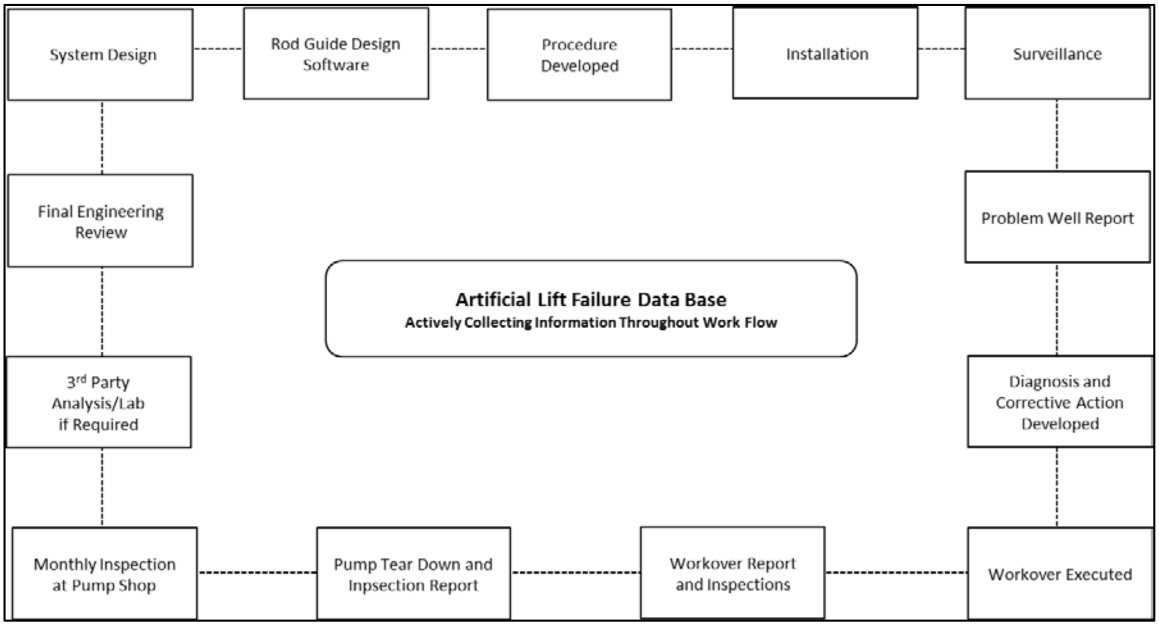

Figure 1 Artificial Lift Work Flow

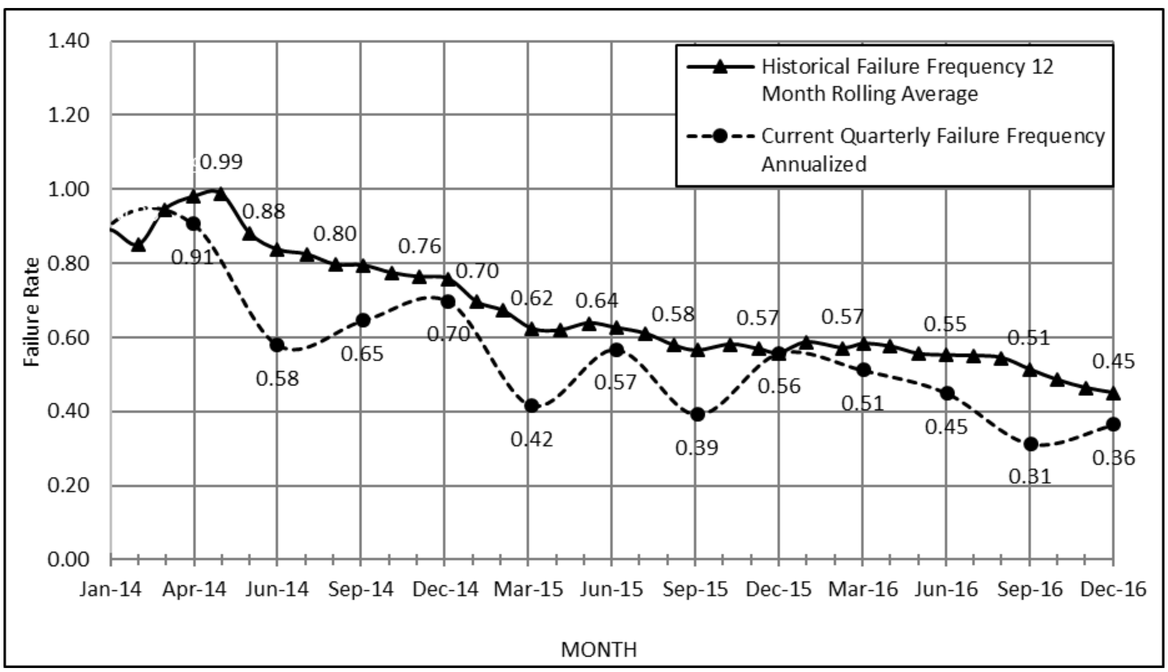

Figure 2 Sub-Surface Failure Rate

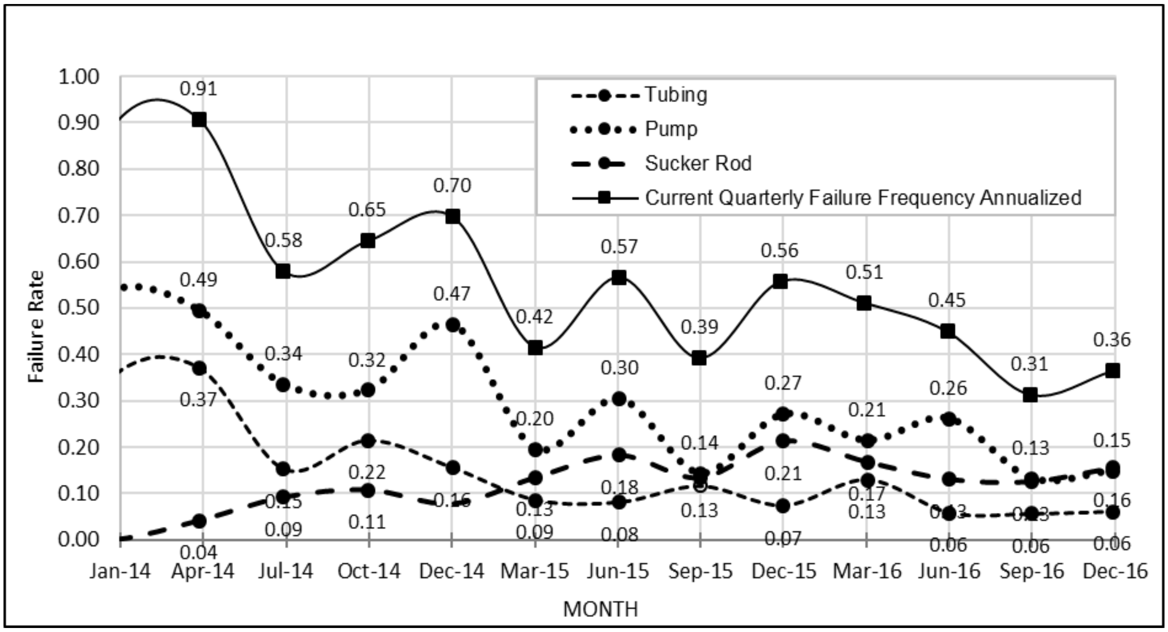

Figure 3 Sub-System Failure Rate by Quarter

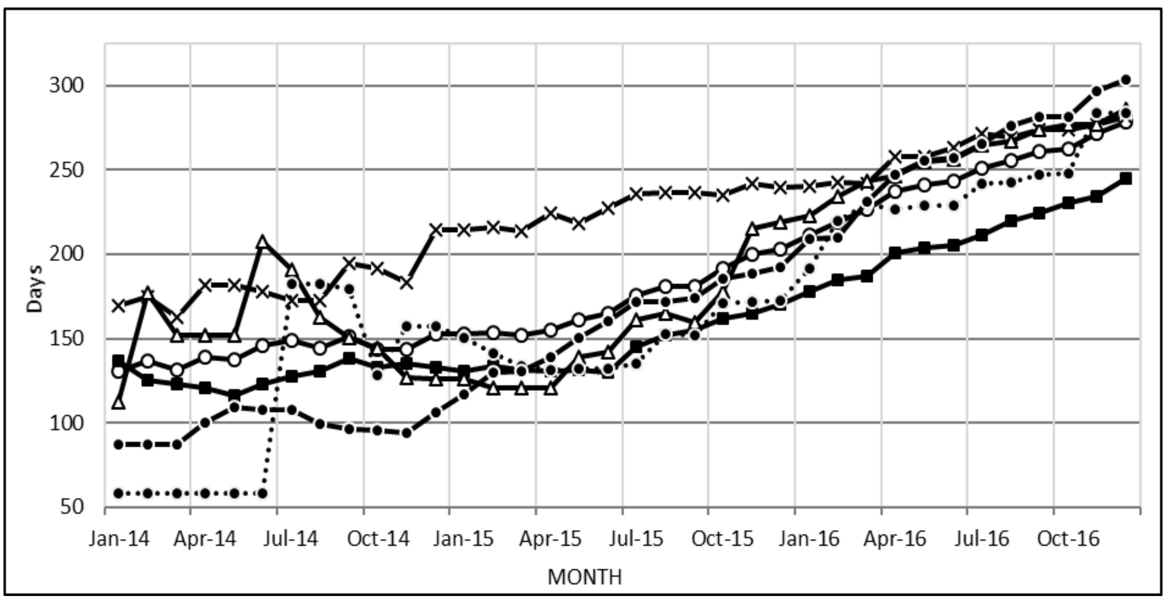

Figure 4 Mean Time Between Failure (MTBF) by Field

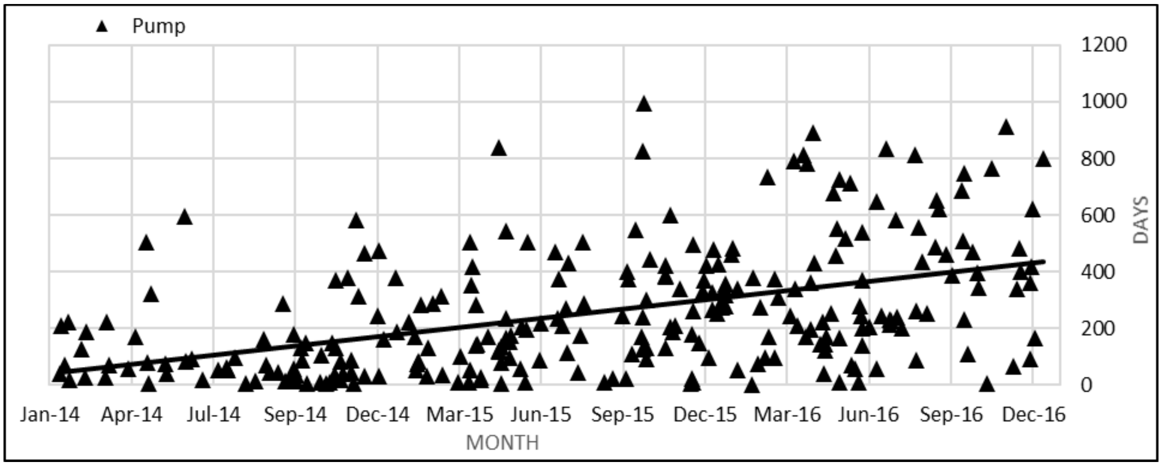

Figure 5 Pump Scatter Plot of Month Failed vs. Number of Run Days to Fail

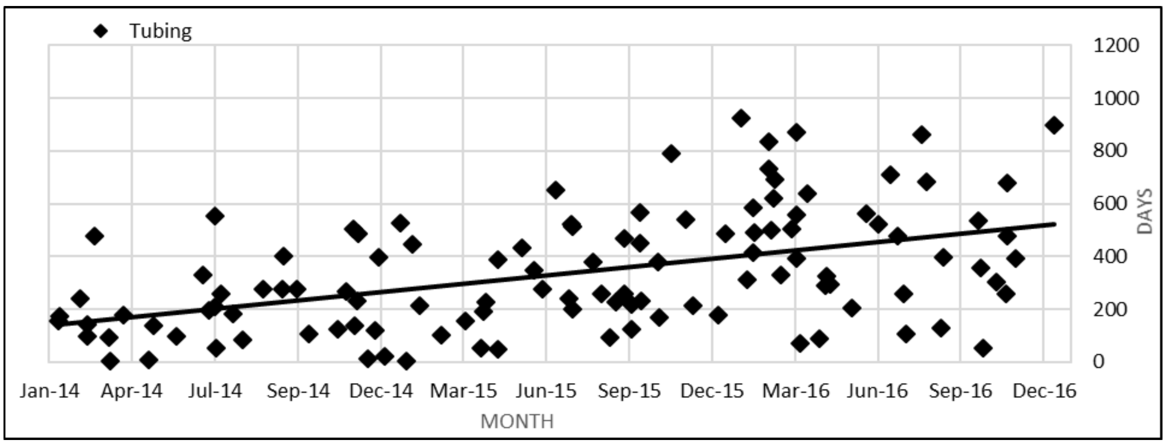

Figure 6 Tubing Scatter Plot of Month Failed Vs Number of Run Days to Fail

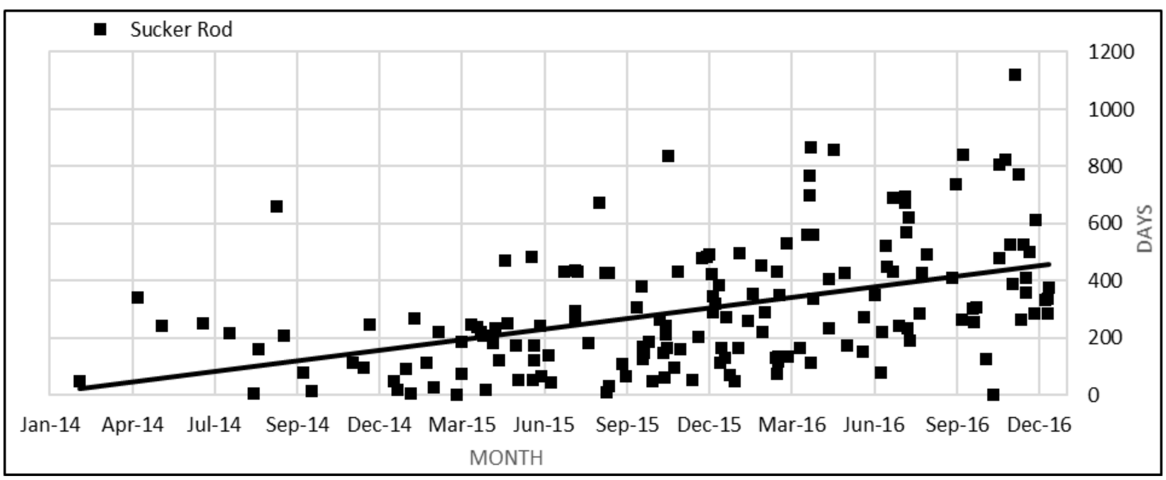

Figure 7 Sucker Rod Scatter Plot of Month Failed vs. Number of Run Days to Fail

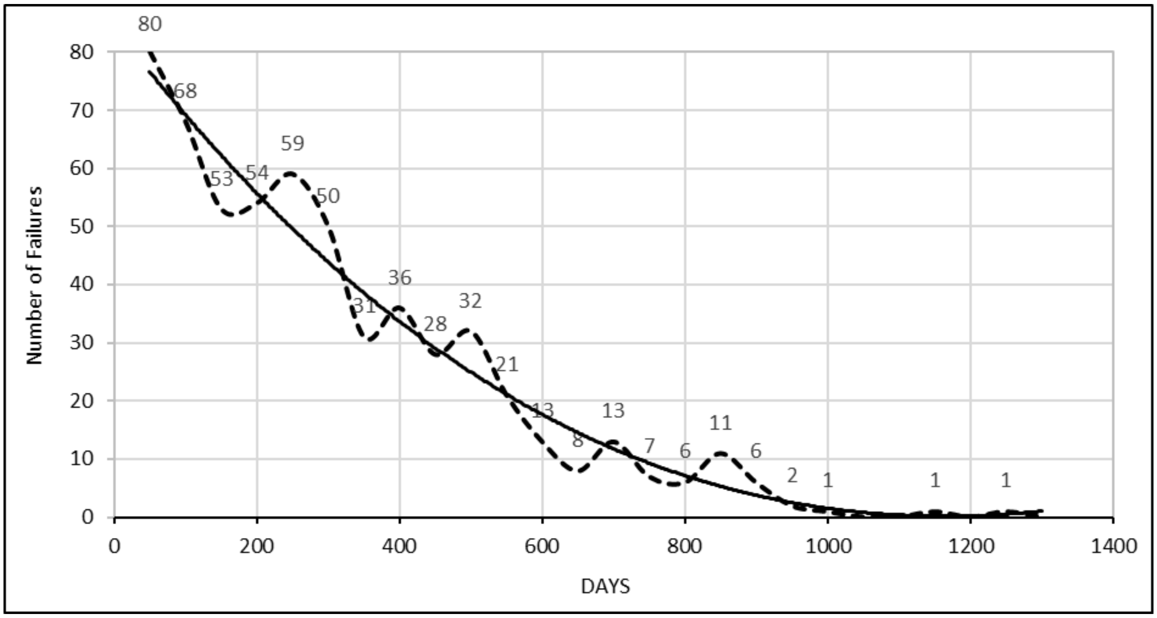

Figure 8 Bathtub Curve Distribution of Number of Failures vs. Days to Fail

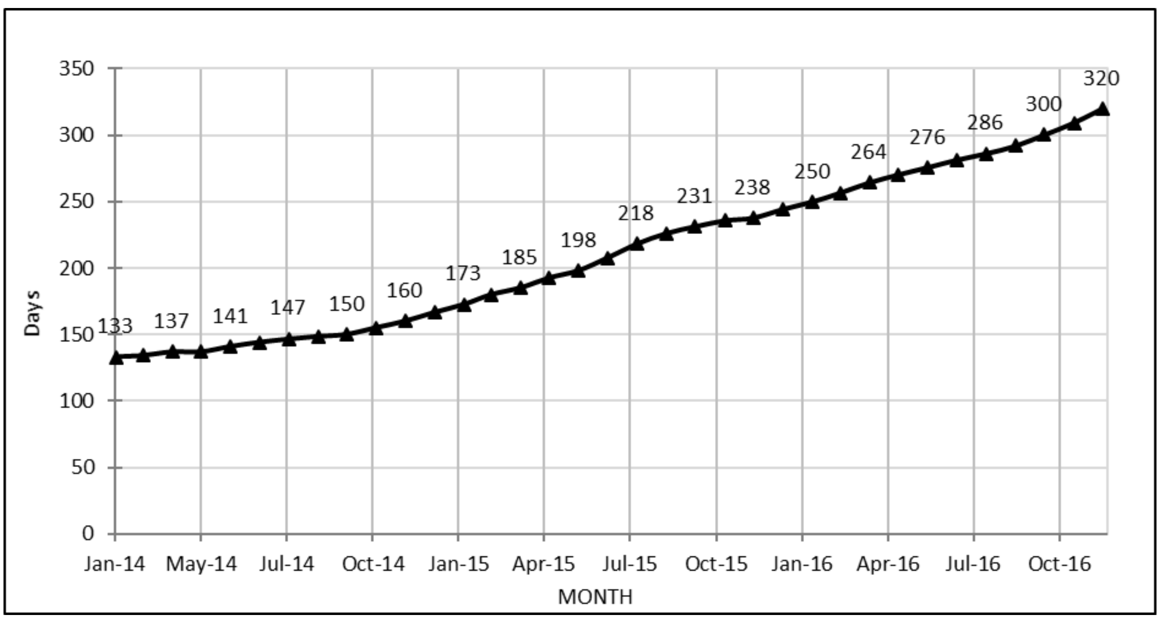

Figure 9 Current Average Run Days

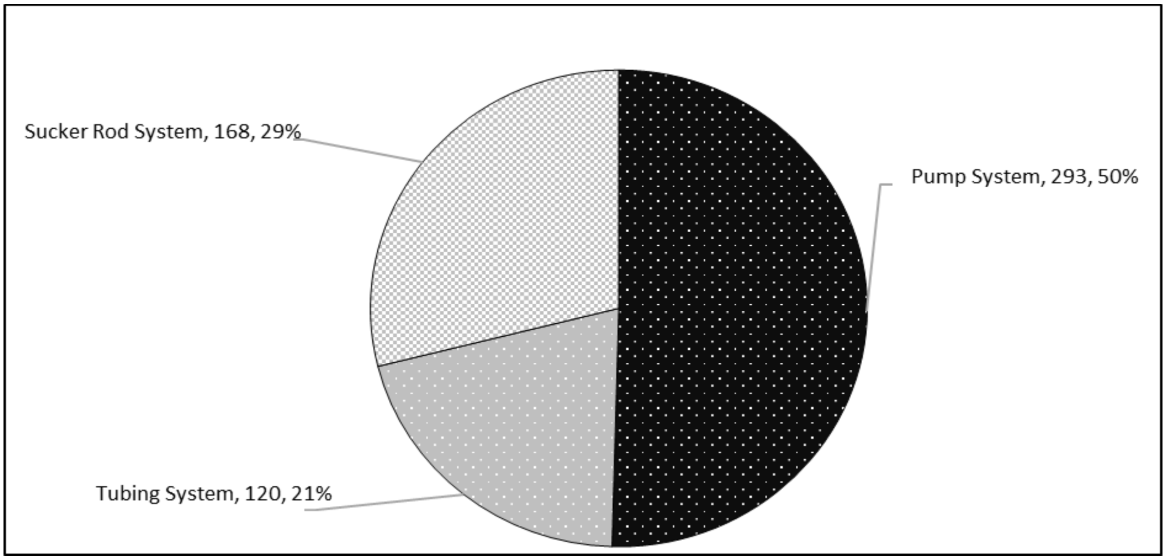

Figure 10 Pie Chart of All Sub-System Failures

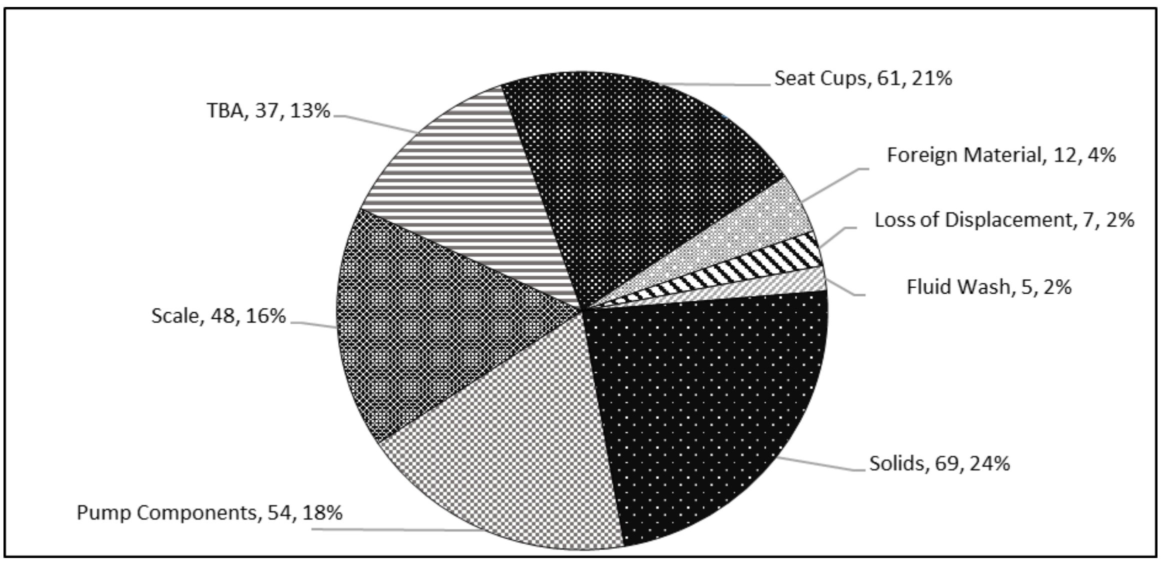

Figure 11 Pie Chart of Pump Sub-System Failures

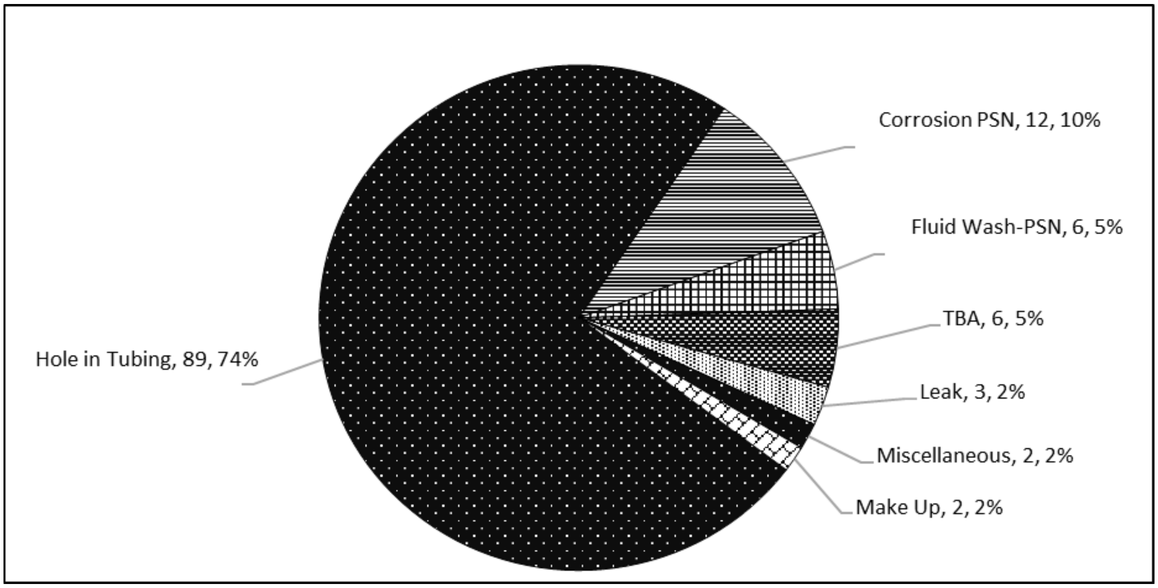

Figure 12 Pie Chart of Tubing Sub-System Failures

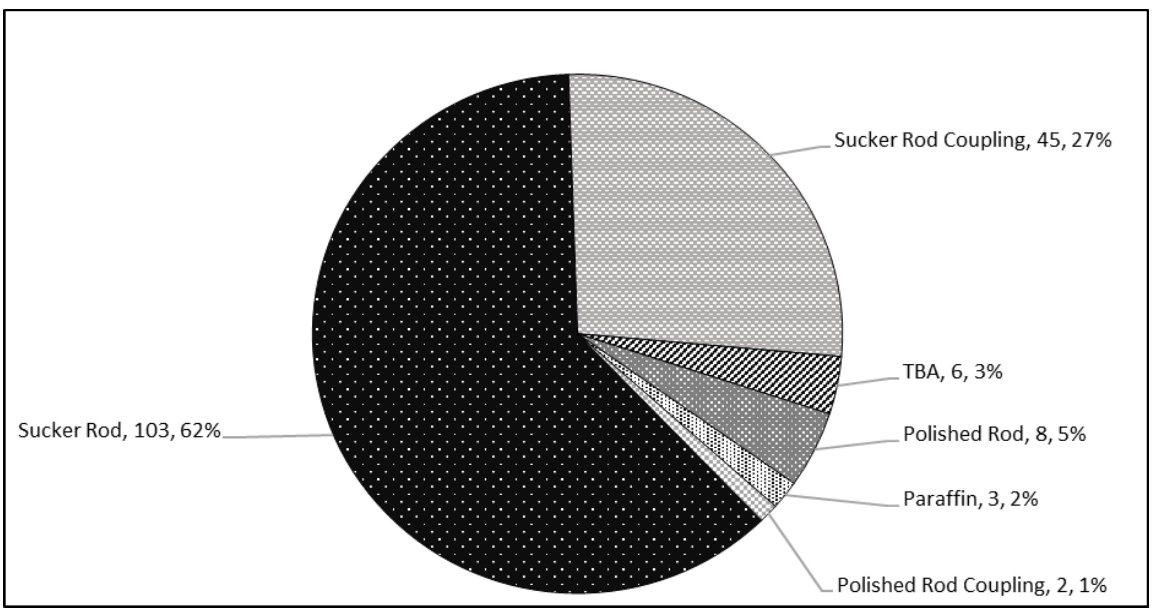

Figure 13 Pie Chart of Sucker Rod Sub-System Failures