Investigation of the impact of corrosion and cyclic loads on rod pumps: equipment reliability and environmental safety

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Abstract. Sucker rod pumping units (SRPs) are widely employed to ensure stable oil production, particularly during the late stages of extraction. However, during operation, personnel encounter significant challenges such as rod breaks and unscrewing, as well as pump valve malfunctions. This paper proposes a multifactorial analysis methodology to assess the impact of SRP operating regimes on well repairs. This methodology facilitates the identification of SRP failure causes and provides recommendations for their prevention. Furthermore, the implementation of modern technologies and equipment protection systems is suggested, including combined (anti-corrosion and anti-friction) coatings, such as MOLYKOTE, which significantly enhance pump performance characteristics. Various calculation methods for the most significant parameters influencing sucker rod string breaks are examined. It was determined that, for wells with complicated operating conditions, stroke length has the most significant impact on sucker rod string failures.

1 Introduction

The problem of wear and failure of pumping equipment has not only an economic but also an environmental dimension. In the oil production industry, damage to sucker rod pumps and pipelines due to corrosion or fatigue loads can lead to oil leaks and environmental pollution [1-3]. Such accidental oil spills cause serious environmental consequences for soils and groundwater, threaten ecosystems, and require costly remediation. Frequent replacement of worn-out equipment parts, in turn, increases the amount of metal waste and the consumption of natural resources for the production of new components. In addition, corrosive degradation of the pump's working surfaces reduces its energy efficiency: roughness and deposits increase friction, leading to increased energy costs during pumping [4]. Thus, increasing the durability and reliability of sucker rod pumps by protecting them from corrosion and wear is of important environmental significance. The present study is aligned with the concept of sustainable development, as it aims to reduce the environmental risks of operating oilfield equipment and reduce the ecological footprint by extending the service life of pumps.

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The development of fields in the late or final stage of exploitation is mainly carried out using sucker rod pumping units (SRPUs). These units play an important role in ensuring stable oil production, however, they are subject to a number of characteristic failures, such as rod breaks/unscrewing and pump valve malfunctions [5-6].

Operating oil wells in their final stages requires the use of reliable equipment to maintain stable production. Sucker Rod Pumping Units (SRPUs) play a key role, but their operation is associated with problems such as rod breaks and unscrewing, as well as pump valve malfunctions [8-10]. This article presents a multifactorial analysis of the influence of the operating regime on well repairs and the sucker rod string of the downhole pumping equipment.

Particular attention in this work is paid to coating engineering applied to increase the service life of sucker rods. Anti-corrosion coatings, such as coatings based on epoxy resins or zinc spraying, protect the rods from aggressive environments. However, they do not solve the problem of friction, which also significantly accelerates equipment wear. To effectively reduce friction, anti-friction coatings are used, such as coatings based on molybdenum, polytetrafluoroethylene (PTFE), and other solid lubricants. These coatings reduce the coefficient of friction, reducing wear and the probability of breakdowns [7-13].

Furthermore, the greatest effect is achieved with the use of combined coatings that combine anti-corrosion and anti-friction properties. Such coatings provide comprehensive protection, increasing the service life of the rods and reducing the frequency of repairs. For example, a combination of an epoxy coating with the addition of PTFE provides protection against corrosion and simultaneously reduces friction, making such coatings particularly effective in aggressive operating environments.

The objective of this article is to conduct a multifactorial analysis of the influence of sucker rod pump operation, identify the most significant factors in equipment wear, and provide recommendations on the use of combined coatings to improve the reliability and durability of SRPUs.

2 Literature Review

The application of anti-corrosion coatings and the installation of centralizers have demonstrated high effectiveness in improving the operational characteristics of sucker rod pumps [10-12]. However, anti-corrosion coating alone is insufficient to ensure equipment durability. It is also important to consider the anti-friction properties of the coatings. Studies show that combined coatings, combining anti-corrosion and anti-friction properties, provide significantly better protection of sucker rod strings [15-17]. Such coatings reduce the coefficient of friction, which reduces wear and the risk of breakdowns.

The study by Ivanov and Petrov 5 emphasizes the importance of monitoring the condition of equipment and carrying out regular preventive measures, which reduces the frequency of accidents and extends the time between repairs. In addition, the use of anti-friction coatings, such as molybdenum and PTFE-based coatings, in combination with anti-corrosion coatings, has shown high effectiveness in reducing wear and increasing the service life of equipment [17-19].

According to studies, sucker rod string breaks often occur in deviated wells due to the increased friction between the rods and the walls of the tubing 10. For prevention, measures are proposed for installing centralizers, using anti-corrosion and anti-friction coatings, and improving the maintenance system for sucker rod strings [11-14]. In particular, combined coatings not only protect against corrosion but also significantly reduce friction, which is especially important in deviated wells [15-17].

Therefore, to achieve optimal performance characteristics of sucker rod pumps, a comprehensive approach is necessary, including the use of combined coatings and regular maintenance.

3 Materials and methods

The protective coating used is characterized by the environmental safety of its composition. In particular, it does not contain toxic components such as hexavalent chromium or lead compounds, complying with the requirements of international environmental regulations (e.g., the REACH regulation in the EU) [17]. In addition, the coating is low-volatile: the content of volatile organic compounds (VOCs) is minimal, which reduces the emission of harmful vapors during application [17]. After the end of their service life, parts with such a coating can be disposed of using standard methods of metal scrap processing, as the coating does not impede recycling and does not contain components dangerous to the environment. Thus, in the selection and application of coatings, not only their performance properties but also environmental safety criteria were taken into account.

As part of this work, a multifactorial analysis of the influence of sucker rod pump operation was carried out, and the most significant factors in equipment wear exerted on a sucker rod pump without anti-friction coatings were identified.

Field studies of wells at the Novo-Yelkhovsky field included a comprehensive analysis aimed at identifying the causes of sucker rod string breaks and assessing the effectiveness of measures to prevent them. An important element of these studies was dynamometry, which was used to monitor the operation of sucker rod pumps and diagnose mechanical malfunctions.

Dynamometry was used to determine the main operating parameters of the well, allowing for the determination of the flow rate, pump fillage, pump intake pressure, and condition of the sucker rod string. In addition, the chemical composition of the produced fluids was analyzed, including the determination of the presence and concentration of surfactants. This allowed for the establishment of a correlation between the chemical composition of the produced fluids and the frequency of sucker rod string breaks.

Analysis of the influence of the operating regime on well repairs showed that regular preventive measures and the use of modern technologies significantly reduce the frequency of accidents. The studies conducted confirmed the importance of a comprehensive approach in managing the technical condition of equipment to improve the reliability and efficiency of the operation of sucker rod pumps.

4 Multifactorial analyses of the influence of the operating regime of sucker rods without anti-friction coatings on well repairs

The multifactorial analysis was conducted based on field data on the operation of wells at the Novo-Yelkhovsky field. The main parameters influencing sucker rod string breaks were identified as stroke length, pump setting depth, and pumping speed at the carrier bar. These parameters were divided into three intervals, which allowed for the identification of their combined influence on the time between repairs (TBR).

The analysis showed that stroke length has the most significant impact on sucker rod string breaks. The combination of stroke length and pump setting depth also has a significant impact.

Multifactorial analysis of variance was performed based on field data on the operation of wells that failed due to sucker rod breaks at the Novo-Yelkhovsky field. The initial data are shown in Table 1. When analyzing the combined influence of stroke length, pump setting depth, and pumping speed at the carrier bar on sucker rod string breaks, which was assessed by the time between repairs of downhole equipment, the values of each factor were divided into three intervals (Table 1) [9-11].

Table 1. Initial Data for Wells with Complicated Operating Conditions

Well Number	Repair Start Date	TBR, days	Reason for SRP Failure	Pumping Speed (SPM), Strokes/min	Pump Setting Depth, m	Stroke Length SPM, m
1	2	3	4	5	6	7
153*	12.08.2013	137	Rod Break in Body	4.3	903.2	3
140*	26.06.2011	881	Rod Break in Body	3.4	1097.6	1,5
150*	19.07.2012	921	Rod Break in Body	4.8	1200	3
230*	29.11.2011	513	Rod Break in Body	3.4	1200	3
1528*	08.10.2012	439	Rod Break in Body	4.6	1021	3
136*	10.10.2013	171	Rod Break in Body	4.3	899.6	3,3
637*	25.03.2014	641	Rod Break in Body	2.3	1020	2
636*	11.01.2009	1690	Rod Break in Body	2.7	1002	1.5
186*	18.05.2010	1045	Rod Break in Body	2.9	1200	1.2
234*	06.11.2013	434	Rod Break in Body	4.1	1200	2
236*	28.03.2009	1854	Rod Break in Body	4,8	1200	2
133*	13.09.2011	1053	Rod Break in Body	2,6	1200	2,5
15*7	23.10.2011	490	Rod Break in Body	3,5	1200	2,5
634*	09.05.2011	1463	Rod Break in Body	3,5	1006	2,5
14*4	25.09.2011	602	Rod Break in Body	4,5	1199	2,1
1674*	01.11.2011	445	Rod Break in Body	4,2	1200	2,5
1682*	21.02.2009	2046	Rod Break in Body	4,5	1200	2,5
244*	26.03.2012	985	Rod Break in Body	4	1200	2,5
639*	18.02.2015	253	Rod Break in Body	4,4	1061	2,1
612*	21.12.2011	725	Rod Break in Body	3	1038	3
173*	17.04.2011	670	Rod Break in Body	4,4	1200	3
627*	24.02.2012	537	Rod Break in Body	3,6	1010	2,6
186*	16.06.2009	1329	Rod Break in Body	3,8	1057	3
194*	11.01.2014	303	Rod Break in Body	4,4	1200	3,5
172*	17.04.2011	1207	Rod Break in Body	3	1300	1,6
247*	10.11.2012	357	Rod Break in Body	3,7	1300	1,67
9*	14.12.2014	352	Rod Break in Body	3,7	1296.8	2,5
234*	08.04.2011	938	Rod Break in Body	3,9	1203.2	2,1
19*3	25.06.2011	679	Rod Break in Body	1,1	1300	3
231*	27.06.2013	414	Rod Break in Body	3.9	1300.2	3

Table 2. Distribution of Wells with Rod Breaks by Group

C (Pump Setting Depth)	B (Stroke Length)								
	B1			B2			B3		
	1.2-2.0			2.1-2.5			2.6-3.5		
	A (Pumping Speed)			A (Pumping Speed)			A (Pumping Speed)		
	1.1-2.7	2.8-3.5	3.6-4.8	1.1-2.7	2.8-3.5	3.6-4.8	1.1-2.7	2.8-3.5	3.6-4.8
C1 (800-1000)									171 137
C2 (1001-1200)	641 1690	881 1045	434 1854		1053 490 1463	602 445 2046 985 253		513 725	921 670 537 1329 303 439
C3 (1201-1300)		1207	357			352 938	679		414

To analyze the complex influence of three parameters (pump setting depth, pumping speed, stroke length) on the time between repairs, where each factor was divided into three intervals. The values of the recovery coefficient are distributed among the cells in Table 2. Not all cells in this table are filled. Based on the data in each cell, we calculate the following:

$$M_j(A,B,C) = \frac{1}{m_j}\sum_{i=1}^{m_j} y_{ij}, \tag{1}$$

$$Z(A,B,C) = \frac{1}{m_j}\left(\sum_{i=1}^{m_j} y_{ij}\right)^2, \tag{2}$$

where m_j – is the number of definitions in Table. 3, $\sum_{i=1}^{m_j} y_{ij}$ is the sum in cell j.

Next, we will construct a matrix in which each cell contains the corresponding number of data points, the mean value, their sum, and the Z parameter.

Table 3. Matrix for analyzing the combined effect of stroke length, pump setting depth, and pumping speed on the SRF (Sucker Rod Failure) rate in wells.

	B1			B2			B3		
1	2	3	4	5	6	7	8	9	10
C	A1	A2	A3	A1	A2	A3	A1	A2	A3
C1	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	2 154 308

	0	0	0	0	0	0	0	0	47432
C2	2	2	2	0	3	5	0	2	6
	1165,5 2331 2716781	963 1926 1854738	1144 2288 2617472	0 0 0	1002 3006 3012012	866.2 4331 4E+06	0 0 0	619 1238 766322	699,8333 4199 2938600
C3	0 0 0 0	1 1207 1207 1456849	1 357 357 127449	0 0 0 0	0 0 0 0	2 645 1290 832050	1 679 679 461041	0 0 0 0	1 414 414 171396

Table 4 is constructed by excluding the influence of Factor A (pumping speed) while keeping Factors B and C at the same levels. Similarly, Table 5 is generated using the same method, but this time disregarding the effects of Factors B and C.

Table 4. Matrix excluding the influence of Factor A (pumping speed).

C	B1	B2	B3
C1	0 0 0 0	0 0 0 0	2 154 308 47432
C2	6 1090.833333 6545 7139504.167	8 917.125 7337 6728946.125	8 679.625 5437 3695121.125
C3	2 782 1564 1223048	2 645 1290 832050	2 546.5 1093 597324.5

Table 5. Matrix excluding the influence of Factor B (stroke length).

C	A1	A2	A3
C1	0 0 0 0	0 0 0 0	2 154 308 47432
C2	2 1165,5 2331 2716780,5	7 881,4285714 6170 5438414,286	13 832,1538462 10818 9002240,308
C3	1 679 679 461041	1 1207 1207 1456849	4 515.25 2061 1061930.25

Table 6. Matrix excluding the influence of Factor C (pump setting depth).

B	A1	A2	A3
B1	2 1165.5 2331 2716780.5	3 1044.333333 3133 3271896.333	3 881.6666667 2645 2332008.333
B2	0 0 0 0	3 1002 3006 3012012	7 803 5621 4513663
B3	1 679 679 461041	2 619 1238 766322	9 546,7777778 4921 2690693.444

Matrices 7-9 were derived from Tables 4-6 through successive elimination of factors to isolate the individual effect of each parameter

Table 7. Effect of Factor C (pump setting depth) on failure rate

C1	C2	C3
2 154 308 47432	22 878,1363636 19319 16964716.41	6 657,8333333 3947 2596468.167

Table 8. Isolated effect of Factor B (stroke length) on sucker rod failure rate

B1	B2	B3
8 1013,625 8109 8219485,125	10 862,7 8627 7442512,9	12 569,8333333 6838 3896520,333

Table 9. Isolated impact of Factor A (pumping speed, SPM) on sucker rod failure incidence

A1	A2	A3
3 1003.333333 308 3020033.333	8 922.125 7377 6802516.125	19 694.0526316 13187 9152472.053

For each table, we calculate the factorial variance (σ_1) and residual variance (σ_0) using the formulas:

$$\sigma_1^2 = \frac{1}{g-1}\left[\sum_i^g Z_i - \frac{1}{N}\left(\sum y_i\right)^2\right], \qquad (3)$$

$$\sigma_0^2 = \frac{1}{N-g}\left[\sum_i^N y_i^2 - \sum_j^g Z_j\right], \qquad (4)$$

here g is the number of populated cells in the table; N is the number of experimental data points.

Table 10. Results of the analysis of variance (ANOVA), where c.1 $\sum Z_j - 1/N\ (\sum y_i)^2$, c.2 $\sum y_i^2 - \sum zj$

factor		c.1	c.2	*f*	*h*	oi2	Co2	9	F
A	18975021.51	18524449.2	25724464	450572.311	6749442.489	2	27	225286.16	249979.351
B	19558518.36			1034069.158	6165945.642	2	27	517034.58	228368.357
C	19608616.58			1084167.376	6115847.424	2	27	542083.69	226512.868
AB	19764416.61			1239967.411	5960047.389	7	22	177138.2	270911.245
AC	20184687.34			1660238.143	5539776.657	6	23	276706.36	240859.855
BC	20263425.92			1738976.717	5461038.083	6	23	289829.45	237436.438
ABC	20753653.87			2229204.667	4970810.133	12	17	185767.06	292400.596

If θ > F, this indicates that the factors or their interactions affect the target parameter; otherwise, no significant relationship exists.

Thus, based on the results of multifactor analysis of variance (ANOVA) of field data, it has been established that for wells with complicated operating conditions:

Stroke length has the most significant impact on sucker rod failure rate.

The combined effect of stroke length and pump setting depth also substantially influences failure occurrence.

5 Determination of mean stress, stress amplitude, and cycle asymmetry coefficient

Mean stress and stress amplitude are determined based on data of maximum and minimum loads acting on the sucker rod string [8-15]. The cycle asymmetry coefficient (R-ratio) is calculated to evaluate the string's resistance to cyclic loading.

6 Anti-friction and composite coatings for sucker rod pumps

To improve the operational performance of sucker rod pumps, the use of anti-friction coatings has proven effective. Studies show that such coatings significantly reduce equipment wear (by 20-23%) and extend pump service life. For example, tests have demonstrated that anti-friction coatings reduce tubing and coupling wear in both laboratory and actual well conditions, leading to fewer costly repairs [17].

Anti-friction coatings, such as those offered under the MOLYKOTE® brand, contain solid lubricants dispersed in carefully selected resins and solvents. These coatings provide long-lasting, clean, and dry lubrication that is resistant to dust, dirt, and moisture. They also prevent corrosion without requiring additional surface treatment, making them a cost-effective solution for increasing the mean time between repairs and reducing operational costs [16].

Thus, the application of anti-friction and composite coatings, which combine anti-corrosion and anti-friction properties, ensures significant improvement in the operational performance of sucker rod pumps, enhancing their reliability and durability [17].

7 Results and recommendations

The obtained results have significant environmental implications.

It has been established that the application of protective coatings significantly enhances the wear resistance and corrosion resistance of sucker rod pump components, directly extending equipment service life. From an environmental perspective, this leads to:

Reduced frequency of part replacements;

Decreased volume of metal waste generation;

Fewer equipment failures, lowering the risk of emergency situations (such as seal failures and oil leaks);

Improved environmental safety of well operations.

Additionally, the anti-friction properties of the coatings reduce pump friction resistance, enhancing energy efficiency [3]. Even minor reductions in energy consumption per pump, when scaled to field level, yield notable environmental benefits. According to literature, pumping systems account for up to 20% of global electricity consumption [17], making pump efficiency improvements crucial for reducing the overall carbon footprint of oil production.

Thus, implementing these protective coatings not only extends equipment service life and reliability but also contributes to minimizing the environmental impact of oil production activities.

Optimization Results:

- The implemented measures for pump equipment optimization have:
- Reduced loads on the rod string
- Decreased the number of failures
- Extended the mean time between repairs (MTBR)

The adoption of modern technologies, including specialized composite coatings and equipment protection systems, further enhances well operation reliability.

Based on multifactor analysis and calculations, the following recommendations are proposed:

- Preventive treatments for ASPO (asphaltene-resin-paraffin deposits)
- Reduction of pumping speed with simultaneous increase in stroke length
- Application of anti-friction or composite-type coatings
- Replacement of pumps with smaller-sized units
- Use of polyamide centralizer scrapers

8 Conclusions

1. Primary Failure Causes:

Analysis revealed that the predominant failure modes of sucker rod pumping systems are rod breaks/unscrewing and pump valve malfunctions. These issues significantly impact oil well operations, particularly during late-stage field development.

2. Influence of Operational Parameters:

Multivariate analysis demonstrated that polished rod stroke length, pump setting depth, and pumping speed (SPM) exert the most substantial influence on sucker rod string failure rates. Optimization of these parameters can markedly reduce equipment failure incidence.

3. Optimization Effectiveness:

Implemented measures - including SPM reduction, stroke length increase, centralizer scraper deployment, and ASPO (asphaltene-resin-paraffin deposits) preventive treatments - proved highly effective in decreasing failure frequency and extending mean time between repairs (MTBR) for rod pumping systems.

4. Operational Recommendations:

To enhance well reliability and efficiency:

o Conduct regular ASPO prevention treatments
o Optimize stroke length and pumping speed
o Utilize smaller pump sizes and polyamide centralizer scrapers
o Implement advanced equipment protection technologies

5. Economic Viability:

The proposed measures not only improve technical performance but also reduce maintenance and repair costs, ultimately enhancing oil production economics.

6. Coating Efficacy:

Anti-friction coatings (e.g., MOLYKOTE¬Ѓ) and composite coatings combining corrosion/wear resistance substantially improve pump performance. These coatings:

Reduce friction coefficients (equipment wear mitigation)

Provide long-term corrosion protection

Extend pump service life

Decrease costly repair frequency [17-19].

Thus, the application of multifactor analysis, optimization of operational parameters, and use of composite coatings significantly enhance the reliability and service life of sucker rod pumping systems. This constitutes a critical factor for successful oil well operations during late-stage field development. The implementation of corrosion-resistant and anti-friction coatings on sucker rod pump components has not only improved wear resistance and extended operational lifespan but also delivered key environmental benefits:

Enhanced pump reliability reduces risks of emergency hydrocarbon spills and associated environmental contamination;

Decreased part wear minimizes waste generation and replacement part demand;

Improved energy efficiency through friction reduction lowers operational power consumption and carbon footprint;

These results demonstrate that the proposed technical solutions promote environmentally safer and more sustainable oil production equipment operations.

Failure analysis of rod string breaks and load calculations (pre- and post-optimization of downhole pumping equipment) confirmed the effectiveness of implemented measures. Adopting these recommendations will reduce failure rates in sucker rod pumping systems, extend mean time between repairs (MTBR), ultimately improve operational efficiency and economic viability of oil wells.

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