Application of the “Bow-Tie” method to assess the risk of incapacitation of the sucker rod pump

S Bochkarev¹, K Leyzgold², S Shilova³

¹ Professor, Department of Microprocessor Means of Automation, Perm National Research Polytechnic University, Perm, 29 Komsomolsky prospekt, 614990, Russia
² Senior lecturer, Department of Microprocessor Means of Automation, Perm National Research Polytechnic University, Perm, 29 Komsomolsky prospekt, 614990, Russia
³ Student of master program Conceptual design and energy efficiency engineering, Department of Microprocessor Means of Automation, Perm National Research Polytechnic University, Perm, 29 Komsomolsky prospekt, 614990, Russia

e-mail: bochkarev@msa.pstu.ru¹, leizgold_ka@pstu.ru²

Abstract. The article presents one of the methods for assessing the risk of electrical equipment accidents at an oil and gas production and transportation enterprise, in order to improve the smooth operation and efficiency of the use of electrical and technological equipment of oil fields. As an example, the operation of a rod pump is considered. The concept of a systematic approach for risk analysis at industrial enterprises is proposed.

1. Introduction
In recent years there is global trend of risk management usage in various areas of industry [1–3]. Typically the concept of "risk management" is associated with economic or safety risks, however, at industrial enterprises it is advisable to apply methods for calculating risks for equipment failure. Equipment failure can lead to downtime and, consequently, economic losses in the end, and also, in extreme cases, can lead to an accident that can cause adverse environmental consequences, since any industrial enterprise is a source of environmental pollution. In particular, It is particular important to develop risk management for enterprises in the resource-extracting and processing sectors.

Oil industry enterprises are among the potentially dangerous enterprises, for which industrial and environmental safety, labor protection and civil protection standards are obligatory.

According to the general rules of explosion protection for explosive and fire hazardous chemical, petrochemical and oil refining industries safety measures should take into account operational information and be based on the results of hazard analysis of technological processes and quantitative analysis of the accidents risk. The selection of the risk assessment method should be guided by considerations of expediency. The list of methods and the possibility of their application are described in state standards or internal regulatory documents of enterprises.

Despite this, operational information about the reliability of equipment can be represented as a non-uniform stream of events that has insufficient accuracy for objective and subjective reasons. In this regard, when solving practical issues on studying the risk of equipment failure and, consequently, durability, it is necessary to compare their reliability in different operating conditions, to take into account the influence of various factors and information obtained from various sources [4]. It should be noted that information about the time of operation of an object may be vague or incomplete.
Therefore, statistical information is important, the analysis of which will allow solving the problem of increasing the operational reliability of equipment.

In addition, when considering the urgent tasks of predicting resource characteristics in the operation of oil production equipment, one can single out:

- providing a forecast, the quality of which can be assessed by a specific criterion;
- flexible response to changes in estimates of resource characteristics associated with the specifics of the operation of oil and gas equipment;
- meeting the requirements that take into account the specifics of collecting, observing, accumulating and processing information flows in conditions of limited initial (undefined or incomplete) information.

Forecasting the resource characteristics of equipment allows you to reasonably make decisions about their physical, economic and design durability. The risk from unreasonably made decisions to terminate the operation of specific equipment or to unreasonably extend the assigned resource is associated with large economic losses.

2. The main tasks associated with the operation of sucker rod pumps

One of the simplest, but widely used methods of solving operational problems is the "bow-tie" method [5–7]. This method can be used as an auxiliary to others, or independently, when you need to assess the risk of a major or frequently repeated event, with the identification of possible causes and consequences. At the same time, it is important to identify barriers that prevent the causes of the event and measures to eliminate negative consequences.

As an example for analyzing the example, we will choose a rod pumping unit.

Oil extraction using rod pumps is the most common method of artificial lifting of oil, which is explained by their simplicity, efficiency and reliability. At least two-thirds of the existing production wells are operated by rod pumps.

The operation of rod well pumps is affected by various negative factors that complicate the operation of the pump and lead to irreparable consequences, if intervened untimely.

The reasons for the failure of sucker rod pumping units at 12 wells of oil fields located in the Perm region were analyzed. Based on the analysis, the main problems in the operation of sucker rod pumps are:

- Corrosion
- Water hammer
- Gas lock
- Asphalt-resinous paraffin deposits.

Corrosion attack, which is common in a large number of wells, destroys downhole equipment. The use of inhibitors is ineffective, so to contain corrosion, it is necessary to pay great attention to the materials the pumps are made of.

If the pump is not completely filled with liquid during the upward stroke of the plunger, a low-pressure gas cap is formed in the upper part of the chamber between the suction and discharge valves. The next time the plunger moves down, the exhaust valve remains closed until it collides with the liquid. This phenomenon is called hydraulic shock, which leads to a strong shock load on the entire pumping unit.

Water hammer is possible in the following cases:

- “rapid pumping” occurs when the fluid pressure in the electric center pump above the pump is less than the minimum pressure required to fill the pump, and the reservoir does not provide enough fluid. Availability is determined by stopping the pump and starting it after a few minutes. If the pump is filled well after starting, and a hydraulic shock occurs after a short period of time, this indicates rapid pumping.
- limited suction occurs where additional pressure is required to fill a pump operating at its designed capacity. In this case, the fluid pressure in the electric center pump above the pump is higher than normal. Availability is determined by stopping the pump and starting it after a few minutes. If a hydraulic shock occurs immediately after restarting the pump, this indicates limited reception.

Damaged equipment due to water hammer.
Wellhead equipment:
- fatigue failure of the rocking machine frame;
- fatigue failure of bearings and gear teeth;
- fatigue failure of the base of the rocking machine.

Downhole equipment:
- fatigue failure of the rod column;
- inside the pump outlet valve and the separator are exposed to the greatest damage. The valve stem and cylinder may also rupture and the suction valve may fail;
- hydraulic shock accelerates the wear of threaded pipe connections, which leads to fluid leakage. This process often leads to breakage of the Elevator column.

An effective way to solve this problem is to design the pump system and adjust the pump supply so that when the pump has an operating efficiency of 80, it lifts the required amount of liquid from the tank. A water hammer that occurs during the first 20 seconds of the plunger's downward stroke is less dangerous than a shock that occurs when the plunger is in the middle stage of the downward stroke, since in the latter case the plunger speed is the highest. When the pump capacity significantly exceeds the oil recovery of the well, it is necessary to change the pumping frequency, the length of the plunger stroke, or its diameter to get as close as possible to the design scheme.

Water hammer can be reduced by adjusting the pumping time to match the well's oil recovery using a percentage timer set in the motor controls.

It is formed when the pump chamber is filled with gas and the plunger does not compress the gas enough to open the exhaust valve when going down. Both valves remain closed for one or more complete pump plunger stroke cycles. An effective way to solve this problem is to reduce the distance between the discharge and suction valves at the moment when the plunger is in the lowest position, increasing the compression ratio of the gas in the pump, which reduces the likelihood of a gas plug.

Asphaltene sediments reduces the cross-sectional area between the rods and the lifting pipes, and also increases the hydraulic pressure on the plunger pair, which leads to fluid leakage through their gaps. Due to the intense deposition of paraffin, the rods will break or collapse in the lower part closer to the plunger when axial loads occur, the load on one of the rocking machine balancers also increases, which disturbs the balance, and the fill factor decreases. When lifting the rods during repairs, the plunger or plug-in pump cuts off the paraffin from the walls of the tubing and forms a solid paraffin plug, which pushes oil out of the pipes and pollutes the area near the well. Sometimes, due to the sealing of paraffin, it becomes impossible to lift the column of rods. This problem is solved with the help of special scrapers that are attached to the rod and without interrupting the working process, clean the pump and compressor pipe column from asphalt-resinous paraffin deposits.

All of the above factors directly affect the operation of the rod pump, the smooth operation of which directly affects the entire process of oil production. Based on the above factors, the bow tie diagram in case of failure of the sucker rod pump will have the form shown in Fig. 1.
Figure 1. “Bow-Tie” diagram for the case of incapacitation of sucker rod pump

On the left of the diagram, factors influencing the operation of sucker rod pumps and barriers to prevent their influence are indicated. On the right are the factors that depend on the operation of the sucker rod pump, as well as the barriers to reduce the impact on these factors of failure in the sucker rod pump.

Applying this approach, it is necessary to supplement the existing equipment operation technology with the possibility of increasing the efficiency of estimation and forecasting of durability indicators [8]. Using the methodology of A. Feigenbaum, it is possible to organize an action plan for the implementation of work to ensure and control the quality of the required performance indicators of the equipment. As an example, we can use the technological triangle model, which interconnected system and technical, structure and methods of application of practical actions.

The main elements of the technological triangle model will allow solving the following problems of predicting the resource availability of equipment:

1. Methods, approaches for assessing and predicting resource capacity.
2. Technique of using control and measuring and testing equipment to obtain initial data and develop measures to identify insufficient reliability margins, susceptibility to the risk of failure, for example, using the “bow tie” method.
3. Mathematical modeling to predict the future behavior of equipment, depending on the influence of internal and external factors on the change in indicators of its resource capacity.
4. Measurement of monitored parameters for evaluating and predicting the resource capacity of equipment.

In the oil industry, unplanned equipment shutdowns are unacceptable. All negative factors affect both individual parts of the oil production system and the operation of the entire system as a whole. All this can lead to a decrease in the quality of oil, which in turn leads to large economic losses for the enterprise.

The concept of risk is based on the knowledge of two independent arguments:

1. The amount of damage associated with the consequences of accidents, failures, catastrophes.
2. The probability of occurrence of the fact of accidents, failures, catastrophes.

Numerically, it can be estimated as the product of these factors, and this value will have the dimension of damage. For its geometric interpretation, you can apply Farmer’s diagrams, which are lines of equal level on the plane

\[ F = Z \cdot P , \] (1)
where $Z$ is the coordinate axis along which the amount of damage is plotted, the $P$ axis is used to indicate the probability of the occurrence of the fact of failure.

Farmer’s diagrams are strictly deterministic, although they are based on a stochastic nature associated with failures, accidents, etc.

The value of the risk of failure of a sucker rod pump can be determined based on the assumption that let $P_i$ be the probability of a pump failure as a result of the $i$-th factor. The probability of the sucker rod pump being in trouble-free condition will be equal to $(1 - P)$. Taking into account the influence of all factors acting on the sucker rod pump, the probability of finding it in a working condition, provided they are incompatible, is equal to the product of all expressions $(1 - P)$. Then the probability of an accident under the influence of at least one factor is equal to:

$$P = 1 - \prod_{i \in M} (1 - P_i) \quad (2)$$

The value of the risk for the case of failure of the sucker rod pump, if the accident occurred under the influence of factor $i$, is equal to:

$$F_i = Z_i \cdot P_i \quad (3)$$

In the case when the losses do not depend on the cause of the occurrence, but are associated only with the consequences of the object's failure, the magnitude of the risk is determined by the following formula (1).

If we assume that hypothesis $H_0$ characterizes a sucker rod pump in which no significant structural or parametric changes have occurred, then it is in a working state, and hypothesis $H_1$ characterizes a sucking rod pump in which significant changes have occurred, then it is in an inoperative state, then $F(H_0 \mid H_0)$ is the expected risk if the hypothesis $H_0$ is valid, if the hypothesis $H_0$ is accepted, and $F_a$ are the risks associated with the maintenance of the sucker rod pump, $F_p$ are the risks associated with the failure of the sucker rod pump.

For the hypothesis under consideration, the loss matrix can be represented as the sum of losses:

$$Z = Z_a + Z_y \quad (4)$$

where $Z_a$ – matrix of losses associated with the maintenance of sucker rod pumping units, $Z_y$ – matrix of losses associated with damage from failure of sucker rod pumping units.

For research, it is allowed to apply a relative risk assessment $Z_{rel}$:

$$Z_{rel} = Z_{act} / Z_{max} \quad (5)$$

where $Z_{act}$ – actual losses from failure of sucker rod pumping units; $Z_{max}$ – maximum losses from failure of sucker rod pumping units.

Consequently the formula for assessing the risk of the hypothesis under consideration ($H_0 \mid H_0$) will have the form:

$$F_a = Z_a \left(1 - P(H_0 \mid H_0)\right);$$
$$F_p = Z_y \left(1 - P(H_0)\right)$$

Since $P(H_0)$ can be considered an almost constant value, having, for example, a value of 0.95, then $1 - P(H_0) = 0.05$, that is, the risks associated with the failure of sucker rod pumps, in this case, are a constant small value.

Considering other hypotheses and constructing a Farmer diagram (Fig. 2), where $P_{pr}$ is the probability of risks associated with the development of an oil production facility and $P_r$ is the area of risks associated with the transition of sucker rod pumping units during operation to the area of limiting states, then the diagram can be distinguished:

1. The area of the reduced risk level, where:
   A – a priori risk zone;
   B – zone of risk arising from the operation of sucker rod pumps;
Figure 2. Farmer’s diagram for the case of incapacitation of sucker rod pump

C – the risk zone associated with the transition of the state of the sucker rod pump to the area of limiting states;

2. Area of increased risk level, where:
   AE – the zone of risks associated with the presence of errors in the development of the oil production facility [9];
   BE – the zone of risks associated with malfunction during the operation of sucker-rod pumps;
   CE is a zone of risks associated with errors in assessing and predicting the resource characteristics of sucker rod pumps [10].

Based on probabilistic modeling scenarios, it is possible to obtain data for numerical risk assessments when monitoring the resource characteristics of sucker-rod pumps.

3. Conclusion

It should be said that risk assessment using the method described above can be the first step in assessing risks at enterprises and forming control actions (Fig. 3). Based on the bow tie diagram, conclusions can be drawn about which factors should be paid attention to first. The second stage will be a quantitative calculation of risks, thus, specific time and probabilistic values of the occurrence of risks will be determined. Using the mathematical apparatus, it is possible to assess the influencing factors for each individual field and their ranking depending on the composition of the oil and external factors. The last stage is the planning of management measures to prevent the occurrence of risks, for example, the timely replacement of worn parts of mechanisms during scheduled repairs.

Figure 3. Consistency in the application of the risk management system
Undoubtedly, for the normal functioning of the risk management system, the presence of a staff of employees with competencies in this area is required. It is most convenient when the risk assessment is carried out by specialists related to the systems of integrated logistics support for the life cycle of an oil production site.

The proposed systematic approach will allow the most complete assessment of the risks of adverse situations and increase the efficiency of the enterprise.

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