Failure prediction of reservoir pressure maintenance system at the Prirazlomnoye Arctic Offshore field

I M Kurchatov
Gubkin Russian State University of Oil and Gas (National Research University)

Contact E-mail: ivan.kurchatov2015@gmail.com

Abstract. Failures of reservoir pressure maintenance system at offshore facilities cause production losses and a significant increase in OPEX. Predicting failures of a water injection pump or its parts can highly improve the overall performance by promptly adjusting operating parameters to prevent failure occurrence or by scheduling maintenance to reduce unplanned repairs and to minimize downtime. This is particularly relevant for Arctic offshore projects, characterized by considerable logistical challenges and substantial environmental safety risks. The paper presents a data-analytic approach for failure prediction for the water injection pump operated at the ice-resistant GBS Prirazlomnaya. The study used pump failure history and field sensor data to predict the technical condition and identify a failed component in advance. An ARIMA model implemented in the R software environment was developed for the analysis. The results demonstrate that the approach works appropriately based on the generalized risk assessment and feedback from subject matter experts.

1. Introduction

The Arctic region as a whole and its shelf zone in particular are characterised by the presence of significant hydrocarbon reserves [1, 2]. Due to the numerous risks associated primarily with the fragile ecosystem and the harsh environmental conditions of the Arctic, owners of oil and gas assets must conduct business in such a way as to reduce harmful effects on the environment, local communities, and personnel, while ensuring economic viability [3]. Efficient process control, competent planning of equipment maintenance, and rational use of materials and resources appear to be some of the key elements in the sustainable performance of offshore production facilities.

It is well-known that failure of oil and gas equipment or its parts can lead to severe environmental, economic, and reputational consequences. On the Arctic shelf, failures at offshore hydrocarbon facilities are extremely critical. Therefore, prompt diagnostics of equipment technical condition and early detection of its failure seem to be important research areas for the industry, since they contribute to increasing the efficiency and reliability of process operation and reducing associated risks. On the other hand, the implementation of artificial intelligence systems based on processing large amounts of data is one of the most promising ways to improve the operational decision-making process.

This study aims to apply modern data-driven approaches to the operational decision making process in order to predict water injection pump failures and, thus, to improve the overall performance of the Prirazlomnaya platform reservoir pressure maintenance system. Prompt adjustment of operating parameters to prevent failures and well-timed maintenance scheduling to reduce unplanned repairs and minimise downtime are the key measures that can be taken as a result of adequate forecasting.
The ice-resistant offshore stationary platform Prirazlomnaya, the first and so far the only ongoing field development project on the Arctic continental shelf of Russia, was selected for the study. The field is located in the Pechora Sea and is operated by Gazprom Neft Shelf LLC. Recoverable reserves are estimated at the level of more than 70 million tons of oil and the expected life of the reservoir is 25 years.

This platform was designed to simultaneously perform the following operations: drilling, production, processing, storage and offloading. Process system of the platform provides all stages of in-field oil processing. The products obtained meet all the requirements for commercial oil. The platform was designed for continuous operation throughout the year with a regular supply of necessary materials every 15-60 days [4].

Since the very beginning of commercial development of the field in 2013, the challenges related to reservoir pressure maintenance have become essential from an operational point of view. In this regard, the water injection pump plays a critical role in ensuring the efficient use of subsurface resources and achieving target economic indicators.

2. Description of the water treatment and water injection processes

The study focuses on the Prirazlomnaya field reservoir pressure maintenance system in general and the water injection pump in particular as one of the most critical components of operational efficiency. The oil-containing water treatment (OCWT) system was also analysed within the study, as it provides the required level of injected fluid quality and therefore strongly affects pump performance.

The OCWT system is designed to remove oil-containing components from injected water. There are three types of feed water on the offshore platform Prirazlomnaya: ballast water displaced by oil from storage tanks (the principle of "wet" oil storage), produced water, and seawater. The system includes the following equipment:

- ballast water heaters designed to heat the liquid to the optimum temperature in order to increase the efficiency of treatment and deaeration, as well as to maintain the necessary injection temperature;
- primary treatment separators that remove suspended solids, free oil, and paraffin;
- induced gas flotation units for further treatment;
- fine media filters for final treatment;
- vacuum deaerator that extracts oxygen from water before injection.

The design capacity of the system is 1,072 m³/h. The treatment process removes up to 98% of mechanical impurities larger than 10 microns, and also provides a concentration of oil products from 30 to 5 mg/l and residual oxygen up to 10 ppm [5].

As oil is produced and pumped into storage tanks, the displaced ballast water is fed to the shell-and-tube heat exchangers, where it is heated to 30 °C. After that, it enters the primary separation units (three plate pack separators), where mechanical impurities greater than 80 microns are removed and the content of the oil products is reduced to 100 mg/l. Further, the fluid, mixing with produced water from the surge tank, enters the secondary separation equipment, which is two hydraulic induced gas flotators with 50% capacity per vessel [5].

The filtration unit, consisting of four nut shell filters, is the third stage of the oil-containing water treatment. These facilities remove irreducible oil and suspended solids to the required content specified above. Then the water is fed to the deaerator, where the incoming flow is deaerated and the oxygen content is reduced to 10 ppm. After passing this stage, the flow enters the booster and main high-pressure pumps for further injection [5].

The reservoir pressure maintenance (RPM) system serves to inject water into wells to maintain reservoir pressure and simultaneously dispose of seawater, ballast, and produced water. The main design parameters are listed in Table 1.
**Table 1.** Reservoir pressure maintenance system design performance.

| Parameter                                                                 | Value | Unit     |
|---------------------------------------------------------------------------|-------|----------|
| Annual water injection                                                   | 9,570 | KT/y     |
| Estimated injection pressure (upstream of the choke)                     | 245.57| bar      |
| Estimated injection pressure (downstream of the choke)                   | 210   | bar      |
| Water injection temperature                                              | 43…44| °C       |
| Number of water injection wells                                          | 12    |          |

The RPM system includes the following equipment:
- four primary and four intermediate booster pumps,
- four water injection pumps, one of which is analyzed in the study,
- water injection system cooler,
- water injection manifold and process pipelines.

Primary booster pumps work in tandem with intermediate ones and are designed to feed water to injection pumps, which supply it to the water injection manifold and further to the wellheads. The cooler is provided to maintain the temperature conditions of the flow [6]. Injection pumps operate in the following modes: one is running and one is on standby.

**Table 2.** Water injection pump specifications.

| Parameter                        | Value   | Unit     |
|----------------------------------|---------|----------|
| Pump flow rate                   | 734     | m³/h     |
| Pump delta pressure              | 162     | bar      |
| Design temperature              | -10…65 | °C       |
| Design pumping pressure          | 322     | bar      |
| Power consumption                | 4,002   | kW       |

The water injection pump selected for the study is a multistage double-casing pump equipped with an edge connector of the outer casing, an internal eight stages sectional cartridge, and a horizontal motor. Its operating speed is 2,980 rpm.

![Figure 1. General layout of the water injection pump.](image-url)
The pump has radial sleeve bearings on each side and a tilted pad bearing with a gimbal-mounted thrust bearing segment at the non-drive end. It is important to note that when operating this type of pump, strict requirements are imposed on the content of mechanical impurities in the pumped medium [7].

3. Analysis of factors affecting pump performance

Although there may be many factors that contribute to the unhealthy performance of the water injection pump, such as the viscosity of the working fluid, the specific density and gravity of the working fluid, cavitation or the vapor pressure of the working fluid [8], this article discusses those that have the greatest impact on its operating parameters based on accumulated experience.

1) Mechanical impurities content in the pumped fluid is one of the main complicating factors that obstruct long-term normal operation of centrifugal pumps. The main damage to the equipment is caused by mechanical impurities in two ways: by clogging the working bodies of the pumps and by abrasion of their free and wearing surfaces [9].

2) The pumped fluid temperature has a direct impact on the design characteristics of the pump. For instance, high-temperature pumping may require special seals, gasketing, and mounting designs.

3) Due to the fact that the Prirazlomnaya offshore platform is located in high latitudes, the ambient temperature, especially during the winter season, affects the performance of the pump a lot.

4. Methods and procedures

In fact, from a mathematical point of view, the problem of predicting the pump instrumentation readings can be described as a problem of forecasting time series. According to the definition [10], any variate value measured at constant time intervals, represent a time series:

\[ y_1, \ldots, y_T, \ldots, y_t \in \mathbb{R}. \]  

At the Prirazlomnove field, the equipment sensors data are sent to the control room with a constant frequency of 1 second, therefore, they can be presented in the form of time series. Otherwise, if the interval between measurements was random, we would be dealing with random processes.

Solving the problem of forecasting a time series means to find a function \( f_T \), which depends on all available information at the time of forecasting (\( T \)), i.e. it accepts all values from \( y_1 \) to \( y_T \) as input, and can also take an additional parameter \( H \) (prediction horizon) showing how much ahead it is necessary to build a forecast [11]:

\[ y_{T+h} \approx f_T(y_T, \ldots, y_1, h) \equiv \hat{y}_{T+h|T}, \quad h \in \{1, 2, \ldots, H\} \]  

There are a variety of time series forecasting models such as Naïve, Seasonal decomposition, Exponential smoothing, ARIMA, GARCH, Dynamic linear models, TBATS, Prophet, LSTM, etc. [12]. In order to promptly predict possible failure of the water injection pump, an ARIMA regression model was selected. The name is an acronym for AutoRegressive Integrated Moving Average.

ARIMA processes are a class of stochastic processes that allow getting accurate forecasts, relying only on information from the history of the predicted series of the pump instrumentation data. These models belong to the class of linear models and can describe well both stationary and non-stationary time series [13].

The full model can be written as [10]:

\[ y'_t = \alpha + \varphi_1 y'_{t-1} + \cdots + \varphi_p y'_{t-p} + \theta_1 \varepsilon_{t-1} + \cdots + \theta_q \varepsilon_{t-q} + \varepsilon_t, \]  

where: \( y'_t \) is the differenced series, \( \varphi_p y'_{t-p} \) is lagged values of \( y_t \), \( \theta_q \varepsilon_{t-q} \) is lagged errors, and \( \varepsilon_t \) is Gaussian white noise. This is so called an ARIMA (\( p, d, q \)) model, where:

- \( p \) stands for an order of the autoregressive part (AR) and shows the number of lags necessary to fit an AR process to the stationary series;
− $d$ is a degree of first differencing involved ($I$) and represents the number of differenced series changed between consecutive observations towards the original series;
− $q$ is an order of the moving average part (MA), which indicates the number of error terms in a series to be regressed to reduce the differenced AR process residual to white noise [10].

In tasks like ours, selecting appropriate $p$, $d$, $q$ values can be complicated. However, the `auto.arima` function available in the R software environment does it automatically.

5. Data processing, model description, and results

As part of the study, an analysis of seven-year data on pump operation was carried out. Failure rates and patterns have become the focal point of analysis. It was found that the main reason for unexpected shutdowns of the water injection pump was an increase in liquid temperature in the balancing chamber-to-suction return line above the operating setpoint of 70 °C. These incidents account for more than 60% of all pump shutdowns. Therefore, for this equipment, it is the balancing line temperature ($T_b$) that is the most critical parameter from the operational reliability point of view.

For the purposes of the study, the 14-day pre-failure dataset of the temperature sensor installed in the pump balancing line was downloaded from the real-time database. Before modeling in the R software, preliminary data processing was carried out by smoothing various data outliers and gaps in the sample, which have a direct impact on the quality of further forecast, as well as eliminating data formats that are unacceptable for modeling. The pre-processed data sample is shown in Figure 2.

![Figure 2. Change of the balancing line temperature before the failure.](image)

The considered time series is stationary if its properties do not depend on the time at which the series is observed. Empirical observation of the time series structure allows us to preliminarily draw a conclusion about its stationarity, as it does not have a trend or seasonality that affects the time series value at different times [10]. It looks like white noise with no predictable patterns in the long-term.

The accumulated operating experience of the water injection pump shows that the main reason for the abrupt change in temperature $T_b$ is the regular process operations carried out in the system of the oil-containing water treatment. One of such operations is the routine backwash of fine filters, which periodically clog up during normal operation. When performing this procedure, a partial carry-over of the filter filler and oil products occurs, which has a direct effect on reducing the flow rate and increasing the temperature of the liquid in the pump balancing line. Regular peaks in a trend indicate the
performance of such periodic operations. Measurement of the content of oil products and suspended solids (\(OC\)) in oil-containing water is carried out by laboratory control once every 24 hours.

At the same time, as noted in section 2, the temperature of the balancing line and therefore the pump performance is influenced by the temperature of the water itself (\(T_w\)), which is controlled by the heat exchange equipment, and the ambient temperature (\(T_a\)). Both parameters are monitored by instrumentation and have also been downloaded from the real-time database.

Thus, the controlled parameter is affected by the external factors (\(OC, T_w, T_a\)), which, of course, should be considered when predicting the pump failures. These external factors are likely to have different weighting factors in relation to \(T_b\). One way to test this is to geometrically interpret their correlation with each other.

![Figure 3. Correlation between balancing line temperature and external factors.](image)

Correlation is the statistical relationship between two or more random variables [14]. As can be seen in Figure 3, the data are somehow correlated, but to a greater extent this can be traced in the relationship between \(T_b\) and \(OC\) – the higher the content of oil products in the pumped fluid, the higher the temperature of the balancing line.

Due to the presence of external (exogenous) factors in the problem of forecasting time series, the algorithm in R was built on the basis of the ARIMA extension, the ARIMAX model. This model represents a composition of the output time series into the following parts: the autoregressive (AR) part, the integrated (I) component, the moving average (MA) part and the part that belongs to exogenous inputs (X) [15].

Applying the `auto.arima` function in the R software, which is available in the “forecast” package, we can find the values of the parameters of the ARIMA model (p, d, q) for the time series \(T_{bi}\) = ARIMA (3, 1, 1). Models for exogenous parameters are selected in the same way. To verify the adequacy of
the predictive models, the data for 3 hours preceding the onset of failure were removed from the initial sample and the rest of the dataset was used as a training sample (short-term forecasting).

Applying the `arima` function in R and substituting the values of exogenous factors (`xreg`) into it, we obtain the predicted values of the controlled critical parameter $T_b$ (Figure 4b). As can be seen from the figure, the predicted values are close to the observed values, which indicates the correct functioning of the fitted model (the prediction interval is marked in gray in Figure 4b).

![Figure 4. Observed (a) and forecasted (b) values of the pump balancing line temperature.](image)

6. Conclusions

As part of the study, the analysis of the operation of the reservoir pressure maintenance and oil-containing water treatment systems of the Prirazlomnaya offshore platform was carried out, as well as the data-analytic approach for predicting failures of the water injection pump was implemented. It was found that the main reason for unscheduled shutdowns of this equipment is the high temperature in the balancing chamber-to-suction return line, which is influenced by a number of external factors, such as the content of oil products and suspended solids in the fluid, pumped medium temperature, and ambient temperature. The data correlation analysis, carried out as part of the study, showed that the oil content has the greatest effect on the increase in liquid temperature in the balancing line.

The ARIMAX model that takes into account the influence of exogenous factors was developed for the analysis and implemented in the R software environment. Using the 14-day balancing line temperature data as a training set allowed us to build a three-hour forecast such that the actual three-hour operation trend lies within the 95% prediction interval, which indicates a reasonably accurate short-term forecast. This prediction horizon provides some flexibility in terms of promptly adjusting pump operating parameters and making operational decisions on scheduling maintenance.

The developed approach has proved to be efficient based on the feedback from the experts involved in the operation of the pressure maintenance system at the Prirazlomnoye field. This study serves as a starting point for the development of an integrated multilevel system aimed at preventing the occurrence and development of failures when operating oilfield equipment, bringing the parameters back to healthy operation, or minimizing damage in the event of possible failures.
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