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Integration of expert and data-driven workflows to manage reservoir and well life cycle in Arctic conditions using innovative SICLO methodology

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Abstract. SICLO (Source of data and information; Input data; Calculation/Analytic; Logic Analysis; Output/Value Delivery) methodology is an innovative concept for smart diagnostic, reservoir/well performance optimization and estimation of remaining reserves based on the integration of Petroleum Data Management System (PDMS) and expert rules. Implementation of SICLO methodology provides the best strategy on how to produce remaining reserves most profitably. PDMS is the foundation of SICLO methodology and provides structured and verified information that follows the Well Life Cycle. Within PDMS, data are organized and structured according to clearly defined principles and rules and filtered by different levels of quality control. Structured data allows integration of production and reservoir information with real-time data to achieve the maximum level of diagnosis of system operation performance according to reservoir and well potentials and system constraints. The built-in workflows and architecture of the whole process are automated and make the task accomplishment faster. SICLO methodology integrates expert-driven knowledge and pattern recognition tools improved by data-driven, artificial intelligence, neural network, and fuzzy logic technologies to deliver adaptive solutions for identifying locations of remaining reserves, optimizing oil and gas production, and minimizing associated operational costs.

1. Introduction

In recent years, most of the technical developments in the oil and gas industry have come from the achievements made in areas of unconventional resources. The demand for energy increases day-by-day, and thereby, the unconventional resources are of paramount importance to ensure the future energy supply. According to the estimates, the largest unconventional oil and gas reserves could be placed in one of the most unexplored and delicate world's regions, the Arctic. The Arctic presents massive potential for exploration companies, but at the same time, complex environmental and climatic



conditions make the environment risky due to any unsafe operations and challenges with the implementation of existing technologies.

According to the information presented by Gubkin Russian State University of Oil and Gas [1], apart from the significant gas reserves, the noteworthy reserves in oil-bearing formations are existing. Generally, the unconventional resources have a sharp decrease in reservoir natural energy, which results in the necessity of the application of artificial lift methods.

In this paper, the SICLO methodology describes the approach of real-time Electrical Submersible Pumps (ESP) monitoring that recognizes threats in the well operation. The approach significantly enhances the pump run life and reduces workover costs. Moreover, the utilization of real-time data generated from ESP systems reduces human impact and workforce requirements in challenging Arctic conditions.

Over the past year, significant improvements in the ESP system design have enhanced the reliability of the systems in offshore locations. By refining the electrical and mechanical subsystem designs, the ESP system has reached the necessary reliability in the North Sea region, which represents the most similar conditions to those on the Arctic [2].

Although many methods are reliable for exploitation in harsh conditions and remote locations, the ESP systems hold features that could be beneficial for newly discovered reservoir formations, and they are summarized as follows:

- Downhole ESP sensors and gauges provide significant reservoir real-time information, which is necessary to reduce uncertainty at the beginning of the exploration stage (transient pressure analyses).
- ESP systems can be sized to pump all produced fluids to the processing facility miles away.
- The system is applicable in large deviations angles and diverse wellbore trajectory designs.
- The Electrical Submersible Pumps are tools that can be remotely controlled (frequency, choke size, and position), which could reduce OPEX costs, and a permanent crew would not be necessary on-site.

The presented methodology aims to interpret the pattern trends generated by downhole and surface measuring devices in order to provide a reliable model for embedding into the controller of the ESP surface control unit, which could operate in arctic conditions. Interpretation of the trends is not possible without knowing other multidisciplinary system information.

2. Levels of downhole and surface data availability

Since the ESP are becoming one of the fastest-growing artificial lift systems in the world, their application varies from low to extremely high production wells. A variety of fluid production ranges directly implicate the data acquisition systems, and data availability differs from field to field. The ESP diagnosis and monitoring solution must be flexible enough to cover different scenarios of real-time data availability. In this section, we clarify the subsurface and surface data channels, of which recordings are used as symptoms in ESP monitoring event detection.

In terms of downhole equipment, the ESP system includes downhole sensors block, motor, motor seal, gas separator, pump intake, pump, motor lead extension, cable, and check valves. Depending on the type of ESP downhole sensors, different downhole parameters are monitored (Pump Intake Pressure, Pump Discharge Pressure, Pump Intake Temperature, Motor Winding Temperature, Motor Oil Temperature, and Two or Three Axial Vibrations).

Despite general data availability from downhole gauges, the surface readings can significantly vary based on the used controllers, Variable Speed Drives (VSD), or Switchboards (SWBT). The high-level automated ESP system represents the monitoring of following surface parameters (Surface Flow Rate, Surface Tubing Pressure, Surface Casing Pressure, Current Leakage, Frequency, Cable Resistivity, and Phase Voltage) through Supervisory Control and Data Acquisition System (SCADA).

In the global picture, the ESP system diagnostic depends on a particular group of monitoring parameters, and not all of them are indispensable. Expert rules define logic relationships and how these parameters relate.

3. Methodology

The significant improvements in the data-gathering technology and the application of smart well technologies have led to the acquisition of countless amounts of data (Big Data) that require interpretation of raw data, to obtain valuable information. In recent years, the oil and gas industry has been moving forward, developing advanced diagnostics and optimization tools based on artificial intelligence techniques that are data-driven. Most autonomous workflows are built on a foundation of statistical analysis and the implementation of artificial intelligence techniques on real-time data with or without the integration of reservoir/well models. However, this raises the most crucial question: “How to predict critical dynamical conditions when the well requires long term actions (workover, chemical application, etc.) and how to maintain optimal well conditions without active downhole monitoring (without sensors)?”. The started research work on the development of Automatic Adaptive Algorithm (A³) is an innovative concept of smart diagnostic and well performance optimization based on the integration between (PDMS) and expert rules to achieve the maximum level of intelligent control of system operation according to reservoir and well performance (Figure 1).

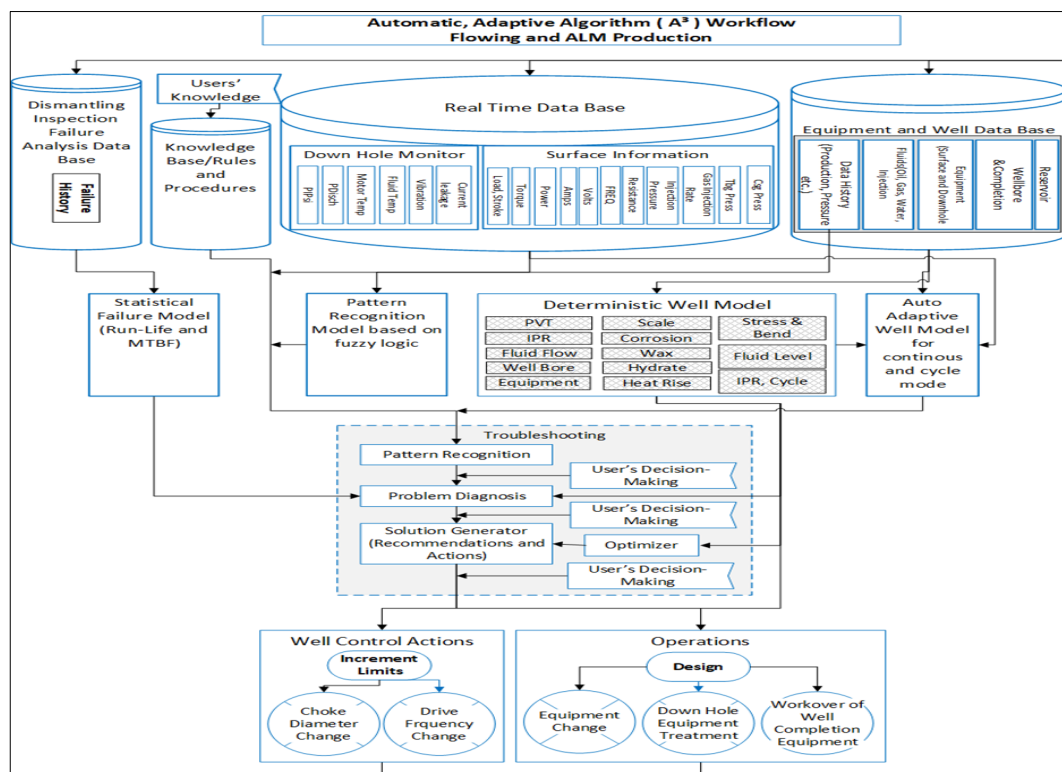


Figure 1. Structure of A³ workflow and principal components of a diagnosis and control modules.

In this paper, the downhole sensor data recorded during operation of ESP and technical details of subsurface and surface equipment data stored in the i-ESP database are used to diagnose the problems of ESP operation (abrasive/gassy/viscous fluids, high-temperature wells, scale, intermittent/continuous operation, etc.).

In general, the concept of SICLO methodology is adapted to manage the operation of ESP, integrate and automate data collection from multiple sources, process them, and provide needed parameters for monitoring, automatic control, problem diagnosis, and recommendations for optimizing ESP operation as shown in Figure 2.

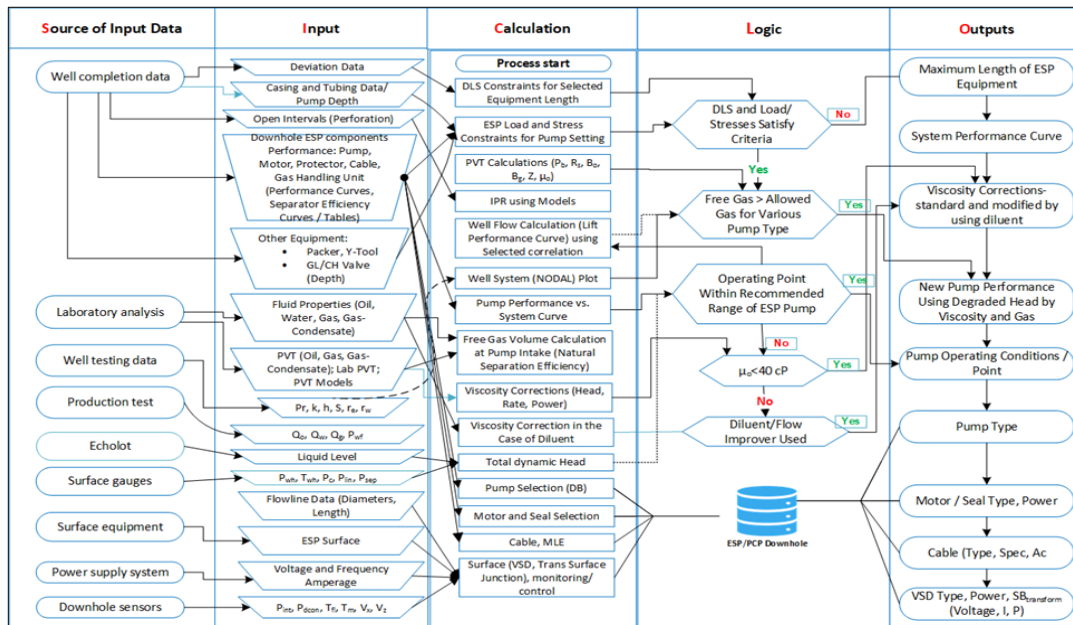


Figure 2. ESP SICLO Workflow of Design Optimization and Problem Diagnosis.

4. Data pre-processing

Sometimes downhole and surface sensors transfer the readings through the SCADA system directly to the real-time monitoring center, but sometimes the data ingestion requires additional software to read data stored at the surface controlling units and convert them to readable files formats. The A³ algorithm requires data available in real-time to recommend preventive actions. However, data captured in real-time can contain a vast of missing data or data out of the range that could lead to misinterpretation. Therefore, this section describes two pre-processing data procedures for different applications.

4.1. Data cleansing and filtering

Firstly, the objective of data pre-processing is to create an algorithm that can eliminate erroneous data, replace missing values, and format entire data set into valuable information that will be interpreted. In the end, the algorithm works autonomously as a cleansing and filtering tool to eliminate meaningless data.

4.2. Well test data preparation

Secondly, the interpretation of data captured during the well test requires a different preprocessing procedure. Real-time monitoring of the pressure at the ESP pump intake allows acquiring a significant amount of data. These large amounts of intake pressure data are converted to the pressure at the referent depth (mid-perforation or top/bottom of the pay zone) and are used for various types of interpretation (buildup/drawdown test, inflow performance of well, virtual pressure and flow metering, etc.). The essential problems of interpretation an acquired data set from the ESP downhole sensors are conversion of the intake pressure to the static/bottom hole flowing pressure using appropriate models (two-phase correlations) and elimination of noise data as in the most situations the derivative of the recorded and converted pressure data cannot be interpreted, or interpretation is wrong. The modified workflow (Figure 3) has been developed to decrease of unavoidable noise caused by the applied derivative procedure of the measured pressure data.

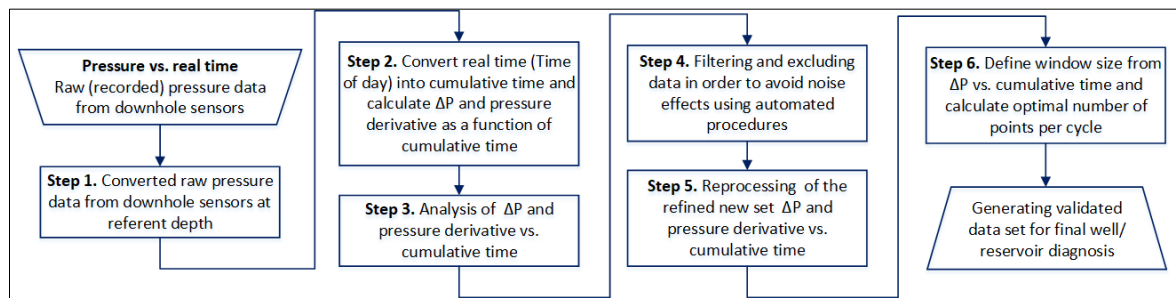


Figure 3. Application of automatic workflow for the data acquisition and processing

5. Trend (Pattern) analysis

The ESP operation parameters are dynamic, and they are changing over time. By tracking down-hole real-time operation parameters, deviation from established trends can be recognized, and actions to improve production and extend the pump life can be taken [3]. The trend analysis tool is designed to extract trend data from the time series for each of the operating parameters. As a result, all individual trends are taken simultaneously into consideration and used to understand specific ESP performance problems.

In the previous section, it was described how the pre-processed data set is created. Furthermore, the ability of the autonomous algorithm to calculate the slope highly depends on the considered period and values included in the dataset. Figure 4 depicts the process steps of the general workflow that is used to generate trends.

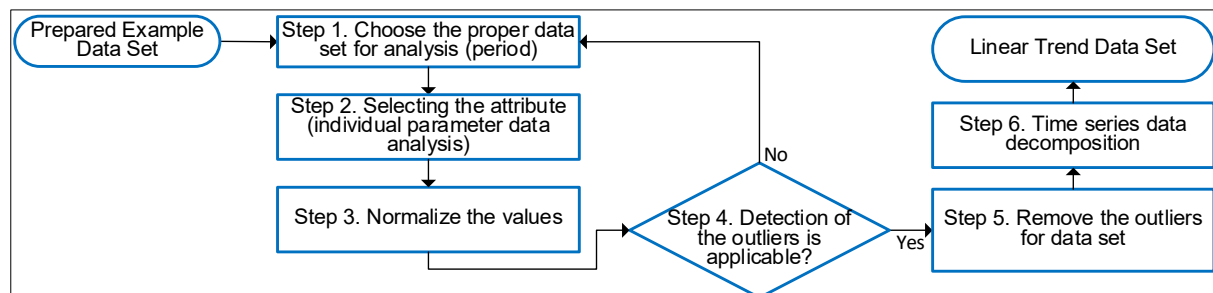


Figure 4. Process steps in the general trend extraction workflow.

Step 1. Recognizing the proper period for trend analysis. Before running the trend analysis, the period must be chosen based on the rules and valuable information from the other ESP databases described in the Methodology section. For instance, removing the period of initial production is obligatory since, at the beginning of the ESP operation, before reaching the nominal operating parameters (commissioning, the well clean up). The mechanism to remove initial well production out of the trend analysis is relying on the fluid production measurements from Production History Database. The turning point is the stable fluid flow rate. Moreover, the intermittent ESP production operation leads to significant fluctuations in operation parameters and requires a specific workflow for trend interpretation, which would be the subject of further research. Also, Run Life & Failure Database provides information on pump operation mode (continuous/intermittent).

Step 2. Data channels prioritization. Different downhole sensor units and different surface units (switchboards/VSDs) can generate a large number of data channels. Some of them are directly measured, while others represent calculated values with different levels of importance. In a variety of data channels, the expert rules are set to choose to most specific parameters that can be indicators of specific ESP problems and prioritize them based on the importance levels.

Nevertheless, the downhole sensors sometimes could have a lack of essential ESP operation data channels, such as missing the pump discharge pressure measurement. In that case, the expert rules are prioritizing data channels based on data channels availability.

Step 3. Data set normalization. Normalization methods represent compromises in achieving particular ends. Normalization involves taking values that span one range and representing them in another range [4].

Although each operating parameter is taken into account separately, the final output of the analysis is a comparison of different trends. The ESP real-time data considerably vary in range, and the comparison requires the scaling of each data set. This scaling is achieved by range value normalization. For example, the values of the voltage are between 0 and 400 volts while at the same time, the current is between 0 and 25 amps. After normalization, both data channels are in the same range, between 0 and 1.

Step 4. Outlier detection. In statistics, an outlier is a data point that differs significantly from other observations. ESP real-time data set can contain a significant number of outliers. The outlier may be due to the variability of measurement or maybe the real measured record, which is not valid for general consideration of data set and decomposition of the trend line. The trips during the pump run life are frequent in ESP operation, but the values measured do not determine the dynamic physical conditions in the well and shall be excluded from further interpretations. For example, electricity power shut-down can create a rapid increase in pump intake pressure or a sharp decrease in values of current. That kind of measurement does not represent the valid historical data for trend analysis.

Step 5. Trend decomposition - Once the time series is thoroughly prepared, and outliers, as well as missing values, do not have any influence, the time-series signal decomposes into a new trend data set. The decomposition algorithm linearly smooths data, and the newly created data set represents values of the linear trend line for each attribute. When the slope data set is generated for each attribute (current, pump intake pressure, etc.), the trend is calculated. Furthermore, the slope value is of essential importance because it provides the final input parameter for pattern recognition.

6. Expert rules

The expert Rules are created based on domain knowledge and significant experience in work with ESP systems. Each event/problem in the operation of the ESP system is defined in the Matrix of Descriptive Trend Explanations (MoDTE) by a qualitative description of the behavior of the essential working parameters in time. The SICLO methodology is based on continuous improvement, and since the failures are typically repetitive, the root cause analysis is always conducted, and MoDTE is updated. MoDTE consists of ESP operation parameters and their descriptive explanations. Each characterization has its slope range, which is characteristic for operation region or field. Figure 5 represents the example of MoDTE for the case of plugged pump intake.

Matrix of Descriptive Trend Explanations: Plugged Pump Intake	Increases Slowly	Increases Gradually	Increases rapidly	Increases Abnormally	Constantly	Decreases Slowly	Decreases Gradually	Decreases Rapidly	Decreases Abnormally
Surface Flow Rate						✓	✓	✓	✓
Current						✓	✓		
Pump Intake Pressure		✓	✓						
Motor Temperature	✓	✓							
Frequency	✓				✓	✓			
Load						✓	✓		
Pump Discharge Pressure							✓	✓	

Figure 5. Matrix of Descriptive Trend Explanations (MoDTE) - Case of the plugged pump intake.

7. Event Prediction

After converting large scale real-time data sets into trends, the value of tangent defines the trend slope, and basically, it is an indicator of the existence of potential problems. Furthermore, to better understand

the trends, the algorithm automatically converts the value of tangent into a descriptive qualitative explanation (linguistic terms). The proactive troubleshooting and recommendation of corrective actions during ESP run life are achieved by matching the descriptive quality explanations with MoDTE. The trend descriptions, along with the expert rules and built-in SICLO methodology, can significantly increase the pump run life and reduce human efforts in the optimization process. Figure 6 depicts the workflow for event prediction.

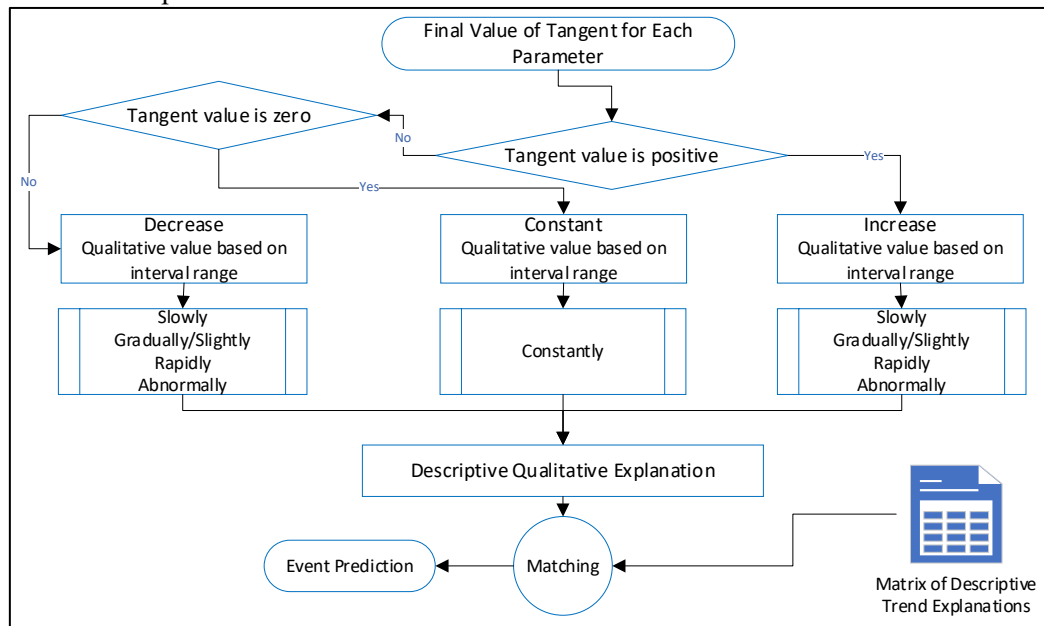


Figure 6. SICLO Methodology workflow for event prediction.

8. Field Case 1

During the well history, a significant number of the well service operations were recorded, mainly due to the well integrity issues (damaged production casing). The installation of 5" production liner resolved the casing integrity problem.

In the last ten years, on the well was performed 14 workover operations. Moreover, after the hydraulic fracturing and production intensification, the rapid increase in water cut has happened along with unexpected problems with Gravel Pack completions due to low inflow, complicated fishing of GP equipment, and low efficiency of gravel placement.

An additional factor that has affected the number of workover operations was a significant reduction in reservoir pressure. The drop-in reservoir pressure led to low inflow performance and high WOC. After the last workover operation, the sample was taken from the pump as well as from the reservoir water. The laboratory analyses proved the presence of sulfur-reducing bacteria in formation water and Ferrous carbonate (FeCO_3) appearance on the pump.

Therefore, the SICLO approach has been applied to analyze the real-time dataset from the well. The following static information has been gathered in databases and interpreted:

- a) Run Life & Failure Database, which allows the user to see the whole workover history and briefly insert new workover descriptions when necessary. All workover data are structured based on the Well Service Operation (WSO) classification. From workover and completion history, as shown in Figure 7, it is evident that the well had frequent and repetitive problems with artificial lift methods in the past.

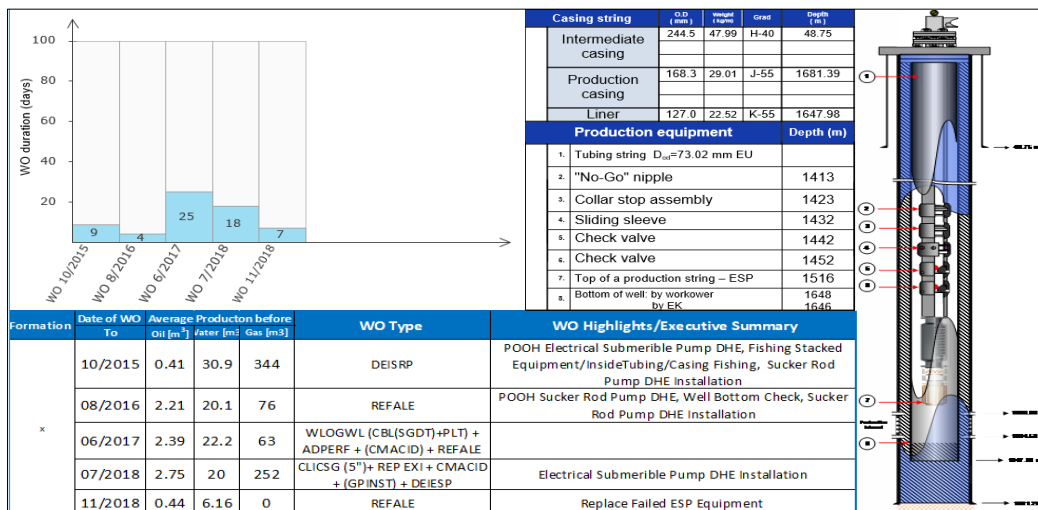


Figure 7. Workover history and well schematic data - Run Life & Failure Database.

- b) Figure 8 (a) provides a complete production history of the example well. However, the period of interest is the period from the last workover job, and Figure 8 (b) shows daily fluid production since the last workover job. The well had gradually decreased in daily production.

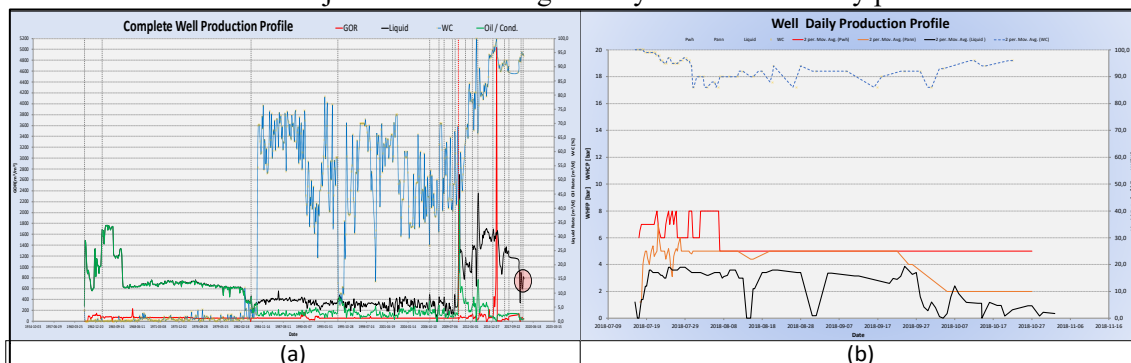


Figure 8 Well production history, a – complete; b – daily production history before failure

- c) Run Life & Failure Database with Teardown Results – this database provides information about the failure root cause analysis. The database is created based on the industry standards for dismantling inspection and failure analysis: API RP 11S1 and ISO 14224. The teardown test showed that the pump failure occurred due to the precipitation of inorganic scale on stages and probably on the pump intake (Figure 9).

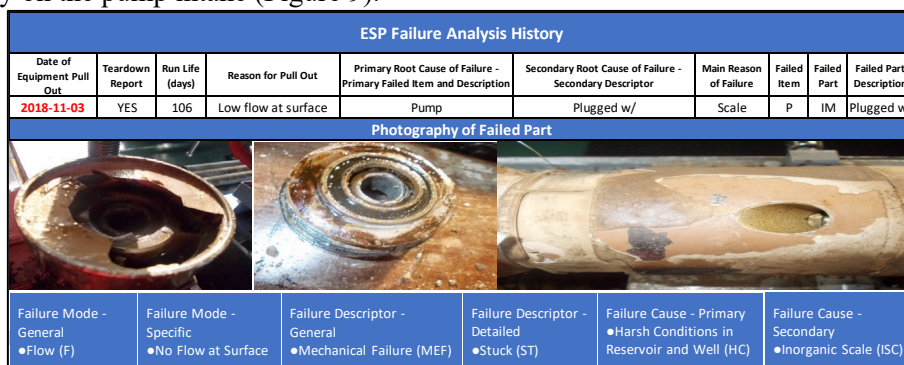


Figure 9. ESP failure analysis.

The recorded ESP parameters at the surface and downhole were used to analyze the real-time ESP data set and to compare the results with failure analysis. Figure 10 (a) gives the insight into raw ESP

data set, where it is difficult to spot any pattern and interpret data, respectively. Initially, raw data were cleansed and filtered. As a result, Figure 10 (b) shows the continuous dataset without discrete values, and it is more apparent that after a period of relatively stable working conditions, the real-time parameters had a sudden change in performance before the ESP system went into intermittent operation.

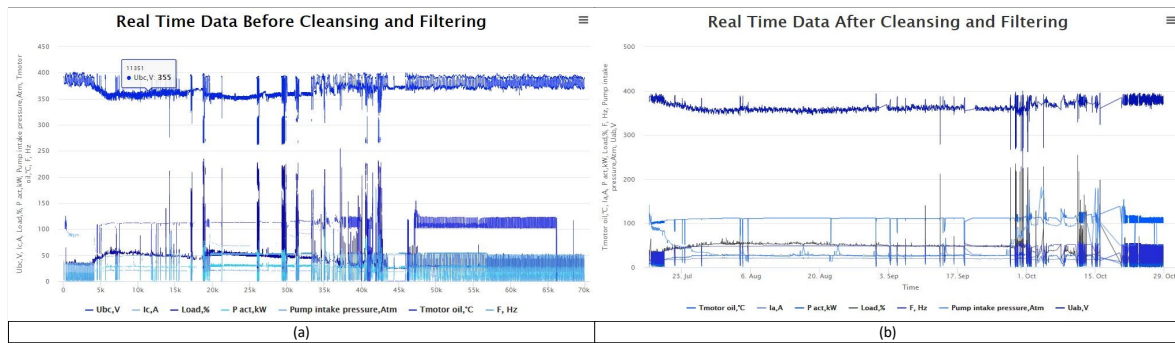


Figure 10. ESP real-time data set; a – raw data; b – cleansed and filtered data.

The trend analysis tool was applied to extract the trend line for each attribute. Figure 11 (a) depicts the first step of the general trend extraction workflow for a single attribute (motor temperature). The application of workflow for recognizing the proper period for trend analysis excluded two periods from EPS operation history, initial production, and intermittent operation period.

The general trend analysis workflow considers data scaling to obtain all data sets in the same ranges. Figure 11 (b) shows the results of range normalization for the value of the current.

The fourth and fifth steps are examining outliers. Based on input parameters, the algorithm automatically detects the outliers, and with the filtering process, it removes them. In this way, the trips and any other well interventions do not influence the trend line. Figure 11 (c) refers to outlier detection in this example. For the values of current, light blue color points out outliers that are removed from further analysis.

As a result of trend analysis, the linear trends are calculated for each attribute, and they are visualized in Figure 11 (d).



Figure 11. Trend extraction procedure; a – raw data; b – cleansed and filtered data; c – outlier detection; d – linear trends

Figure 12 contains the normalized trend slopes and qualitative descriptions of each of the ESP operating parameters. The corresponding slope descriptions are matched with the MoDTE database. The plugged pump intake is the best match for the real-time ESP operation parameters.

Time Series / Trend Description	Increases Slowly	Increases Gradually/ Slightly	Increases Rapidly	Increases Abnormally	Constantly	Decreases Slowly	Decreases Gradually/ Slightly	Decreases Rapidly	Decreases Abnormally	Slope Shape/Rate	
										Color	Value
Surface Flow Rate							✓				-0.000001022000
Current						✓					-0.000000456127
Frequency	✓										0.000002769031
Pump Intake Pressure			✓								0.000020374735
Load						✓					-0.000001163219
Motor Oil Temperature	✓										0.000001138371

Figure 12. Qualitative and Quantitative Pattern Description.

The decrease in surface flow rate was the clear indicator that something is happening with the pump performance, and if the pump performance curve is checked, it is clear that at the given frequency pump is underperforming.

The real-time performance analysis indicates that the pump had a problem with plugged pump intake before the pump went into the intermittent production regime and before the pump failed. Also, it was known from well production history that well had a problem with scale and paraffin.

The recommendation, in this case, before the failure, would be to take appropriate corrective actions such as chemical treatment since the pump had a restricted flow rate.

9. Field Case 2

The objective of field case two is to show well test data preparation and interpretation. The pressure at the ESP pump intake in the well was recorded in real-time over 460 hours. After a production period of 110 hours, well was shut-in for build-up for 350 hours. Preparation of the recorded pressure data, their filtering and validating for further analyzing in pressure transient analysis or production analysis are conducted using the A³ algorithm throughout the following steps:

Step 1. Raw sensors pressure data in real-time at a depth of ESP installation are converted into pressure at referent depth (in this case at the middle of the perforated interval) using modified Beggs & Brill model for multiphase flow through the wellbore of any geometry (vertical, slant and horizontal), illustrated in Figure 13-a.

Step 2. In order to get a build-up type curve (basics for well test interpretation), a real-time date-time format (time of day) is converted into cumulative time upon which, dp and pressure derivative is calculated (Figure 13-b).

Step 3. Analysis of the shape of the build-up pressure derivative using the total number of recorded data points, it is evident, that enormous noise data hides the valid reservoir signal.

Step 4. The automated procedure for filtering and excluding redundant data is applied to avoid noise effects noticed in the previous step. The use of this procedure significantly reduces the data amount.

Step 5. Reprocessing of the refined data set gives the shape of the build-up pressure derivative (Figure 13-c) from which the reservoir model could be recognized, but it is still necessary to further improve upon the data set.

Step 6. Defining window size and calculating the optimal number of points per cycle will provide a clear and unambiguous reservoir signal with the minor influence of noise effects (Figure 13-d).

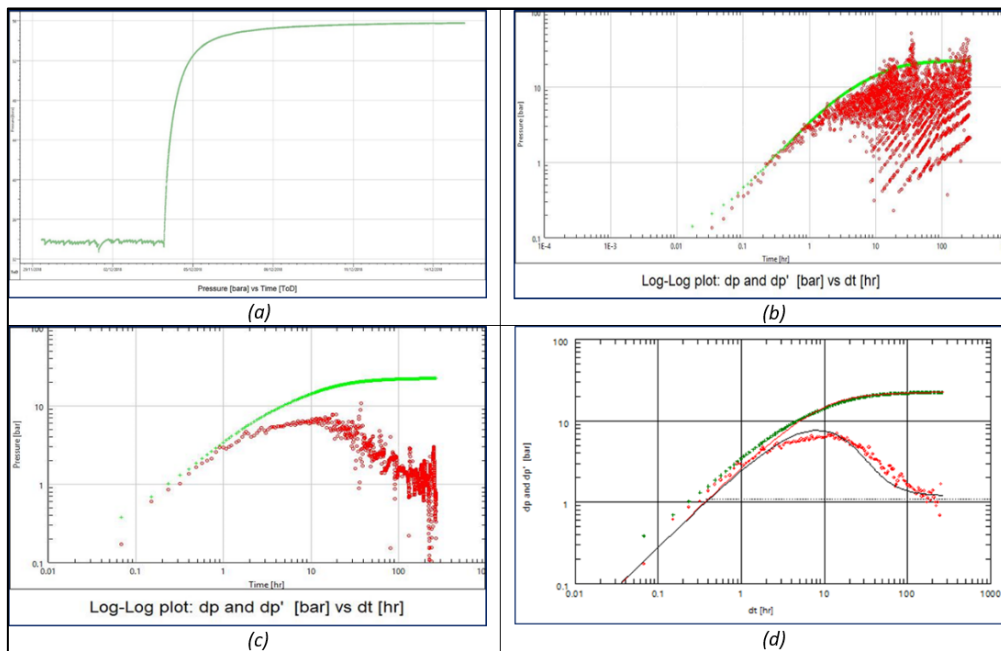


Figure 13. Well test data preparation; a - Converted raw pressure data from the downhole ESP sensor at referent depth in real-time; b - Calculated dp and pressure derivative as a function of cumulative time in log-log scale; c - Refined new set of dp and pressure derivative as a function of cumulative time in log-log scale; d - Generated valid data set and well test interpretation

Based on generated valid data using the A³ algorithm, it is significantly easier to interpret well test data to get parameters necessary in further well/reservoir analysis (reservoir pressure, permeability, skin, distance to barriers if they exist), as shown in Figure 14.

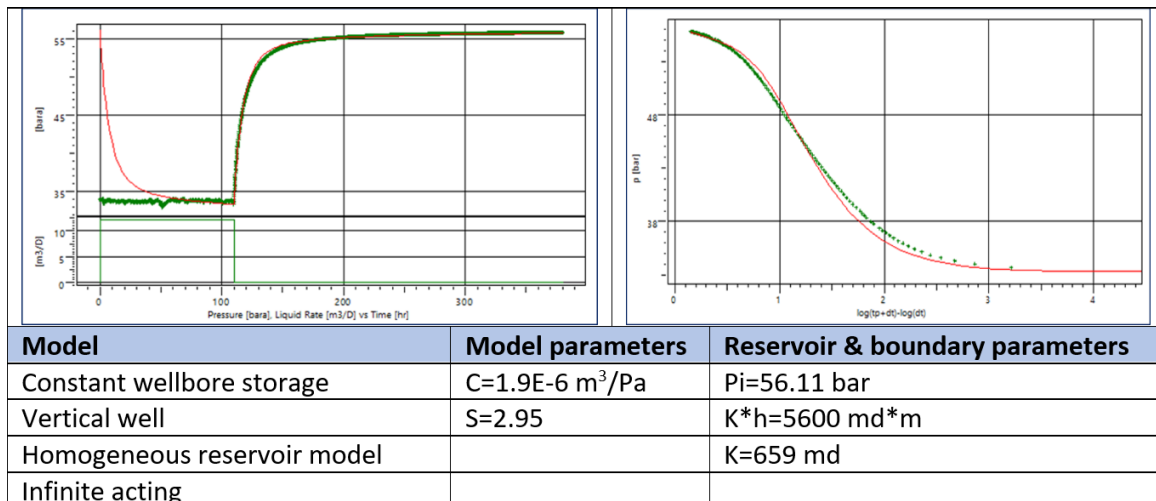


Figure 14. Results of well test interpretation.

10. Conclusion

In challenging Arctic conditions, the need for autonomous operations is higher than ever. In this paper, the SICLO methodology suggests the approach that significantly relies on ESP real-time operation parameters, and by the interpretation and comparison of those parameters, the maximum level of intelligent control can be achieved along with the reduction in the workforce requirements in challenging Arctic conditions.

Moreover, the SICLO methodology and Automatic Adaptive Algorithm (A³) can be embedded in the SCADA system as an advisory tool that can predict the failures, enhance the pump run life, and reduces workover costs. Nevertheless, A³ controls the ESP system under reservoir and field performance. Field cases demonstrated the benefits of A³. In the first case, the pattern recognition system would be beneficial to detect an event before the failure happens and to suggest the appropriate corrective actions. The second case shows the ability of the A³ algorithm to interpret well test data to get the necessary parameters in further well/reservoir analysis.

Abbreviations

SICLO	Source of data and information; Input data; Calculation/Analytic; Logic Analysis; Output/Value Delivery
PDMS	Petroleum Data Management System
ESP	Electrical Submersible Pump
VSD	Variable Speed Drives
SWBT	Switchboards
SCADA	Supervisory Control and Data Acquisition System
i-ESP	Intelligent - Electrical Submersible Pump database
A³	Automatic Adaptive Algorithm
MoDTE	Matrix of Descriptive Trend Explanations
WSO	Well Service Operation

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