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AUTOMATIC DETECTION AND DIAGNOSIS OF PROBLEMS IN DRILLING GEOTHERMAL WELLS

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ABSTRACT

Sandia National Laboratories and Tracor Applied Sciences have developed a proof-of-concept Expert System for the automatic detection and diagnosis of several important problems in geothermal drilling. The system is designed to detect loss of circulation, influx, loss of pump efficiency, and sensor problems. Data from flow sensors (including the rolling float meter), the pump stroke counter and other sensors are processed and examined for deviations from expected patterns. The deviations are transformed into evidence for a Bayesian Network (a probabilistic reasoning tool), which estimates the probability of each fault. The results are displayed by a Graphical User Interface, which also allows the user to see data related to a specific fault. The prototype was tested on real data, and successfully detected and diagnosed faults.

INTRODUCTION

The most costly problem routinely encountered in geothermal well drilling is lost circulation. Lost circulation costs represent an average of more than 10% of total well costs in mature geothermal areas. Reducing the cost of lost circulation would thus significantly reduce overall geothermal costs and help expand the role of geothermal energy. One of the more significant ways lost circulation costs can be reduced is by making the right decisions sooner. That requires that the driller be better informed in real time.

The timely detection and characterization of lost circulation is problematic with the tools now available to the geothermal driller. This paper reports on the first phase of a project to develop a tool to rapidly detect and diagnose the onset of lost circulation or fluid influx (steam and gas kicks), and thus aid in localizing the problem in the borehole. Moreover, this tool is designed to include: optimized problem detection through advanced statistical analysis of measured data; diagnostic capabilities in a reasoning module; expert advice from an expert advisor module; and training support for geothermal drillers. This tool provides timely information about loss of circulation and other problems, allowing the driller to make the right decisions faster. This will reduce the quantity of fluid lost, provide a more stable well for cementing operations, and increase the reliability of cementing operations: thus the cost of geothermal drilling can be significantly reduced.

Previous work (Mansure and Glowka, 1995) determined that measured data contain information about the nature of lost circulation events. Such data, if analyzed in real time, could aid the driller in making the right decision sooner with less trial and error, thereby reducing costs. The current state-of-practice for processing incoming data significant to lost circulation is to display data on strip charts and rely on human recognition of events. With the advent of new data sources significant to lost circulation, this approach is inadequate because a person can not continuously analyze and correlate all the relevant data (inflow and outflow, standpipe pressure, pump speed, penetration rate, mud density and rheology, pit volumes, etc.) fast enough to identify events and make recommendations in real time. For example, one generation of new data sources, the rolling float and Doppler meter combination for measuring outflow and inflow (Whitlow, Glowka, and Staller, 1996 and Schafer, et al., 1992), can identify lost circulation down to as little as 10 gal/min. allowing the early detection of lost circulation. The most practical way to make this information available to the driller in real-time, 24 hours a day, is to automate the processing of

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the raw data from the meters via an Expert System.

This paper describes the approach being used by Sandia National Laboratories and Tracor, Inc. to develop the Circulation Monitoring System (CMS). Future papers will report on the field testing and application of the system. The CMS builds on Sandia National Laboratories' experience and research in lost circulation (Glowka, 1997) and Tracor's development of the Well Site Advisor (WSA) under funding by the Drilling Engineers' Association (DEA49).

WSA is a PC-based system used to prompt and train rig-site personnel on the proper actions to take during a kick. In addition to generating kill sheets and performing all necessary kill calculations, WSA contains a sophisticated model of the kicking well. The model is updated using standpipe pressure, casing pressure, and pit volume gain throughout the kill as the kick is circulated out of the well. The model includes advanced statistical procedures used to detect circulation problems during the kill. Upon problem detection, an expert system can be activated to diagnose the problem and, given a problem, an advisor can recommend corrective action.

The success of WSA in detecting and diagnosing circulation problems with real kick data has led Sandia National Laboratories and Tracor to apply similar technology to automatic monitoring and problem-detection in geothermal drilling.

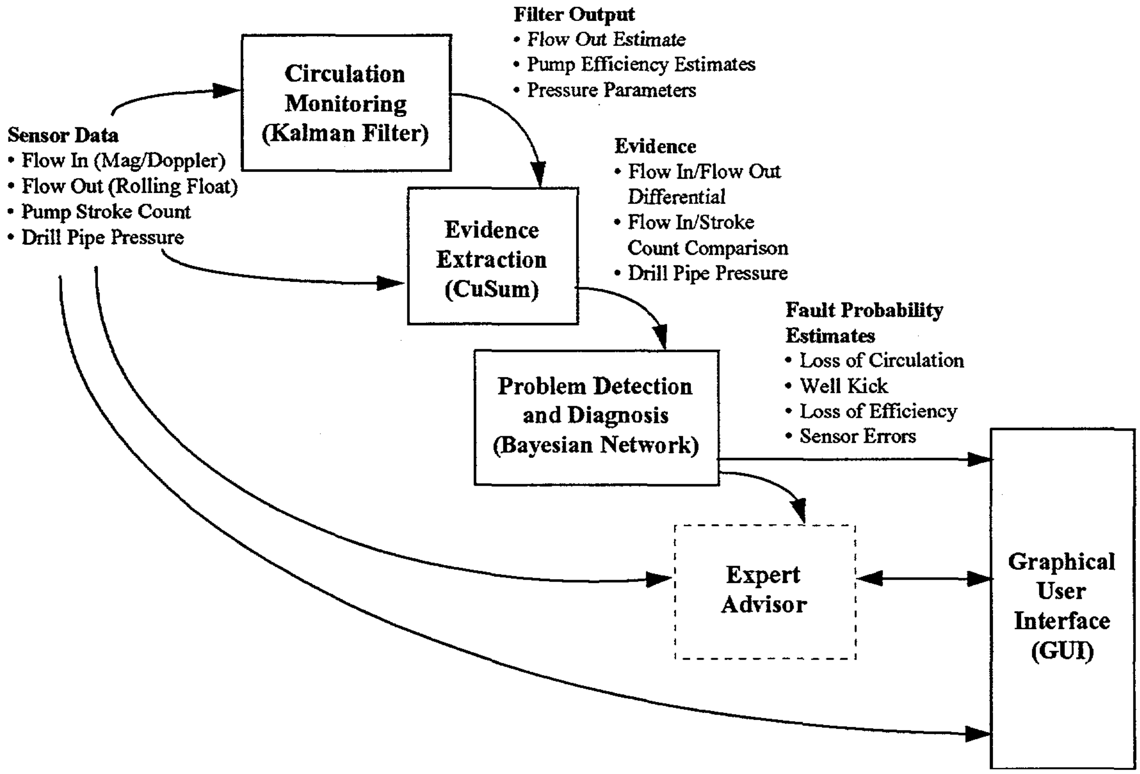

Figure 1 - CMS Flow Diagram

SYSTEM OVERVIEW

Figure 1 contains a data flow diagram of the prototype Circulation Monitoring System (CMS). The five components of the system are:

- *Circulation Monitoring* - Normal drilling operations are modeled using a five-state Kalman filter (Gelb, 1974).
- *Evidence Extraction* - Evidence is extracted from the output of the Kalman filter using the CuSum sequential statistical process (Dobben, 1968).

- *Problem Detection* - A Bayesian belief network (Pearl, 1987) is used to estimate problem/fault probabilities based on incoming evidence.

- *Expert Advisor* - Expert advice is provided to the user based on *a priori* knowledge and the estimated problem/fault probabilities. At present this module has not been prototyped.

- *Graphical User Interface* - Problem/fault probability estimates are presented to the user along with options to view data related to a specific problem or fault.

The Kalman filter smoothes measurements of outflow. It also estimates pump efficiencies and parameters which relate circulation pressure to flow. (The pump efficiencies and circulation pressure parameters cannot be measured directly.) At any time, the values of these quantities define the state of the well. State estimates are an optimal (minimum mean squared error) combination of projections from the state model of the well and measurements of well parameters. The measurements used are flow meter readings, the pump-stroke counter reading, and the drill-pipe pressure. When a state estimate is desired, the state model is used to project ahead from the last estimate. A set of measurements is taken and combined (using an optimally generated Kalman gains matrix) with the projected state to form a new state estimate at the current time.

The CuSum test uses cumulative sums of deviations to detect both large deviations from an expected value or smaller systematic deviations from an expected value. The test has several tuning parameters that can be used to balance detection time with false alarm rate. The deviations considered in CMS are inflow minus outflow and the difference between estimated pump efficiency and a perfect efficiency of one. The results of the CuSum test are written to output files for use by the Bayesian network.

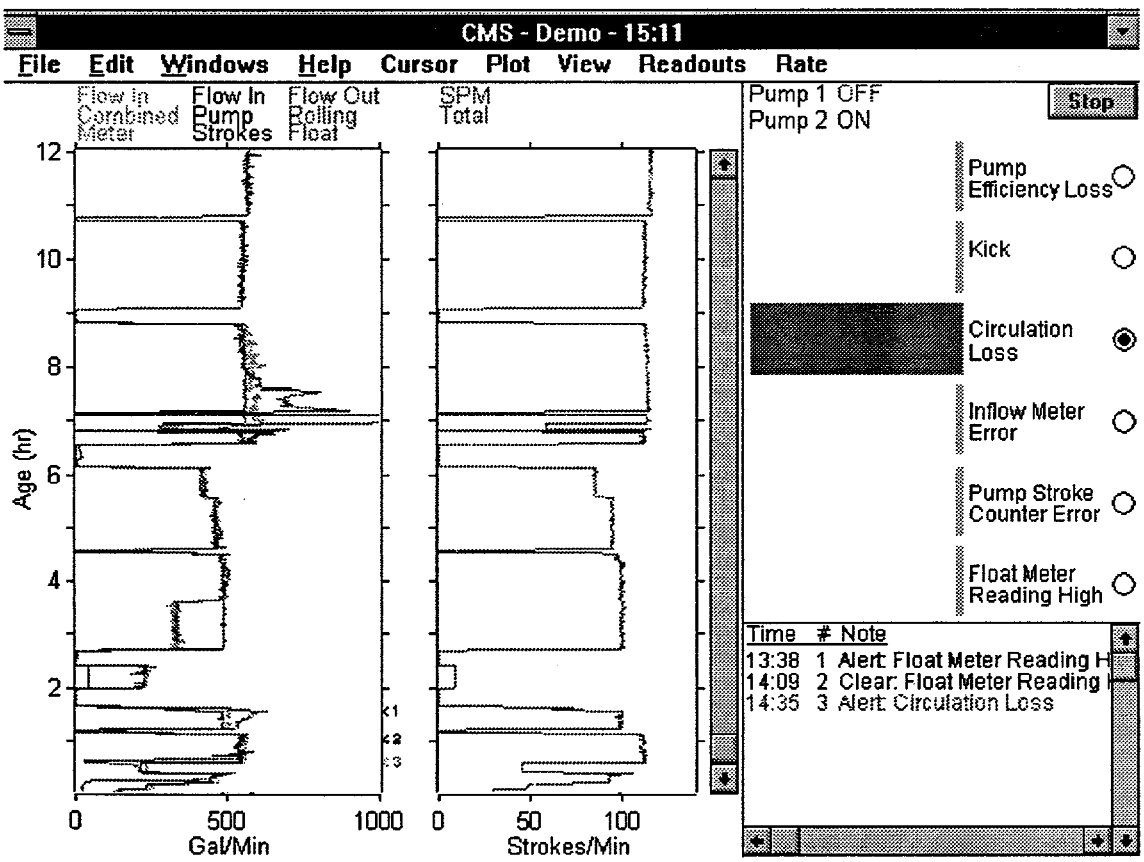

Figure 2 - Graphical User Interface

The Bayesian network uses evidence generated by the CuSum test to estimate the probabilities of faults. (A symptom detected by the CuSum test does not necessarily indicate a specific fault. For example, an apparent excess of outflow over inflow could be caused by a sensor error or a well kick.) The faults detected by CMS are loss of circulation, well kick, loss of pump efficiency, inflow meter fault, and outflow meter fault.

The Expert Advisor (which has not yet been prototyped) may be used in conjunction with the output of the Bayesian network or independently. It has advice for every problem which can be diagnosed by the system. Advice for other faults can be added, and all advice can be modified according to company policies. The advisor gives advice for problems currently diagnosed by the system and for problems selected by the user.

The Graphical User Interface (GUI) allows the user easily to monitor fault status and to view well information. The GUI displays the outputs of the Bayesian network in such a way as to draw attention to areas where there is a high probability that a fault is occurring. The GUI also displays plots of raw well data so that an operator can see why a fault is being diagnosed and can investigate the fault. The operator also has the option of displaying data readouts or notes. The data readouts are for operator-selected well data at either the current time or for any time within the past twenty-four hours. The notes can be manually entered by an operator or are automatically generated when the Bayesian network determines that a fault has occurred or has ceased occurring. An example of the prototype GUI is contained in Figure 2. The upper right section of the GUI shows beliefs in faults based on evidence available at time 15:11 in a demonstration data set that has been pieced together from several real data sets. The diagnosis is for a loss of circulation. The note section at lower left shows that this diagnosis was originally made at 14:35. The plot section in the left section of the GUI shows plots of inflow and outflow in the first plot. The operator has selected to plot total strokes per minute as the second plot. The time of the circulation loss diagnosis is indicated to the right of the first plot by the small "3" (corresponding to note 3). In future prototype systems the GUI will also be the method for the user to interact with the Expert Advisor and to provide information to CMS that may not be contained in the raw data (e.g., that a meter has just been checked and is operating correctly).

SYSTEM DESIGN RATIONALE

The Kalman filter is used in the Circulation Monitoring System to increase flexibility in the handling of data, and is particularly important in the estimation of pump efficiency, which can not be measured directly. Clearly the main indicator of pump efficiency is a comparison of inflow measurement(s) and the flow estimates from the pump stroke counters. (Measurements of outflow are also relevant, but are influenced by other conditions.) The Kalman filter uses these data to estimate pump efficiency, and produces covariance estimates. With this approach the system can deal correctly with any combination of pump speeds and any arrangement of inflow sensors. If one pump is running the filter gives a good estimate of efficiency for that pump. If both pumps are running and inflow is measured for each pump the filter gives good estimates of both pump efficiencies. If both pumps are running at constant speed and only combined inflow is measured then separate pump efficiencies cannot be estimated but the filter gives a good estimate of combined efficiency. In all cases the covariance estimates produced by the Kalman filter shows which estimates are reliable. (For very low pump speeds the covariance estimates may show considerable uncertainty in all efficiency estimates.) This is better than simply examining the difference between inflow measurements and pump stroke counter estimates, since these could be large for high (but not perfect) pump efficiencies when pump speeds are high.

Suppose that there is only one inflow sensor (on combined inflow). If the pumps are run at constant speeds the Kalman filter estimates a weighted average of pump efficiency, but if pump speeds vary the filter may be able to estimate individual efficiencies. For example, suppose loss of efficiency is diagnosed (from the weighted average) at a time when both pumps are running and it is desirable to maintain flows. Increasing the speed of either pump while holding that of the other constant will allow the filter to estimate both efficiencies, and in particular to determine which pump has lost efficiency. If necessary, the inefficient pump can then be stopped.

The output of the Kalman filter is a collection of time series, each of which under normal circulating conditions has a stationary mean. Extraction of evidence involves the detection of loss of stationarity in any of these time series (e.g., inflow is consistently higher than that predicted by the pump flow model). The CuSum statistical method is a standard, tunable, sequential process control procedure that is ideally suited to this purpose.

The Bayesian network captures many aspects of human causal reasoning, and therefore handles many possibilities correctly without complicated rules and exceptions. For example, suppose that the inflow measurement is significantly less than one would expect from the pump stroke counter readings. This can be caused by loss of pump efficiency or by a problem with the inflow meter. If the inflow measurement is indeed less than the true inflow then (in the absence of other problems) the outflow measurement will be greater than the inflow measurement. If the flow measurements agree then the sensors are probably working correctly, so pump efficiency has been lost. Suppose instead that the inflow reading is less than the outflow reading. By itself, this could be caused by a well kick, an error in the inflow meter or an error in the outflow meter, but the discrepancy between inflow reading and pump stroke count would lead a human to suspect a problem with the inflow meter. In the Bayesian network, the symptoms not only increase belief in inflow meter error, but also combine to support a coherent diagnosis. Since the discrepancy with stroke count increases the likelihood of inflow meter error it helps to explain the flow discrepancy, and thus makes the beliefs in well kick and outflow meter error less than they would be with flow discrepancy alone. Similarly, the flow discrepancy helps to explain what would otherwise suggest a drop in pump efficiency, and reduces belief in that fault. The result is a high belief in inflow meter error and lower beliefs in the other faults. The probability calculations in the network automatically handle such considerations.

Another advantage of the Bayesian network is that it can easily accommodate new types of evidence and the absence of evidence. Suppose again that the inflow reading is significantly lower than would be expected from the stroke count and is lower than the outflow reading. The net would diagnose inflow meter error, but an operator might know that the meter has been checked and is definitely working correctly. If this information is injected into the network then it does not merely reduce the belief in inflow meter error to 0: since this change in belief eliminates the explanatory effect described above, the beliefs in other faults increase. In particular, belief in loss of pump efficiency increases (nearly) to 1 and beliefs in well kick and in outflow meter error rise (so that their sum is close to 1). In these examples, a standpipe pressure anomaly would increase the belief in a well kick and a normal pressure evolution would reduce belief in a well kick. If for some reason drill pipe pressure is not available neutral evidence is injected at that node: the net then performs as it would without the standpipe pressure node.

PROTOTYPE DEVELOPMENT ENVIRONMENT

The prototype Circulation Monitoring System has been implemented on a 486 PC running Windows 3.1. The Circulation Monitoring and Evidence Extraction modules, and the Graphical User Interface have been implemented using MatLab 4. The Problem Detection and Diagnosis module has been implemented in Ergo, a commercially available Bayesian network development tool.

Real data for design development were written to MatLab matrix files, and MatLab-based tools were developed to characterize and analyze the data, to tune the CuSum process, and to set design parameters for the Kalman filter and Bayesian network.

CONCLUSIONS

The prototype Circulation Monitoring System has demonstrated the feasibility of real-time circulation monitoring and problem detection for geothermal wells. The prototype Circulation Monitoring System successfully detected circulation problems including loss of pump efficiency, loss of circulation, and sensor inflow and outflow errors. False alarms were minimal. Future work will concentrate on building an advanced development system for testing at the well site.

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