An expert system for detecting leaks in recovery-boiler tubes

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This expert system can help boiler operators distinguish between a major tube rupture and other less critical events that trip the boiler.

Prevention of explosions in kraft black-liquor recovery boilers remains a high priority for the pulp and paper industry. Of particular concern are explosions resulting from contact between boiler water and smelt in the lower section of the furnace cavity.

Much of the responsibility for preventing explosions falls on the shoulders of the recovery-boiler operator, who must monitor a complex array of raw data and supplemental information about the state of the recovery system. During a potentially critical situation, it can be difficult to process all this information quickly enough to take appropriate action. Particularly troublesome is the task of distinguishing between a catastrophic boiler-tube rupture and other, less critical process upsets. A computer-based advisory system that analyzes current and recent process data can help the operator make better decisions.

On-line expert systems can be designed to assess problems using the same principles that guide the judgment of an experienced operator. The advantage of an expert system is that it can swiftly evaluate a large number of process variables and assess the situation on a consistent, continuous, and timely basis. The Recovery Boiler Advisor™ is an expert system that is being developed under the financial sponsorship of the American Paper Institute's Recovery Boiler Research and Development Subcommittee (*1*). At its present state of evolution, the system contains the logic required to detect major tube ruptures in several sections of the boiler. The system also can diagnose less-critical situations that an operator might misinterpret as a tube rupture. A demonstration version of the system contains a menu from which the user can select among various tube-failure simulations and other scenarios. The user interface is designed so that all critical messages, system data, and recommended actions are displayed on a single screen.

This article describes the architecture of the system, examines the logic of the rule base, and presents results obtained with a simulated boiler model. A prototype version has been installed in a host mill so that the system's actual on-line performance can be evaluated.

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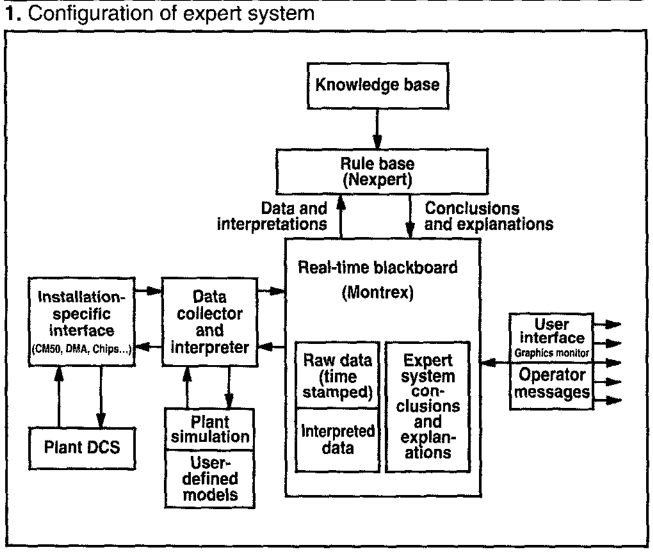
1. Configuration of expert system



Real-time expert systems

Expert systems, also known as knowledge-based systems, are playing an increasingly important role in the analysis of mill operations. These computer advisors employ practical reasoning strategies based on rules that permit conclusions to be drawn from both quantitative information (sensor readings) and qualitative information (interpretations about the accuracy or importance of a sensor reading). The usual format for the rules is the IF–THEN structure—IF one or more conditions exist, THEN some conclusion can be made. Qualitative conclusions are derived using rules established by experts who are thoroughly familiar with the system or process at hand. Expert systems thus solve problems the same way as a human expert, and the qualitative information can be expressed with varying degrees of confidence or importance.

Real-time expert systems base their conclusions and recommendations on data obtained from several sources, including the distributed control system (DCS), the computer where the historical operations database is stored, and computer models. Data from these and other sources are monitored and analyzed continuously, and the logic within the system interprets the results to provide useful conclusions in a timely fashion.

System configuration

The expert system is configured to provide maximum flexibility for mill installations. The system's core software resides on a single workstation computer and provides the architecture for real-time expert-system applications. This architecture is generally referred to as a blackboard architecture. Typically, a blackboard contains raw process data, interpreted process data, history of the raw and interpreted data, conclusions reached by the expert system, explanations, and advice associated with the conclusions. The blackboard implemented in the Recovery Boiler Advisor is a software product called Montrex™ (*2*). This software provides a repository for data from various sources and is accessible from a variety of tasks without interrupting the normal flow of data in the process-control system. **Figure 1** shows the configuration of the Recovery Boiler Advisor. The version currently installed utilizes a VAXStation computer (Digital Equipment Corp.).

Data acquisition and interpretation

The advisor system must have access to real-time recovery-boiler process data. **Table I** lists the data accessed by the data-collector module. These data are readily available for boilers operating within guidelines recommended by the Black Liquor Recovery Boiler Advisory Committee (*3*).

Access to the data can generally be accomplished using software provided by the vendor of the DCS. This method usually supports faster access to data, which is key for several of the parameters monitored by the Recovery Boiler Advisor. Access to the data also can be accomplished through a software link to a mill-wide system.

Different types of data are accessed and interpreted at different intervals. The interval is selected based on several criteria, including the availability rate of the data from the source (DCS, mill-wide network) and the nature of the monitored sensor under both normal and upset conditions.

The data-collection module itself serves a dual role of both collecting and interpreting data to detect trends or changing conditions. The use of data interpretation in a module separate from the expert system's rule base has several clear benefits:

- An efficient, dedicated software module is needed to access the dozens of process parameters on a repeated basis. Critical parameters, such as furnace draft, are preferably scanned as frequently as once per second.
- Translating raw data into qualitative statements makes it possible to write complicated rules using clear, concise language.
- Additional calculations can be performed at the interpretation level, thus increasing the significance of interpretations.

Common calculations include derivatives, standard deviations, autoregressive moving averages, fast Fourier transforms, and stoichiometric mass balances. A more advanced method uses data reconciliation to improve the quality of the process data (*4*). With these values, the rules have access to processed information in addition to raw process data.

When a change in the interpretation of the value or trend of a sensor is determined, the expert system is called upon to interpret the significance of the change. **Table II** is a partial listing of the qualitative interpretations that the data-collection module can make.

I. Key process parameters for recovery-boiler operation

Ash mix tank		
	Inlet flow	
	Tank outlet flow	
	Tank level	
Black liquor		
	Density	
	Diversion system signal	
	Flow	
	Percent solids	
	Pressure	
	Temperature	
	Trip signal	
Boiler feedwater		
	Flow rate	
	Header pressure	
Fans		
	Draft controller output	
	Forced-draft failure alarm	
	Induced-draft fan speed	
	Primary air flow	
Flue gas		
	Moisture	
	Opacity	
	Oxygen content (wet or dry)	
	Pressure	
		after 1st superheater
		after 2nd superheater
		after boiler tubes
		after economizer
	Temperature	
		after 1st superheater
		after 2nd superheater
		after boiler tubes
		after economizer
	Total reduced sulfur	
Furnace		
	Pressure	
	Temperature	
Green liquor density		
Steam drum		
	Levels	
	Level alarm	
	Pressure	
Steam production		
	Header pressure	
	Production rate	
	Temperature to header	
Weak wash		
	Density	
	Flow	

Rule base

The goals of the expert system's rule base are as follows:

- Detect the situation where a major tube rupture has occurred without tripping the boiler.
- Determine the cause of a boiler trip, enabling the operator to

II. Partial listing of parameter interpretations within the data-collection module

Controllers and sensors	
	is_extremely_high
	is_very_high
	is_high
	is_higher_than_normal
	is_normal
	is_lower_than_normal
	is_low
	is_very_low
	is_extremely_low
	is_rising_quickly
	is_rising
	is_steady
	is_falling
	is_falling_quickly
	noise_is_high
	noise_is_normal
	noise_is_low
	is_good
	is_stable
	is_in_manual
	is_unavailable
Digitals	
	auto_manual
	digital_value
	scan_flag
	is_good
	is_in_manual
	is_open
	quality
	reverse

III. Upset conditions that can be diagnosed by the rule base

Major ruptures of internal pressure parts		
	Water wall (or screen) tube rupture	
		with trip
		without trip
	Superheater tube rupture	
		with trip
		without trip
	Boiler-bank tube rupture	
		with trip
		without trip
	Economizer tube rupture	
		with trip
		without trip
Major ruptures or failures of external pressure parts		
	External steam line rupture or loss	
		upstream of the superheater
		downstream of the superheater
	Other pressure-part failures (drain valves, blowdown valves)	
Non-pressure-part failures resulting in trip		
	Improperly operating sootblower	
	Pressure-switch failure	
	Loss of induced-draft fan	
	Improper ignition of boiler with auxiliary burners	
	Low or high steam-drum level	
	Loss of forced-draft fan	
	High flue-gas temperature	

2. Rule for concluding rupture of boiler-bank tube

Rule:	**Conclude_possible_major_tube_rupture_in_bb (#126)**
If:	**there is no evidence of Confirmed_trip**
	And there is evidence of Found_furnace_pressure_increase
	And there is evidence of Found_ID_fan_load_increase
	And there is evidence of Found_unexpected_drum_level_decrease
	And there is evidence of Found_water_balance_mismatch
	And there is evidence of Found_ash_mix_tank_level_increase
Then:	***Possible_major_tube_rupture_in_bb* is confirmed**
Message	**"Possible major tube rupture in boiler bank (MSG-06.5)."**

IV. Parameters used in the water-balance model

Boiler feedwater flow rate
Blowdown flow (if available)
Sootblow steam flow rate (if necessary)
Black-liquor flow
Black-liquor solids content
Drum level
Drum pressure
Steam production

make a better informed decision about the necessity of a rapid drain.

- Discriminate between a major tube rupture and other less critical events that result in a boiler trip.
- In the case of a major tube rupture, attempt to advise the operator in what section the failure occurred.

Table III lists the recovery-boiler upset conditions that can be diagnosed by the current system.

Since erroneous data can significantly hinder the system's ability to reach accurate conclusions, some method of data validation is necessary. This is done by dividing the rules into two levels. The first level is used to verify an abnormal condition of a process variable. The second level combines all known verified conditions; these provide the basis for a final conclusion.

Verification of the data at the first level is accomplished through one of the following three techniques:

- Comparing the suspect value with values obtained from other sensors

- Comparing the suspect value with a value obtained from an on-line computer model established to deduce the value from other values
- Comparing the interpretation of the suspect value for compatibility with other interpreted trends and changes.

The interpretations of the process data are passed on to the rule base for evaluation whenever there is a change in interpretation. For example, a change in the interpretation of the furnace draft from *is_normal* to *is_high*, or a change in the interpretation of its trend from *is_steady* to *is_rising_quickly*, invokes an immediate evaluation of the change by the rule base. The system normally evaluates several changes simultaneously.

As an example, consider the following. In a boiler where three furnace draft sensors are within close proximity of each other, it would be expected that a major tube rupture would increase furnace pressure and would affect each of the three sensors similarly. Rules in the first level check each furnace draft sensor interpretation. In this example, all values should be *higher_than_normal.* If all interpretations are consistent, this information is forwarded to the second level of rules as an intermediate conclusion, such as *found_furnace_pressure_increase.* An inconsistency in the interpretations may be forwarded as *found_furnace_draft_discrepancy_high.* The rules at the second level combine the intermediate conclusions to obtain a final conclusion, which is passed on to the operator.

Figure 2 shows one such rule where several intermediate conclusions are combined to confirm that there is a strong possibility of a major tube rupture in the boiler-bank section. This particular rule is used in the situation prior to, or in the absence of, a boiler trip.

Rules at the second level are also used to eliminate possible conclusions. For example, to conclude that a major tube rupture is present—particularly when it has resulted in a high-furnace-pressure trip or a low-steam-drum-level trip—the rules must first exclude other events that may have resulted in the trip situation. Such events include improper fuel ignition or normal drum shrink caused by, for example, an increase in header pressure. **Figure** 3 shows a rule used to eliminate failure of non-pressure parts as the cause of the boiler trip.

Figure 4 shows a rule used to help establish that the low drum level is a result of normal operations and not the result of a major water loss somewhere in the system. This rule uses one of the data-validation techniques discussed previously, namely, evaluating the trend in one parameter in terms of expected changes in the trends of other related parameters.

The Recovery Boiler Advisor rule base is implemented using the expert system software shell Nexpert Object (*5*). The shell has been linked directly with the Montrex system, enabling the expert system to evaluate its entire rule base in fractions of a second. The expert system currently operates with approximately 150 rules. This number is likely to increase as the system is expanded to cover additional scenarios.

3. Rule to eliminate failure of non-pressure parts as cause of boiler trip

Rule:	**Check_all_non_pressure_part_failures_resulting_in_trip (#99)**
If:	**there is no evidence of Possible_ID_fan_failure** **And there is no evidence of Possible_improperly_operating_sootblower** **And there is no evidence of Possible_faulty_furnace_pressure_switch** **And there is no evidence of Possible_improper_aux_fuel_ignition** **And there is no evidence of Possible_impending_trip_caused_by_high_economizer_outlet_temp** **And there is no evidence of Possible_trip_caused_by_low_drum_level_only** **And there is no evidence of Possible_FD_fan_failure**
Then:	***No_non_pressure_part_failures_resulting_in_trip* is confirmed.**

4. Rule for concluding a normal decrease in drum level

Rule:	**Check_steam_drum_level_drop (#39)**
If:	**there is evidence of Observed_drum_level_decrease** **And there is evidence of Observed_steam_drum_pressure_increase**
Then:	***Found_expected_drum_level_decrease* is confirmed.**

Boiler simulation

Approach

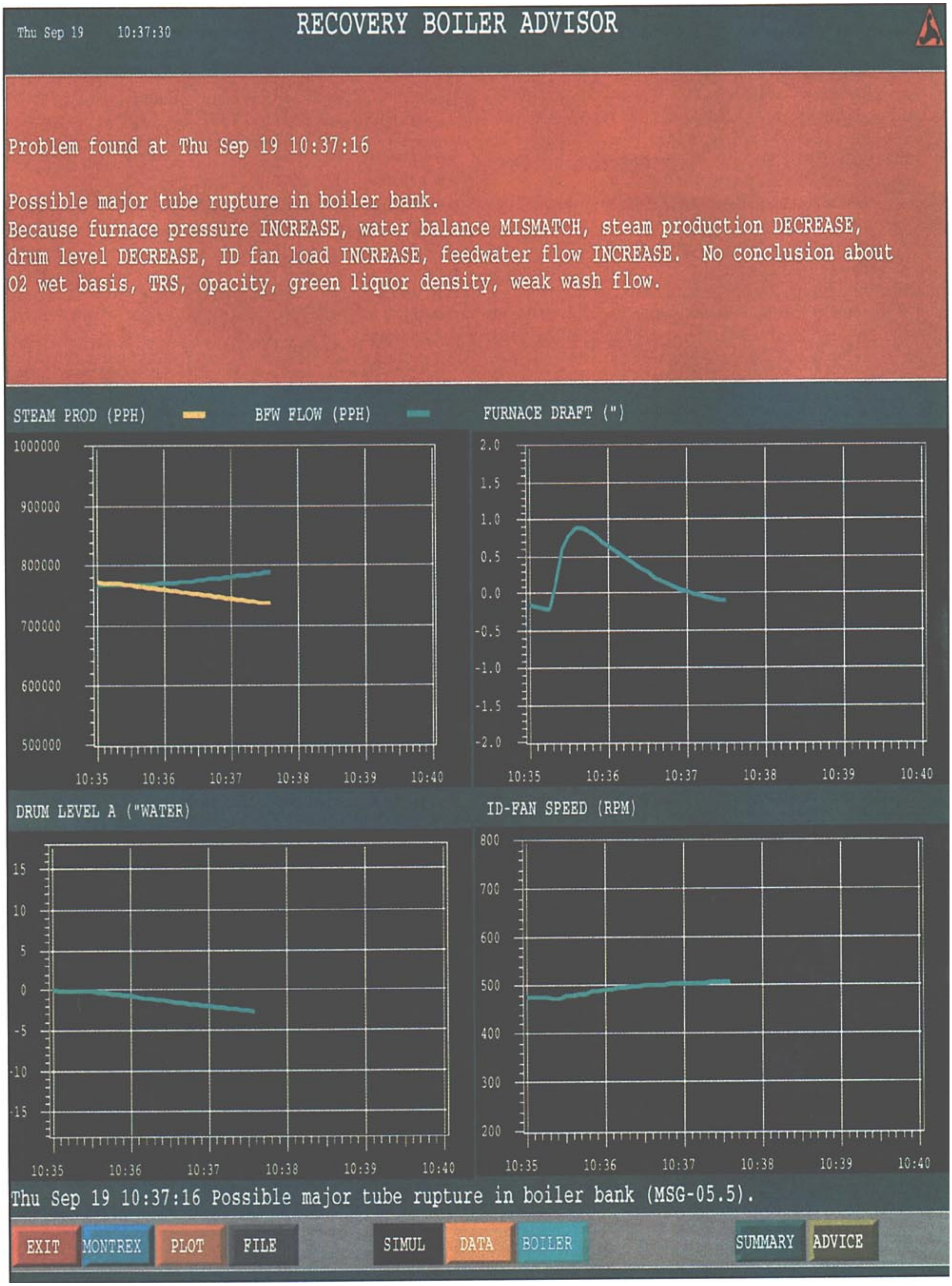
The ideal test tool for the expert system would be a complete, accurate, dynamic simulation of a recovery boiler. However, such programs generally take many months to perfect. Since the focus of this project was to investigate the use of expert systems, it was decided not to generate a truly dynamic simulation program. Rather, tests are run using a rigorous steady-state simulation of a boiler to generate an initial and final state of the boiler.

Steady-state simulation is performed using Weyerhaeuser's PROSPR-RECBOIL simulation program (*6*). By calculating a steady-state simulation for the normal operation and the final state of a malfunction (e.g., a major tube rupture) without tripping the boiler, a baseline is created for the dynamic simulation. The dynamic behavior of the variables between initial and final state is calculated using one of two methods.

- Decay based on individual time constants. This is the technique used to predict most boiler variables.
- Complete dynamic simulation. This is the technique used to predict the behavior of the two most important control loops in the boiler, i.e., the draft control and the flow control for boiler feedwater.

The furnace draft is controlled using a single PID (proportional, integral, derivative) loop by manipulating the speed of the induced-draft (ID) fan. The fan laws and actual design data were used to predict the behavior of the ID fan. Sootblowing is simulated by a step change in the furnace draft. A sootblowing cycle consists of 5 min of steam blowing followed by a 30-s period without blowing. The boiler feedwater rate is controlled by a three-element control loop with drum level, steam production, and actual feedwater flow as inputs.

5. Operator interface showing major tube rupture



Random noise is added to most variables to create more-realistic readings. In important cases, noise is propagated from dependent variables. The noise in the steam production, for example, is partially based on the noise in the black-liquor flow and the solids contents of the black liquor.

Level alarms and temperature alarms result in an immediate fuel trip. A high-furnace-pressure alarm will result in a trip if the pressure remains high for at least 10 s. Following a fuel trip, all simulated variables are assigned a new final value based on the condition after the fuel is shut off.

For modeling purposes, the amount of water or steam entering the furnace during a tube rupture ranges from approximately 10–40% of the total steam production rate. A portion of this water is assumed to leave the boiler immediately without affecting the heat and material balance of the combustion process. The remaining water is assumed to mix adiabatically with the flue gas. This determines the distribution of the water between the liquid and the vapor phase.

Mismatch between boiler feedwater and steam production

Partial evidence of a major water leak is a mismatch between the feedwater entering the drum and the steam and blowdown leaving the boiler. Any major tube leak will result in a large mismatch in this water balance. However, several disturbances in the boiler can create the illusion of a leak by causing a temporary mismatch in the water balance. It is important that the expert system compensate for such disturbances.

A model was developed to predict change in drum level caused by a change in the void fraction in the tubes which, in turn, is affected by changes in drum pressure and heat input (shrink and swell). The time constants for shrink and swell are based on research by Poon (*7*), while the actual level changes are based on the geometry of the steam drum and boiler tubing. The model inputs are shown in **Table IV**. To minimize the effect of instrumentation errors, the water-balance model compensates for the average mismatch calculated over the previous 24 h.

User interface

The success of any computer system requires the acceptance of the end user. This is particularly important in the recovery-boiler operator's environment, where the amount of visual data and the number of audible and visual alarms continue to increase. The user interface of the Recovery Boiler Advisor provides the operator with critical messages, data, and recommendations on a single, convenient display screen. **Figure 5** is a photograph of a typical screen. The graphical user interface software utilizes DataViews (*8*). The system also can utilize existing control-system hardware to display or print critical operator messages.

The interface displays five critical parameters that should be closely monitored to detect major tube ruptures. These are the steam production rate, boiler feedwater flow rate, furnace draft, ID-fan speed, and the primary drum level indicator. These strip charts can be modified, if necessary, based on mill preference.

The area at the top of the screen is left blank unless there is a critical operator message. The operator can see at a glance whether the expert system has detected any major problems in the boiler. If desired, an audible alarm can be set as an additional alert for the operator. In a situation when a major tube rupture is detected, as shown in Fig. 5, the top portion of the screen contains a colored, time-stamped message indicating the possible problem. This message contains a concise description of the evidence used to identify the problem. Information that has not been incorporated into the conclusion is also listed.

Using the information in the message window, the operator can further investigate the evidence shown as well as the missing information. Such information provides the operator with immediate guidance in making a decision regarding the presence of a major tube rupture in the boiler.

The operator or supervisor also has access to (a) a complete logic trace leading to the conclusions, (b) any mill-specific procedures or advice to deal with the upset condition, and (c) plots of all data used by the expert system in the evaluation. It is also possible to print graphics and data before and after the conclusion was made.

Conclusion

Real-time expert systems can help operators efficiently utilize the large quantities of process data provided by modern instrumentation and control systems. This technology can be incorporated into the operation of kraft black-liquor recovery boilers to help in rapidly detecting major tube ruptures.

The Recovery Boiler Advisor has been tested using accurate simulated recovery-boiler data. Nevertheless, the technology likely will benefit from current testing at an actual mill site. □

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