APPLICATION OF APACS IN A POWER PLANT

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ABSTRACT

APACS (Advanced Process Analysis and Control System) is a system for monitoring and diagnosing failures in industrial processes. The main objective of this applied research program is the development of advanced simulation and knowledge-based systems to carry out real-time diagnosis of plant malfunctions and the prediction of plant behaviour. APACS is a non-intrusive computer simulation technology system that compares the plant instrumentation outputs (those that are monitored by the plant control computers), with the optimum state. APACS will identify the root cause of a sudden process upset. The system will also provide accurate diagnostic evaluation of any non-optimal process system performance, thus allowing opportunities for improved efficiency and for the planning of corrective/preventive maintenance measures. Its first application was to the Ontario Hydro Bruce Nuclear Generating Station feedwater system which was chosen as a representative process system for the use of the station engineers.

Previous reports on APACS have been based on testing which was carried out on high fidelity engineering and training simulator testbeds. This year, an actual data link was established that provides access to plant data under varying operating conditions for off-line testing. APACS was placed on-line and live at the plant in August, 1997. This paper describes the accommodations that were required to move to the plant environment. It will also present examples of situations in which APACS accurately diagnosed station problems.

1.0 INTRODUCTION

Technological advances in information systems and control theory, combined with increased computing power, have created an opportunity for major innovations in the process control industry. The concept was initially presented in [2]. The APACS technology holds significant promise by allowing plant engineers and power plant operators to reduce unplanned outages and to plan maintenance activities more effectively. In general, this technology will enable station staff to detect very small changes in process parameters which would otherwise not be annunciated by the plant control computers, and to take corrective maintenance or operator action prior to the initiation of a forced outage. The benefits of implementing APACS include improved efficiency of plant operations, better predictive maintenance, a reduction of plant forced outages, faster recovery from outages, avoidance of equipment damage, and the extension of component lifespan due to early problem diagnosis and maintenance.

APACS is a new technology consisting of several advanced, information-based and simulation technologies. The system is capable of on-line diagnosis and the detection of plant malfunctions. The diagnostic capabilities of APACS also allow equipment characteristics and performance to be closely monitored for effective, proactive maintenance of system equipment. The system involves running a real-time simulation of an industrial process to analyze the correlation between the simulation and the operating plant. If differences are detected, a deductive process determines the reasons for the divergence. While existing plant annunciation systems are based on simple threshold tests, APACS is capable of continually comparing actual and predicted plant performance through its on-line tracking simulation. The APACS approach to model-based diagnosis is illustrated in Figure I.

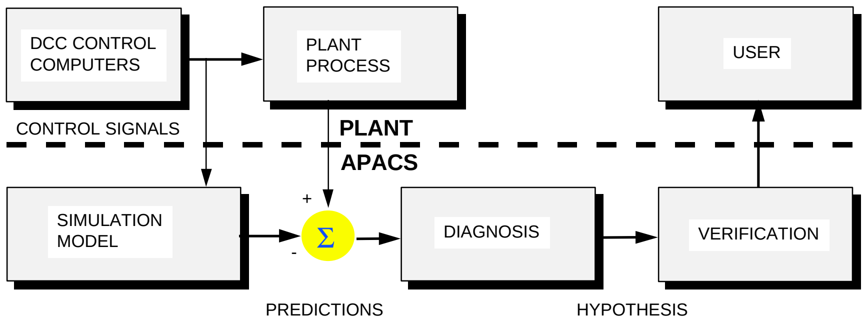

Figure I APACS Model Based Diagnosis

Diagnosis of continuous processes is a difficult problem and an area of active research [17]. Early attempts at diagnosis consisted of rule-based systems such as MYCIN [15] but these systems have been found inadequate because they are brittle, difficult to maintain, and too closely tied to a particular application. Recent research in diagnosis has focused on model-based techniques ([3], [14], [5]). In a model-based diagnosis, a diagnostic inference engine uses a knowledge-based model of the domain in order to find the cause of the problem. The model is generally a qualitative description [4] of the behavior of the devices being diagnosed. Model-based approaches have typically been applied to systems such as digital circuits, where it makes sense to use a model consisting of equations describing equilibrium conditions. Attempts to apply the model-based approach to continuous processes are included in references [6] and [12] in which the model of the domain consists of a qualitative simulation. Other approaches to developing systems for monitoring and diagnosing continuous processes include ARTIST [16], IOMCS [13], CA-EN [1], and REAKT [7]. While these systems share the goals of APACS, they have generally been applied to small problems and lack high-fidelity real-time quantitative simulations, tracking algorithms, and the APACS capability for self verification.

APACS is unique because it integrates model-based diagnostic techniques with mathematical, quantitative simulations of the monitored processes in order to generate discrepancies and to test candidate hypotheses [2]. A major advantage of the model-based approach is that it avoids the proliferation of rules linking symptoms to faults which is a prominent feature of rule-based systems. The installed system has less than 100 rules. APACS has included the development of key technologies in the areas of real-time, model based diagnosis, on-line plant simulation, and the verification of a diagnosis with faster-than-real-time simulations [10]. The cost effective, generic design will allow it to be re-used in new applications.

The APACS project is being designed and built by an applied research and development team initiated and led by Ontario Hydro along with CAE Electronics, AECL, and the University of Toronto, with funding by the Canadian Federal Government and participating industries through PRECARN Associates Inc. APACS is being applied to the Ontario Hydro Bruce B Nuclear Generating Station (BBNGS) boiler feedwater system. The installation of the live system at BBNGS involved only the establishment of data links with the plant control computers; there were no physical changes to the station. The feedwater system was selected because it has a history of being a cost effective process. The project has involved testing on an operator training simulator to define the APACS user requirements and to evaluate it as a diagnostic and predictive maintenance tool for station personnel through plant field trials. This paper focuses on the application of the APACS technology. It provides an overview of the APACS components and a description of changes necessitated by installation at the plant. It then describes some examples of plant equipment degradation which APACS has correctly detected.

2.0 APACS OVERVIEW

The APACS functional block diagram is shown in Figure II. The overall function of APACS is to monitor the plant and report changing equipment characteristics. This is accomplished by continuously comparing the readings from sensors in the plant with values generated by a plant model; discrepancies are reported and explained should they occur. The plant model is run in three different modes. The first mode, which involves simply running the model on its own, is called the unadjusted (*UAM*) model. The second mode is called *Tracking;* the model's parameters are continuously modified by a parameter adjustment algorithm. The third mode is called *Verification* and involves running the model as a testbed against plant historical data in order to validate a hypothesized malfunction or equipment behavior. The *Verification* simulation (running faster than real-time) is used to analyze a list of possible root causes in order to determine which hypothesis matches the plant data. The simulation components of APACS are referred to as the plant analyzer.

Plant data is compared to the predictions of the Tracking and UAM Models in the *Monitoring* component; this process generates symbolic descriptions of discrepancies called *events*. The *Diagnosis* component then generates one or more fault hypotheses that might explain these discrepancies. Finally, historical plant data is compared with the output of the *Verification* model testing the candidate fault hypotheses. The errors calculated by the *Verification Algorithm* are used to compute scores which allow the selection of the best hypothesis. The fault is then incorporated into the plant model allowing subsequent failures to be detected. APACS is presented to the user through the Operator Machine Interface (*OMI*). The *OMI* is illustrated in Figure III correctly diagnosing a flow transmitter failure at the plant.

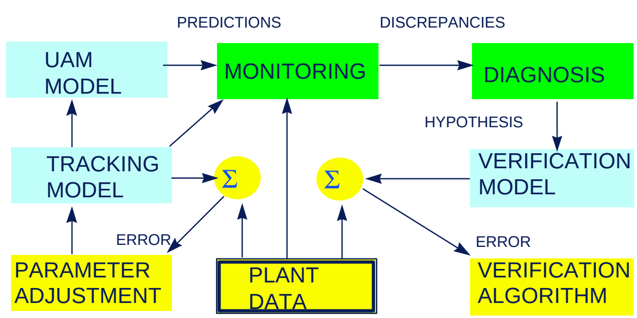

Figure II
APACS Functional Block Diagram

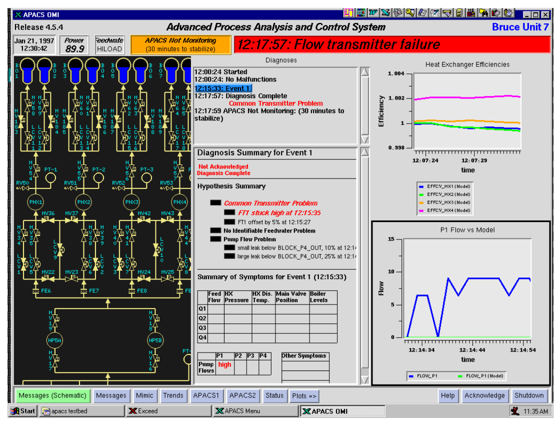

Figure III
Plant Flow Transmitter Diagnosis

2.1 Plant Analyzer

The plant analyzer simulation of the hydraulic network (the feedwater system) utilizes an admittance matrix method [8] to compute internal pressures from measured values at the boundaries of the subsystem and admittances calculated from the pressures at the previous time step. In addition to measured values, the boundary conditions include real-time control signals from the plant control computer. The tracking algorithm uses an iterative numerical approximation algorithm [9] to calculate changes in parameters to the model in order to reduce the differences between the plant and the corresponding outputs of the model. Small changes in these parameters allow the model to adapt to a plant which is always changing and to compensate for inaccuracies in the model. Large changes in the parameters indicate that there is a problem in the plant. The process model can be built from standard simulation libraries or it can be generated by a graphical simulation building tool.

Process analysis of the station data has identified the key characteristics required for the modeling of the process equipment. This has allowed the creation of a simulation library for APACS applications including standard heat exchanger, pump, and first and second order valve models. Simulation fidelity issues, such as process noise and mismatches between model and plant dynamics, were key issues. The operating plant equipment is not in the original design and calibrated state. These effects could result in undesirable performance of the APACS system such as a high false alarm rate or incorrect root cause identification of process upsets.

In order to resolve theses issues, signal filtering on noisy signals and the development of an *auto reset* function to automatically tune the plant simulation were required. On a daily basis, the plant analyzer carries out an *auto reset* function by alternating between the model's operating modes of *tracking* and *UAM*. The *auto reset* function calculates current equipment characteristics such as valve and sensor gains, offsets, pump curves, and heat exchanger efficiencies. This update of the model's internal parameters ensures that the model remains similar to the plant. The accumulated value of the auto reset parameters represents the deviation from design value of the component's characteristics. An important benefit of the *auto reset* function is that the data can be made available to plant engineers who can then use it to monitor equipment and determine which items may require calibration or repair.

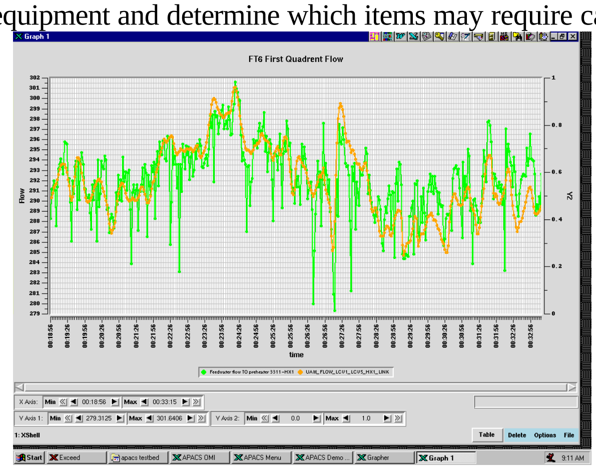

Figure IV
Plant Flow and *UAM* Prediction vs. Time

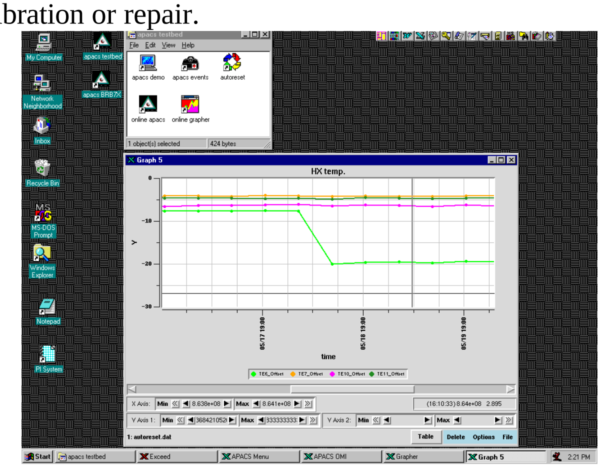

Figure V
Plant Temperature Transmitter Offset

During normal full power plant operation, the discrepancy between values predicted by the *UAM* plant simulation and the actual plant measurements are within 2% for valve position, 1% (50 kpa) for pressure, .5% (1 deg. C.) for plant temperature, and 5% (15 kg/sec) for filtered flow. The time-trend of plant flows and *UAM* predictions, seen in Figure IV, shows the high level of noise in the flow transmitter signals. An APACS *OMI* plot of the *auto reset* data is illustrated in Figure V and shows the development of a large offset on a plant temperature transmitter.

2.2 Monitoring

The real-time, knowledge-based [11] *Monitoring* component accepts plant data, *UAM* predictions, and *Tracking* parameter estimates; it then creates *events*. *Events* are qualitative descriptions of detailed plant behavior together with an assessment of the normalcy of each. APACS examines the following items in making this assessment:

- deviations between *Tracking* parameters and the expected values
- deviations between plant data and the corresponding values predicted by *UAM*

- deviations between plant data and the corresponding setpoints
- asymmetries in the plant data.

In most cases, rates of change are checked as well as actual values. *Monitoring* uses conditions to specify the way in which inputs are to be checked; these refer to thresholds to determine descriptions and assessments. Based on the plant state, the thresholds can be changed and conditions can be turned 'on' and 'off'; this process is controlled by rules. *Monitoring* can also apply filtering and can require that a condition output persist for a specified period of time before it is deemed valid and may be emitted. All of the objects, rules, and conditions describing the monitoring and diagnosis tasks for a particular plant are stored in a Common Knowledge Base (CKB).

Monitoring thresholds and persist times were issues in the adaptation of APACS to a plant. If the *Monitoring* thresholds are too tight, a great many *events* could be produced during a process upset and many of them would either be repetitive or would not be indicative of an actual problem. The *Diagnosis* task of processing these *events* can become time consuming and error prone. Conversely, if the processing is performed within bounds of time and amplitude which are too wide, then too few *events* might be generated resulting in the system missing faulty plant behavior.

2.3 Diagnosis

Diagnosis computes a qualitative, causal explanation for the events which are output by *Monitoring*. In abnormal situations, this explanation will include a fault hypothesis that directly or indirectly explain the *Monitoring* outputs. *Diagnosis* operates by chaining backward from *events*, hypothesizing immediate causes for events, and using generic rules that propagate physical changes over linked plant components. Causal chains from different input events are joined when they reach a component in common. Constraints on the times of events are propagated by a temporal reasoner. A fault hypothesis is generated when a single failure event is the root of causal chains leading to all of the symptoms. A fault hypothesis, which APACS successfully generated to diagnose a sticking valve at the plant, is illustrated in Figure VI.

In both *Monitoring* and *Diagnosis*, the rules are written in terms of classes of components. Therefore, APACS grows with the number of different types of components, not the number of components in the modeled system. Experience has shown that the number of rules grows linearly with the number of classes of components. The system usually takes less than 5 minutes to diagnose a fault at the plant. An algorithm was designed during the plant installation that calculates a common time range for *Verification* to test the set of hypothesis generated by *Diagnosis*. This time range calculated by *Diagnosis* is usually approximately 2 minutes. This is the minimum time required between sequential plant faults for APACS to correctly diagnose and verify a plant failure.

2.4 Verification

Verification is used by *Diagnosis* to select between possible root causes for the problem plant behavior. Each hypothesized plant malfunction is modeled and the *Verification* simulation model is run faster than real-time during a specified period following the occurrence of the hypothesized fault. A scoring algorithm was designed for plant installation that weights the differences between the recorded history of the plant sensors and the values predicted by the model. It then calculates the hypothesis having the smallest value for the measure of the difference. Since *Diagnosis* can only compute the approximate time and severity for a hypothesized fault, *Verification* searches a space of different times and severity using a hill climbing algorithm that identifies the combination with the best score. Figure VII illustrates the scoring surface which was successfully generated by APACS to verify a sticking valve at the power plant.

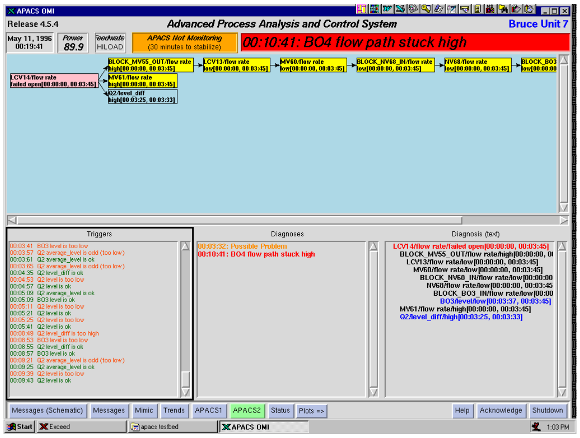

Figure VI Plant Valve Failure Fault Hypothesis

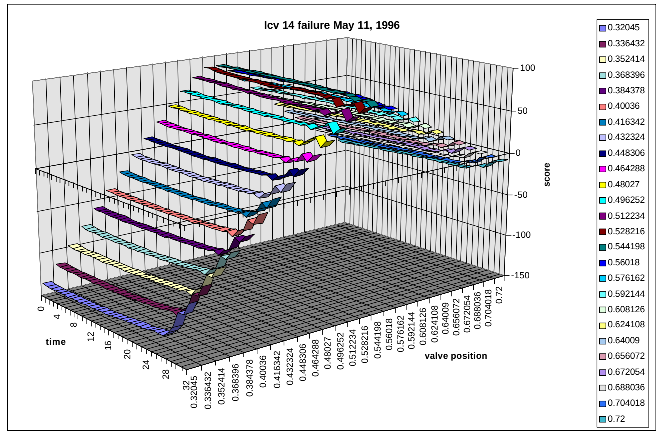

Figure VII Plant Valve Failure Verification Surface

2.5 User Interface

The OMI (operator-machine interface) is the component that manages interaction with the user. During 1996 and 1997, a 'testbed' APACS prototype was installed at the operator training simulator and was demonstrated on many occasions to Bruce plant staff, including trainers and System Responsible Engineer (SREs) from the Station Technical Unit. This effort was part of an evaluation to determine how APACS could be utilized by station staff. Control Room operators are responsible for the operation of the plant under normal and abnormal operating conditions. Their objective is to ensure that the plant is functioning safely and efficiently. The SREs are responsible for scheduling maintenance activities of process systems and require advance indication of component degradation and failure.

Evaluation of APACS on the training simulator demonstrated that control room operations could be improved if APACS alerted operators of impending component failures. This ability to identify faulty equipment at an early stage permits remedial alternative actions. Feedback from operator trainers indicated that operators would prefer information in the form of lists and graphs of observed symptoms and possible causes. This would allow them to confirm APACS' diagnostic output using their own judgment, examination of control room displays, and investigations by field operators. These requirements were incorporated into the User Interface installed at the plant as illustrated in Figure III.

The SREs requirement for APACS was that it assists them in monitoring the health of the process system. APACS' ability to detect deviations from normal behavior and to identify faulty equipment allows the SRE to proactively schedule maintenance activities rather than waiting until failures have caused operational problems. The time frame with which the SRE is concerned is of much longer duration than that of the control room operator. APACS would be used on a continuous basis to track the characteristics and status of the equipment and to identify equipment degradation. The SRE was identified as the initial primary user of the installed APACS.

2.6 *APACS Framework*

The APACS architecture has been designed as a framework for building process monitoring and diagnostic systems. This framework is designed to be cost effective by allowing generic knowledge and design to be reused in new applications and by supporting flexible configuration or replacement of components. APACS is adaptable to new problems in two ways: first, domain-specific knowledge, stored in the CKB, is kept separately from the knowledge encoded in the components; and second, the communications architecture, based on a commercial object broker, makes it simple to add, remove, or replace components as appropriate for the new application. For example, one might want to replace the *OMI* when moving to a different plant or process. An indication of the overall efficiency of the APACS approach to model-based diagnosis is the fact the currently installed system is running on a single 70 Mhz workstation.

Other architectural changes arose from the on-line plant installation requirement to run reliably 24 hours a day. Modifications were required to handle computer restarts and network problems. Important features were added including 'persistence' to remember malfunctions in the event of restarts, and the clearing of transient malfunctions or misdiagnoses. Another important architectural change was the development of a client server, APACS *OMI* , and the ability of the system to present summaries of on-line results through email. This allowed APACS to be presented to users in the form of a LAN application which appears as an icon on their desktop environment.

3.0 APACS TEST RESULTS

APACS models approximately 100 specific equipment malfunctions including pipe leaks, valve and sensor sticking, gains and offsets, and heat exchanger and pump efficiencies. The evaluation of APACS included testing with recordings of failures that are modeled in the training simulator at different levels of severity and under different plant conditions. The first part of the project has been completed and testing on the operator training simulator demonstrated that APACS is capable of detecting equipment faults or slowly degrading equipment in advance of any control room indications.

The second part of the project involved evaluating APACS as an on-line, diagnostic and predictive maintenance tool by using recorded and live on-line data from the Bruce B plant feedwater system. The first 'live', on-line test of APACS was carried out in August, 1997 and identified a sticking boiler 7 trim valve on Unit 7. A follow-up examination of the valve during a scheduled plant outage in September revealed an air leak on the valve actuator mechanism. The following table summarizes significant equipment characteristics and deficiencies which the system has identified to date. It also shows the equipment's current status.

Table I APACS Detection of Plant Feedwater Equipment Degradation

Plant Feedwater Equipment	Problem	Status
Pump 1 Flow transmitter	60 kg/s offset	recalibrated, currently erratic
Pump 3 Flow transmitter	erratic	recalibrated, later failed
Preheater 1 Temperature element	30°C offset	report raised
Boiler 3 trim valve	sticking	outage inspection scheduled
Boiler 7 trim valve	sticking	valve actuator air leak found
Boilers 3 & 4 main valve	sticking	unchanged
Boilers 7 & 8 main valve	12% offset	recalibrated after valve failure

APACS models two kinds of failure at transmitters: *transmitter stuck* and *transmitter offset*. *Verification* models *transmitter stuck* by fixing the value of the transmitter at the hypothesized time of the fault. For *transmitter offset*, *Verification* assumes that the actual process value is a fixed distance away from the transmitter measurement. If the transmitter is, in fact faulty, there will be a minimal difference between the model's predicted value and the measured value over the time of the verification run; thus the hypothesis will have a high score. All other plant transmitters will match the predicted model values because the *UAM* model does not use the plant transmitter values and is being driven by the plant control signals. The diagnosis of non-redundant sensors in a process system has traditionally been a viewed as a very difficult problem. Significant transmitter failures usually result in feedback control actions that can cause dramatic process changes. APACS' ability to analyze failures at a system wide level, rather than just at the component level, allows APACS to discern between sensor and process failures. The *auto reset* function can calculate any value of offset on a valve, temperature, flow, or pressure transmitter. Between *auto resets*, APACS can diagnose a transmitter calibration drift as small as 5% accumulated value.

APACS is able to detect very subtle level control valve faults including offsets. Valve sticking over a period of five seconds can be detected. It is impossible for an operator to continually monitor all process trends in order to observe a transient failure or a situation in which the control system can compensate and recover the process values to their setpoint. This occurs in the intermittent boiler trim behavior detected by APACS, wherein the plant control system compensates by adjusting the trim valve in the neighboring boiler. *Monitoring* can detect the deviations of the boiler levels from their set points and the fact that the flow, pressure, and temperatures at sensors upstream from the particular boilers deviate slightly from the model. This results in several events which *Diagnosis* explains by a failure that allows extra flow through a particular valve. For this kind of failure, *Diagnosis* requests that *Verification* check both the possibility that the valve is stuck at some position and that the valve is consistently offset from its demanded position, as well as the possibility of sensor fault.
It is important that APACS does not report failures incorrectly. Accordingly, APACS always generates a "no failure" hypothesis for *Verification* in which the plant history is compared to a model of the feedwater system. The model assumes that the feedwater system is behaving normally. Failures are only reported if the verification score exceeds the "no failure" *Verification* score by *a no fault tolerance* setting to avoid misdiagnosis. Determination of the value of the *no fault tolerance* and the *Monitoring* thresholds are the major settings which minimize misdiagnosis. Another issue involves the fact that if a disturbance occurs outside of the modeled process, APACS must not diagnose a failure. An example of this occurred when implementing APACS on the feedwater system and concerned the boiler blow down operation. This operation involves taking water samples from the boilers for chemistry control. APACS correctly recognized that the resulting effects on boiler levels did not originate within the model boundaries since the predicted simulation process values closely matched the sensors within the feedwater system.

Another important feature of the APACS design is its ability to diagnose multiple faults that occur in sequence. Once *Diagnosis* has determined the best hypothesis, with a time and severity as computed by the verification algorithm, *Diagnosis* instructs the APACS components to modify their models and to take these faults into account. The on-line APACS runs with multiple equipment degradation. The *auto reset* function sets the equipment and sensor offsets and gains to compensate for the fact all operating equipment and transmitters require some calibration.

4.0 CONCLUSIONS

In summary, the APACS project has developed a technology for monitoring and diagnosing industrial processes and has demonstrated, on-line in the plant, that it successfully diagnoses equipment failure and degradation, including transmitter failures and very subtle failures. Key factors in this success include the use of a quantitative simulation as a reference model for detecting subtle excursions in plant behavior and distinguishing between hypotheses, and the use of the *auto reset* function to carry out parameter adjustments in order to match the reference model to the plant over longer periods of time. APACS is cost effective due to its model-based approach. Fixed front end costs for a station installation include development of the APACS data acquisition and *OMI*. Applications to subsequent plant processes will drop in price through the utilization of standard process models.

The results demonstrate that APACS can provide early problem diagnosis to assist the System Responsible Engineer. This will result in better predictive maintenance, extension of component lifespan, avoidance of equipment damage, reduction of plant forced outages, faster recovery from outages, and improved efficiency of plant operations.

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