DEMONSTRATION OF INNOVATIVE APPLICATIONS OF TECHNOLOGY FOR THE CT-121 FGD PROCESS

at

Georgia Power's

Plant Yates

Final Report

Volume 3b
Instrumentation and Controls / Data Acquisition System

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LIST OF ABBREVIATIONS

CAD	computer-aided design
CEM	continuous emission monitor
DAS	data acquisition system
DCS	distributed control system
FC	fail closed
FGD	flue gas desulfurization
FO	fail open
FRP	fiberglass-reinforced plastic
I&C	instrumentation and controls
ID	induced draft
MHz	megahertz
MFT	master fuel trip
MMA	Martin Marietta Aggregates
P&ID	process and instrumentation diagram
PVC	polyvinyl chloride
RAM	random access memory
RTD	resistance temperature detector

VOLUME SUMMARY

The instrumentation and controls and data acquisition system used for the CT-121 scrubber demonstration were designed for ease of use, adaptability, and ease of data analysis. Several key aspects of these systems are discussed in this volume, including:

- Design approaches;
- Equipment descriptions;
- Preoperational testing;
- Discussions of operating experiences; and
- Lessons learned.

One of the key design objectives, operating the scrubber without increasing power plant personnel, was achieved through the use of innovative control techniques and a high degree of automation. Significant preoperational testing proved to be invaluable, allowing a very smooth startup and developing a base of operational and maintenance experience for operators and technicians.

An automated data collection and reduction system was designed by integrating several software packages with the scrubber's distributed control system. This system was used successfully throughout the demonstration for producing reduced data in the form of plots and reports. These data were instrumental in helping the process engineers monitor the scrubber's performance and make operating decisions during a wide variety of test programs.

Several systems were evaluated for control of the most important process variables. The most suitable methods for monitoring and controlling pH, JBR level, slurry density, flue gas components, tank levels, and flue gas flow are discussed in this volume. JBR pH and level control, the most critical of the process variables, proved to be the most difficult to develop appropriate control schemes for; however, adequate methods were developed and tested during the demonstration. This volume contains detailed discussions of the systems evaluated, as well as recommendations for control methods for each process variable.

1.0 INTRODUCTION

The instrumentation and controls (I&C) and data acquisition system (DAS) for the CT-121 demonstration project at Plant Yates were designed to provide a robust system for developing and testing scrubber control methodologies while providing the means for gathering, reducing, and storing scrubber operating data for subsequent analysis. A highly automated, operator-friendly design was selected to provide the required high degree of equipment availability while minimizing the workload of the operators and process engineers.

This volume of the final report describes the design and operation of the I&C and DAS systems of the CT-121 demonstration project. Section 2.0, Equipment Description and Technical Approach, discusses system design objectives; I&C and DAS hardware components; data collection and reduction systems; preoperational control system verification, simulation, and training; and startup. Section 3.0, Results and Discussion, discusses the operation of the various process instrumentation and control system sensors, and operating experience with the primary control loops. Section 4.0, Conclusions, presents a summary of the lessons learned, and Section 5.0, Recommendations, discusses how the lessons learned could be applied to future flue gas desulfurization applications using the CT-121 technology.

2.0 EQUIPMENT DESCRIPTION AND TECHNICAL APPROACH

2.1 System Design Objectives

The principal design objectives for the instrumentation and control system included:

- Operating the CT-121 scrubber system without increasing the number of power plant operating personnel, and
- Providing a robust control and data acquisition system to meet the demonstration project requirements.

Meeting these objectives required the specification of an automated slurry pump sequencing system, redundant sensing devices (e.g., multiple switches on slurry valves), and a digital distributed control system (DCS) with redundant processors to access and provide the large amounts of data needed to conduct a thorough evaluation of the demonstration scrubber system. A diagram of this system is shown in Figure 2-1.

Originally the project was to be designed for a two-year operating life followed by decommissioning. However, during the design phase, the design operating life was increased to 10 years, corresponding to the remaining projected life of the Plant Yates Unit 1 boiler. Increasing the life of the CT-121 scrubber required that the durability of the instrumentation that came in contact with the process fluids be increased by specifying high-alloy materials (e.g., 317L and C-22 stainless steels).

The overall philosophy driving control system software development was to “keep it simple for the operators.” A process and instrumentation diagram (P&ID) style was chosen for the control screens. This style, shown in Figure 2-2, utilizes diagrams of process piping, tanks, vessels, and valves, with process parameters such as temperature, flow, level, and pressure superimposed on the images representing the piping and vessels. The operator console was a standard 386/25MHz

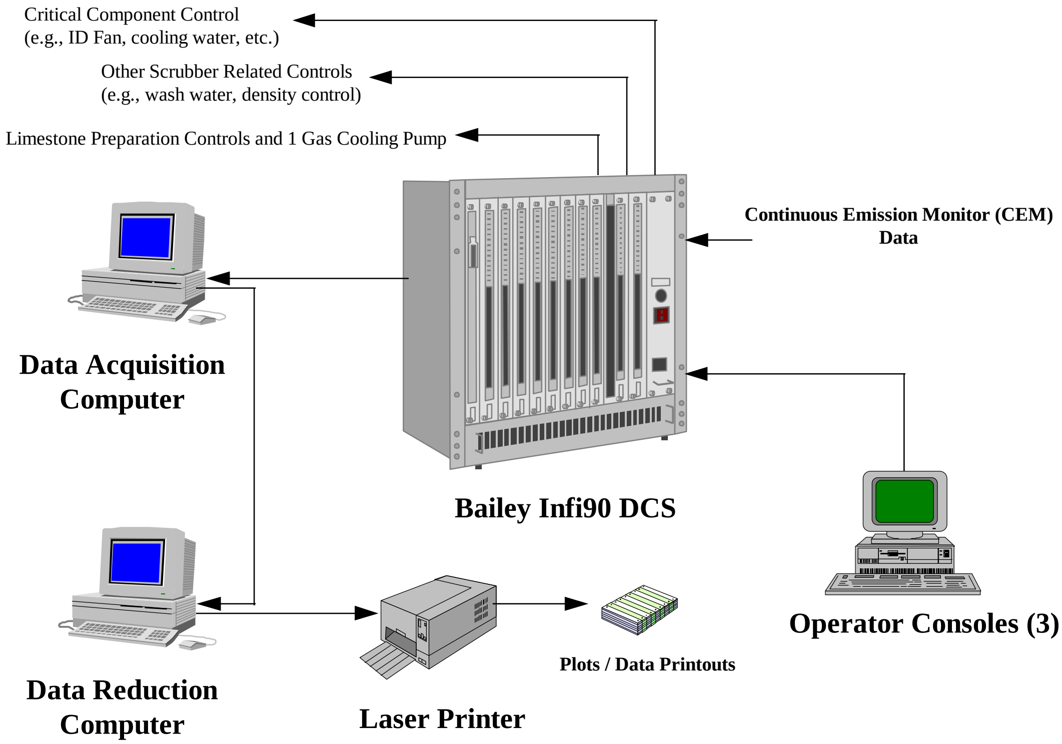

Figure 2-1. Yates CT-121 DCS and Associated Equipment

IBM-compatible computer running the DCS vendor's real time and multi-tasking QNX™- based software package.

To encourage the operators to follow prescribed slurry pump startup and shutdown procedures (e.g., backflushing, draining, and filling), operating procedures were embedded in the control software. Following these procedures minimized the accumulation of compacted slurry in pump casings and associated inlet and discharge piping during pump startup and shutdown. It is important that pump intakes and associated piping be cleaned of slurry pluggages prior to equipment startup to reduce the chances of pump impeller binding or pump cavitation. Such a condition could cause excessive pump and motor vibration and heat or otherwise damage the pump and piping.

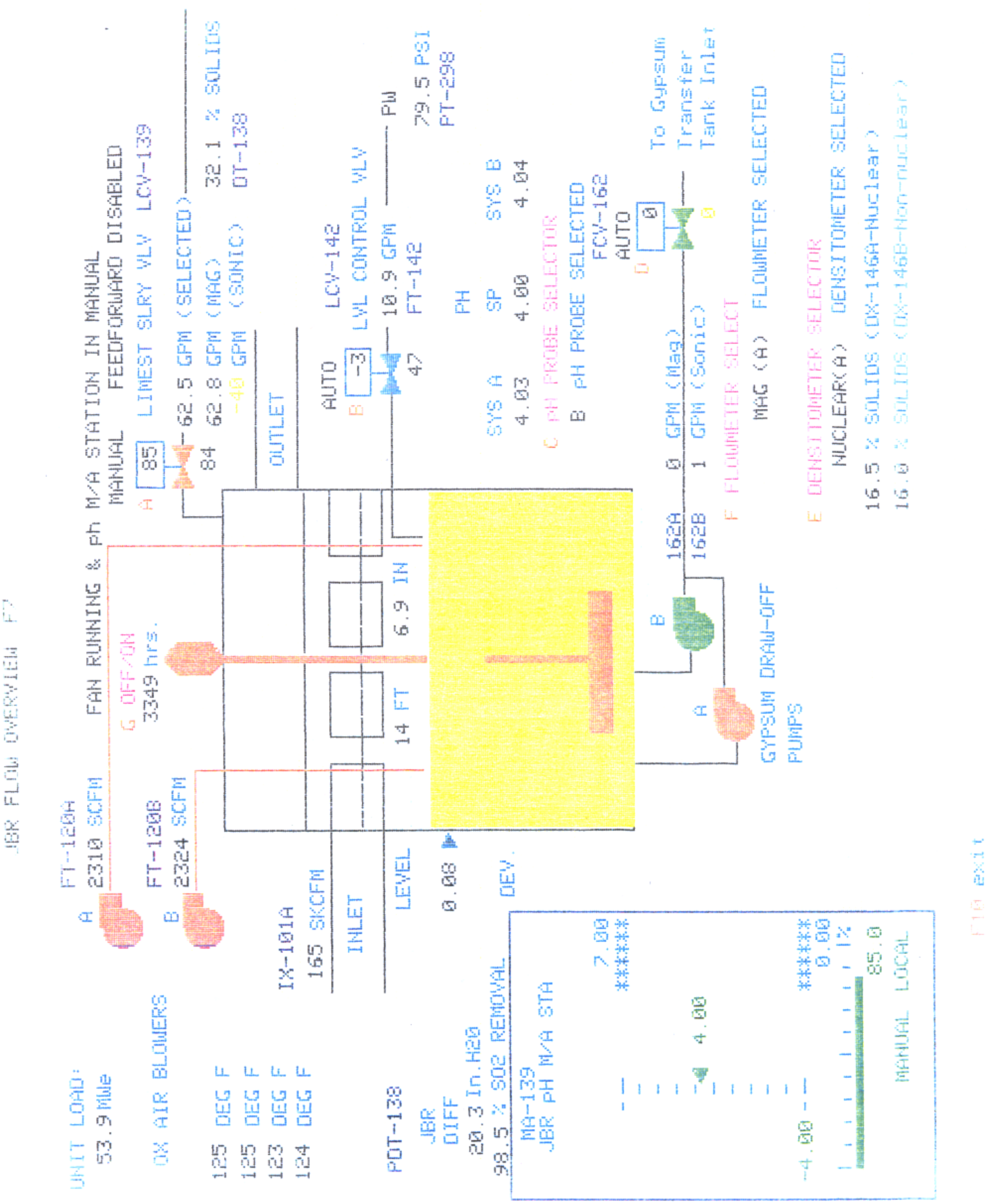

Figure 2-2. Process Control Screen

Manual and semiautomatic control modes were provided in the event that bypassing certain steps in the startup procedure became necessary. For example, bypassing some steps could become necessary to complete a startup or shutdown following the failure of a sensor, such as a valve position indicating switch.

2.2 I&C and DAS Hardware Components

The control hardware selected for the CT-121 demonstration project had to be suitable for furnace and boiler control in addition to scrubber system control and data acquisition. The existing induced draft (ID) fans for the boiler were replaced with a single, larger ID fan that served as a combination forced draft for the CT-121 scrubber system and ID fan for the boiler. Although a typical retrofit configuration may require only an additional booster fan, in this case, a new armor-plated ID fan was required to accommodate high-ash testing. Since the new ID fan was essential for boiler as well as scrubber operation, its reliability was of critical importance.

To improve control system availability, the DCS featured redundant processors and communication channels. Should one processor or channel fail, the redundant processor or channel would instantly assume the control or communication function without upsetting the process. The Bailey Infi90® DCS was procured with three control processor pairs. Each pair consisted of a primary processor and a standby (redundant) processor. The first of the three control processor pairs was assigned critical process components such as the ID fan, JBR agitator, and emergency cooling and normal cooling water control. The second pair was used for the remainder of the scrubber-related controls such as washing water flow and gypsum density control. The third pair was dedicated to the limestone ball mill and one of the gas cooling pumps. This arrangement also provided added safety, since it assured that the gas cooling pumps were not all controlled by the same pair of processors.

Other CT-121 process control tasks provided by the Bailey Infi90® control hardware included the sequencing of slurry pumps, pH and density control, flow and level control, and data acquisition, trending, and alarming. The DCS chosen for this project had the ability to execute digital logic and analog logic seamlessly. It also offered user-friendly development and maintenance software tools that closely matched those used in the host site's existing control system, thus significantly reducing training and maintenance expenses.

Control algorithms were entered into the DCS via the supplier's computer-aided design (CAD) system. Symbols representing control functions were placed on the AutoCAD™-style work area, and the data ports were connected with lines to link the control functions. These drawings were compiled into code by the CAD system and downloaded to the control processors. This system feature also allowed these control function drawings to be printed and used for subsequent maintenance and troubleshooting. In the troubleshooting mode, the CAD system painted live values next to the associated logic symbols, allowing the control engineer to quickly diagnose problems in the system logic.

While many features of the DCS were familiar, some of the features of the control system used for the CT-121 scrubber system were new to the plant staff. One example was the specific "man-machine interface" used. A man-machine interface allows the power plant operator to start and stop motors, open and close valves, and control process flows manually. Using the information from these inputs, the DCS calculates output information for controlling the processes automatically. The new DCS was based on the use of a personal computer-based operator interface. The existing operator interface used in the host power plant's DCS relied upon control switches, indicators, and specialized control stations called "manual-auto stations" for the man-machine process interface. This style of man-machine interface, typically called a benchboard interface, is becoming obsolete and is being replaced by newer technology that uses computer monitors and keyboards. The new personal computer interface for the CT-121 scrubber system is completely controlled via the PC's keyboard with the exception of the ID fan which had manual-auto stations as a backup method of control. The operators easily adapted to this new method of control and came to prefer it over the traditional benchboard interface.

2.3 Data Collection and Reduction Systems

A separate data collection and archiving system was designed and implemented for data acquisition, reduction (i.e., converting 15-second readings into 15-minute averages), and long-term storage since the software provided by the DCS vendor was not designed to perform these tasks. Data collection, reduction, and graphing capabilities were provided by a separate, cost-effective system, consisting of the five third-party software packages listed below:

- Win90 by Moore Inc. (for data collection);
- dBase IV version 2 by Borland International (for data reduction);
- SigmaPlot by Jandel Scientific (for graphing and plotting);
- Hard Disk Menu by Microfox (for scheduling software execution); and
- Stackkey, a shareware program (for emulation of keyboard key strokes).

Process data were continuously collected and verified using inputs from over 150 analog and digital points. Two IBM-compatible 486 computers were used for this task: a data collection computer and a data reduction computer.

The dedicated data collection computer was attached to the DCS to poll for point data every 15 seconds and write the data to disk in hourly files. The collection computer was a 486/25 MHz computer with 8 megabytes of RAM and a dial-up modem. It was attached to the DCS via a computer interface card supplied by the DCS manufacturer. Third-party data collection software (Win90) running under Microsoft® Windows™ 3.1 allowed multitasking of the data collection software and the communications software. The collection computer could also be interrogated for maintenance purposes, if needed, from any company office. The hourly files written to the hard drive had to be periodically deleted manually to conserve hard disk space. This disk maintenance was performed by the lead process engineer once per month.

The data reduction computer, which also served as the process engineer's personal computer, retrieved the data from the collection computer at night and reduced it to 15-minute averages in dBase IV format. From the database file, process summary reports and plots of pH, flows, and density, among other parameters, were generated and printed automatically each morning. The summary and the plots provided the process engineer with a “snapshot” of the previous day’s performance, which was useful for troubleshooting. The level of automation afforded by the plotting routine freed the process engineer to perform other tasks. The data reduction computer was a 486/66 MHz computer with 16 megabytes of RAM and a dial-up modem. All the software associated with the data reduction and graph generation was Microsoft DOS® based. Inexpensive third-party software (Hard Disk Menu) was used to link the stand-alone communications, database, and plotting packages together to automatically function in the proper sequence. The reduced data, in the form of a large dBase file, were backed up weekly to magnetic tape by a technical assistant.

Test data were kept in large contiguous files containing over 10,000 records each so that simple routines could be easily written for additional data reduction and analysis. The database files were archived by test block for easy reference.

2.4 Pre-Operational Control System Verification, Simulation and Training

Software verification is a validation step for ensuring that the final software product meets the end-user’s requirements. These requirements were typically detailed in the control system specification. For this project, the control system specification evolved continually as more was learned about the Chiyoda process. The end user team for the software verification consisted of the process engineers, the plant I&C technicians, and plant operations personnel. The control specification was a detailed list of tasks and procedures that the software was to be able to accomplish.

Control software verification was performed at the design office by the end-user team. The control system specifications and check-out procedures developed by the programmers were used as a guide. Using plant staff in both the design and programming phases of this effort helped to familiarize them with the equipment and process. Additionally, miscommunications were reduced because the initial control system design was determined to be acceptable to all parties during the check-out. The familiarity that the plant personnel gained with the control system helped ease the transitions from design, through startup, to production testing.

The most complex software to verify was the slurry pump sequencing logic, which had four valves and required sixteen steps from startup to shutdown. For the first phase of the test, the DCS was connected to switches and lights mimicking limit switch feedback and the pump motor controller. Once the basic sequencing logic was verified, the checkout method became more sophisticated as timing problems and interactions needed to be identified on a real-time basis. This was accomplished by using time delay relays that simulated open-close valve actuators and limit switches, latch relays that simulated switchgear, and standard relays that simulated electrically held motor starters. Verification of analog loops was accomplished with test current sources and meters.

Simulation of the CT-121 demonstration facility within the DCS was an outgrowth of software verification in the I&C laboratory. The predicted behavior of the scrubber subsystems was programmed into the DCS, and the analog data paths were looped into the system inputs. The response of the scrubber system was tested for various upset as well as normal operating conditions. The simulation allowed plant operators, I&C technicians, and procedure writers to get a head start in training. Training of all the key personnel was accomplished within one week. Although additional training would have been beneficial, the tight construction schedule made it difficult to retain the equipment in the laboratory for another week. During functional testing and startup, the value of this training became apparent because the operators had been able to learn the fundamentals of scrubber process operation in a relaxed environment. By using the simulator, the operators were less fearful of the consequences of a mistake as they would have been during actual operation. This provided them with realistic expectations during subsequent scrubber check-out and startup.

2.5 Startup

Once the construction phase was complete for each subsystem, it was turned over to the startup group for pre-commissioning activities. Instruments were calibrated and pumps, motors, piping, and electrical systems were checked and energized. The last checks that were performed included three groups of functional tests:

- Dry tests for checking system operation without process fluid;
- Wet tests for testing checking subsystems with water at normal operating pressures and levels; and
- Slurry tests for evaluating subsystem performance under near-operating conditions.

In concept, the slurry test seemed appropriate given the startup group's overall lack of experience with flue gas scrubbers, but the system performed so well that all subsystems were validated by the process engineer during demonstration testing. Only tuning adjustments were subsequently required.

The dry tests identified problems with sequencing logic such as slurry pump startup and shutdown procedures and valve failure modes. As a result of this testing, valve stroke times were adjusted, failure positions were corrected, and wiring errors were discovered and fixed. Integration problems with variable speed control packages were also identified and corrected.

The wet tests allowed instrumentation calibration to be verified and the "as-installed" characteristics of control valves to be well-understood. Tuning of a majority of the various sub-systems commenced during this phase.

Initial startup of the CT-121 demonstration scrubber took place in October 1992. All systems were placed in automatic control mode except for pH, which was controlled manually until the process chemistry stabilized. Because each sub-system had previously been thoroughly checked out, initial operation was smooth and uneventful.

3.0 RESULTS AND DISCUSSION

This section summarizes the results of the instrumentation and control system evaluation and discusses the lessons learned over the course of the CT-121 demonstration project. This section is divided into two discussion areas: process instrumentation and control systems sensors (Section 3.1) and experiences with the scrubber system's primary control loops (Section 3.2).

3.1 Process Instrumentation and Control System Sensors

This section provides a discussion of the experience gained with the various types of instruments used in the CT-121 demonstration unit.

3.1.1 pH Sensors

Measurement and control of pH was an area of great concern in the design phase of the project. This was due to the importance of pH as a one of two operator-controlled variables that significantly affects scrubber performance. Measurement systems supplied by three different vendors were evaluated during the demonstration program. Two were "smart" systems, supplied by TBI-Bailey and Electro-Chemical Devices; the third was a standard probe-transmitter system featuring a Rosemount transmitter coupled to a Van London probe. The Electro-Chemical Devices system was used to monitor gypsum slurry transfer tank pH. The TBI-Bailey and Rosemount transmitter/Van London probe systems were evaluated for monitoring pH in the JBR.

Of the three systems evaluated, only the Van London probe-Rosemount transmitter combination proved adequate for use during the entire demonstration project. This was due to the durability of the Van London probe and the simplicity of design of the Rosemount transmitter. The TBI-Bailey instrument and field calibration device were too easily short-circuited by slurry sprayed during sampling. Because of their unreliability, the TBI-Bailey system was replaced with a Van London/Rosemount system. The individual Van London pH probes were found to have a life of approximately 3-5 months, with the response time degrading significantly near the end of the probe life. To avoid the problems caused by response time degradation, the probes were replaced every two months.

The two pH measurement systems in the JBR were located 90 degrees apart at the perimeter of the vessel and were inserted into the reaction (froth) layer via hot tap assemblies positioned about nine inches below the flue gas injection point. The hot taps facilitated removal of the pH probes for cleaning, bench calibration, and replacement. The pH of the froth zone (reaction layer) was measured and maintained by the control system. Spatial separation of the probes allowed the extent of mixing across the reactor to be evaluated from differences in the pH measured at the two locations. The difference in pH readings of the two probes was typically less than 0.4-0.5, although this difference sometimes led to temporary difficulties when control was interchanged between the two sensors.

To mitigate the effects of differences in measured pH between probes, one probe was relocated to within two feet of the other during the second year of the demonstration. The configuration of the probes in the JBR, both before and after this modification, is shown in Figure 3-1. Following this modification the readings were more consistent, although a potential disadvantage of this arrangement was that a large piece of circulating debris such as a fiberglass test panel could easily have broken both probes. This was not a problem at Yates because the tips of the probes are protected by a fiberglass-reinforced plastic (FRP) shield. Some publications recommend that three probes be installed in the same area, with the median value being selected for control purposes. The advantage of such an arrangement is increased reliability through redundancy, as well as increased response time and less noise in the median signal.

During the demonstration project, new probes were found to be too sensitive, so that dampening of the input signal was required. As the probes reached the end of their useful life, they were very slow to respond and tended to develop memory or drift. During the demonstration project’s test phase the signal from the older of the two probes was used for process control. The newer probe was allowed to stabilize for a week or two before being used for pH control.

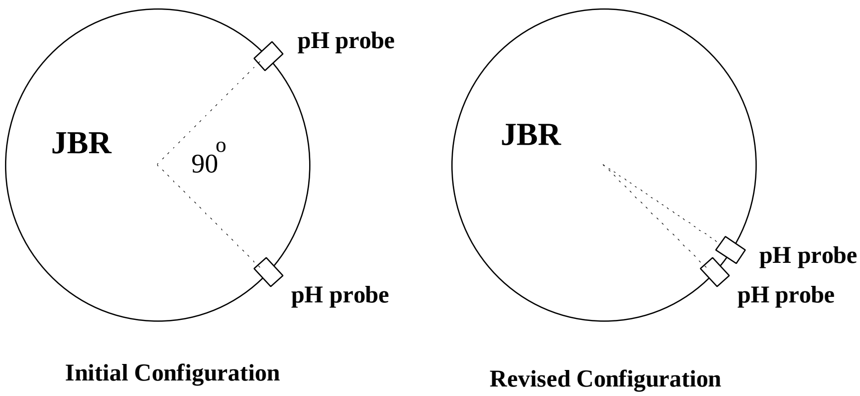

Figure 3-1. pH Probe Configuration (Plan View)

3.1.2 Process Flow Meters

Three different types of liquid flow meters were used in the design of the CT-121 demonstration facility: magnetic, sonic (Doppler), and differential pressure meters. For slurry flow measurement, magnetic and sonic flow meters were evaluated. For water flow measurement, differential pressure transmitters and magnetic flow meters were evaluated.

Based on the experience obtained during the two-year test period at the CT-121 demonstration facility, sonic flow measurement was found to be somewhat unreliable. The electronics in both sonic units failed in less than 16 months. Sonic flow meters from other manufacturers were also tested without success.

The most accurate and reliable flow meters were the magnetic type. Both Yokagawa and Rosemount units were evaluated. The Yokagawa magmeter was easier to install because of its integral grounding rings, and it also had much greater turndown capability. However, the construction electricians felt that the Rosemount meter was physically more durable. By the end of the two-year test period, none of the magmeters had failed while both of the sonic units and three differential pressure transmitter units had failed during the same period.

The ceramic magmeter manufactured by Johnson-Yokagawa proved to be trouble-free, seemingly immune to nearby lightning strikes, and very accurate. The time response and stability of the instrument were exceptional even at low flow rates. The ceramic flow tube contained cermet-powdered platinum-aluminum oxide electrodes molded and fired with the ceramic lining, thus making the instrument appear to be electrodeless. Since there was no internal protrusion of the electrode past the flow tube, this configuration allowed the limestone slurry to flow past the electrodes with minimal abrasion. No problems were experienced due to scaling, solids buildup, or wear in the flowtube or the electrodes. The built in grounding rings allowed for easy installation of the magmeter and the long-term integrity of the grounding rings was excellent, partly because of the lack of wires between casing and rings that could otherwise break loose.

3.1.3 Temperature Switches

The P&IDs provided by Chiyoda for the CT-121 demonstration facility called for a (boiler) master fuel trip via temperature indicating switches to provide emergency shutdown protection to the JBR. The switches selected proved to be easily tampered with and were unreliable over the long term. Since the high temperature trip point for the JBR is only 15-20 °F above the normal operating temperature (to protect the temperature-sensitive PVC sparger tubes), a better design would be to use resistance temperature detectors (RTDs) with a separate emergency shutdown device. Because of the importance of this measurement, 4-wire RTDs oil-immersed in tapered thermowells should be considered for improving accuracy and response time. The selection of a suitable material for the thermowell would require special care, given the aggressiveness (i.e., low pH and high solids content) of the environment in which it would be placed.

3.1.4 Temperature Transmitters

The temperature transmitters used for this project were provided by Ronan. In this application, the Ronan transmitters failed to provide reliable temperature information. The electrical contact surfaces corroded quickly in the outdoor environment, even though they were housed in a NEMA

4X enclosure. No such problems were encountered with the electrical contact surfaces of other instrumentation used in the project.

3.1.5 Limit Switches

Valve-mounted limit switches provided the interlocks for the automatic pump flushing performed during startup and shutdown. These limit switches were supplied as part of the valve assembly by the manufacturer. During operation of the demonstration facility, the failure rate of these limit switches was unusually high. The reason for the failures was deterioration of the switch internals caused by moisture getting into the internal mechanisms. General Electric limit switches with more robust multiple internal seals were used to replace some of the failed switches. The GE switches worked well as long as freezing rain did not bind the operator. A better choice for use in this outdoor application would be a hermetically sealed proximity switch such as one offered by GO Inc. Although these switches cost three times as much as a standard limit switch, they can operate fully submerged and in wet and freezing environments.

3.1.6 Valve Actuators

The valve actuators were specified with a spring return to the appropriate failure mode (fail open - FO or fail closed - FC) instead of an air to open/air to close (fail locked - FL) type. Although this specification successfully protected the system from possible plugging due to an air or electrical failure, it created the possibility that large volumes of makeup water might enter the process before the faulty component could be identified and “valved out” (isolated). Operational problems with these valves included a tendency to bind upon spring return. In retrospect a better approach might have been to make all the slurry valves and actuators fail locked and flush valves and drain valves be fail-closed. The control system could be programmed to alert the operator in the event of valve failure.

3.1.7 Rotameters

Rotameters were used to meter makeup water into the humidification lines for the oxidation air, and into the purge lines in the level control system. During operation, the glass and metal floats would rapidly become coated with contaminant deposits (mostly iron), originating in the makeup water (which came from the ash sluice pond), rendering the rotameter unreadable after about one week of service. The meters had to be taken apart and cleaned frequently. As an alternative, an all-Teflon unit (such as a model available from Fluoroware Inc.) might function longer before requiring cleaning.

3.1.8 Ultra-Sonic Level Transmitters

Ultra-sonic level transmitters were applied to all tanks except the JBR, including the limestone silo and area sumps. The setup and calibration of these instruments was trouble-free and user-friendly. Their overall performance and reliability were excellent, although the transducers were occasionally destroyed by nearby lightning strikes. Ultra-sonic level transmitters worked well for vessels of several different configurations, from open-top agitated slurry tanks and sump pits to a closed-top washing water tank and a closed-top limestone silo. Even with the dust that was present during filling operations, level measurement in the limestone silo proved to be accurate and repeatable.

The washing water tank level measurements proved to be unreliable because of the placement of the transducer; this was the only vessel for which the level transducer manufacturer's installation recommendations were not followed. The flange for the transducer was fabricated in the center of the parabolic domed top of the tank. At a certain level the transducer lost its ability to discern level and started "hunting," which caused the transmitter output to ramp up and down over the 4-20 ma transmitter current output range. This, in turn, caused the washing water pumps to trip and led to poor operation of the level control system. However, in general, the non-contacting nature of ultra-sonic level detection, overall reliability of the systems, and ease of installation make this technology well suited to the measurement of auxiliary tank levels for the CT-121 process.

3.1.9 JBR Level Measurement

Level measurement around the JBR froth zone was the most difficult instrumentation challenge to overcome. The means specified in the original design consisted of three differential pressure-type instruments, spaced 120 degrees apart on the perimeter of the JBR. Experience with this system during the demonstration project showed that the sensing lines of the instruments were prone to plugging due to the high solids content of the scrubber slurry, which resulted in erroneous readings. Wash water was supplied to the instruments in an attempt to keep the reference and indicator legs free of solids. While the wash water was effective in eliminating solids buildup, balancing the flows to the two instrument legs proved difficult, and erroneous readings continued.

A suggested improvement to this system would be to measure the level directly in a stilling well using a compensated capacitance probe such as a Drexelbrook Coat-Probe, or to use a separate stand pipe and a differential pressure transmitter. Another option would be to use diaphragm-type pressure sensors, which can be mounted as an integral part of the JBR reaction zone wall. Scaling should not be problematic because of the flexible nature of the diaphragm.

The most reliable and stable JBR level measurements were obtained using the differential pressure across the JBR as a surrogate for JBR liquid level, and compensating for the dynamic effects of flow-induced differential pressure (i.e., dynamic head). Flow-induced differential pressure can be calculated from the flue gas flow rate (which is directly related to unit load in MWe), and assuming constant-temperature flue gas. This assumption will be valid if the quench spray is operating properly, thus cooling the flue gas to its adiabatic saturation temperature. One difficulty in using the gas-side differential pressure as a surrogate for JBR level is that the dynamic head may also change due to progressive fouling of the sparger tubes.

3.1.10 Densitometers

Two types of densitometers were used in the FGD system; two nuclear units and two vibrating tube "straight-through" units. The nuclear units were manufactured by Texas Nuclear Inc., and the vibrating tube units were provided by Solatron Inc. Both types were applied in the limestone slurry and gypsum slurry draw-off lines for comparison. There were strengths and weaknesses in both technologies.

The nuclear densitometer was pluggage-free since its measurement was non-invasive to the process (i.e., the unit was strapped on to the process piping). The vibrating tube unit required a slip stream of fluid for measurement of density and was affected to a small degree by entrained bubbles. From time to time the unit would plug and have to be cleaned. Both types provided comparable accuracy but the nuclear unit had a maintenance advantage in that it was not prone to plugging. Each type also suffered occasional electronics failures and calibration difficulties. Overall, the nuclear unit was more reliable and easier to incorporate into the process design and install. However, the vibrating tube unit could be substituted if necessary.

3.1.11 Flue Gas Flowmeters

Two duct-mounted Doppler shift flowmeters were used to monitor the flue gas flow rate through the scrubber system. One of the two flowmeters was placed in the inlet duct, and provided input to the feedforward loop of the JBR limestone slurry addition controller. The other flowmeter was used to monitor the flue gas flow at the stack. This measurement was integrated into the continuous emission monitoring (CEM) system that was installed in compliance with Clean Air Act acid rain regulations.

In general, the accuracy, repeatability, and reliability of these flowmeters were all satisfactory. Initial problems with installation, calibration, connector corrosion, and lightning strikes which seriously degraded the units' performance required several months to overcome. It also took some time for the plant I&C technicians to develop a working knowledge of the maintenance and calibration procedures of these flowmeters because of the lack of adequate documentation and training.

From the point of view of reliability as control elements, the flue gas flowmeters were found to be inadequate. Reliability problems together with an inherent 120-second lag time made the flowmeters marginal as feed-forward sensing element. Consideration should be given to using the differential pressure across the mist eliminators and/or the unit load (MWe) output to develop flue gas flow rate estimates for use in feed forward control algorithms.

3.1.12 Continuous Emission Monitoring System

The CEM system provided a scrubber outlet SO_2 signal for feedforward control as well as environmental compliance information for federal and state authorities. Two dry, fully-extractive CEM systems (inlet and outlet) sharing a common instrumentation shed comprised the total CEM package. One system, mounted upstream of the quench water system in the flue gas inlet duct, provided scrubber inlet SO_2 readings. The scrubber outlet SO_2 monitor was located in the fiberglass stack. Together, the two systems provided SO_2 removal efficiency information that was compared with and used to refine predictive statistical models.

Use of the CEM for feedforward control was only marginally successful. A nine-minute lag time and CEM system failures caused by calibration drift, plugged filters, and component failure made this system impractical for control purposes. The large swings in scrubber outlet SO_2 concentration observed during the demonstration program would probably require a control element having a maximum response time of 90 seconds. Use of a fuzzy logic controller may alleviate the need for such a responsive SO_2 feedforward system.

Since the end of the demonstration project, the dry, fully-extractive system has been replaced with a more modern wet-based dilution extractive system (note that this type of system had not achieved its current level of reliability when the CEMs were initially specified). As a result, system reliability has increased significantly, since the system internals are no longer being exposed to high-temperature non-diluted samples.

3.2 Operating Experience with the Primary Control Loops

Key control loops in the CT-121 scrubber system, including JBR slurry pH, density, level, JBR deck and mist eliminator washing, JBR inlet flue gas quench, and furnace pressure control and protection are discussed in this section.

3.2.1 pH Control

Control of the JBR slurry pH is important because of the impact of pH on several key scrubber operating parameters, including SO_2 removal efficiency, limestone utilization, and gypsum scaling tendency. For example, operating the JBR at higher pH levels generally results in increased SO_2 removal efficiency; however, operating at pH levels above certain thresholds (e.g., 5.3 for low-ash conditions) may result in sharply decreased limestone utilization (i.e., the ratio of the amount of limestone dissolved divided by the total amount of limestone added). Low limestone utilization can, in turn, lead to gypsum scaling, which can result in poor performance due to plugging in the scrubber.

Proper functioning of a pH control loop depends upon the degree of mixing, SO_2 pickup rate, limestone utilization, vessel size, location of measurement and control elements, and the magnitude and frequency of pH perturbations. The JBR's single agitator provided sufficient mixing to produce a loop dead time of less than 30 seconds (i.e., the time lapse between a step change in the limestone slurry feed rate and the detection of the change by the pH probes).

To aid in understanding JBR pH control, several observations are listed and will be explained in detail:

- Shutting off the limestone slurry valve to the JBR causes pH to drop rapidly during normal, steady-state CT-121 operations;
- Opening up the limestone slurry valve 100% will cause pH to recover, but much less quickly than it fell;
- Attempting to force the JBR to recover pH as quickly as it fell by leaving the limestone slurry valve open for an extended period of time will cause the JBR to become overcharged with limestone slurry solids;
- Operating the JBR overcharged with limestone slurry solids may cause scaling of the gas sparger tubes and other areas, including the inlet plenum and mist eliminators;
- Overcharging the JBR with limestone slurry (i.e., decreasing limestone utilization) causes the pH to reach a maximum level of about 6, until the limestone solids are dissolved and reacted;
- pH is more difficult to control at higher pH than at lower pH setpoints;
- Aluminum fluoride-inhibited limestone dissolution (Al-F binding) degrades the stability of the pH control system; and
- Reactivity of the limestone affects control system stability.

To understand pH control a review of simplified scrubber neutralization chemistry is needed (refer to Figure 3-2). In equation 1a the limestone particle dissociates in water to form calcium and carbonate ions. At typical CT-121 scrubber pH values, the carbonate ions achieve equilibrium with water to form bicarbonate (HCO_3^-)and hydroxyl ions (OH^-), as shown in equation 1b. It is the hydroxyl ion that neutralizes the hydrogen ions freed by the absorption of the sulfur dioxide in water as shown in equation 2. This neutralization raises the pH as indicated in equation 3.

1a. $CaCO_3 \xrightarrow{H_2O} Ca^{+2} + CO_3^{-2}$ (dissolution)

1b. $CO_3^{-2} + H_2O \leftrightarrow HCO_3^- + OH^-$ (equilibrium)

2. $SO_2 + H_2O \rightarrow HSO_3^- + 2H^+$ (absorbtion / dissociation)

3. $OH^- + H^+ \rightarrow H_2O$ (neutralization)

Figure 3-2. Simplified FGD Neutralization Chemistry

Under full load stable operating conditions the JBR contains a certain amount of carbonate in the liquid phase as well as in the solid phase. At equilibrium the calcium carbonate in the solid phase cannot pass into the liquid phase until some of the liquid phase carbonate is reacted through neutralization. When the limestone slurry valve is shut the liquid phase carbonate will be completely reacted within 1.5 minutes, while at full load and burning 2.5 % sulfur coal. As the liquid phase is depleted, dissolution of solid phase carbonate will continue. Theoretically, all the solid phase carbonate will be reacted in another 1.5 minutes; however, the actual period of time is more like 5-10 minutes. The dissolution of solid calcium carbonate in not instantaneous. Like dissolving sugar in water, it takes time for solid carbonate to dissolve in water. Once dissolved, neutralization can proceed. Once all of the carbonate is consumed, the pH of the JBR drops rapidly. Theoretically, at full load (100 MWe) it should take about 10.5 seconds for pH to decrease from 4.0 to 3.5 and another 33.9 seconds to drop from 3.5 to 3.0. In actuality, more time is needed to drop the pH from 4 to 3 than 44.4 seconds, due to incomplete mixing in the JBR; however, the calculations do show the theoretical expected response to closing the limestone slurry valve.

When pH drops rapidly the initial reaction of the operators is to manually open the limestone slurry valve to effect a rapid increase in pH. In the course of this action, the operator sees the effect of the liquid phase carbonate component contained in the limestone slurry neutralizing the hydrogen ions. What he does not anticipate is the huge amount of solid carbonate entering the JBR, which will not dissolve instantaneously. This overcharges the JBR with $CaCO_3$, and as the solids are dissolved, the pH is pushed upward toward 6, the saturation limit of the gypsum slurry. Now the operator must close the limestone slurry valve. Operating the JBR overcharged with limestone increases the scaling likelihood (e.g. gas sparger tubes develop a thick scale of limestone and gypsum deposits which restrict the flow of gas and ultimately degrade removal efficiency). The correct operator response should be to restore the slurry valve to operation, in automatic mode, and allow the control system to maintain pH. If manual intervention is desired, it is best to add limestone for brief periods, and allow the system to respond so the impact of large quantities of limestone slurry can be assessed incrementally.

The properties of the reagent and flue gas are described by their titration curve. For this scrubber system the curve is typical of a strong acid/weak base and is characterized by its steep slope in the lower pH scale range, as shown in Figure 3-3. The pH range for normal scrubber operation (i.e., 4.0 - 5.0) is centered in the steep portion of the curve. Notice that a set point of 4.5 would occur near the center of the steep portion of the curve, so small changes in the SO_2 pick-up rate or the limestone slurry feed rate would result in large changes in pH. At a pH of about 3.5 the curve becomes less steep and the pH becomes more controllable. Calculations show how little limestone slurry (at 30 wt.% solids) would be required to raise the slurry pH from 4.0 to 4.5 (2.6 gallons) and from 4.5 to 5.0 (0.8 gallons) in the 140,000 gallon JBR. Because more slurry is required to raise the pH from 4.0 to 4.5 than 4.5 to 5.0, the process tends to be more controllable at lower pH values. During the demonstration program, control stability problems were in fact encountered during parametric testing at high pH set points.

Another property of limestone that is important in determining control system stability is its reactivity (i.e., how quickly the limestone will react with dissolved SO_2). The reactivity of limestone is indicated by its dissolution rate, which in turn varies with the type of limestone, process temperature, grind size, and the amount of carbonate existing in the liquid phase.

There is disagreement in the instrument and control community as to the applicability of various control schemes while using limestone as a reagent. According to one author, the dissolution rate of the limestone form of calcium carbonate is too slow to allow for feedback control even when pulverized into small particles[1]. Although this may be true for ambient temperature reactions, the JBR slurry process temperature is between 125 and 135°F, and there is continuous absorption and reaction of SO_2 with calcium carbonate (in the limestone) to produce gypsum.

Two limestones used during the demonstration offer different reactivity (and dissolution) rates. The Martin Marietta Aggregates (MMA) limestone neutralized sulfuric acid over twenty times faster than the Dravo limestone between a pH of 3 to 5, as shown in Figures 3-4 and 3-5. The MMA limestone required only a simple feedback controller for the pH loop and was controllable for large swings in SO_2 pick-up rate (unit load) even at high pH setpoints, that is, above 4.5 pH.

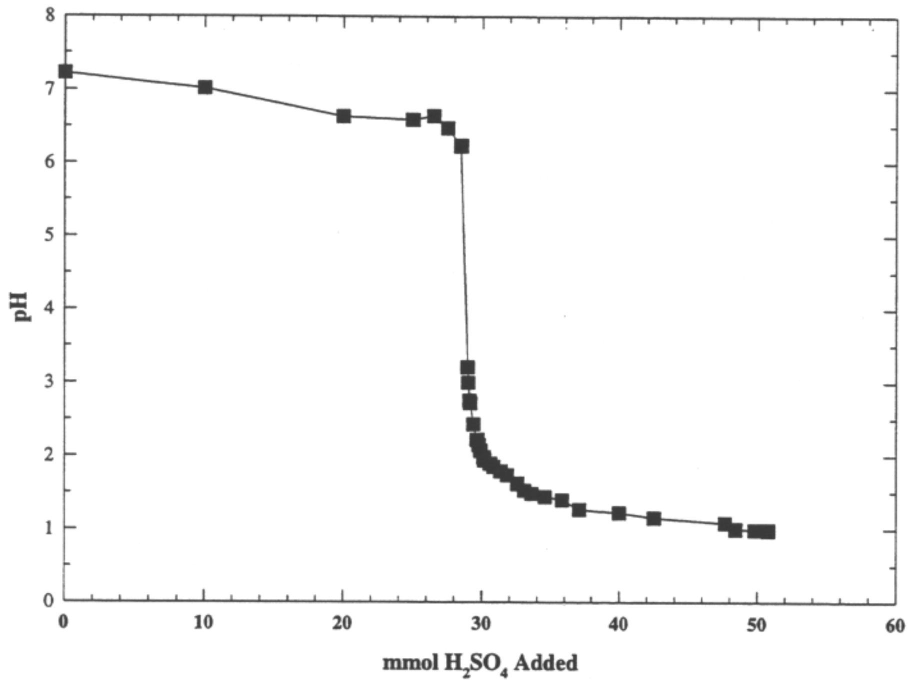

Figure 3-3. **Limestone Reagent Titration Curve**

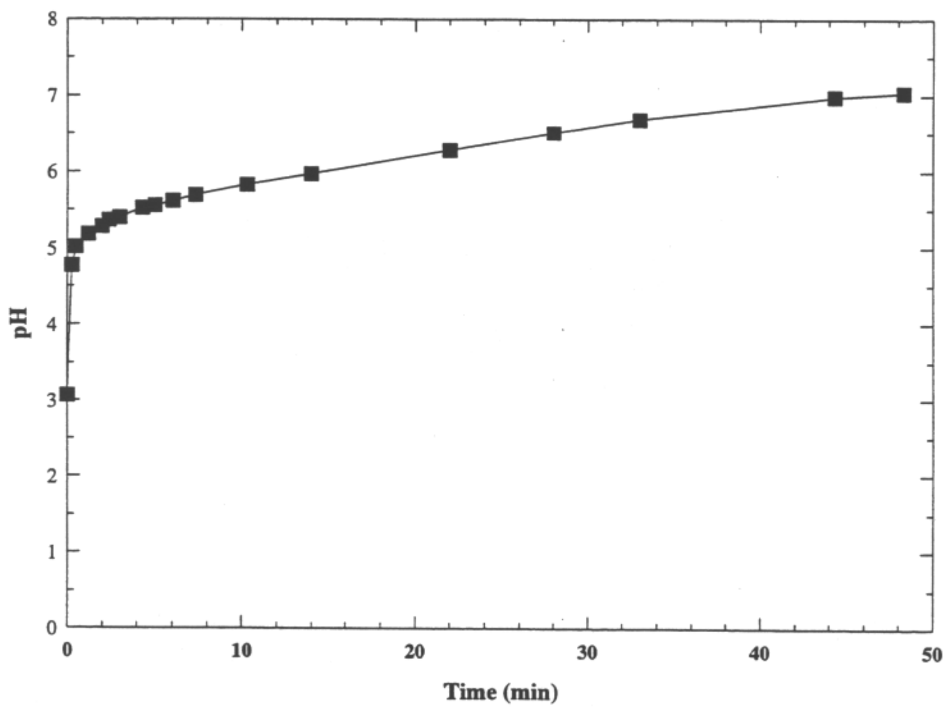

Figure 3-4. **Reactivity Curve of MMA Limestone**

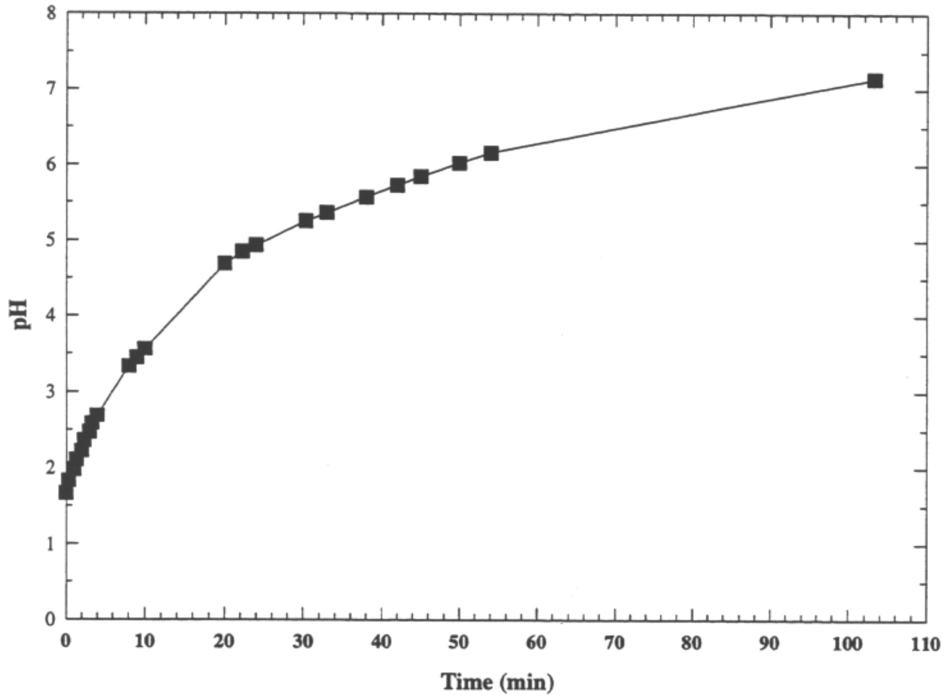

Figure 3-5. Reactivity Curve of Dravo Limestone

The Dravo limestone did not provide the reactivity needed to keep the pH control loop stable at high pH setpoints, during significant load swings using a feedback only controller. There, a combination feedforward/feedback controller best suites the Dravo limestone.

The previous discussion of pH control shows that the JBR operates with very little calcium carbonate in the solid phase, which is why pH falls quickly whenever the SO_2 pick-up rate increases rapidly or the limestone slurry valve is shut. Al-F blinding is an example of when there can be a large amount of carbonate in the solid phase and pH remains unaffected or even decreases. Blinding tends to occur more easily during high fly ash loading conditions (e.g. when the precipitators are turned off), due to the higher aluminum concentration in the scrubber.

An example of the effect of excess limestone loading and the slow rate of dissolution that occurs during incidences of Al-F blinding is shown in Figure 3-6. During the period of time shown, the

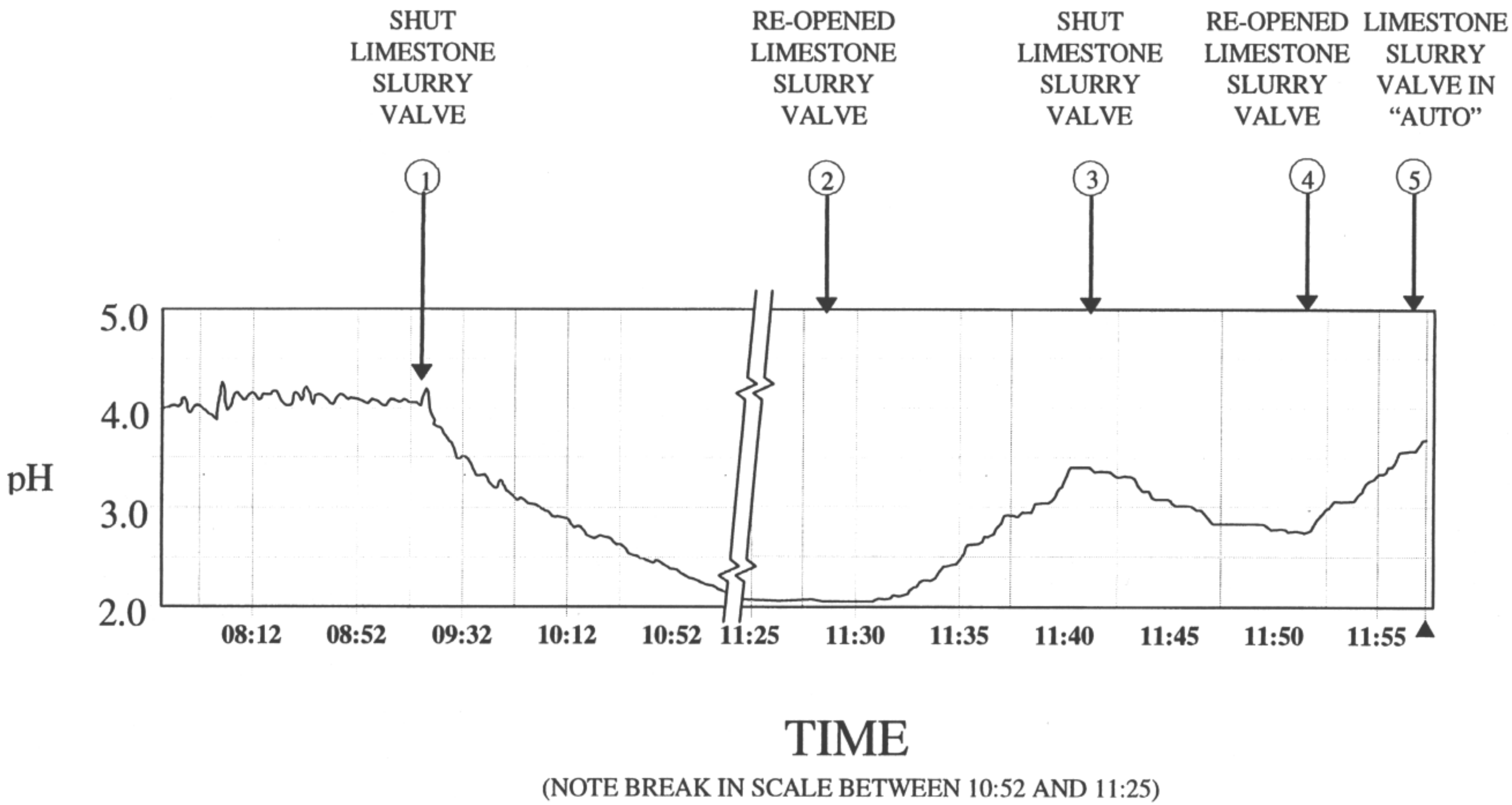

Figure 3-6. Aluminum Fluoride Blinding Affected pH Transient

unit was operating at 75 MWe, SO_2 pick-up was 71.4 lb/min, and the JBR slurry pH was stable at 4.1 ± 0.1. To demonstrate upset recovery, the limestone slurry valve was closed fully (event #1). It took two hours for the pH to decrease to a value of 2. The limestone slurry feed valve was then fully re-opened (event #2) until the a pH of 3.3 was reached and then the valve was again closed (event #3). The partial recovery of pH between events 2 and 3 took 10 minutes. Following event #3, the pH was allowed to decrease for 10 minutes until it reached a value of 3, the lower operational limit. Then the valve was re-opened (event #4). The operating set point pH of 4.1 was reached within 10 minutes; however, blinding eventually returned at this pH. This rapid response is due to the fact that Al-F blinding will not occur below a pH of 3.8.

The ratio of the scrubber residence time to control loop dead time is an important factor that must be considered in ensuring that the pH of a system is controllable. Simply put, one would not want the contents of a vessel pumped out before a pH measurement and correction could be made. In the demonstration facility, the residence time of the JBR is much greater than the loop dead time, which provides a large time constant-to-dead time ratio. A higher ratio provides greater stability since the slope of the titration curve is steep and the target control band is 0.3 pH unit. Disturbances to the stability of the slurry pH control system were mainly due to changes in unit load (which is directly proportional to the flue gas flow rate).

Fluctuations in the sulfur content of the coal did not present a control problem because of the buffering action of the undissolved limestone in the JBR slurry. Even when the coal source was changed, the effects of the transition from one coal type to another were observed but control stability was easily maintained. Sharp changes in unit load provided the greatest pH control difficulty. With the pH set point between 3.0 and 4.5, load changes of up to about 5 MWe per minute did not cause stability problems while using feedback-only control. Higher pH set points and sharper load swings were easily accommodated when feedforward control was used.

Several pH control schemes were used during the demonstration project. The most reliable system while using the MMA limestone was a simple pH feedback method. Since loadswings were usually minimal, a single element controller was normally adequate for pH set points between 3.0 and 4.5. Above a pH set point of 4.5, performance was degraded, and stability could be lost during load changes of greater than 5 MWe per minute. The reaction chemistry was modeled, and a feedforward equation (with feedback trim) using inlet SO_2, unit MWe output (a surrogate for inlet duct flow), limestone slurry flow, pH, JBR differential pressure, and limestone wt.% solids was developed. The inlet duct flow measurement had a built-in 120-second lag, and the inlet duct SO_2 measurement had a transport delay of 9 minutes. Even with these inherent delays, the feedforward equation provided a more stable control than pH feedback alone at high pH set points and large load disturbances.

In spite of its stability, the use of feedforward control based upon the mathematical model was hampered because the process sensors were not sufficiently reliable. For this control mode to be successful, the instruments measuring limestone slurry density and flow, pH, slurry density and draw-off flow, inlet and outlet SO_2 concentrations, JBR differential pressure, and unit load would need to function without drifting or failing. In fact, although most instruments did drift, foul, or fail, the primary difficulty was with the continuous emission monitor (CEM) which developed problems more than once per day on average.

A simpler version of the feedforward control loop was developed using the generator megawatt transducer signal (i.e., unit load) and the assumption that certain key parameters would remain constant, including the SO_2 pick-up rate (which is a function of unit load, coal sulfur content, and SO_2 removal efficiency), and the solid calcium carbonate concentration in the limestone slurry. The trend shown in Figure 3-7 plots boiler load, limestone slurry feed rate, and pH vs. time in hours. Note how closely the slurry feed rate matches the unit load, as would be expected for a stoichiometric reaction process. The plotted data in Figure 3-8 shows a close relationship between flue gas flow and unit load (MWe). This too is expected since the energy output of the generator is proportional to the potential energy of coal input to fire the boiler.

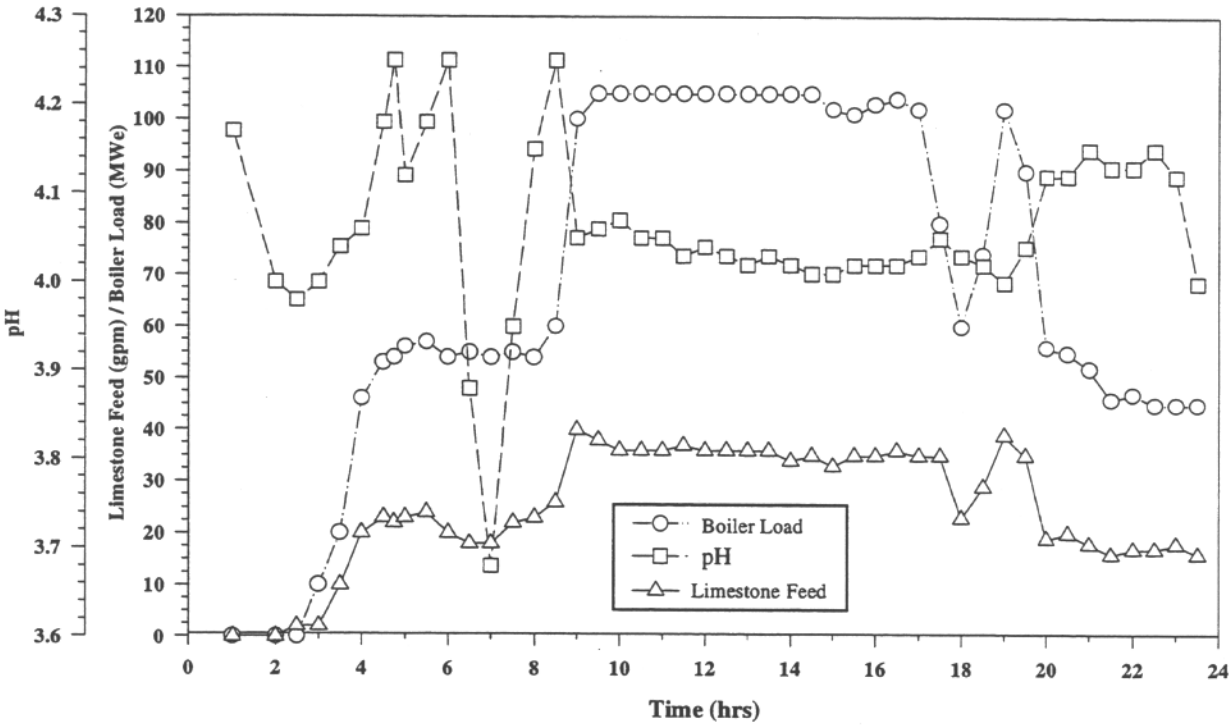

Figure 3-7. Effects of Boiler Load on Limestone Feed Rate and pH

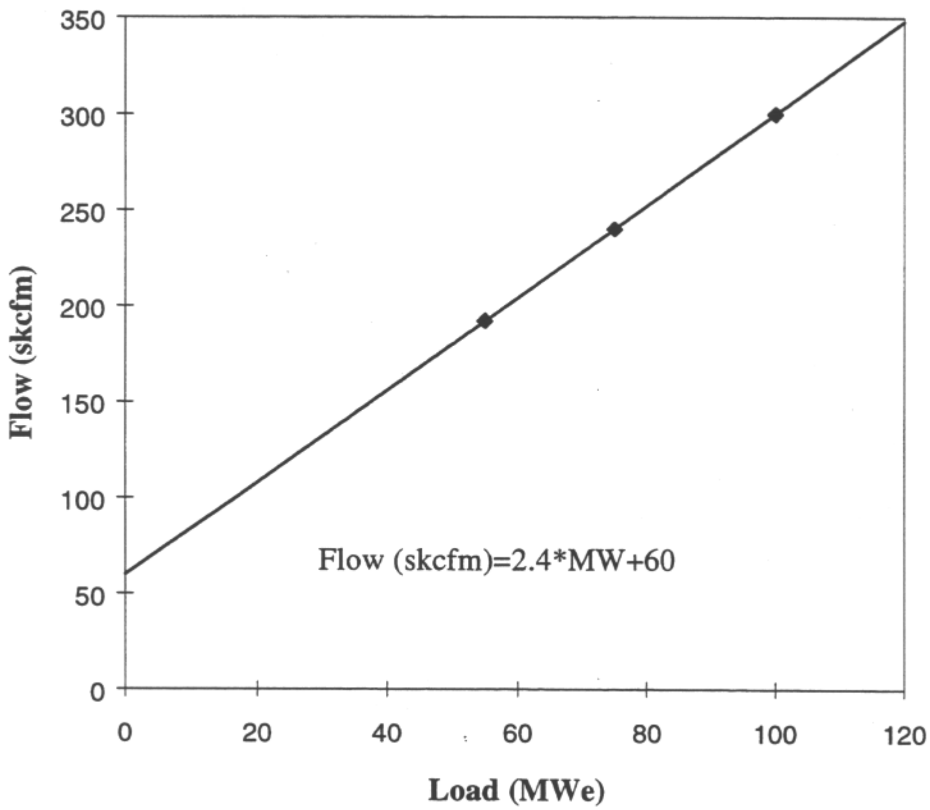

Figure 3-8. Unit MWe vs. Flue Gas Flow

Typically, variations in SO_2 removal efficiency occur slowly, allowing time for the feedback controller to make corrections without disturbing JBR pH. Disturbances to SO_2 removal efficiency can be caused by changes in JBR level due to oxidation air blower switching and loss of limestone slurry feed due to line plugging. Variations in sulfur content of the coal are usually small and not noticed except when a change in coal supplier has occurred. Changes in flue gas sulfur content due to unit load changes were minimal and easily mitigated by the enhanced mass transfer and rapid limestone dissolution rate in the JBR reaction zone.

The feedforward control scheme included logic (i.e., feedback trim) to shut off the limestone feed valve in the event that the pH exceeded a pre-set limit. This controller is illustrated in Figure 3-9. Automatic control, including the feedforward logic, resumed once the JBR pH neared its set point. Adding limestone slurry (via the feedforward logic) prior to the JBR pH reaching setpoint allows time for the solid phase calcium carbonate to dissolve, therefore minimizing controller overshoot. To further enhance the pH control system, the pH controller gain was changed (adapted) over the unit load range. Since the process was more stable at high loads than at low loads, the boiler load signal was input to a function generator f(x), to obtain the proper gain setting for any unit load (MWe) output.

Chiyoda's suggested JBR pH control scheme uses the inlet duct SO_2 concentration combined with a flue gas flow signal for the feedforward signal. The flow signal may be measured with a differential pressure-type flow meter in the duct, calculated from boiler load in megawatts, steam flow and drum pressure, or derived from any other signal which correlates to flow. Should the feedforward signal change abruptly, additional summing corrective action is injected by the derivative (i.e., rate of change) of the feedforward signal. This provides a momentary boost or buck to the slurry flow should the feedforward signal increase or decrease abruptly.

The idea behind Chiyoda's algorithm is to determine the rate at which the unit load is changing as well as to calculate a stoichiometric quantity of reagent required in the process. As the rate of change of unit load increases beyond a preset limit, limestone slurry in excess of the required stoichiometric rate is added to the process. As unit load decreases below a preset limit the

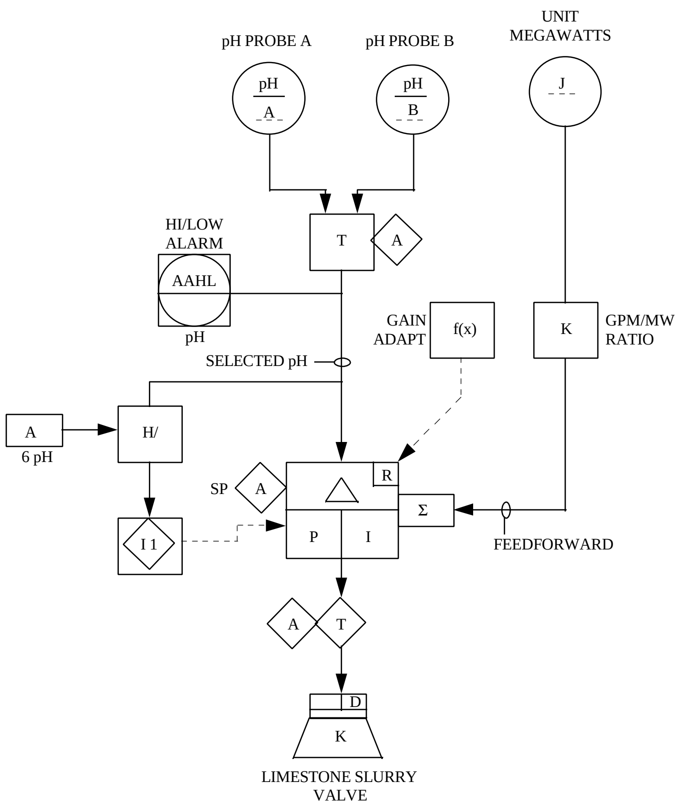

Figure 3-9. pH Feedforward Control Logic Diagram

process is “starved” (i.e., limestone is added at a substoichiometric rate) by a proportional amount. Since the JBR agitator causes the pH measurement signal to be noisy, special conditioning of the signal is required. Additionally, the gain of the trim controller is varied depending upon the SO_2 pick-up rate (i.e., boiler load).

Selection or development of a pH control algorithm depends upon the target SO_2 removal efficiency. From a design point of view, in most cases it is economically prudent not to specify SO_2 removal efficiencies greater than actually needed to comply with environmental regulations. In general, the best control system maintainability and reliability will be achieved by using the simplest control algorithm that will result in the required removal efficiency.

3.2.2 JBR Slurry Density Control

During the CT-121 demonstration project, the control algorithm for JBR slurry density (i.e., weight percent solids) was simply to open the gypsum draw-off valve when the slurry concentration reached the high density set point. This action removed slurry from the JBR, causing the level controller to add water to raise level to the setpoint via the makeup water line. When the low density set point was reached the draw-off valve was closed. The on/off operation of the ceramic draw-off valve when using this control scheme decreased wear and ultimately maintenance costs. Post-demonstration testing showed that the operating density could vary from 5 to 15 wt.% solids rather than trying to operate at 22 - 24 wt.% solids, as was the case during the demonstration, without adversely affecting the process. The advantages of operating the scrubber at the lower slurry concentrations include reduced plugging and reduced wear of the JBR internals.

3.2.3 JBR Level Control

As discussed in Section 3.1.9, JBR level measurement was the most difficult instrumentation challenge in the project. Because erroneous readings resulted from frequent plugging of the instrument sensing lines, several different solutions were attempted during the demonstration project. The most successful of these solutions was to use the existing JBR gas-side differential pressure as a surrogate for JBR level. The drawback to this method of JBR level control was that the gas-side differential pressure was not always directly proportional to the actual JBR level. For a given level and flue gas flow rate, the measured pressure drop increased over time due to gradual fouling of the sparger tubes. Also, at different boiler loads and flue gas flow rates, the dynamic head component of JBR pressure drop was different, even at the same JBR slurry level. These impacts were successfully compensated for, and adequate JBR level control was maintained.

3.2.4 JBR Decks and Mist Eliminator Washing

Solid deposits on the JBR decks and mist eliminator were removed periodically by washing with water. The source of wash water for both of the JBR decks and the front and back of the first stage of the mist eliminator was return water from the gypsum surge pond. Fresh makeup water was used to wash only the front of the second stage of the mist eliminator.

To avoid overloading the wash water pumps, a washing sequence was included in the control system logic that ensured that only one surface was being washed at a time. Each deck or mist eliminator section contained a header with a series of valves, each of which supplied a group of spray nozzles. Valves on the header were opened in sequence and not closed until the next valve on the header opened, which reduced the effects of water hammer on the fiberglass wash water feed pipes.

The solids-laden wash water gravitationally drained to the JBR, which caused a slight increase in level as well as temporary production of a localized positive water balance. At high loads, the excess water quickly evaporated into the flue gas and was removed via the stack. At low loads, the excess water was not completely evaporated, resulting in a reduced JBR solids concentration and requiring that the JBR level control system remove the excess water through the draw-off valve. This problem was resolved by decreasing the header duty cycle (i.e., wash frequency) at lower loads. The unit load (MWe) transducer was used to determine the overall period for the sequence, which varied from 24 hours at full load to 48 hours at minimum load. However, the cycle time for each wash water feed valve remained the same (i.e., 1 minute).

3.2.5 Inlet Duct Water Quench

The purpose of the inlet water quench was to saturate and cool the incoming flue gas stream. Saturation of the hot flue gas stream is required to prevent a wet/dry interface from forming in the inlet plenum and in the sparger tubes, thus reducing the scaling potential at the gas/slurry bed interface. Water quenching the flue gas also serves to protect the sparger tubes by lowering the flue gas temperature below the melting point of PVC (approximately 150 °F). To maintain the proper water balance within the JBR at low loads, the quench water flow controller was modulated based on unit load (MWe).

To further protect the PVC sparger tubes during a high-temperature event, a separate, hardwired emergency shutdown system was provided that would actuate both the makeup water and pond water valves simultaneously and issue a master fuel trip (MFT) to the boiler. Both these sources were connected to the quench water header.

3.2.6 Furnace Pressure Protection Control

The furnace supplying the flue gas to the FGD is a Combustion Engineering, Inc. tangentially fired unit. Though the furnace was originally designed for positive pressure operation, it was converted to operate in balanced draft mode during the original construction of the boiler house. There was concern that the furnace may collapse should it be subjected to a large negative pressure transient since the original design did not include a large negative pressure specification. To mitigate the effects of pressure swings the furnace pressure control and protection system was upgraded to include the following:

- 2 out of 3 furnace pressure switches to trip fuel should high or low pressure exceed + 1.5 or - 2 inches of water column;
- 2 out of 3 furnace pressure switches to trip fan should high or low pressure exceed + 1.75 or - 3.5 inches of water column;
- Fan speed blocking - Should a high or low speed exceed a high or low limit, + 1.0 or - 1.5 inches water column, increases or decreases of fan speed were blocked in the direction that would exacerbate the over/under pressure condition;
- On a master fuel trip (MFT), the ID fan inlet dampers were driven closed to a predetermined point for seven seconds and then released to automatic operation; and
- On extremely high or extremely low furnace pressure conditions, the damper to the existing stack was automatically opened to neutralize the furnace pressure excursion. The setpoint was approximately ± 10.5 inches of water column.

The protection scheme described above is standard on any modern boiler, but was a retrofit for the Yates Unit 1.

Nation Fire Protection Association code requires the natural draft purge of the boiler to remove suspended combustibles from the furnace while minimizing the effects of altering the fuel/air ratio of combustibles remaining in the furnace. Natural draft through the JBR is not possible due to the static liquid head imposed by the slurry bed covering the gas sparger tubes. To allow for natural draft purge the isolation damper to the existing stack was opened five minutes after a fan trip. This provided an unobstructed path from the inlet of the furnace to atmosphere.

Concern for the safety of the furnace is important in application of any add on FGD to an existing unit. Figures 3-10 and 3-11 are furnace pressure plots for a negative pressure master fuel trip and a positive pressure master fuel trip. In Figure 3-11, the unit was at light-off condition when a forced draft fan went into overspeed and tripped the unit. Notice that in figure 3-10 the maximum negative pressure never drops below -7.11 inches of water column. This may be due in part to the large number of leaks in the furnace walls.

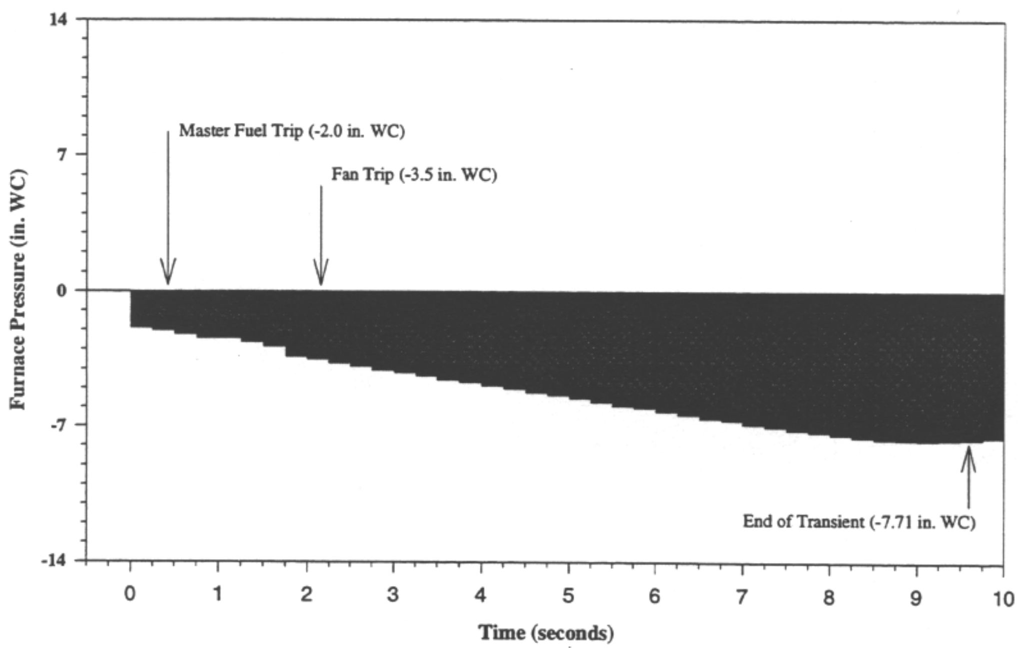

Figure 3-10. Furnace Underpressure Trip During Normal Boiler Operation

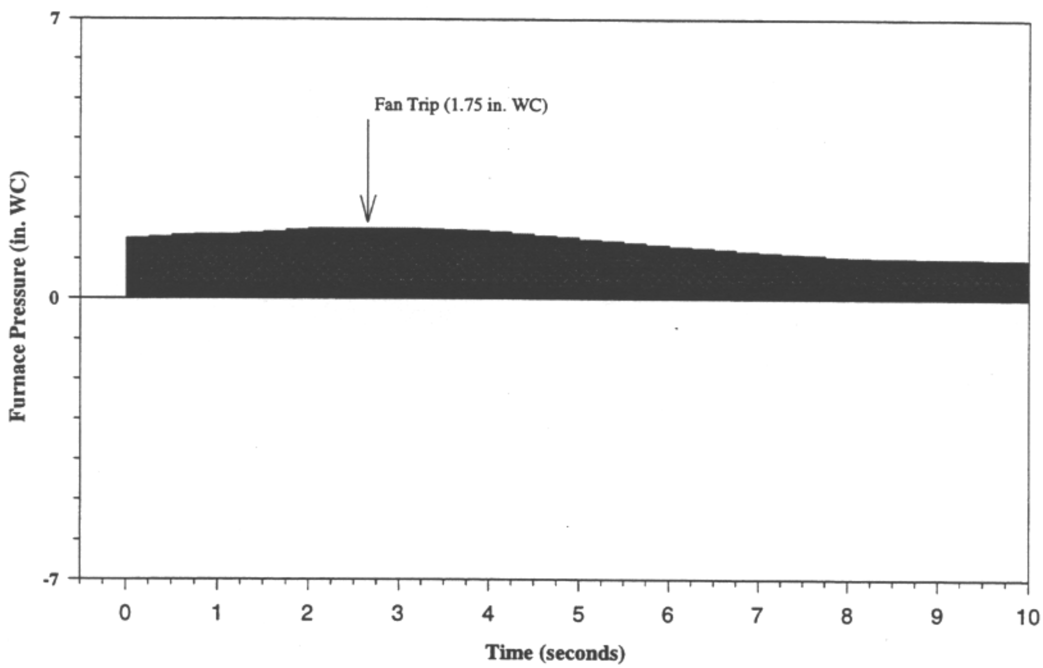

Figure 3-11. Furnace Overpressure Trip Prior to Boiler Light-off

3.3 References

1. McMillen, Gregory, *pH Control,* Instrument Society of America, 1984.

4.0 CONCLUSIONS

In general, the instrumentation and controls and data acquisition systems designed and installed for the CT-121 demonstration project at Plant Yates were able to meet the objectives of adequately controlling the operation of the scrubber and providing the data needed for subsequent analysis. With a few exceptions the various process measurement instruments worked well. The lessons learned over the course of the project with regard to instrumentation and controls are summarized below.

4.1 Distributed Control System

The digital DCS offered several excellent features that made it easy to use by both engineering and operating personnel. These features included user-friendly development and maintenance software tools that closely matched those with which host plant personnel were already familiar. This familiarity also helped reduce training and maintenance expenses. Although the computer-based control system interface was different from the conventional bench board interface already in use in the power plant, the operators found the transition very easy, and came to prefer it over the conventional method.

Embedding a number of the operating procedures in the control software (e.g., slurry pump startup and shutdown procedures) was useful in encouraging the operators to follow prescribed procedures designed to protect the integrity of the process equipment. In other cases manual and semi-automatic control modes were provided so that some steps could be bypassed if necessary (e.g., due to sensor failure).

Hands-on experience during the control software design, programming, and verification phases was very helpful in familiarizing the end-user team (engineers, technicians, and operators) with the relatively new equipment involved in the flue gas scrubbing process, and easing the transition from design through startup to production testing. Using the process simulation capabilities of the

DCS as a training tool allowed all personnel to learn how the process responded to changes in key control variables in a low-stress environment.

Initial scrubber startup and operation were smooth and uneventful due, in part, to precommissioning tests that were conducted on each subsystem as it became available after construction, including instrument calibration, equipment energizing and checkout, and functional tests.

4.2 pH Monitors

Of the three pH monitoring systems evaluated, only the Van London probe-Rosemount transmitter combination was able to last for the entire demonstration project. This was due to the durability of the probe and simplicity of design of the transmitter.

Individual Van London pH probes were found to have a useful life of 3-5 months. In practice, the probes were typically replaced every 2 months to avoid the problems caused by response time degradation that occurred near the end of the probe's life. The new pH probes were found to be very sensitive, so they were allowed to stabilize for a week or two before being used for pH control. To allow consistency in pH measurement, the probes were replaced on an alternating schedule (i.e., one of the two was replaced each month).

The use of hot taps for pH probe installation was very helpful, since it facilitated removal of the probes for cleaning, bench calibration, and replacement without having to shut the scrubber down.

While the two pH probes used in the JBR were initially installed offset by 90 degrees, they were later moved in close proximity to one another. This helped to eliminate inconsistent readings that had been caused by incomplete radial mixing in the JBR.

4.3 Aqueous Stream Flow Meters

Of the flow meters evaluated during the scrubber demonstration, the magnetic type were found to be the most accurate and reliable. While Johnson-Yokagawa meters had a greater turndown capacity, were easier to install, and featured a design that helped minimize problems due to scaling and wear, Rosemount meters were more physically durable.

4.4 Temperature Switches

Temperature indicating switches installed to provide emergency shutdown protection to the JBR proved to be inadequate; they were easily tampered with and were unreliable over the long term.

4.5 Temperature Transmitters

The Ronan temperature transmitters used for this project did not provide reliable information because their electrical contact surfaces quickly corroded in the outdoor environment, even though they were housed in a NEMA 4X enclosure. None of the other instruments used in the project showed this type of corrosion problem.

4.6 Limit Switches

The failure rate of the valve-mounted limit switches that provided the interlocks for the automatic pump flushing performed during startup and shutdown was unusually high. The failures were caused by deterioration of the switch internals caused by moisture intrusion. Hermetically sealed limit switches are one potential solution to this problem.

4.7 Valve Actuators

The valve actuators, which were specified with a spring return to the appropriate failure mode (fail open or fail closed), successfully protected the system from possible plugging due to an air or electrical failure. However, this design created the possibility of large volumes of makeup water entering the scrubber system before the faulty component could be identified and manually valved out. The valves also had a tendency to bind upon spring return.

4.8 Rotameters

The rotameters used to meter makeup water to the oxidation air humidification lines and the JBR level control system purge lines required very frequent maintenance. They had to be taken apart and cleaned after only a week of service because of rapid scaling of the glass and metal floats due to contaminants (e.g., iron) in the ash sluice pond water that was used as makeup water.

4.9 Level Transmitters

The overall performance and reliability of the ultra-sonic level transmitters that were installed in all process tanks (except the JBR) were excellent and this type of instrument appeared to be well suited for the measurement of auxiliary tank levels for the CT-121 process. Setup and calibration were trouble free, and accurate readings were obtained even for the limestone feed silo, which was a dusty environment. Experience with the washing water holding tank demonstrated the importance of installing these devices in accordance with the manufacturer’s recommendations.

4.10 JBR Level Measurement

Measurement of the JBR froth zone level was the most difficult instrumentation challenge that had to be overcome. The differential-type instruments installed were prone to plugging due to the high solids content of the scrubber slurry. Wash water was effective in eliminating solids buildup, but balancing the flows to the two instrument sensing legs proved difficult. Ultimately, the gas-phase pressure differential across the JBR was used as a surrogate for the froth zone level.

4.11 Flue Gas Flow Meters

In general, the accuracy, repeatability, and reliability of the duct-mounted Doppler flowmeters used to monitor the flue gas flow rate in the JBR inlet duct and in the discharge stack were satisfactory. However, a number of problems with these units were not successfully resolved until several months after startup, including problems with installation, calibration, connector corrosion, and damage from lightning strikes. These flowmeters were found to be inadequate from the standpoint of reliability as control elements.

4.12 Continuous Emission Monitor

Use of the CEM (with its dry, fully-extractive systems for inlet and outlet SO_2 concentration monitoring) was only marginally successful for feedforward control. The system was impractical for control purposes due to the nine-minute lag time and problems caused by calibration drift, plugged filters, and component failures.

4.13 pH Control

A key to the successful operation of the CT-121 scrubber was control of the JBR slurry pH. Because of the nature of the relationship between pH and the reactions between limestone and dissolved SO_2, the process was more controllable at lower pH, as expected. Control stability problems were encountered during parametric testing at high pH set points (i.e., above pH 5). Fluctuations in the flue gas flow rate were found to be the major factor influencing the stability of the slurry pH control system. Fluctuations in flue gas SO_2 concentration (caused by changes in coal sulfur content) did not present a control problem due to the buffering capacity of the undissolved limestone in the JBR slurry.

When the scrubber pH set point was between 3.0 and 4.5 and boiler load changes were less than about 5 MWe per minute, stable scrubber control was achieved when using feedback-only control. Higher pH set points and sharper load swings were easily accommodated using feedforward control (based on a mathematical model of scrubber operation). In spite of its stability, the feedforward control method was hampered because of problems with the process sensors. The primary difficulty was with the CEM, which developed problems on the average of more than once per day in measuring flue gas SO_2 concentrations.

4.14 JBR Slurry Density Control

A very simple control algorithm was used for JBR slurry density. The gypsum draw-off valve was opened when the slurry concentration reached its high density set point, and the volume of slurry drawn off was replaced with makeup water. When the low density set point was reached, the draw-off valve was closed. By calling for the ceramic draw-off valve to operate either fully-open or fully-closed, valve wear and maintenance costs were lowered.

Scrubber testing conducted after the demonstration period has showed that the JBR slurry can be controlled at a lower solids loading (from 5-15 wt.% solids rather than the 22 - 24 wt.% solids used during the demonstration tests) without any noticeable reduction in SO_2 removal efficiency.

4.15 Wash Water Control

The JBR decks and mist eliminator are periodically washed with water to remove solid deposits. To avoid overloading the wash water pumps, a washing sequence was included in the control system logic that ensured that only one surface was being washed at a time. The effects of water hammer on the fiberglass wash water feed pipes was reduced by sequencing the spray nozzle feed valves so that each valve on the header was not closed until the next valve on the header opened.

Temporary scrubber level increases and process water balance upsets caused by returning the solids-laden wash water to the JBR were overcome by decreasing the wash water cycle time in response to boiler load.

4.16 Quench Water Control

The rate of quench water addition to the JBR inlet flue gas for gas humidification and protection of the PVC sparger tubes was modulated based on unit loading. This also helped maintain the proper water balance within the JBR. To further protect the sparger tubes during a high-temperature event, a separate hardwired emergency shutdown system was provided that would actuate both the makeup water and pond water valves simultaneously and issue a master fuel trip to the boiler.

5.0 RECOMMENDATIONS

Based on the experience with the instrumentation & control systems evaluated during the CT-121 scrubber demonstration project at Plant Yates, the following recommendations are provided for possible future utility scrubber projects using this technology.

5.1 Control System Training

The time spent in training the operators and other key personnel by using the digital control system as a process simulator was very valuable. During functional testing and startup, such training was found to be well worth the cost because the operators had been able to learn the fundamentals of scrubber process operation in a relaxed environment. With the simulator the operators were not as fearful of the consequences of a mistake as they would have been during live operation, and they knew what to expect from the process during subsequent scrubber check-out and startup.

5.2 pH Probes

The advantages of locating all of the JBR pH probes as close as possible outweighs the potential disadvantages (e.g., the possibility that some event might occur that would damage all of the pH probes). In fact, some publications recommend that three probes be installed in the same area, with the median value being selected for control purposes. The advantages of such an arrangement are increased reliability through redundancy as well as improved response time and less noise in the median signal.

5.3 Temperature Switches

Since the high-temperature trip point for the JBR is only 15-20 F above the normal operating temperature (to protect the PVC sparger tubes), an improvement to the use of tamper-prone and unreliable temperature switches might be to use RTDs with a separate emergency shutdown device. Because of the importance of this measurement, 4-wire RTDs, oil-immersed in tapered thermowells should be considered for improving accuracy and response time. The selection of a suitable material for the thermowell would require special care, given the aggressiveness of the environment in which it would be placed.

5.4 Limit Switches

The limit switches used in the demonstration facility were subject to failure due to moisture intrusion. A better choice for an outdoor application such as a flue gas scrubber may be to use hermetically sealed proximity switches. Although hermetically sealed switches are more expensive than standard limit switches, they can operate fully submerged and in wet and freezing environments.

5.5 Valve Actuators

As an alternative to selecting fail-open or fail-closed valve actuators, a better approach may have been to make all the slurry valves and actuators fail-locked and flush valves and drain valves be fail-closed. The control system could be programmed to alert the operator in the event of valve position failure.

5.6 Rotameters

The conventional rotameters used to meter makeup water for flue gas moisturization and level controller purge lines were subject to fouling due to the buildup of scale from makeup water contaminants. Alternatives might include using a cleaner source of makeup water or specifying all-Teflon rotameters (which might require less frequent cleaning).

5.7 Ultra-Sonic Level Transmitters

Ultra-sonic technology is well-suited to the measurement of auxiliary tank levels in the CT-121 process, because of its non-contacting nature, overall reliability, and ease of installation. Care should be taken to strictly follow the manufacturer's installation instructions.

5.8 JBR Level Measurement

A better system of level measurement for this high-solids application might be direct measurement in a stilling well using a compensated capacitance probe such as a Drexelbrook Coat-Probe, or a separate stand pipe and a differential pressure transmitter. Another option would be to use diaphragm-type pressure sensors, which can be mounted as an integral part of the JBR reaction zone wall. Scaling should not be as great a problem because of the flexible nature of the diaphragm.

5.9 Flue Gas Flow Meters

As alternatives to duct-mounted Doppler flowmeters, consideration could be given to measuring the differential pressure across the mist eliminators and/or to estimate the flue gas rate using a correlation based on the unit load (MWe) output. The former would be useful as long as solids buildup on the mist eliminators could be adequately controlled.

5.10 Continuous Emission Monitor

Improved CEM system reliability can be achieved by using wet-based dilution extractive systems instead of dry fully-extractive systems for obtaining flue gas samples (at elevated temperatures) for SO_2 concentration measurement. System internals are less likely to suffer damage when they are not exposed to high-temperature non-diluted samples.

5.11 pH Control

Selection or development of a pH control algorithm depends upon the specified SO_2 removal efficiency. From a design point of view, it is in the customer's best interest not to specify removal efficiencies greater than actually needed to comply with environmental regulations. Control system maintainability and reliability will be enhanced by using the simplest control algorithm that results in the required removal efficiency.

5.12 JBR Slurry Density Control

Post-demonstration testing showed that the operating density could vary from 5 to 15 wt.% solids (rather than the 20% solids used during most of the demonstration runs) without noticeable reduction in SO_2 removal efficiency. The advantages of operating the scrubber at the lower slurry concentration include a reduced rate of solids accumulation in the gypsum stacking area and reduced wear of the JBR internals.