Effect of Switching to Powder River Basin Coal on Increased Attemperator Use and Cold Reheat Piping Thermal Quench Damage

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EPRI Project Manager

B. Carson

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

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The following organizations, under contract to the Electric Power Research Institute (EPRI), prepared this report:

Intertek Aptech
601 West California Avenue
Sunnyvale, CA 94086

Principal Investigator
C. Lee

Yagen Consulting
366 Shoreline Place
Decatur, IL 62521

Principal Investigator
J. Yagen

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PRODUCT DESCRIPTION

Powder River Basin (PRB) coal consumption has grown rapidly over the past several years. The combination of low cost and low sulfur content makes PRB coal an ideal choice to meet low SOx and NOx emission standards. Many utilities have switched to PRB coal in boilers not designed for its use, and there are significant downsides to the use of this coal.

Because of the insulating quality of PRB coal ash, much of the heat from PRB coal combustion that would normally be absorbed by the waterwall tubes is carried up to the radiant components of the boiler. These components include the superheater and reheater. This overheating of the radiant components calls for attemperator spray to reduce the temperature of the steam prior to entering the turbine. The reheat attemperator is located in the cold reheat (CRH) piping and cools the steam prior to entering the reheater in the boiler. This system was designed as an emergency measure because the reheat attemperator spray degrades efficiency. Increased attemperator use has led to increased thermal fatigue damage in several CRH piping systems, including leaks in the CRH piping.

Results and Findings

This report documented one of the potential consequences of a fuel change from an Eastern Kentucky 10,500 Btu/lbm design basis coal to 8,000 Btu/lbm PRB coal. In order to reach full load with this unit using PRB coal, the CRH attemperator spray flow had to be increased from 2% of CRH flow to 13% of CRH flow. This resulted in a load-dependent increased frequency and severity of quench events on the pipe elbow located approximately 25 ft (7.6 m) downstream of the attemperator. Thermal shock events on this elbow resulted in through-wall cracking, which occurred in 2006. Thermocouples attached to the crack-prone CRH elbow were installed to help determine the frequency and severity of thermal shock events and to help adjust the attemperator operating logic.

Challenges and Objectives

The goal of this Phase I project is to develop a better understanding of the increased magnitude and frequency of damaging attemperator spray quench events in the CRH piping after a switch to PRB coal has been made. This information will then be used to estimate the increased likelihood and the shortened time to initiate attemperator-induced thermal quench damage and the damage accumulation rate. This Phase I project will also identify possible solutions to this damage mechanism that should be investigated in further detail in a follow-on project.

Applications, Value, and Use

A Phase II project is anticipated that will perform more detailed investigations of the thermal quench events in CRH piping (using added diagnostic and troubleshooting monitoring, thermocouples, and strain gages) in combination with finite-element, computational fluid dynamics, and thermal-fatigue damage models. The Phase II project would also perform more detailed evaluations of the costs and potential benefits of corrective action alternatives.

In addition, a Phase III project is envisioned that would focus on performing field trials of promising corrective action alternatives.

EPRI Perspective

EPRI has sponsored this work so that its member utilities might enjoy a minimum of forced outages, improved operating efficiency, and lower maintenance costs. The information contained in this report should assist plants in their run/replace/repair decisions.

Information contained in this report will aid in condition assessment. Ensuring that the best method is applied at the location of greatest risk of damage typically requires expert knowledge, such as that compiled in this report. Recently, EPRI has been working to produce service-relevant documents to assist in the process of ranking the susceptibility of components for damage.

Approach

To achieve the project objectives, the following tasks were performed:

- Task 1: Collect information about the overall design and operational characteristics of units that have switched to firing PRB coal. A data collection template was created for the utilities that would provide input to this project. Using this data collection request and template, the Electric Power Research Institute (EPRI) would obtain the requested key design and operational data from up to four utilities that have switched to PRB coal. The background data would include key design attributes and a review of the hourly MW as well as other key plant historian operational attributes for at least one year prior to the switch to PRB coal and for up to one year with PRB coal firing.
- Task 2: Collect and analyze plant historian data for operational periods before and after switching to PRB coal. The detailed data from the plant historian with CRH steam flow/pressure/temperature and attemperator spray water attributes would be analyzed with a rainflow cycle counting algorithm to determine the frequency and magnitude of CRH attemperator spray events prior to and after the switch to PRB coal firing. Estimates of the relative thermal-fatigue damage accumulation rates per unit operating time for operation before and after the switch to PRB coal would be made using these data.

Keywords

Powder River Basin coal
Cold reheat piping
Attemperator spray flow
Case studies
Thermal model

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1 INTRODUCTION

Background

Powder River Basin (PRB) coal consumption has grown rapidly over the past several years. The combination of low cost and low sulfur content makes PRB coal an ideal choice to meet low SOx and NOx emission standards [1]. Many utilities have switched to PRB coal in boilers not designed for its use. There are significant downsides to the use of PRB coal, including the following:

- PRB coal has a lower heating value per pound than eastern coals.
- More coal must be burned to achieve the same boiler output.
- Additional ash handling is required because of the lower heating value.
- PRB coal is prone to spontaneous combustion if not compacted.
- PRB coal is very sticky and adheres to waterwall tubes.
- The fouling and slagging caused by PRB coal requires additional effort to remove the ash.

Because of the insulating quality of PRB coal ash, much of the heat from PRB coal combustion that would normally be absorbed by the waterwall tubes is carried up to the radiant components of the boiler. These components include the superheater and reheater. This overheating of the radiant components calls for attemperator spray to reduce the temperature of the steam prior to entering the turbine.

The reheat attemperator is located in the cold reheat (CRH) piping and cools the steam prior to entering the reheater in the boiler. This system was designed as an emergency measure because the reheat attemperator spray degrades efficiency. Increased attemperator use has led to increased thermal fatigue damage in several CRH piping systems, including leaks in the CRH piping.

Objective

The goal of this Phase I project is to develop a better understanding of the increased magnitude and frequency of damaging attemperator spray quench events in the CRH piping after a switch to PRB coal has been made. This information will then be used to estimate the increased likelihood and the shortened time to initiate attemperator-induced thermal quench damage and the damage accumulation rate.

This Phase I project will also identify possible solutions to this damage mechanism that should be investigated in further detail in a follow-on project.

A Phase II project is anticipated that will perform more detailed investigations of the thermal quench events in CRH piping (using added diagnostic and troubleshooting monitoring, thermocouples, and strain gages) in combination with finite-element, computational fluid dynamics, and thermal-fatigue damage models. The Phase II project would also perform more detailed evaluations of the costs and potential benefits of corrective action alternatives.

A Phase III project is envisioned that would focus on performing field trials of promising corrective action alternatives.

Work Scope

To achieve the project objectives, the following tasks were performed:

- Task 1: Collect information about the overall design and operational characteristics of units that have switched to firing PRB coal. A data collection template was created for the utilities that would provide input to this project (see Appendix A). Using this data collection request and template, the Electric Power Research Institute (EPRI) would obtain the requested key design and operational data from up to four utilities that have switched to PRB coal. The background data would include key design attributes and a review of the hourly MW as well as other key plant historian operational attributes for at least one year prior to the switch to PRB coal and for up to one year with PRB coal firing.
- Task 2: Collect and analyze plant historian data for operational periods before and after switching to PRB coal. The detailed data from the plant historian with CRH steam flow/pressure/temperature and attemperator spray water attributes would be analyzed with a rainflow cycle counting algorithm to determine the frequency and magnitude of CRH attemperator spray events prior to and after the switch to PRB coal firing. Estimates of the relative thermal-fatigue damage accumulation rates per unit operating time for operation before and after the switch to PRB coal would be made using these data.

Conversion Factors for Units Used in This Report

1 in. = 25.4 mm

1 psi = 6.89 kPa

°C = (°F - 32) x 5/9

1 ft = 0.3 m

2
CASE STUDIES

Havana Power Station, Unit #6, Havana, IL

The original scope of work called for data from up to four utilities that had made the switch to PRB coal. The final scope of work was reduced to a single utility and power plant: Dynegy's Havana Unit #6. Havana Unit #6 has experienced a long history of CRH problems and has undergone significant changes to the CRH piping and to attemperator hardware and operation.

Cold Reheat Piping History

Havana Unit #6 began operation in June 1978. The unit was designed for cycling duty and was equipped with a hot side electrostatic precipitator. The boiler was supplied by Babcock & Wilcox, and the turbine was supplied by Kraftwerk Union (now Siemens). The unit produces 427 NMW during the summer and 430 NMW in the winter. The CRH piping is 33.625 in. outside diameter (OD) x 0.825 in. minimum wall thickness. The CRH piping was built to ASTM A-155 Grade KC60 Class 1. The design specification is 650 psi at 672°F. Figure 2-1 shows an isometric view of the CRH piping. The CRH attemperator is located near the top of the vertical riser, approximately 25 ft below the elbow.

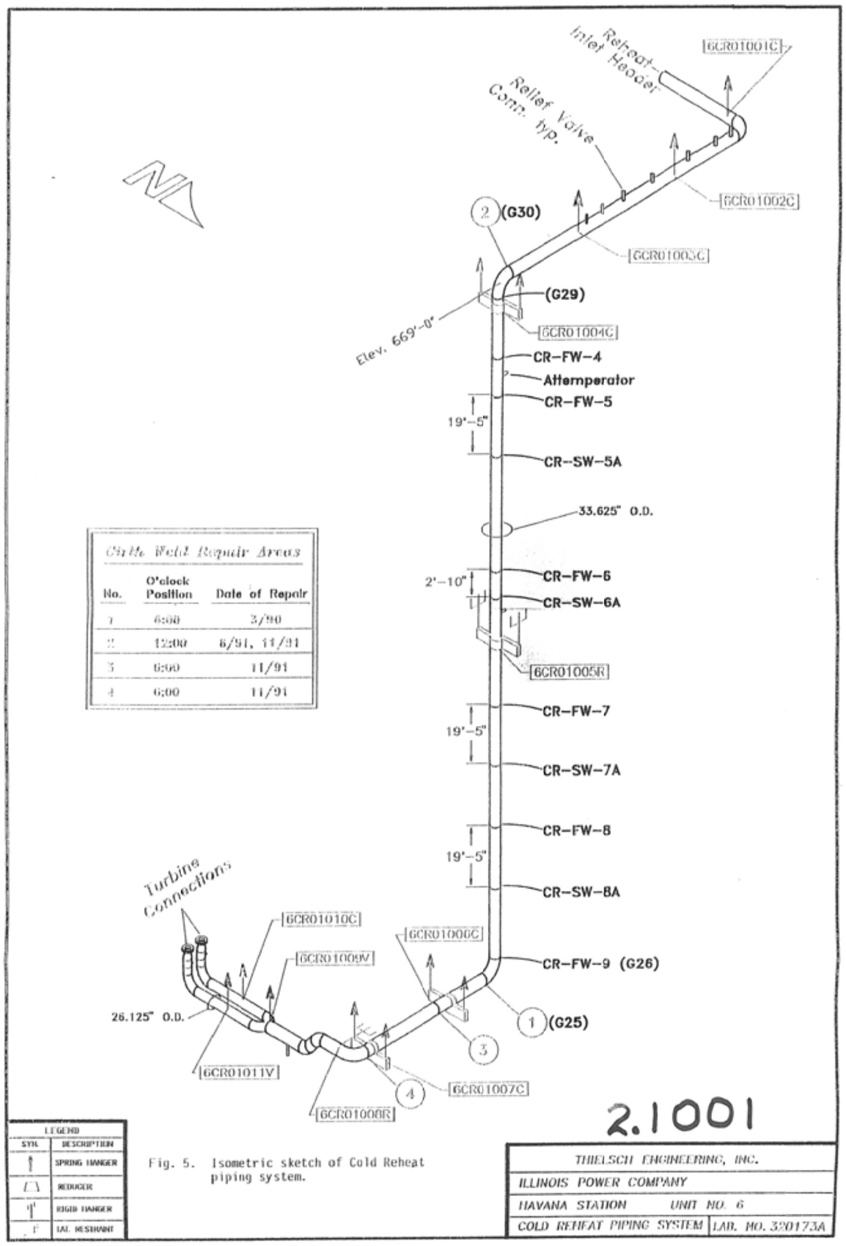

Figure 2-1
Isometric View of the Cold Reheat Piping (the attemperator is located near the top of the vertical riser)

The CRH piping system has had problems, since the beginning of operation, with water hammer on startup. Several repairs were made over the years due to excessive pipe movement and subsequent mechanical fatigue cracking and, in some cases, failures at the girth welds. In addition, leaking of the attemperator spray valve resulted in thermal fatigue failures at the bottom of the riser. Major repairs included the addition of a hanger on the lower horizontal run and an anchor to restrict excessive movement. An additional low-point drain was also added.

Nondestructive testing of the piping began in the 1990s with the stripping of the piping system. Wet fluorescent magnetic particle testing (WFMT) revealed several mechanical fatigue cracks at girth welds. This was followed with the inspection of one or two girth welds each outage using WFMT for surface flaws and using time-of-flight diffraction (TOFD) or shear wave ultrasonic testing (UT) for flaws initiated on the inside surface or within the wall of the pipe.

In 2003, a Quantitative Acoustic Emission Nondestructive Inspection (QAENDI) system was installed on the piping to assist in selecting girth welds for inspection. In 2003, QAENDI indicated activity in the piping before the attemperator at the bottom of the riser, at the attemperator, and after the attemperator at the top of the riser. Subsequent inspection with TOFD on the seam welds and UT on the girth welds found no flaws large enough to report.

Plans for the conversion of Havana Unit 6 from Eastern Kentucky Coal to PRB coal called for several changes. The Btu content of PRB coal is in the 8,000 Btu/lbm range, while Havana Unit #6 was designed for 10,500 Btu/lbm. More coal must be burned to achieve the same boiler output, and more ash must be handled. In order to reach full load with this unit using PRB coal, the attemperator spray not only had to be used, but the spray flow increased from 2% of CRH flow to 13%. To allow for this flow rate, the attemperator spray valve trim was changed.

In January 2005, the switch to PRB was completed during the scheduled outage for Havana Unit #6. The QAENDI inspection was repeated. This inspection showed increased activity at and above the attemperator. Because no flaws were large enough to be seen by advanced ultrasonic methods in 2003, no further nondestructive evaluation (NDE) was performed.

On August 11, 2006, a steam leak was observed at the girth weld of the elbow at the top of the riser downstream of the attemperator (see Figure 2-1). The “mirror image” girth weld at the bottom of the riser was inspected because pipe movement was suspected as the root cause due to earlier failures. The unit was repaired and restarted. On August 14, 2006, a steam leak was observed at the intrados weld of the same elbow at the top of the riser.

The piping was examined for additional damage. Advanced ultrasonics including linear phased array (LPA) and TOFD were used in addition to radiography and magnetic particle testing (MT). The inspection revealed several girth and seam welds with cracks in the area of the attemperator and in the elbows downstream and upstream of the attemperator. All cracks that were discovered had initiated on the inside surface of the piping, which is consistent with thermal fatigue caused by liquid water from the attemperator repeatedly hitting the hot piping surface.

A review of the Process Information (PI) system® data prior to failure showed that the pipe was being shocked thousands of times by the cycling of the attemperator spray control. The pipe would get up to temperature, the attemperator spray would come on and shock the pipe, and then the attemperator spray would turn off. This sequence of events happened hundreds of times per day.

A thermocouple was welded to the extrados of the elbow and a second thermocouple to the intrados. After the unit was returned to service and the spray flow begun, a differential of 300°F was immediately shown between the thermocouples. This indicated that liquid water was striking the inside surface of the extrados of the elbow, 25 ft above (downstream of) the attemperator.

Knowing the root cause of the failure and still needing to achieve full load, the following plan was used. As the load increased in the morning, the attemperator spray was manually actuated, shocking the hot pipe once. The attemperator spray was left on and not allowed to cycle off and on. The continuous spray did not allow the pipe to heat up and be shocked due to the differential temperature between the pipe and the spray water. In this way, the piping system was limited to only one shock per day.

In May 2007, the elbow at the top of the riser was replaced with a seamless elbow. Operation of the attemperator continued in the manual mode. An attempt was made to replace the original attemperator with a new one. However, because the new attemperator atomize the spray but did not supply sufficient flow, it was replaced by the original attemperator.

In May 2008, a second attemperator was added upstream of the original attemperator. Both attemperators were then in service, with the combined flow increased to 300 kilopascals per hour (kpph) from a maximum of 200 kpph for the single original attemperator.

In the spring of 2009, the entire CRH piping system was replaced. The new system is specified as SA-106 Grade B. The 90° elbow is SA234 WPB. Both of these specifications are for seamless material. The pipe and elbow are 31.75-in. inside diameter with a minimum wall thickness of 0.842 in.

During the same outage, a new attemperator was located 80 ft below the elbow at the top of the riser. A total of 10 ft of the lower portion of the reheater pendants was removed to reduce the heating surface. This reduction in heating surface reduced the need for attemperation; as a result, RH spray flow was reduced from 300 kilo pounds per hour (klbh) to 200 kpph.

To ensure that the elbow at the top of the riser was not being thermally shocked by the attemperator spray, thermocouples were attached to the top of the extrados of the elbow and to the bottom of the intrados of the horizontal portion of the elbow. If, in fact, the elbow was being shocked, there would be a large differential between the thermocouples.

The CRH piping experienced an average of 38 thermal shocks in a range of 150°F to 160°F over a period of 30 days. After the spring outage of 2009, the number of thermal shocks was reduced to 8 within the same temperature range in a period of 30 days.

3
DATA ANALYSIS

Comparison of Data from Before and After the Switch to PRB Coal

The list of information shown in Appendix A was supplied to Dynegy in the spring of 2010. Three years of data taken at 1-minute intervals were collected: 2004, the year before the switch to PRB coal; 2005, the year after the switch to PRB coal, and 2006, the year the elbow failure occurred.

The data for 2004–2006 were reviewed, with an emphasis on the following parameters:

- Gross generation
- CRH fluid temperature at the attemperator
- Saturation temperature in the CRH piping based on the CRH pressure at the turbine
- Attemperator flow rate

The CRH attemperator operates by taking water from the boiler feed pump and spraying it into the CRH piping. The attemperator is designed to atomize all of the water sprayed into the CRH so that no droplets remain to impact the CRH pipe wall. The CRH temperature at the attemperator is a measurement of CRH bulk fluid temperature taken at a thermowell downstream of the attemperator. Measurements of CRH temperature that are near the saturation temperature of the steam indicate both that water has not been totally atomized by the attemperator and that the thermowell is being struck by water droplets. This is an indication that the CRH inside pipe wall surface is also being hit by water droplets. What is not necessarily true, however, is that if the measured CRH temperature is well above saturation, the CRH walls are not being hit by water droplets.

Figure 3-1 shows the average attemperator flow rate for 2004 and 2005 versus gross generation (the columns, along with the primary y-axis on the left side, represent the flow). The figure shows increased attemperator usage in all load ranges due to the switch to PRB. The increased attemperator usage is significantly higher up to loads of 300 MW. The figure also shows the average CRH superheat based on the attemperator fluid temperature and the CRH pressure at the turbine (the data points, along with the secondary y-axis on the right side, represent the superheat). The average CRH superheat tended to be lower after the changeover, which is a reflection of the increased attemperator operation.

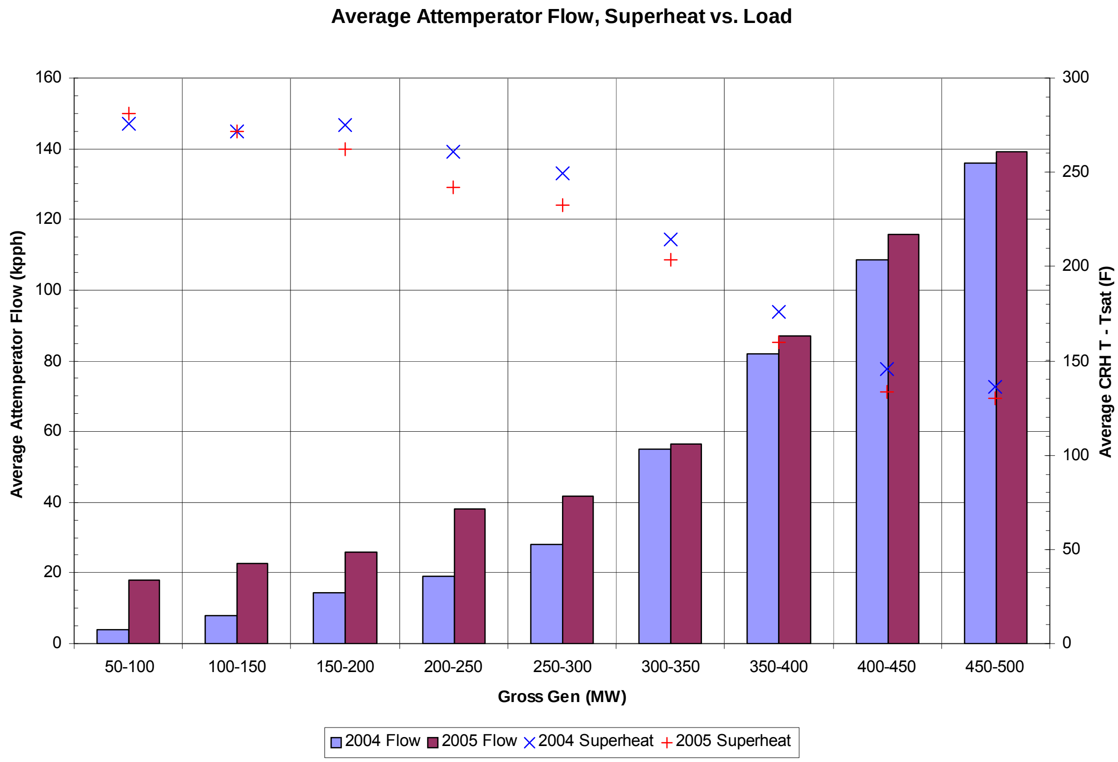

Figure 3-1
Average Attemperator Flow: Average Superheat Versus Gross Generation

Figure 3-2 shows the same average attemperator flows but with the minimum values of superheat at the attemperator. The minimum CRH temperatures after the switch to PRB coal in 2005 are consistently close to or below the saturation temperature for loads less than 400 MW (that is, the superheat is near zero or less than zero), while the minimum CRH temperatures before the switch to PRB coal in 2004 are significantly higher. Superheat values near zero are an indication that the attemperator thermowell is being hit by spray water, which is an indication that the CRH pipe wall is also being hit by spray water. This phenomenon is seen before the switch to PRB coal, but it is exacerbated by the increased attemperator usage after the switch to PRB coal. Because of the inability of the attemperator to completely atomize the spray flow, the increased spray flow at the lower loads is causing more spray water to hit the CRH wall.

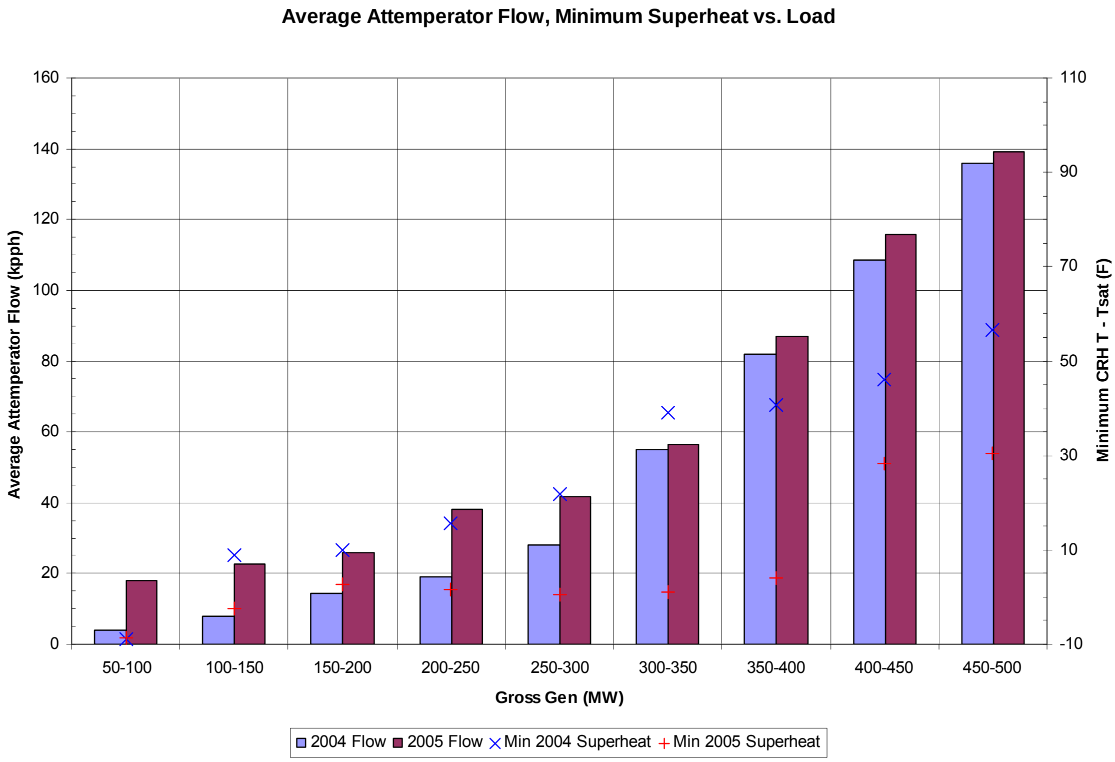

Figure 3-2
Average Attemperator Flow: Minimum Superheat Versus Gross Generation

Figure 3-3 shows the average attemperator flows along with the average hot reheat (HRH) temperature at the turbine versus gross generation. The data after the switch to PRB coal in 2005 show that the HRH reaches design temperature at much lower loads than before the conversion (shown by the data points and secondary y-axis on the right side), which is an indication of the need for increased attemperation.

Average Attemperator Flow, HRH Temperature vs. Load

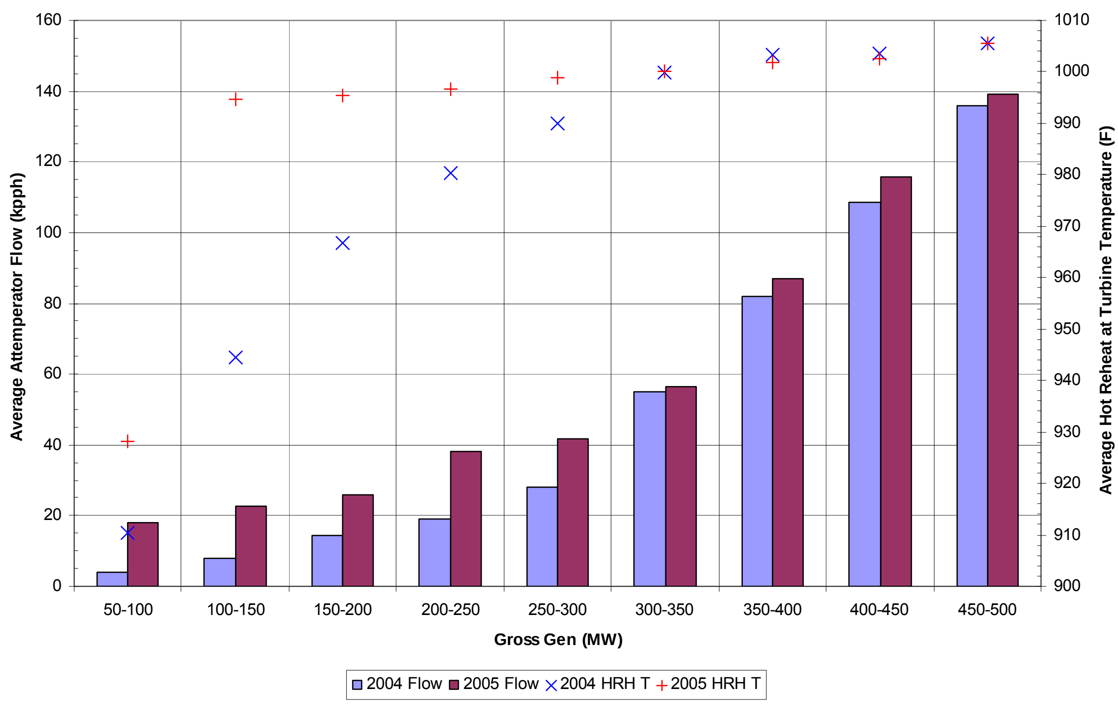

Figure 3-3
Average Attemperator Flow: HRH Temperature at the Turbine Versus Gross Generation

Figure 3-4 shows the percentage of time attemperation required versus gross generation (the columns, along with the primary y-axis on the left side, represent this percentage). The figure shows that the percentage of time at each load range spent with the attemperator in operation increased with the switch to PRB coal, with the highest increases for loads less than 300 MW. The increased use of the attemperator at all loads after the switch will result in increased damage to the CRH because of the increased volume of spray flow hitting the walls. The figure also shows the percentage of time spent at each load range. The unit tended to spend more time at lower loads in 2004; the unit spent 56% of operation at 450–500 MW in 2005 compared to only 37% in 2004. The columns show that the attemperator is on the entire time the unit is at 450–500 MW, regardless of the coal. Figures 3-1 through 3-3 show that the average attemperator spray flows are highest in the load range of 450 to 500 MW. The increased amount of time spent at full load after the switch will also result in increased damage to the CRH because of the higher spray flow rates seen by the CRH over a longer period of time.

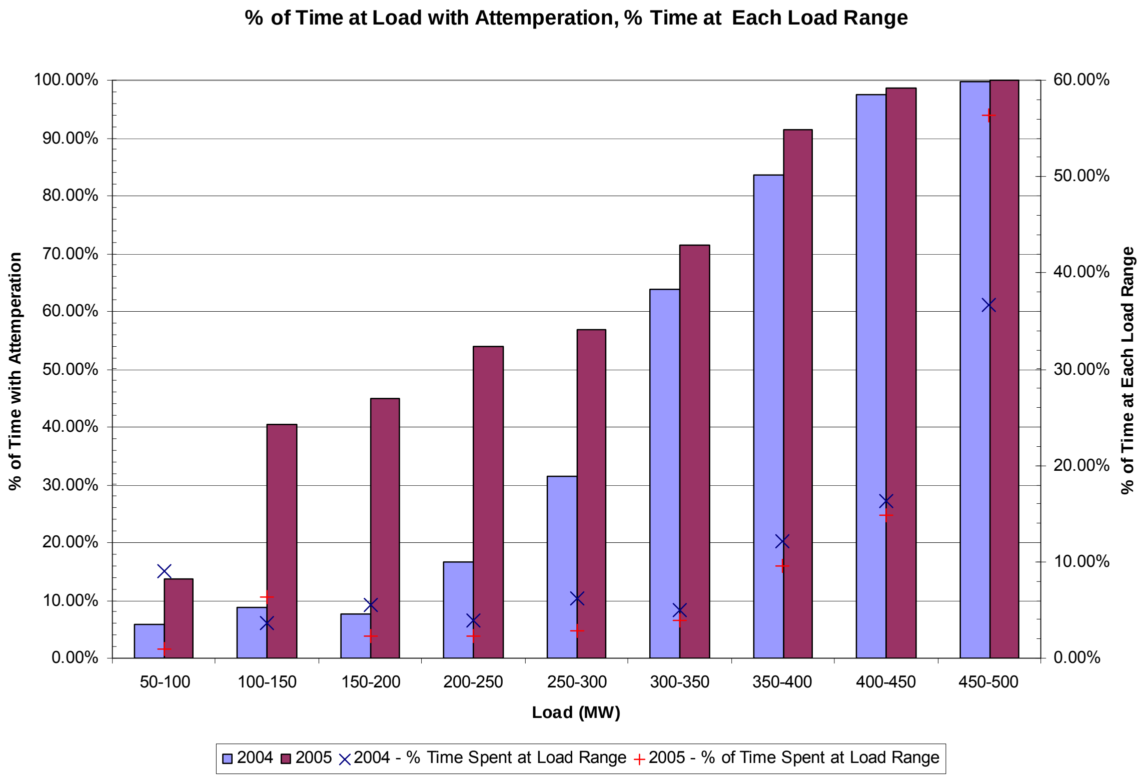

Figure 3-4
Percentage of Time Spent at Each Load Range Versus Gross Generation

Figure 3-5 shows the range of CRH temperatures versus attemperator flow rates for 2004 and 2005. The maximum CRH temperatures are similar for 2004 and 2005; the minimum CRH temperatures for 2004 are generally higher than for 2005. In both years, many of the minimum CRH temperatures are near the minimum saturation temperature at each flow rate, although this happened more often in 2005 than in 2004. This is again indicative of spray water hitting the attemperator thermowell. The increased need for spray at all loads and spray flow rates because of the switch to PRB coal exacerbates this problem, which is shown by the lower minimum temperatures in 2005 and the increased number of temperatures near saturation. One other interesting item to note is that, at flow rates greater than approximately 140 kpph, the range between the maximum and minimum CRH temperatures starts to decrease, with the maximum values decreasing more rapidly than the minimum values increase. In addition, the minimum values consistently stay above the saturation temperature at these higher flow rates.

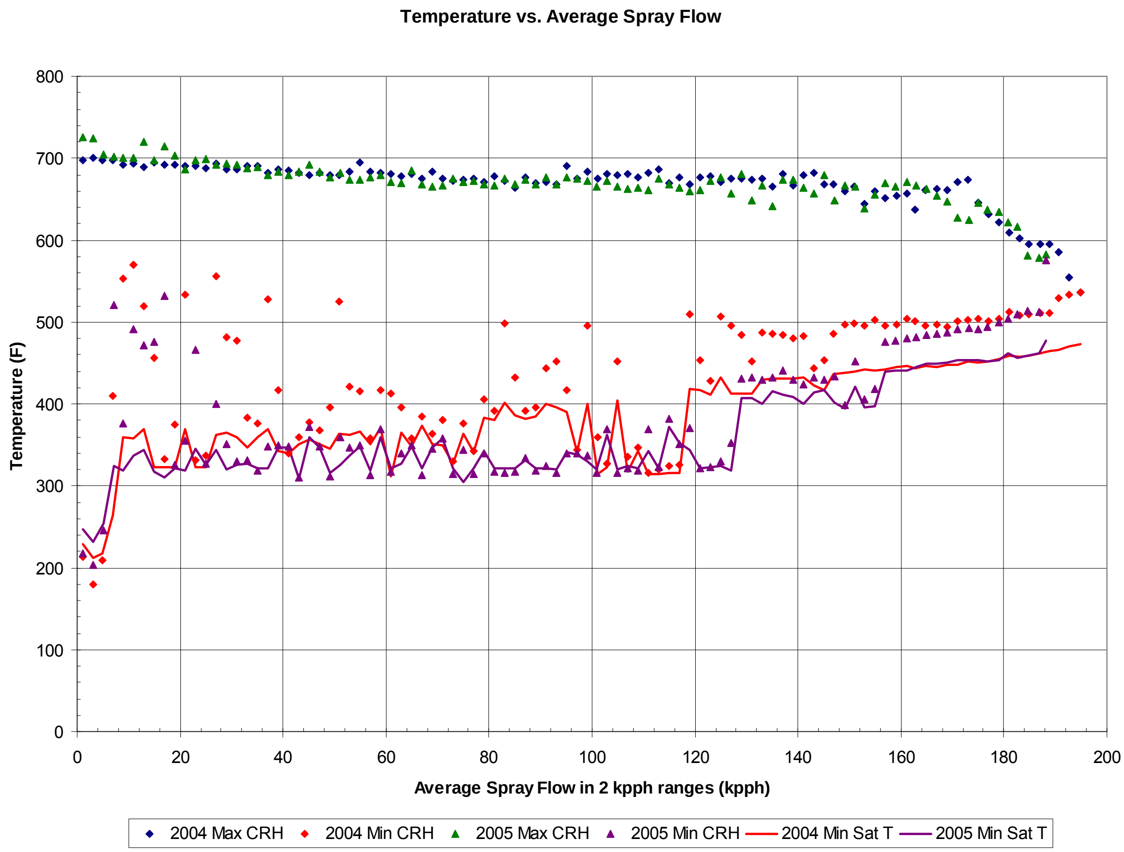

Figure 3-5
CRH Temperature Range as a Function of Attemperator Spray Flow

Figure 3-6 shows the range of CRH temperatures versus gross generation for 2004 and 2005. The same conclusions for Figure 3-5 can be drawn for Figure 3-6: the maximum CRH temperatures are similar, and the 2004 minimum CRH temperatures are generally higher than for 2005. The spray water hits the attemperator thermowell at many load ranges, which is truer for 2005 than 2004. The CRH temperature range decreases at higher loads, which correspond to the higher attemperator spray flows.

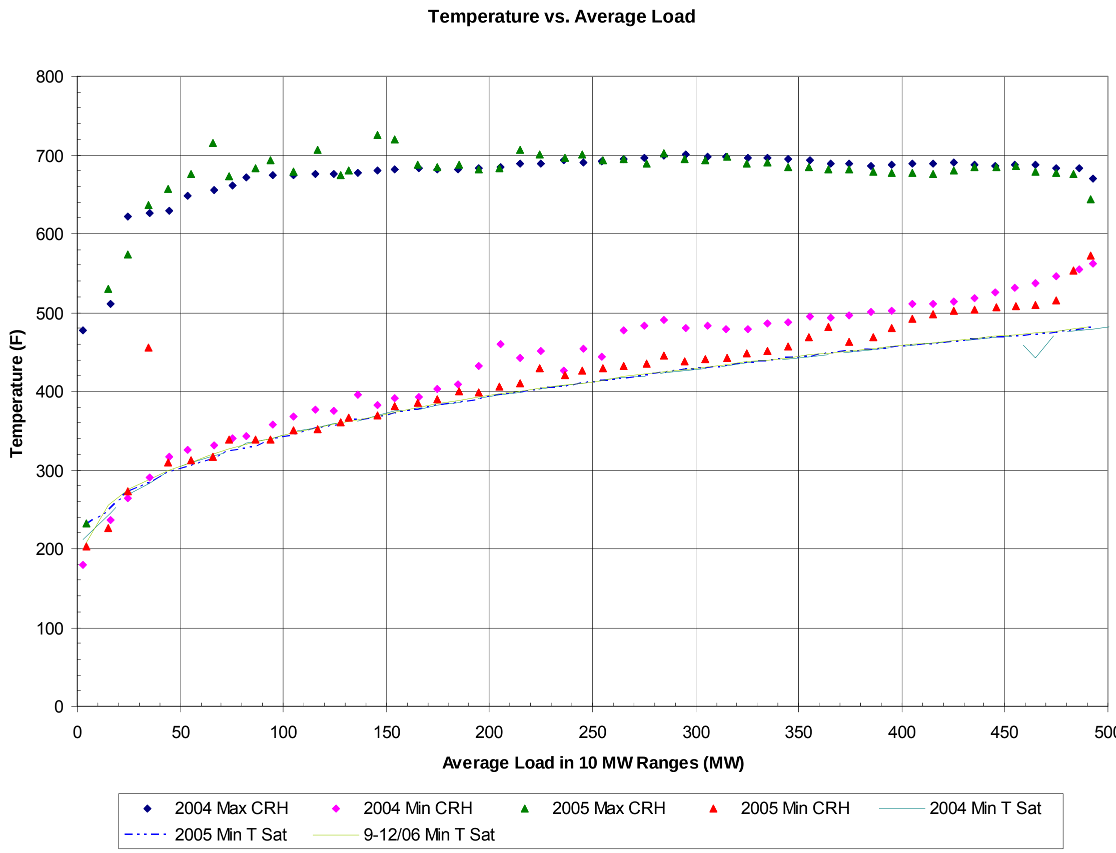

Figure 3-6
CRH Temperature as a Function of Gross Generation

Although the CRH temperature at the attemperator, as measured by the thermowell downstream of the attemperator, gives an indication of times at which the CRH pipe wall downstream of the attemperator might be hit by spray water, there are no direct pipe wall measurements for 2004 and 2005. Direct measurements are found in the 2006 data.

The 2006 data were split into two time periods: January through August, and September through December. The data from September through December 2006 contain the elbow extrados OD thermocouple, which was installed after the August 2006 leak. Attemperator operation was also changed after the leak in August 2006 to manual activation once per day. The attemperator operated in the same manner from January 2005 through August 2006.

The September through December 2006 data were reviewed with an emphasis on development of a thermal model that could be used to determine an estimate of the temperature drop across the wall of the CRH piping. The model would then be used to estimate the temperature drop across the CRH pipe wall for 2004 and 2005, when no elbow extrados thermocouple existed. The thermal model is discussed in Section 4 of this report.

Figure 3-7 shows the range of CRH temperatures for 2004 through 2006. The figure contains the same data as shown in Figure 3-5, with the addition of the 2006 data. Figure 3-7 shows that the maximum CRH temperatures for both time periods in 2006 are similar to the 2004 and 2005 data, although both are slightly lower at high attemperator flow rates. The minimum values for January to August 2006 are similar to those for 2005, with many values near the minimum saturation temperature. The results of the change in operation to manual activation of the attemperator can be seen in the minimum CRH values for September to December 2006. The minimum values at flow rates up to approximately 120 kpph are substantially higher than for the previous time periods, including in some cases the data for 2004. The CRH temperature ranges for 2006, as with the previous data, also start to converge at attemperator flow rates above approximately 140 kpph.

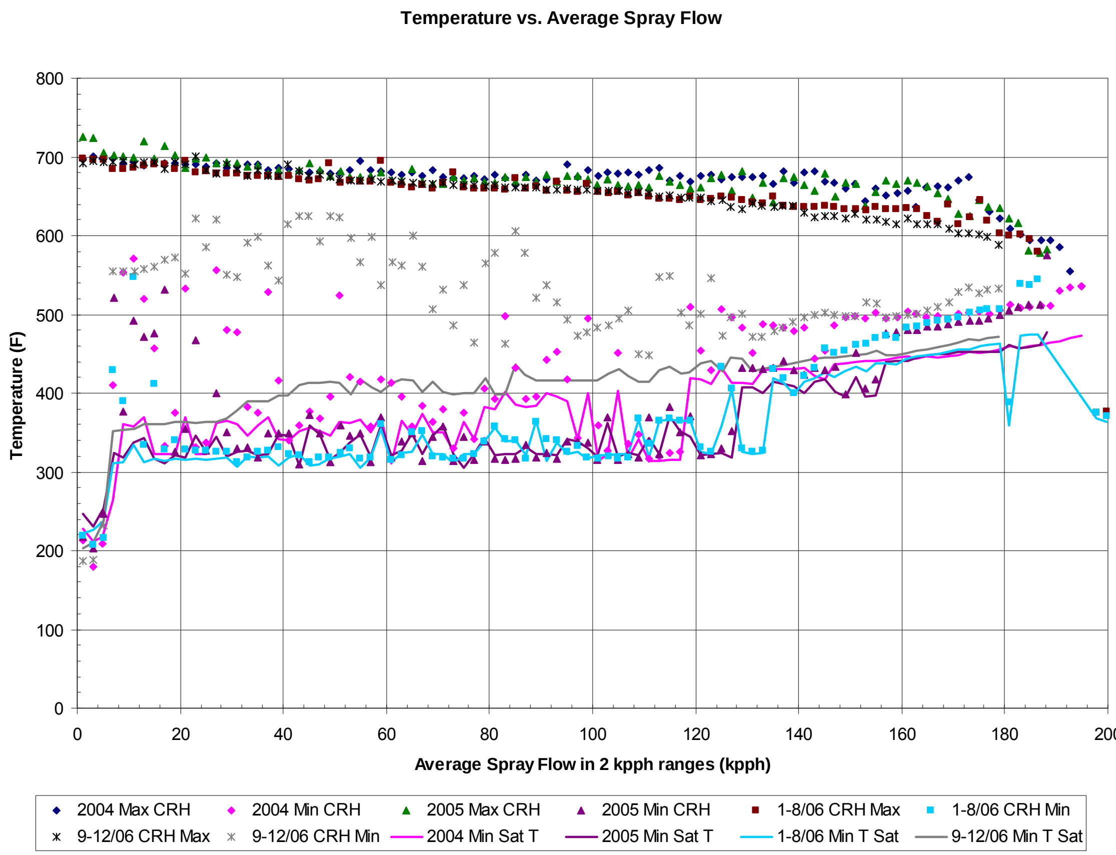

Figure 3-7
CRH Temperature Ranges for 2004 Through 2006 as a Function of Attemperator Spray Flow

Figure 3-8 shows the same data as Figure 3-6, with the addition of the 2006 data. The maximum CRH temperatures are similar for all data; the minimum values for the September to December 2006 data are substantially higher at loads up to approximately 250 MW. The minimum CRH temperatures are near the saturation temperature for the data from 2004 through August 2006 for loads up to approximately 300 MW, although the 2004 data tend to be higher.

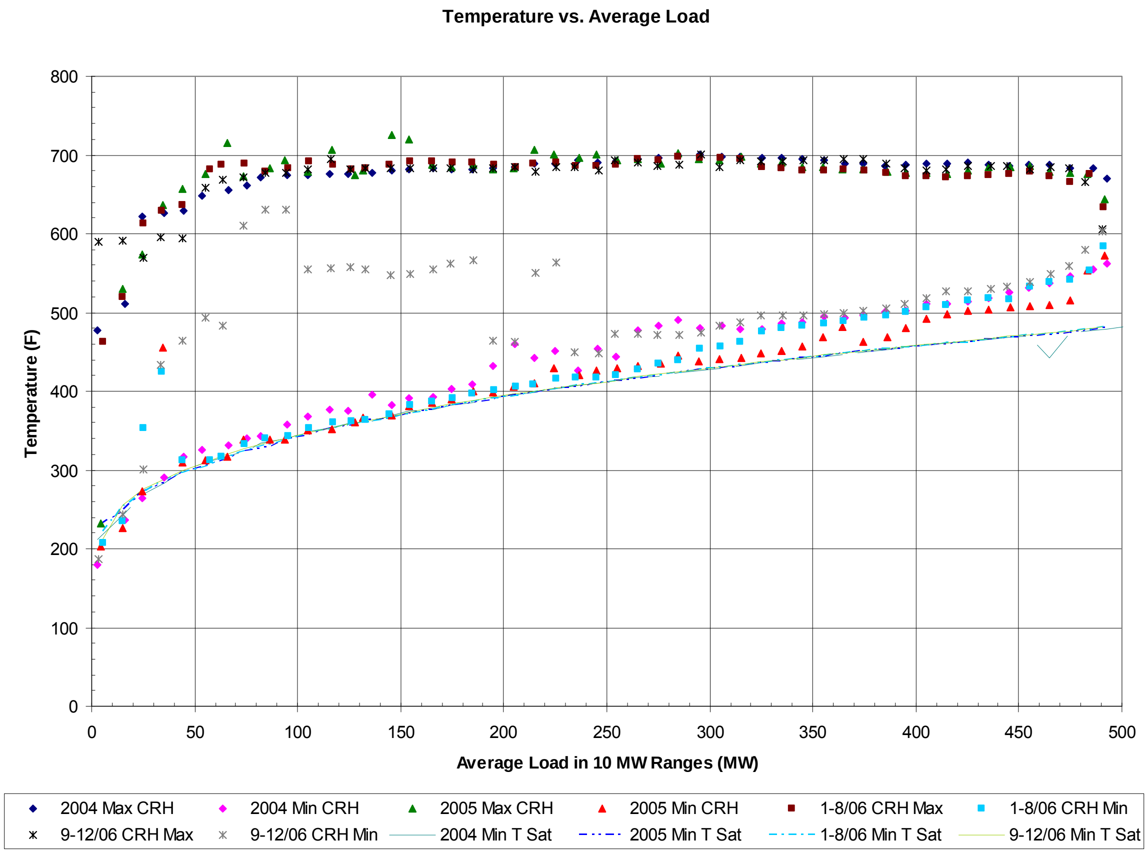

Figure 3-8
Temperature Ranges for 2004 Through 2006 as a Function of Gross Generation

Figure 3-9 shows both the CRH fluid temperature and the elbow extrados OD temperature as a function of attemperator spray flow. The minimum elbow extrados OD temperature follows the minimum saturation temperature for all spray flows, regardless of the minimum CRH temperature. This implies two things: first, the elbow is being hit by water droplets for all ranges of attemperator spray flow; second, the temperature of the water hitting the elbow is not the same as that measured by the CRH attemperator thermowell. The maximum elbow extrados OD temperature follows the CRH temperature until attemperator flow rates greater than approximately 100 kpph are achieved, when the maximum values start to decrease. At attemperator flow rates greater than approximately 150 kpph, the range between the maximum and minimum elbow extrados OD temperatures decreases to a small value. This is indicative of a condition in which the high spray flow results in the elbow being constantly hit by spray water.

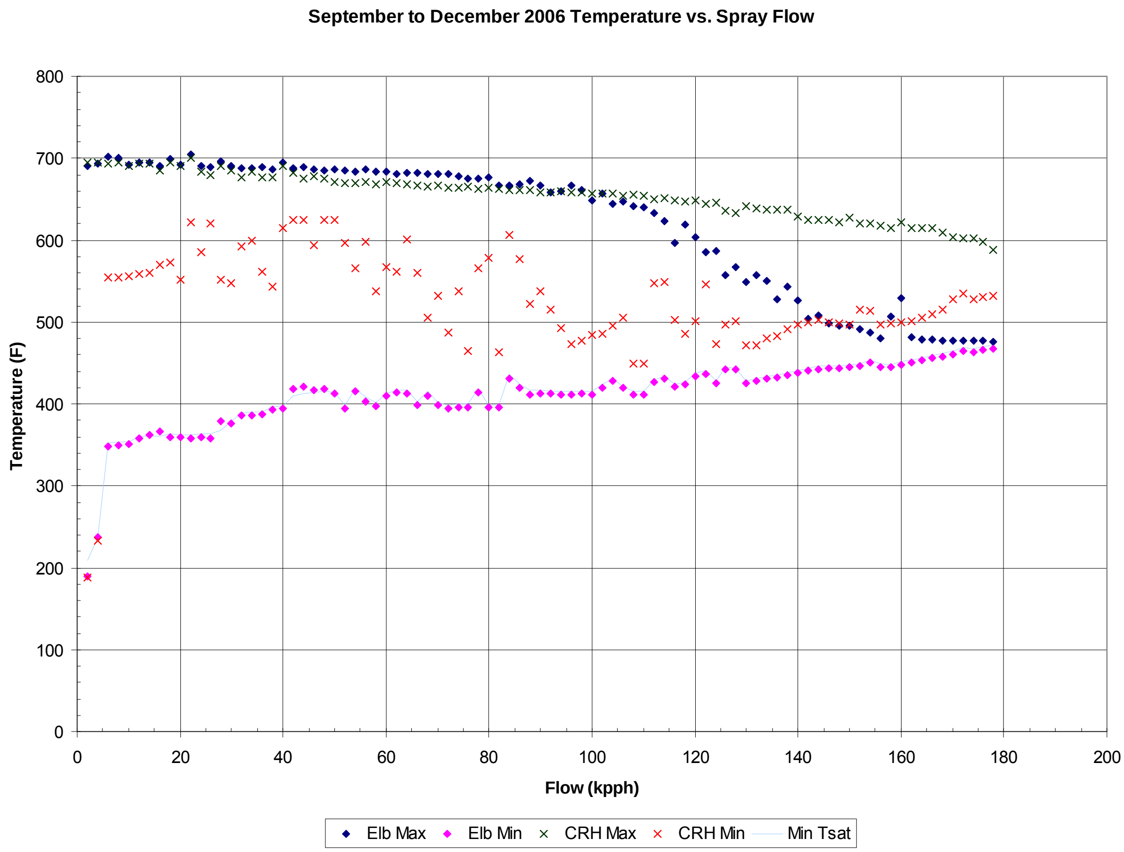

Figure 3-9
CRH and Elbow Extrados OD Temperatures as a Function of Attemperator Spray Flow

Figure 3-10 shows the elbow OD temperatures as a function of gross generation from September to December 2006. Again, although the minimum CRH temperatures are higher because of the change in operation, the minimum elbow temperatures are still around the minimum saturation temperature at each load. The maximum elbow temperatures follow the maximum CRH temperatures, which together with Figure 3-9 indicate that the elbow temperature is a strong function of the attemperator spray flow rate and not a strong function of the gross generation (in other words, a function of the CRH steam flow rate).

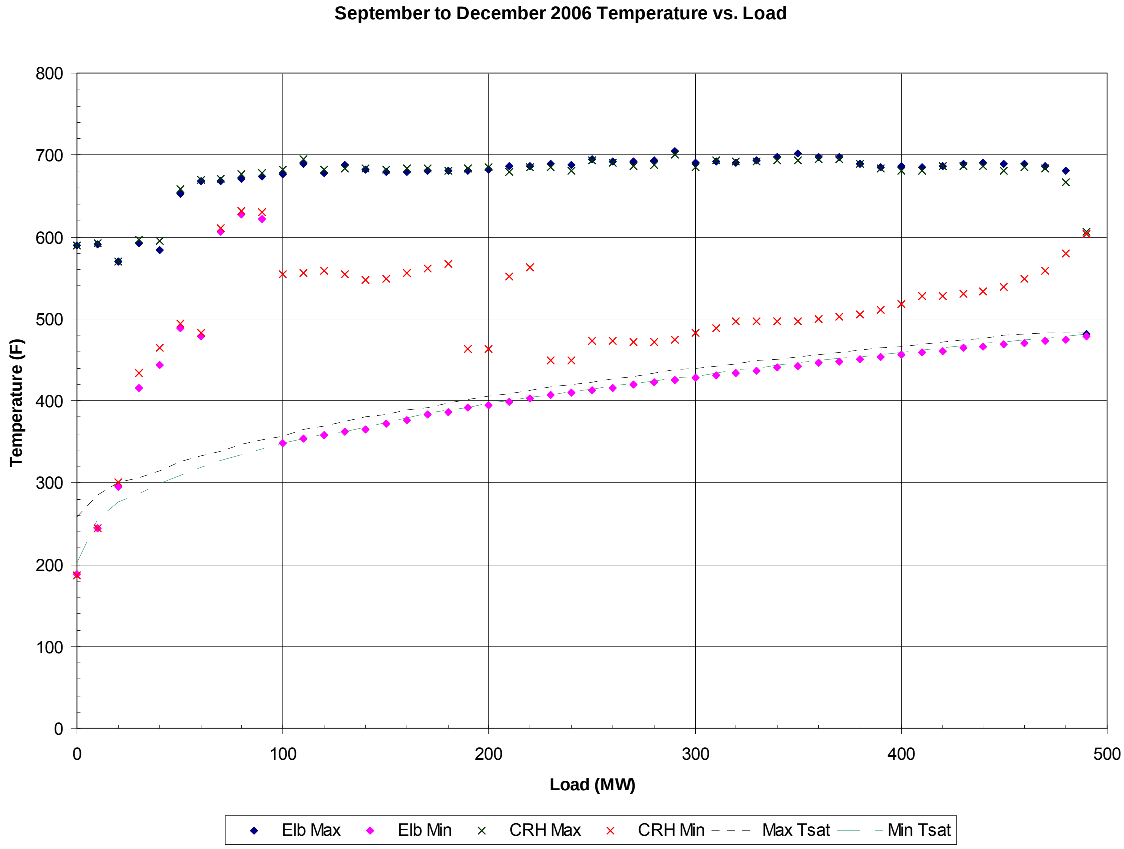

Figure 3-10
CRH and Elbow Extrados OD Temperatures as a Function of Gross Generation

Review of specific time periods reveals in more detail the physical situation occurring in the elbow. Figure 3-11 shows data from September 2006. The attemperator spray flows are generally low (less than 100 kpph), and the elbow temperature stays high. The elbow temperature drops to the saturation temperature when the spray is ramped from zero flow, and it drops down at a later time as the spray flow increases. Small perturbations in spray flow appear to have significant impact on elbow temperature at some times, while at others the effect is not as significant. The CRH temperatures somewhat mirror the perturbations seen in the elbow temperatures.

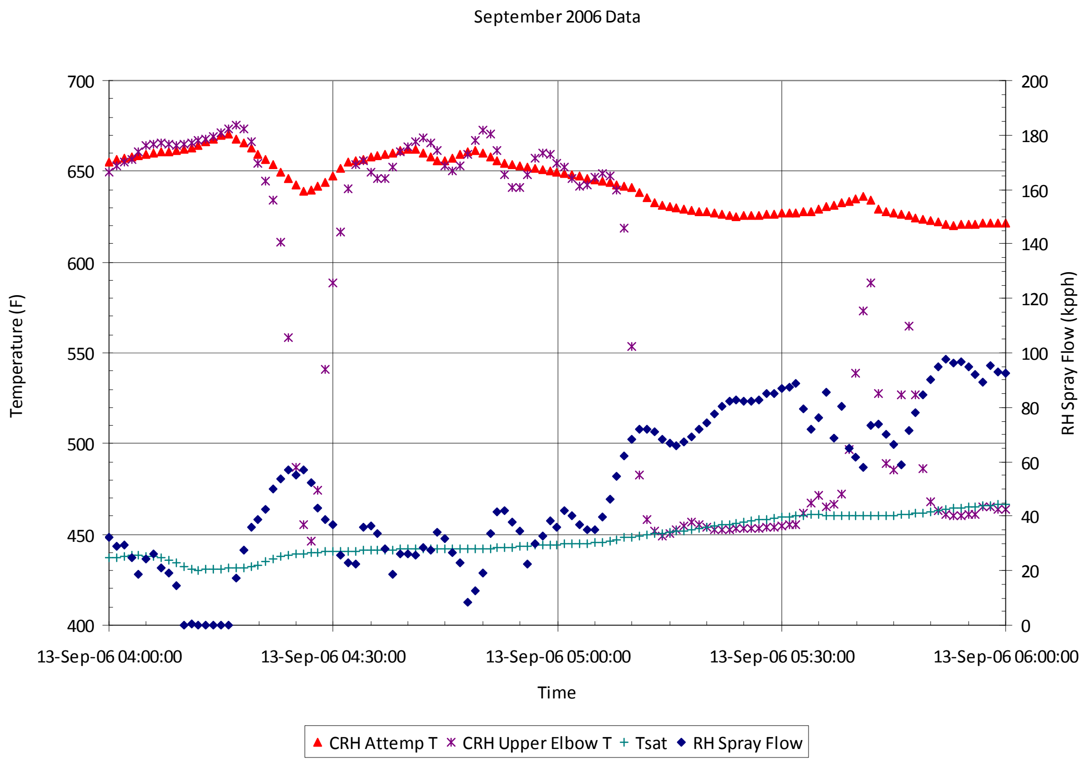

Figure 3-11
Temperatures Measured in September 2006

Figure 3-12 shows data from October 2006. In this time period, when the spray flow is constant, the elbow temperature decreases gradually until a very small increase in spray flow causes a large drop in elbow temperature to near saturation. Perturbations in elbow temperature occur until the spray flow rates reach a relatively constant value. The spray flow rates are below 100 kpph for the entire time period. The CRH temperatures do not show these perturbations and remain relatively constant during the entire time period.

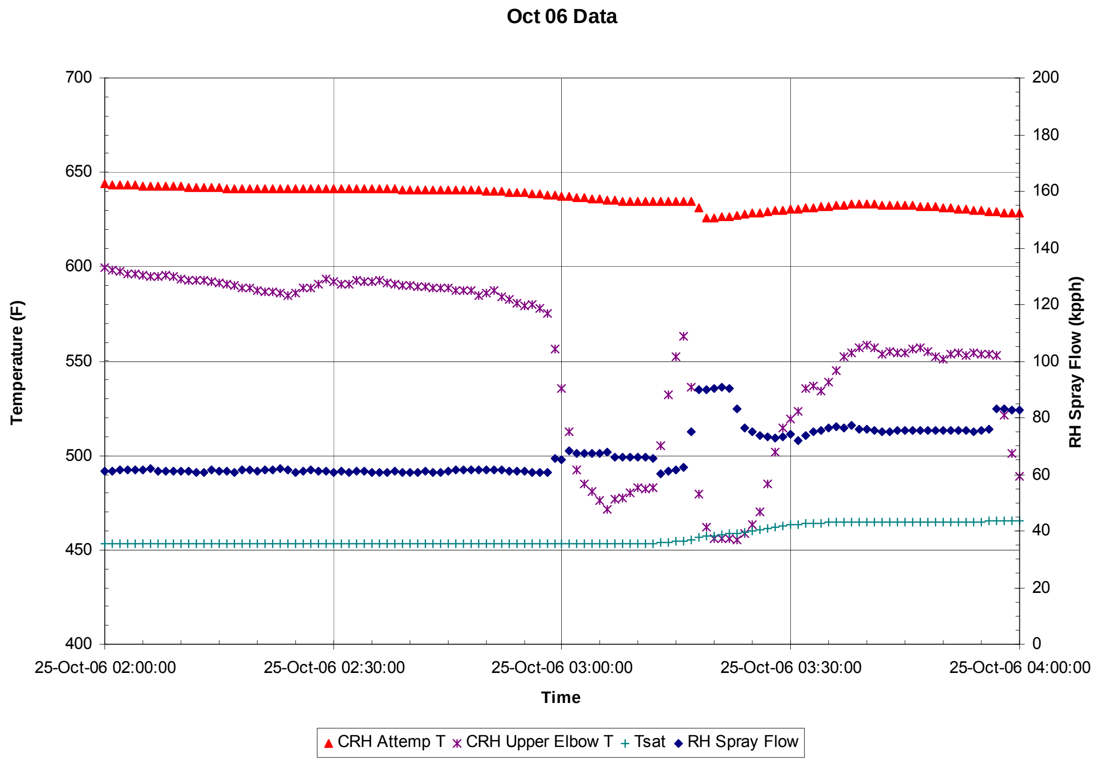

Figure 3-12
Temperatures Measured in October 2006

Figure 3-13 shows November 2006 data. In this case, the elbow temperature does not drop down to saturation levels regardless of the flow rate cycling. The flow rates in this case are relatively low (less than 50 kpph). The elbow temperatures here appear to mirror the spray flow cycling relatively well. The CRH temperatures somewhat mirror the elbow temperatures.

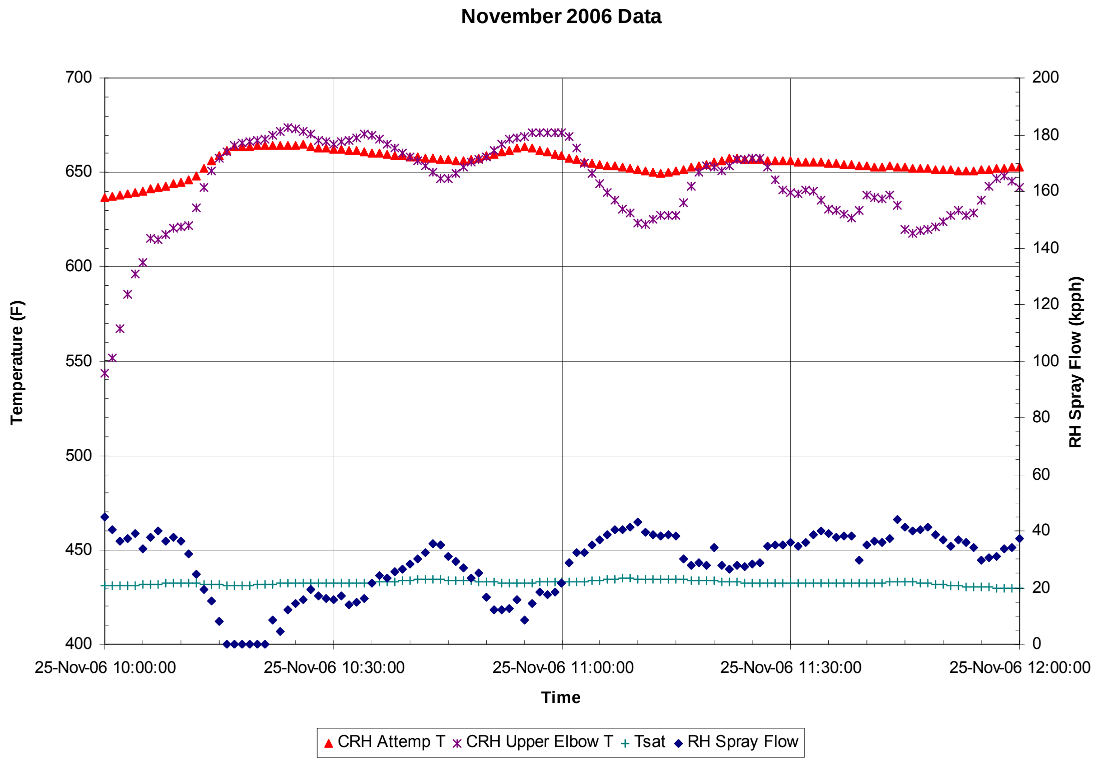

Figure 3-13
Temperatures Measured in November 2006

Figure 3-14 shows another time period in November 2006. The spray flow rates are high (above 100 kpph), which results in elbow temperatures near saturation. The elbow temperatures do not mirror the spray flow because of the high flow rates. The CRH temperatures here mirror the high spray flow rates, and temperatures at times fall to within 50°F of the saturation temperature.

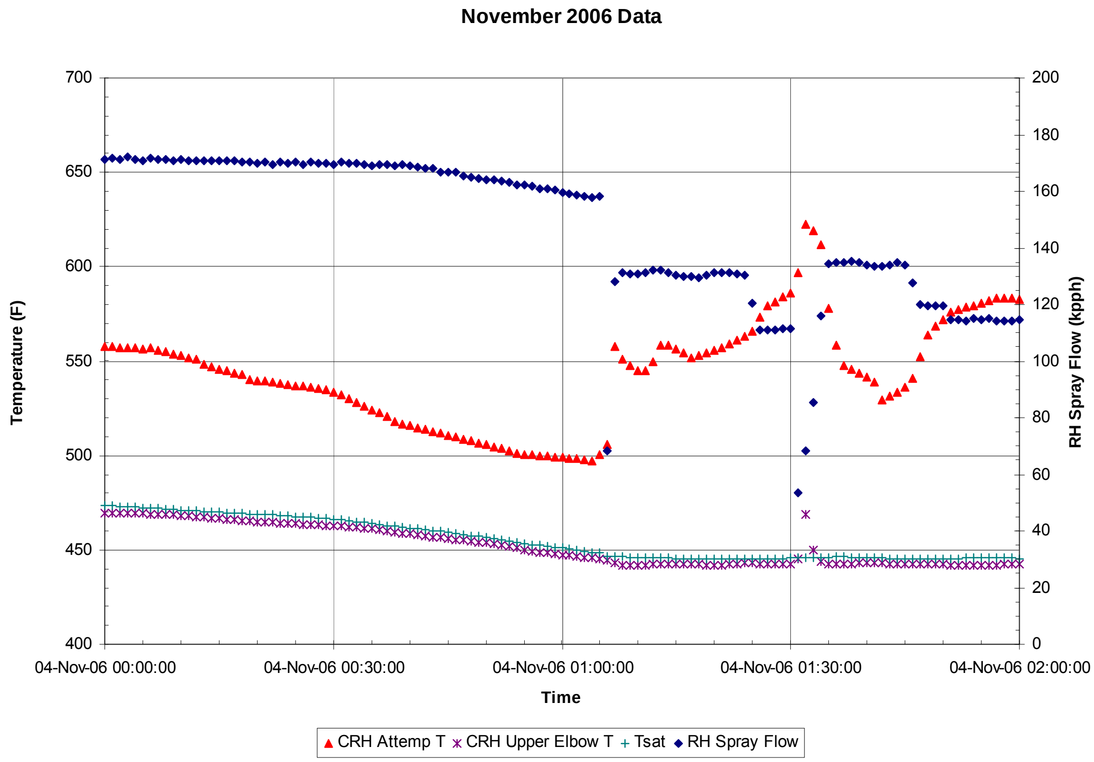

Figure 3-14
Additional Temperatures Measured in November 2006

Figure 3-15 shows December 2006 data. The attemperator flow starts out high (above 100 kpph), and the elbow temperature is near saturation. As the spray flow drops, the elbow temperature increases. Perturbations in the elbow temperature occur while the spray flow remains constant. These cycles appear to be occurring independently of the spray flow or the CRH temperature. The CRH temperatures somewhat mirror the elbow temperature cycles.

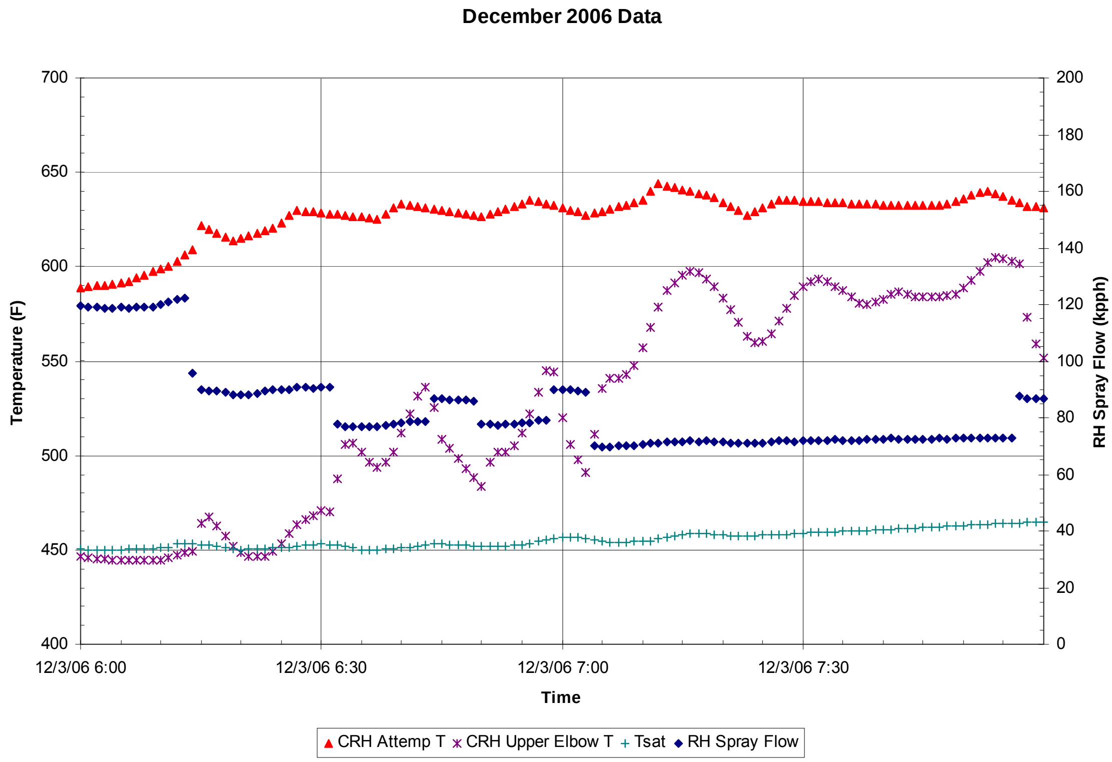

Figure 3-15
Temperatures Measured in December 2006

Review of the September to December 2006 data revealed several points:

- The elbow might be hit by spray water at any spray flow rate; that is, the attemperator allows water to hit the pipe wall because of its inability to completely atomize the water.
- The chances of the elbow being hit by spray water increase when the spray water flows are greater than 100 kpph; for flows greater than 150 kpph, the wall is always hit by spray water.
- The elbow OD temperature is the best indication of whether the pipe wall is hit by spray water.
- The CRH temperature is not necessarily a good indication of the temperature of the water hitting the elbow. Some of the measured CRH temperatures are 150–200°F higher than saturation, but the corresponding measured elbow OD temperatures are near saturation. However, the elbow temperatures were near saturation when the CRH temperatures were near saturation.

The results of the analysis of the data in this section were used to develop the thermal model discussed in the next section.

4
THERMAL DAMAGE ANALYSIS AND POTENTIAL SOLUTIONS

Thermal Model

A thermal model that can be used to determine the temperature gradient through the wall of the CRH piping must deal with a variety of scenarios. If the attemperator is able to atomize the water spray completely, the CRH piping will have a fully mixed steam flow at relatively constant temperature contacting its inner surface. There is no circumferential variation of the pipe wall temperature. If the attemperator is not able to atomize all of the spray water, water droplets of varying size, frequency, and flow rates will hit the pipe inner surface. These droplets will sometimes hit the pipe at a constant rate and other times more randomly, depending on the attemperator. In addition, the water might hit local spots, such as the extrados or intrados of the elbow, causing circumferential variations in pipe wall temperature.

A thermal model was developed using the data from September to December 2006. The model was used to estimate the temperature gradient through the CRH pipe wall, which determines the thermal stress in the pipe. Circumferential pipe wall temperature variations were not addressed with this model. The model was applied to the data and the results analyzed.

From these results, a modified thermal model was then developed that did not require pipe OD temperature data. The modified model was again applied to the September to December 2006 data for comparison to the original model. When the results of the model gave satisfactory results, the model was applied to the 2004 data before the switch and 2005 data after the switch to PRB coal.

The temperature gradient through the CRH pipe wall can be determined by a standard thermal resistance model [2]:

$$q = \frac{\left(T_f - T_{OD}\right)}{\left(\frac{1}{h_f} + \frac{r_{ID}}{k_{pipe}} \ell n\left(\frac{r_{OD}}{r_{ID}}\right)\right)}$$

where:

q = heat flux through the pipe wall, Btu/hrft^2

T_f = CRH fluid temperature, °F

T_{OD} = elbow extrados OD temperature, °F

h_f = fluid at the pipe wall heat transfer coefficient, Btu/hrft^2°F

r_{ID} = pipe inside radius, ft

r_{OD} = pipe outside radius., ft

k_{pipe} = thermal conductivity of the CRH pipe, Btu/hrft°F

The following information was required to create this model:

- CRH steam conditions: temperature, pressure, and flow rate
- Pipe wall thickness and thermal conductivity
- Pipe OD temperature
- Attemperator flow rate

The fluid conditions at the pipe wall are the driving force behind the pipe wall temperature gradient. The pipe wall will see one of two scenarios: steam that contains no spray water (that is, fully atomized spray mixed with the CRH steam flowing by the wall) or spray water that is not fully atomized and travels downstream from the attemperator and hits the pipe wall. When the attemperator fully atomizes the spray water, the heat transfer from the steam to the pipe wall may be determined by calculating the convective heat transfer coefficient for the CRH steam mass flow using the following equation:

$$Nu_f = \left(\frac{h_f D_{ID}}{k_f} \right)$$

where:

D_{ID} = pipe inside diameter (ID), ft

k_f = thermal conductivity of the CRH fluid, Btu/hrft°F

Nu_f = Nusselt Number, defined as [3]:

$$Nu_f = \left(\frac{\mathrm{Re}\,\mathrm{Pr}\left(\frac{c_f}{2} \right)}{\left(1.07 + 12.7\left(\mathrm{Pr}^{2/3} - 1 \right)\sqrt{\frac{c_f}{2}} \right)} \right)$$

where:

Re = Reynolds Number

Pr = Prandtl Number

$c_f/2$ = friction factor

When the attemperator does not fully atomize the spray water, either local or large areas of the pipe wall are hit with spray water. The heat transfer coefficient in this scenario is much larger than the CRH steam convective heat transfer coefficient. The situation is similar to spray cooling of steel in a slab continuous casting machine. Correlations for spray cooling heat transfer coefficients are the subject of research to this day. Various correlations were investigated for use in this scenario [4]. A value of 1000 Btu/hrft^2°F was used as an estimate of the spray flow heat transfer coefficient. Figure 3-9 shows that the maximum elbow OD temperature decreases with increasing spray flow rate above 100 kpph. The heat transfer coefficient applied to the pipe wall for the transition region of flow rates between 100 kpph and 150 kpph (when the maximum and minimum OD temperatures converge) was an interpolation of the convective and spray heat transfer coefficients.

The analysis of the data in Section 3 determined that the elbow extrados OD temperature was the best parameter to determine if the elbow is being hit by spray water. The thermal model used any of three conditions to determine if the elbow is being hit by spray water:

- The elbow extrados temperature is within 30°F of saturation.
- The attemperator spray flow rate exceeds 100 kpph.
- The CRH steam temperature is within 50°F of saturation temperature.

The heat transfer coefficient was adjusted accordingly, depending on the scenario at the pipe wall. When the heat flux was determined using the previous equations, the ID wall temperature was calculated using the following equation:

$$T_{ID} = T_f - \frac{q}{h_f}$$

where:

T_{ID} = Pipe ID wall temperature, °F

The CRH pipe wall temperature gradient is simply:

$$\Delta T = T_{ID} - T_{OD}$$

Figure 4-1 shows calculated values of T_{ID} and ($T_{ID} - T_{OD}$) for a period of time in December 2006.

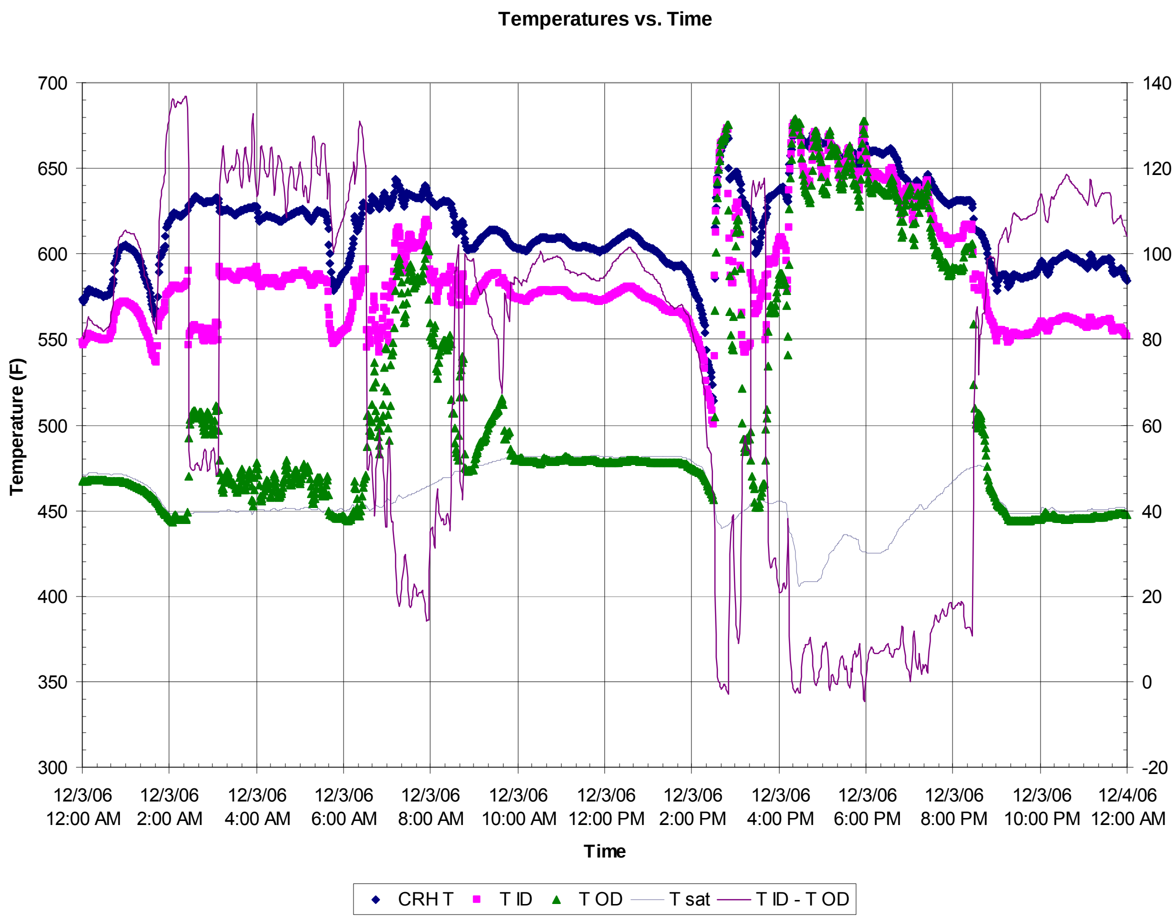

Figure 4-1
Calculated Values of Inside and Outside Pipe Wall Temperatures Versus Time

The modified thermal model required calculating the pipe wall temperature gradient without the benefit of the elbow extrados OD temperature. To use this model, estimates had to be made for the heat flux through the wall for any point in time. The heat fluxes calculated from the initial model for September to December 2006 were plotted as a function of both spray flow rate and heat transfer coefficient. Curve fits were created to estimate heat flux for a given heat transfer coefficient and spray flow. The heat fluxes were then used to determine the ID and OD wall temperatures. Although the absolute values calculated with the modified model might vary from the initial model, using the modified model for the 2004 and 2005 data will give a relative indication of the increased damage resulting from the switch to PRB coal. Figure 4-2 shows a comparison of the initial and modified models for the same time period in December 2006 as shown in Figure 4-1. The modified model shows conservative results at some points and nonconservative results at others, compared to the initial model.

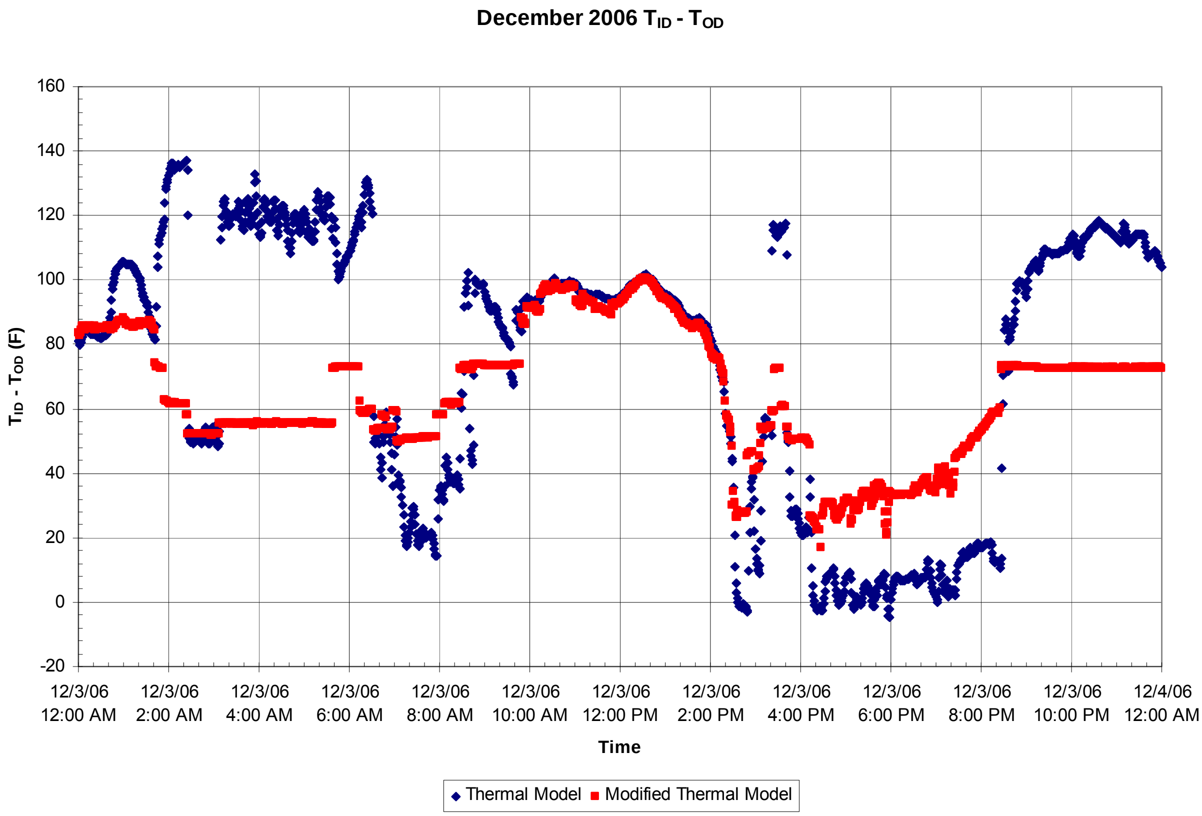

Figure 4-2
Comparison of (T_{ID} – T_{OD}) Calculations Using the Thermal Model and Modified Thermal Model for Data from December 2006

The modified thermal model was then applied to the 2004 and 2005 data.

Rainflow Cycle Counting

The results from the modified thermal model analysis of the 2004 and 2005 data were input into a rainflow cycle [5] counting program to determine the frequency and severity of the calculated through-wall temperature gradients before and after the switch to PRB coal.

Figure 4-3 shows the results of the rainflow cycle counting analysis. The majority of the delta temperature (T_{ID} – T_{OD}) cycles seen by the CRH piping are of smaller magnitude (30°F or less). The analysis shows that the switch to PRB coal in 2005 resulted in an increase in the frequency of damaging thermal cycles on the CRH pipe. Figure 4-2 shows that the current modified model might under-predict some of the thermal gradient calculations, so the actual plots might shift more to the right—that is, higher frequency at higher delta temperature ranges than is shown.

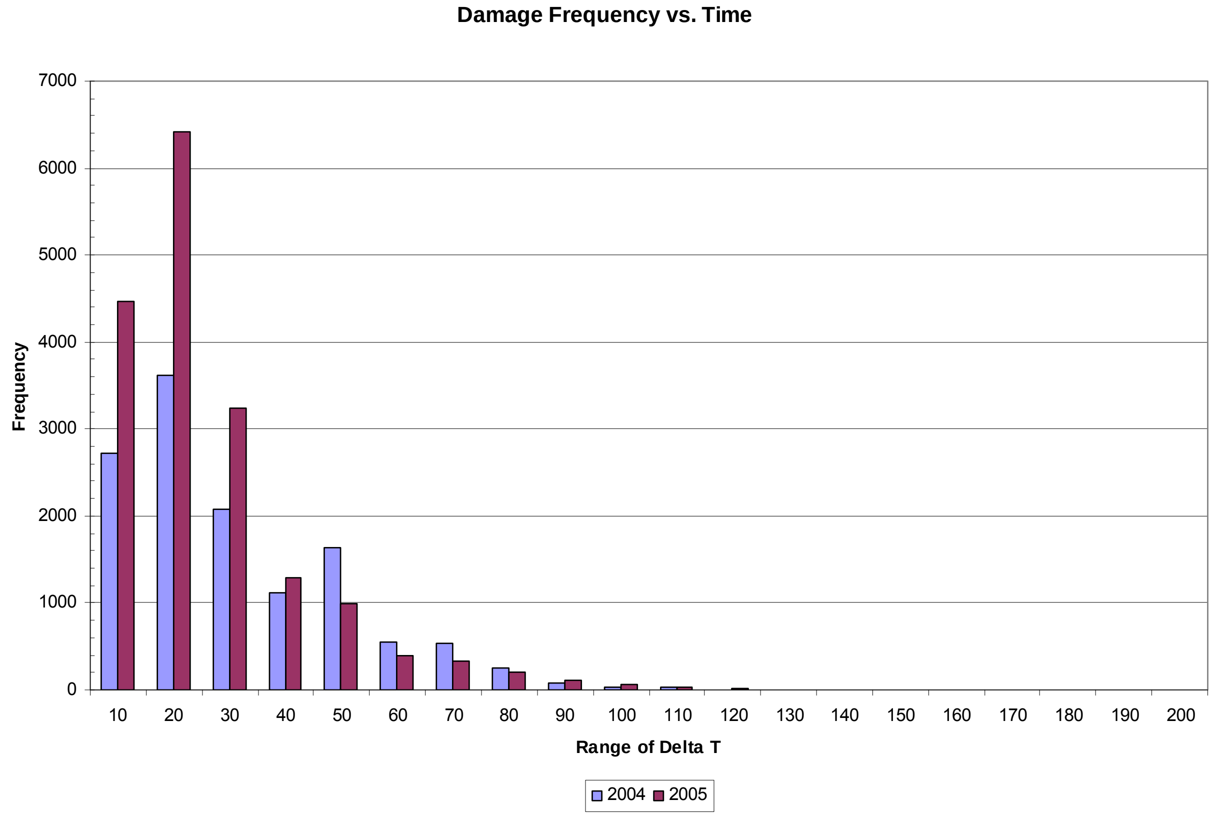

Figure 4-3
Comparison of the Frequency of Delta Ts (T_{ID} – T_{OD}) for 2004 and 2005

Figure 4-4 shows a three-dimensional (3-D) plot of the frequency of delta temperature cycles versus gross generation and attemperator spray flow rate for 2004. The single most significant damage frequency occurred at low flow rates (0 to 50 kpph) at 300 to 400 MW. The damage frequency at flow rates of 0 to 50 kpph is possibly a reflection of the start and stop of attemperator operation cycles. A high frequency of damage cycles occurs at all attemperator flow rates for loads from 400 to 500 MW.

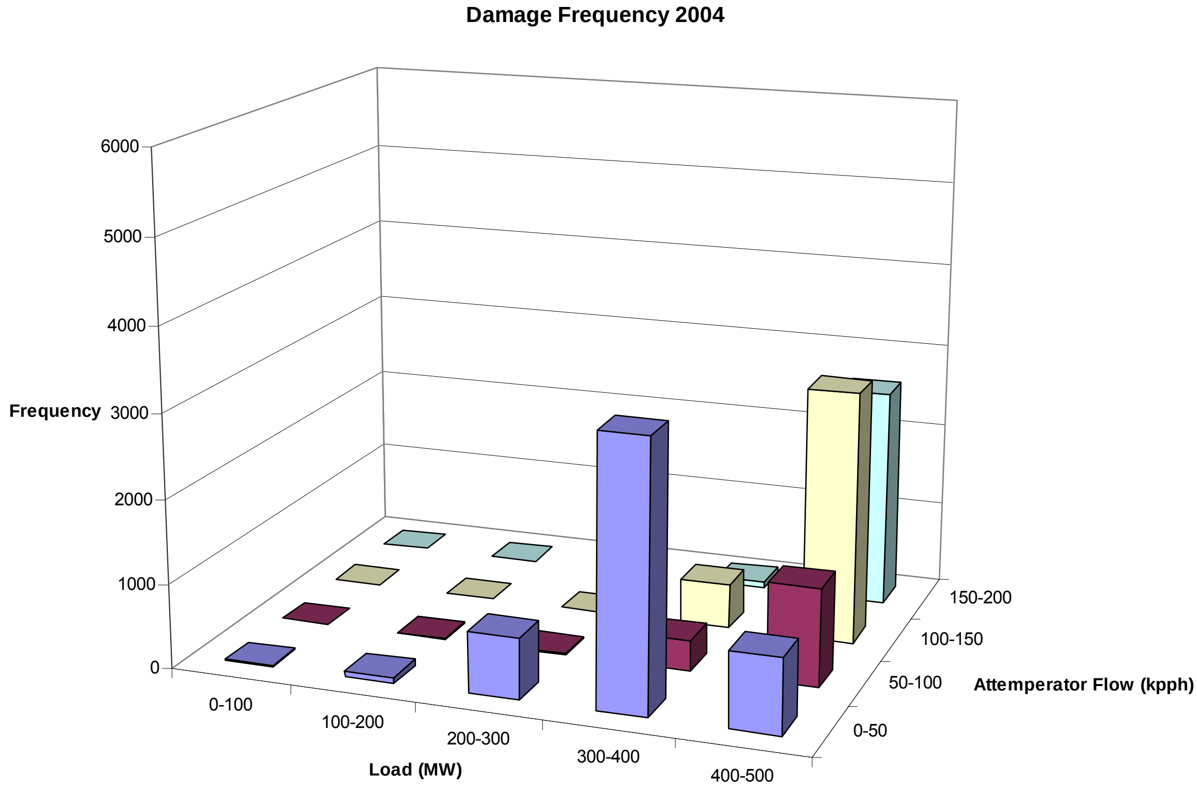

Figure 4-4
Damage Frequency for 2004 Versus Gross Generation and Attemperator Spray Flow Rate

Figure 4-5 shows a 3-D plot of the frequency of delta temperature cycles versus gross generation and attemperator spray flow rate for 2005. The single most significant damage frequency occurred at high flow rates (150 to 200 kpph) at 400 to 500 MW. The unit was run a majority of time in the 400 to 500 MW range in 2005, and the damage frequency is reflected here; most of the damage is at the higher attemperator flow rates because of the need to attemperate after the switch to PRB coal. The damage frequencies at flow rates from 0 to 50 kpph again might reflect attemperator operation cycles.

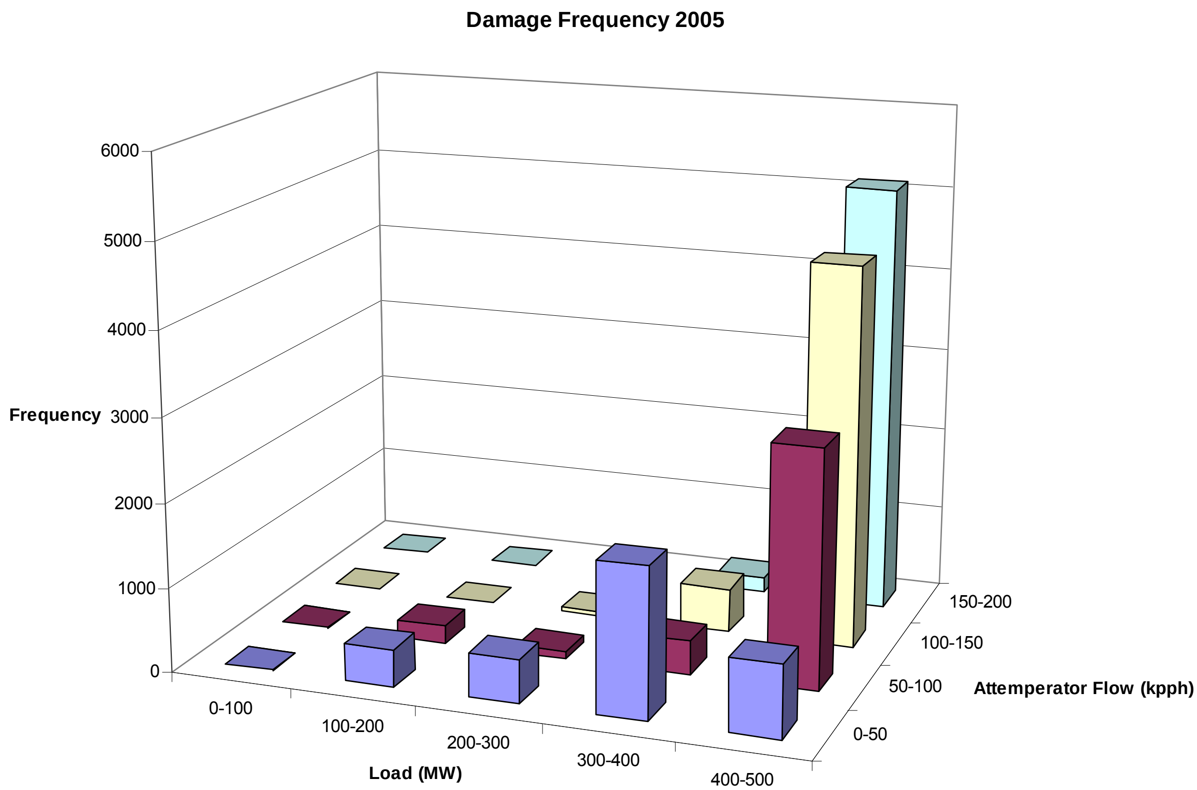

Figure 4-5
Damage Frequency for 2005 Versus Gross Generation and Attemperator Spray Flow Rate

The results of the modified thermal model and rainflow cycle counting analysis showed that a relative determination of damage resulting from the switch to PRB coal can be made. Quantitative results would require refinement of the model, which might include installing additional instrumentation, such as OD thermocouples at the quarter points circumferentially on the pipe, at locations both upstream and downstream of the attemperator. Finite-element analyses and fracture mechanic analyses could be used to quantify crack growth rates for the results of nondestructive evaluation (NDE).

Potential Solutions

The CRH piping at Dynegy's Havana Power Station, Unit #6, has had a history of problems since the inception of operation. Dynegy has attempted a series of solutions for the problems, culminating in the complete replacement of the CRH piping and the relocation of the attemperator. The history of these solutions might be instructive for determining what possible solutions might work in the future.

After the elbow leak in 2006, Dynegy changed the operation of the attemperator to manual activation once per day. This significantly reduced the temperature differential between the extrados and intrados of the elbow. Although this will reduce the number of thermal shocks caused by sudden impact of the spray water on a hot surface, there is unquantified damage to the pipe wall because of the constant impact of spray water at high spray flow rates. The inability of the attemperator to completely atomize the spray water was unchanged even with the change in operation. In addition, it was seen from the data that spray water hit the pipe wall even with small changes to the spray flow rate.

A second attemperator was added upstream of the original to increase the spray capacity required by the switch to PRB coal. No analysis has been done that would determine the effect of the upstream attemperator on the original attemperator.

The final solution employed by Dynegy was to not only change the attemperator, but also to move it further upstream so that additional distance is given to allow complete atomization and to help avoid any spray water hitting the downstream elbow. The results of this change appear to be good so far.

A potential course of action for examination of an attemperator would be the following:

- The attemperator and liner should be examined for problems.
- OD thermocouples should be installed at the quarter points on the circumference of the CRH piping, both upstream and downstream of the attemperator.
- Plant historian data should be collected, along with the thermocouple data, to analyze the thermal cycles experienced by the pipe.
- If the CRH piping contains NDE indications or leaks, finite-element and fracture mechanics analyses may be used to estimate the crack growth rate.
- If a change in operation of the attemperator appears to be a potential solution, the same data should be collected for the new operation.
- The data might indicate that the attemperator does not sufficiently atomize the spray water; if so, analysis of the change in thermal cycles would be required to determine if the reduction in thermal cycles is of enough benefit to delay replacing the attemperator.
- Replacement and/or relocation of an attemperator might be the most effective solution. Data should be collected for an extended period of time after replacement and/or relocation if this option is chosen.
- Continued NDE should be performed if prior indications of damage have been found.

5
SUMMARY AND FUTURE RESEARCH

This report documented one of the potential consequences of a fuel change from an Eastern Kentucky 10,500 Btu/lbm design basis coal to 8,000 Btu/lbm PRB coal. In order to reach full load with this unit using PRB coal, the CRH attemperator spray flow had to be increased from 2% of CRH flow to 13% of CRH flow. This resulted in a load-dependent increased frequency and severity of quench events on the pipe elbow located approximately 25 ft downstream of the attemperator. Thermal shock events on this elbow resulted in through-wall cracking, which occurred in 2006. Thermocouples attached to the crack-prone CRH elbow were installed to help determine the frequency and severity of thermal shock events and to help adjust the attemperator operating logic.

Corrective actions that appear to have ameliorated the thermal shock damage included the following:

- Modifying the attemperator operation logic
- Moving the attemperator positions farther away from the nearest downstream pipe elbows
- Replacing the attemperator and CRH piping
- Reducing the RH tube surface area

This report also identified the need for a more sophisticated system to clearly determine the timing and severity of CRH pipe elbow thermal shock events. To overcome this deficiency, the following research is recommended:

1. Identify a similar unit to Havana #6 that is undergoing a switch to heating value PRB coal.
2. Install a specially designed and fabricated instrumented elbow or pipe spool at the most thermal shock–prone location downstream of the CRH attemperator. This instrumented elbow or spool is envisioned to have eight near-ID thermocouples and eight equally spaced OD thermocouples.
3. Use measurements of the magnitude, severity, and timing (with respect to operational conditions) of measured thermal shocks to estimate the thermal fatigue life at this location and to attempt to develop improved heat transfer relationships for this situation.
4. Use the information gleaned from this enhanced monitoring and modeling to help develop, and then verify, the success of corrective actions that will substantially reduce or eliminate the attemperator thermal shock damage.

6
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2. W. M. Rohsenow and H. Y. Choi. *Heat, Mass, and Momentum Transfer*. Prentice-Hall, 1961, pp. 98–100.
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4. S. G. Hibbins, "Characterization of Heat Transfer in the Secondary Cooling System of a Continuous Slab Caster," M.S. Thesis, Department of Metallurgical Engineering, University of British Columbia, 1982.
5. Annual Book of ASTM Standards 2001, Section Three, Metals Test Methods and Analytical Procedures, Volume 03.01, Metals—Mechanical Testing; Elevated and Low-Temperature Tests; Metallography. E1049—85, Standard Practices for Cycle Counting in Fatigue Analysis.

A
STATEMENT OF WORK

The following statement of work was sent to prospective utilities to provide a blueprint for the data required for this project.

ATTACHMENT A

STATEMENT OF WORK

Intertek-APTECH Industrial Services

EP-PXXXX/CXXXXX

"Effect of Switching to PRB Coal on the Increased Attemperator Use and Cold Reheat Piping Thermal Quench Damage"

EPRI Work Order ID: 061226

1. Introduction & Background

   Many utilities have switched to Powder River Basin (PRB) coal due to its low sulfur content, and are burning the coal in boilers not designed for it. One of the effects on operation is high reheat temperatures. To lower hot reheat temperatures to the correct range, many utilities have had to increase the use of attemperator sprays. Thermal fatigue damage in cold reheat piping systems has been found in several of these systems.

2. Objectives

   The goal of the Phase I project is to develop a better understanding of the increased magnitude and frequency of damaging attemperator spray quench events in the cold reheat piping after a switch to PRB coal has been made. This information will then be used to estimate the increased likelihood and the shortening time to initiate attemperator-induced thermal quench damage and the damage accumulation rate.

   The Phase I project will also identify possible solutions to this damage mechanism that should be investigated in further detail in a follow-on project.

   A Phase II project is anticipated that will perform more detailed investigations of the thermal quench events in the CRH piping (using added diagnostic/troubleshooting monitoring, thermocouples, and strain gages) in combination with finite element, computational fluid dynamics, and thermal fatigue damage models. The Phase II project would also perform more detailed evaluations of the costs and potential benefits of corrective action alternatives.

A Phase III project is envisaged that would focus on performing field trials of promising corrective action alternatives.

3. Scope of Work/Task Descriptions

To achieve the project objectives, Contractor will perform the following tasks:

<u>3.1 Task 1 – Collect information about the overall design and operational characteristics of some units that have been switched to firing PRB coal</u>

Using the data request and template that the Contractor has already prepared, the Contractor will visit with Dynegy and obtain the requested key design and operational data for Havana Unit 6 which switched to PRB coal after December 2004. The background data will include some key design attributes and a review of the hourly MW and a few other key plant historian operational attributes for at least one year prior to the switch to PRB coal and for up to one year with PRB coal firing. The background information will be summarized in a case study in the final report (Task 3).

<u>3.2 Task 2 – Collect and analyze plant historian data for operational periods before and after switching to PRB</u>

The detailed data from the Havana Unit 6 plant historian with cold reheat steam flow/pressure/temperature and attemperator spraywater attributes will be analyzed with an incremented damage accumulation algorithm to determine the frequency and magnitude of cold reheat attemperator spray events prior to and after the switch to PRB coal firing. Estimates of the relative thermal fatigue damage accumulation rates per unit operating time for the operation before and after the switch to PRB coal will be made using this data.

<u>3.3 Task 3 – Reporting</u>

In addition to monthly contractor cost performance reports (CCPRs), a short final report documenting each of the tasks above will be prepared. The report will include a case study for Havana Unit 6 and will include suggestions for needed future research to further understand the cold reheat thermal quench events and possible corrective action alternatives.

4. Project Requirements

   To perform this project, the Contractor will have an ex-Dynegy Engineer (Mr. Jim Yagen) visit Dynegy to help collect the information required for this project. It is assumed that this information retrieval effort will be successful. If it is found that the required Havana Unit 6 information is not available then the project will immediately be put on hold and the Contractor will have discussions with EPRI regarding the best path forward.

5. Deliverable

   The work will provide the industry with some preliminary conclusions with regard to the influence of the switch to PRB coal on the frequency and magnitude of cold reheat attemperator spray. A preliminary list of possible corrective actions and means to determine their effectiveness in Phase II and Phase III projects will also be provided. Deliverable shall be a technical update document.

6. Schedule

Task Description	**Completion Date**
Task 1 – Collect Unit Background Information	Information request letter provided to EPRI within 2 weeks after the project has started. The on-site collection of background information will be completed with 8 weeks after the project start.
Task 2 – Collect and Analyze Detailed Operational Data	2 months after the requested data has been obtained from each of the utility participants.
Task 3 – Final Report	1 month after completion of Task 2 but no later than November 1, 2010.

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com