

Inspection of Power Plant Headers Utilizing Acoustic Emission Monitoring

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Fossil power plant high energy, high temperature steam headers have been found to be susceptible to thermal fatigue assisted creep degradation. These mechanisms initiate and grow cracks in chrome molybdenum headers, from the bore hole edges and stub tube-to-header welds. Linking up of multiple cracks can lead to explosive expulsion of tubes and severe shorting of the header life. In order to extend the header life and operate safely, a better understanding of crack growth that may occur during specific plant operating conditions is needed. With that understanding, harsh operating conditions that may be causing excessive crack propagation and header damage can be curtailed. Acoustic emission monitoring of headers was performed to assist in identifying operating conditions that lead to header damage. This Electric Power Research Institute (EPRI) sponsored program found acoustic emission activity levels correlated to identified crack growth and analytically calculated stresses. Utilizing these results, draft EPRI guidelines have been developed to aid electric utilities in performing acoustic emission monitoring on superheater headers.

Keywords: acoustic emission, cracks, creep, finite element method, stress

Introduction

High energy, high temperature chrome-molybdenum (2-1/4 Cr - 1 Mo and 1-1/4 Cr - 1/2 Mo) superheater outlet headers in fossil power plants have been found to be susceptible to creep degradation, as compounded by thermal fatigue^{[1][2]}. This has exhibited itself in two ways; ligament cracking between the stub tube bore holes, and stub tube-to-header weld cracking, as shown by Figure 1.

Tube-to-header weld cracks typically initiate either at the weld root or at the weld toe on the outside surface. They grow radial and circumferential until completely breaking the tube from the header. Ligament cracks initiate from thermal cracks that radiate from tube bore holes. Link up of adjacent tube radial cracks creates the ligament crack. Linking up of multiple ligament cracks can eventually lead to explosive expulsion of tubes and severe shorting of the header life. In order to extend the header life and operate safely, a better understanding of crack growth that occurs during specific plant operating conditions is needed. With that understanding, harsh operating conditions that may be causing excessive crack propagation and header damage can be curtailed.

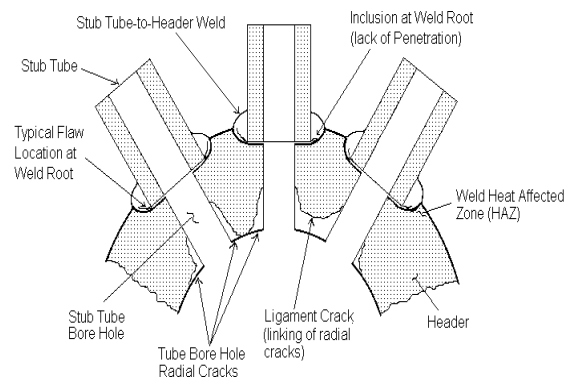


Figure 1 Ligament and Stub Tube-to-Header Weld Cracking

A program was put together to develop Acoustic Emission (AE) monitoring techniques for detection of cracking in fossil plant high energy systems susceptible to creep damage. This cooperative research was jointly supported and funded by the Electric Power Research Institute (EPRI) and Pacific Gas & Electric (PG&E) company, under EPRI's research program RP1893-20. The program investigated use of AE monitoring for detection of cracks in seam-welded Hot Reheat Lines^[1], and detection of header ligament and stub tube-to-header

weld cracks. This paper summarizes results for the header program. The elements of the program were field monitoring of a header during typical plant operation and characterization of crack signal features in the laboratory. Correlation between acoustic emission activity levels, identified crack growth, and analytically calculated stresses were found to exist. Utilizing these results, draft EPRI guidelines have been published to aid electric utilities in performing acoustic emission monitoring on superheater headers^[3].

Crack Locations

Stub tube-to-header welds contain inclusions, such as lack of penetration and lack of fusion. Cracks can initiate at the weld root, where the inclusions typically exist. They create stress concentrations, which are strained by material creep. The stress/strain concentration is compounded by the presence of additional stress mechanisms, such as residual stresses from tube fit-up to the header and thermal fatigue. The resulting condition creates and grows cracks radially and circumferentially until a complete break of the tube from the header occurs. This is both a safety issue and a cause of plant down time. Detection of the cracking can be difficult, as it may initiate at the weld root, where the socket weld geometry complicates inspection by ultrasonics or radiography. Typically, there is a fit-up gap between the tube and header's machined socket. The gap ending at the weld root. An ultrasonic signal has difficulty discriminating between the gap's end, and its extension by either lack of penetration or cracking.

Stub tube bore hole radial cracks are common occurrences and, by themselves, are not a major concern. They are generally self-limiting, but their potential link-up into ligament cracks creates concerns. As ligament cracks, they may grow into a through-wall crack with potential for major structural damage to the header. Importantly, ligament cracks in creep damaged thick-walled chrome-molybdenum headers have not been demonstrated to be repairable. The ultimate solution is replacement of the header with substantial replacement cost and plant down time. Another possible solution is curtailment of plant operation to minimize the rate of temperature change during plant load cycling and plant heat-up/cool-downs.

As thermal fatigue is the driving mechanism, the identification of acceptable temperature ramp rates is an important issue. Calculation of header stresses by finite element analysis and fracture mechanics crack

growth rates is one method. Results from such calculations would define limits on plant operation.

Real-time feedback on the actual crack growth rates that occur during plant operation can be of great value for comparison to assumed crack growth rates. Some evidence suggests that these ligament cracks can become self-arresting or experience reduced growth under many of the plant operating conditions^[4]. The difficulty is to identify changes in crack growth rate. Sizing individual crack depth and length extension can be difficult due to the numerous radial cracks growing from the bore holes. Figure 2 shows a wet fluorescent particle exam of a header inside diameter (ID) at a tube row.

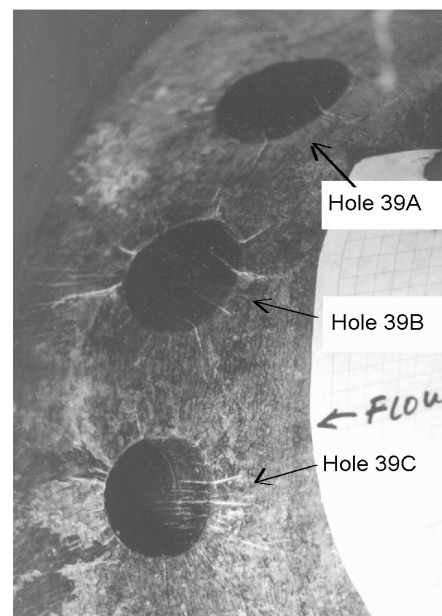


Figure 2 Radial Cracks from Tube Bore Holes

A possible method of verifying that crack growth has self-arrested or is limited to specific plant operating modes is by AE monitoring. The basic approach is to attach, with waveguides, AE sensors to the header near selected known crack locations, and to monitor AE events during a typical range of plant operating conditions. The intent is to identify which, if any, of the operating conditions are producing crack growth.

Field Monitoring of High Energy Header

The primary superheater outlet header at PG&E's Pittsburg Unit 6 power plant in Pittsburg California was monitored for crack growth from September 1991 through March 1992. The header had

substantial ligament cracks with evidence of creep and creep-fatigue damage. The largest crack being 2.9 cm in depth and connecting two adjacent tube bore holes. At the start of monitoring, the header was estimated to have a residual life of less than 5 years, based on this initial crack size and continued operation at design temperature limits.

The decision was made to restrict temperature ramp rates, while monitoring header and tube temperatures. Frequent ultrasonic inspections at critical crack locations were conducted to monitor crack growth. The intent was to replace the header in the near future, but in the interim provide augmented inspection and monitoring. This presented an excellent opportunity to determine the degree of correlation between AE activity levels, change in ultrasonic size, and expected crack growth.

Acoustic emission sensors were located near the deepest crack locations. Figure 3 shows the monitoring equipment setup. Waveguides were welded to the header outside surface surrounding the crack locations. The resonant sensor frequency was selected to high-pass the steam flow noise. Thermocouples were mounted on both the tubes and on the header surface for recording the temperature time histories.

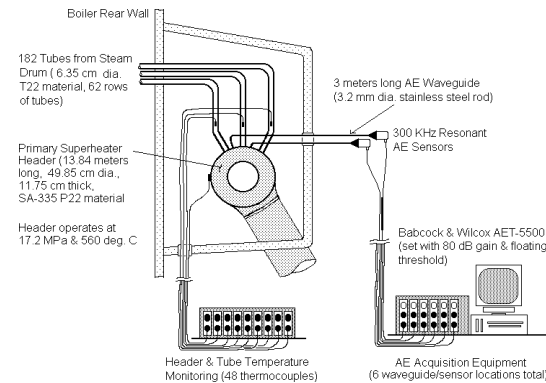


Figure 3 AE and Thermocouple Monitoring Setup at Pittsburg Power Plant Unit 6

Results showed that the AE generation was related to header/tube temperature changes. This is shown by Figure 4 for a two-day period when the plant load (Net Megawatts) was cycled. The figure shows the highest AE rate correlated to the greatest temperature changes. The temperatures were measured at two outside diameter (OD) skin locations - on the header and at Tube No. 40B.

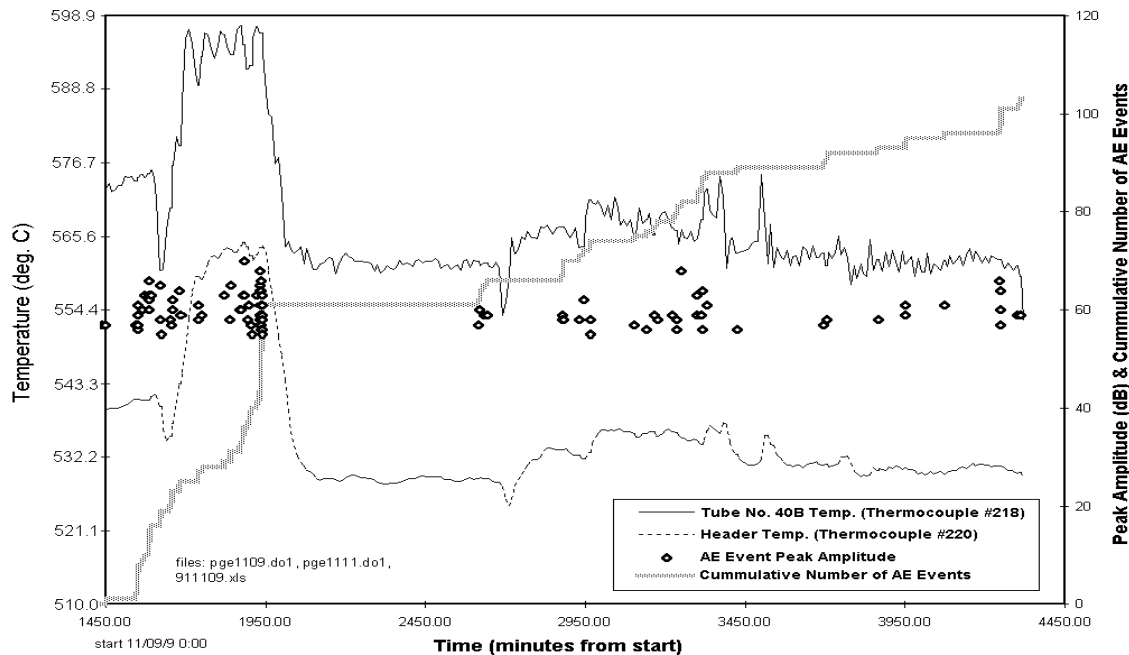


Figure 4 AE Activity Related to Plant Load Change

Monitoring regions of a header section, as shown by Figure 5 separated the located AE events. Comparing AE waveform arrival times at the six waveguide/sensor locations defined these regions (AE monitoring zones). Zones were created using a zone calibration system built into the AE monitoring equipment (B&W model AET-5500). AE signals were generated by lead breaks and pulsers on a header section – on the OD, ID and inside tubes. By applying many signals throughout a region, a look-up table of wave arrival times (detected at least at three sensors) was generated. The range of arrival times for each sensor, and the order in which they arrived provides the boundary of acceptable AE events that will locate within the zone. The lookup tables provide a method of filtering AE hits. If the arrival times and order of arrival fall within a boundary the AE hit is defined as a located event within the related zone. If not, then the AE hit is either noise or originates outside all zones. Typically, if only a single sensor detected an AE hit, it was assumed to be noise and rejected.

Two small regions (1 & 2) were specifically designed to identify events occurring on the header ID near or at the bore holes. Ligament cracks existed directly below the six AE waveguide attachment points (Tube Rows No. 39, 40, & 41). The other regions (3, 4 & 5) provided coverage mainly for the header OD. Figure 6 shows AE activity by monitoring region - the majority of events were located in Regions 3, 4, and 5. This corresponds to the outside diameter near tube-to-header welds. Very little AE appeared to be originating from the header ID near the existing ligament cracks.

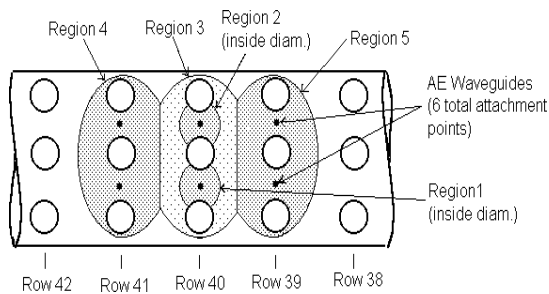


Figure 5 Schematic of the monitoring regions of a header section.

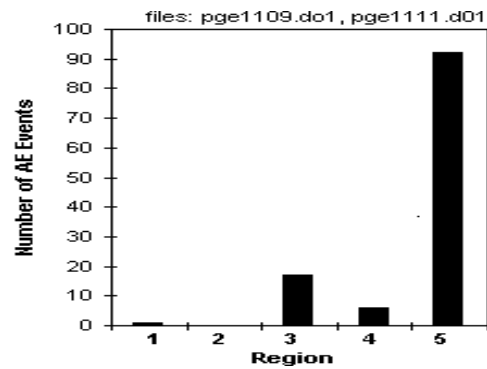


Figure 6 AE Activity by Header Region

Inspections were performed before and after monitoring. Prior to monitoring, ultrasonic sizing of the ligament cracks showed crack depths ranging from 2.0 to 2.9 cm. After monitoring in March 1992, the cracks were again ultrasonically sized. They did not show any measurable increase in ligament crack depths during the monitoring period.

Exams of the stub tube-to-header weld areas indicated significant creep damage. Magnetic particle exams in 1990, identified weld cracks on tubes 39B and 40B. Tube 40C had completely failed and was ejected. Replications of the tube 39C base metal, heat affected zone (HAZ), and weld metal showed aligned creep voids (3 of 5 on damage scale). The damage scale being: 1- isolated cavities, 2- orientated cavities, 3- cavity linkage, 4- microcracking, 5- macrocracks. Tube 40B showed isolated creep voids (2 on damage scale) in the header base metal and weld to micro creep cracks (4 on damage scale) in the HAZ. The 39B, 40B and 40C welds were repaired prior to the AE monitoring. Again in 1992 after the header was replaced, spot replicas were performed. Tube 40C, which did not show any damage in 1990, showed isolated creep voids in 1992.

From these correlations and other evidence, it appears that the AE events were associated with stub tube-to-header welds and not ligament cracks. Overall, these results are not surprising. The curtailed operation likely reduced or stopped ligament crack growth but failed to stop stub tube-to-header weld damage.

Acoustic Emission Laboratory Testing

The superheater outlet header was removed and replaced in March 1992. Three header sections were cut out and brought into the laboratory for testing.

The section with the largest ligament cracks was heated to grow, and AE monitor, cracks in a controlled environment. Figure 7 shows the header section in the laboratory, with mounted waveguides and AE sensors. Heat induction coils were attached to a pipe and positioned inside the header for heating. Using controlled temperature ramp rates, the coils heated the header section to 480 °C at atmospheric pressure. Thermocouples were attached on the outside and inside header surfaces, as well as in the tube bore holes. This allowed for inside-to-outside diameter and adjacent tube temperature differentials to be measured.

The first heating cycle used a relatively slow temperature ramp rate that peaked at 83°C/hr on both the heat-up and cool-down. It produced maximum temperature differentials (inside to outside surface) of +28 °C for heating and -11 °C for cooling. Despite the fact that tube holes were blocked and no air flowed through them, the maximum temperature differential between adjacent tube surfaces was found to be 28 °C. These ramp rates and temperature differentials greatly exceeded those monitored in the field testing. Using the higher rates insured that ligament cracks would be grown during the lab testing.

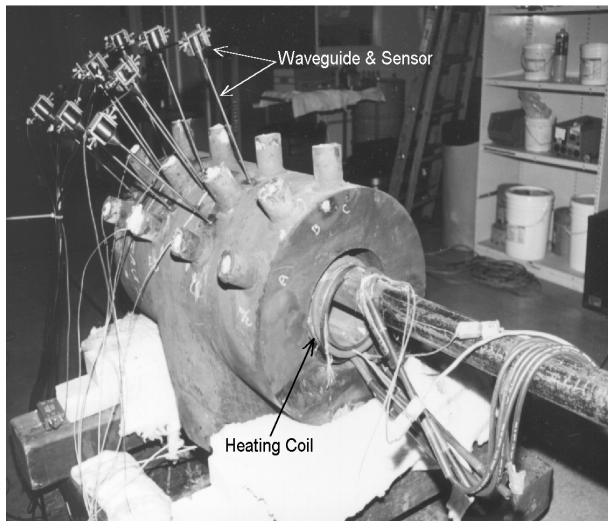


Figure 7 Laboratory AE Monitoring of Header Section

After the first heating cycle, a wet fluorescent particle exam was conducted on the inner surface. Holes 36A & 36B had new radial cracks initiated and existing ones grown. Crack extensions were also observed for tube row 39. Two large radial cracks on each side of tube hole 39B had widened and lengthened. The

ligament crack between holes 39A & 39B had widened, becoming more visible to this surface exam.

AE was monitored during heating and cooling, recording waveforms and signal features. Figure 8 top plot shows AE events generated during the first heating. These AE events originated at the header region between tubes 39A & 39B. This region includes the inside surface and part way up the tube bore holes. It specifically excludes the header outside surface. The bottom plot shows inside surface temperature and temperature differential between inside and outside surfaces. It shows a higher temperature inside surface on the heat-up. After temperature peaked and cooling begun, the inside surface is placed in tension. If the tensile stress was sufficiently high, this is the likely point where cracks should open and extend. The top plot shows the corresponding AE event rate. Most AE was generated on cooling, stopping completely at about 650 minutes, where the temperature differential reaches its maximum negative value (i.e., where inside surface is coolest compared to outside surface).

These are results for just one location. Other locations with known crack growth were investigated. Their evaluation shows that most locatable AE events were generated from header inside diameter locations that had visible evidence of crack extension. In addition, little acoustical noise was generated from other possible sources, such as inside surface oxide fracture. As such, it is believed that the generated AE shown in Figure 8 was associated with crack movement and extension.

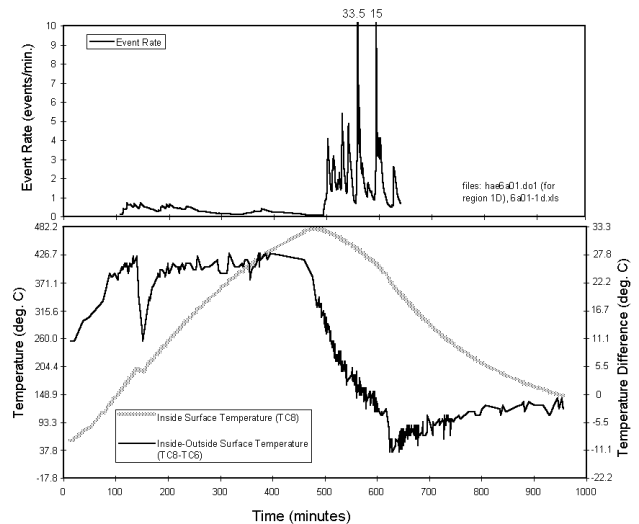


Figure 8 AE Activity from Laboratory Heating for Tubes 39A & 39B

Stress Analysis and Comparison to AE Activity

The thermocouple measurements made in the field-testing were used as input in a finite element model to calculate principal stress time-histories. The stress time-histories were used for comparison to the AE activity time periods - determining if periods of high stress matched periods of increased AE activity.

Figure 9 shows the finite element model. It uses the COSMOS finite element software to determine tri-axial stress time histories^[5]. Figure 10 shows an example of high stresses at a particular time point. They were generated on a thick wall structure in the ligament areas. The figure shows tensile stresses on the OD and compressive on the ID for stress in the pipe axial direction. Typically stress is tensile on the ID and compressive OD, but when a slug of cooler steam enters the header it lowers ID temperatures to near or below OD temperatures. This is the maximum stress condition.

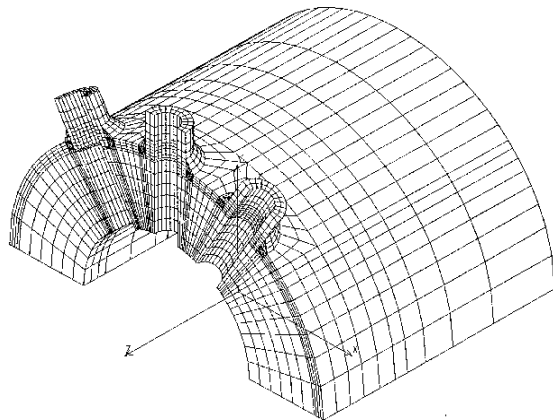


Figure 9 Three-Dimensional Finite Element Model of a header section with a row of three tubes. As only the temperature difference between tubes and header are of interest, the bottom half of the header is not included in the model. The mesh is designed specifically for calculating stresses from temperatures in the ligament and tube-to-header weld areas.

Figure 11 plots the stress time history to show correlation between AE activity during a 12 hour period of the field monitoring. The top curve indicates the temperature difference between tube and header. Essentially the tube temperature is the same as the steam temperature, as the tubes have thin walls. Therefore the temperature difference is the difference across the header thickness. When the cooler steam slug occurs, the difference is negative. The bottom curve provides the pipe axial stress for a

finite element node in the ligament area. Note the high stress points occur at the negative temperature differences. The middle curve is the AE activity for events located by the zones. It shows that activity occurs for the negative temperature difference. It also shows a lack of activity at other times.

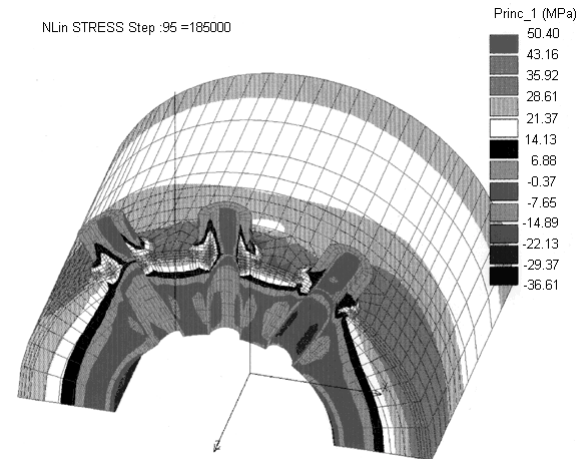


Figure 10 Thermal stresses generated by thermocouple temperature input for the Finite Element Model. This figure shows the change in stress from tensile on the OD to compressive on the ID.

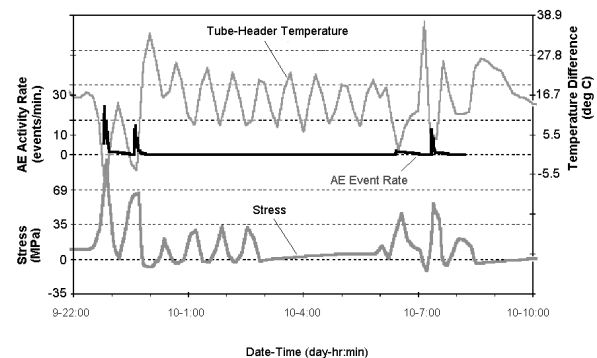


Figure 11 Correlation of AE Activity and Header Thermal Stress during a 12 hour Period

Figures 12 and 13 focus on the time periods in Figure 11 with AE activity for 3 hour periods. They show AE activity matching very closely in time with the stress peaks. Some variation is expected in the match, as the finite element time step is relatively coarse. Thus the actual stress peak may vary by 10 minutes from calculated stress peak. These stress to AE activity correlations suggest that a threshold effect is occurring. Below certain stress levels, little AE activity is evident. This was very evident during the field monitoring. While constant AE activity

occured through out the 6 month monitoring, there were time periods when no zone located AE occurred. Thus supporting the expectation that the unlocated AE hits were related to noise and not crack extension or initiation. This stress to AE correlation also suggests an on-line monitoring method of indicating when material damage is occurring. The appearance of locatable AE events suggests that damage is occurring, and the plant operating conditions should be abated. Typically increasing the time to change from one plant power level to another provides the abatement by reducing the temperature ramp rate and correspondingly stresses. It is a trade-off between preventing damage and reducing the plant's ability to quickly change power levels to meet demand.

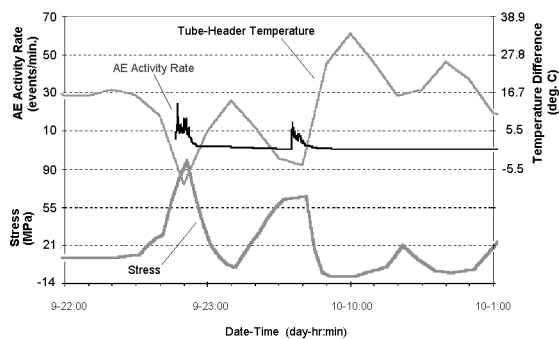


Figure 12 First Period of AE Activity (detail from Figure 11)

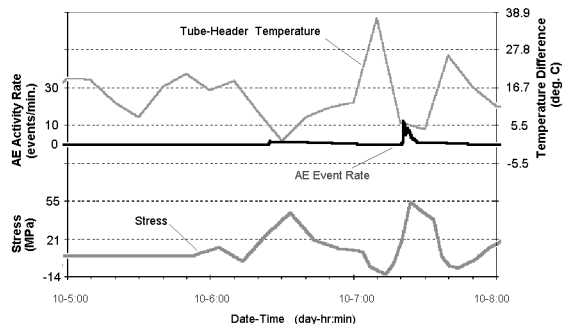


Figure 13 Second Period of AE Activity (detail from Figure 11)

Monitoring Guidelines Development

Using the field and lab tests, draft guidelines have been developed to use AE monitoring for crack growth detection in high energy headers^[3]. Guidance is provided for two uses: detection of cracking over the entire header length, and

monitoring known cracks in a localized header area for growth during plant operation. Both of these uses would entail short term monitoring (1 to 2 weeks). The intent is to provide periodic condition assessment to determine if a particular plant operating mode is causing material damage. The monitoring interval is determined by crack growth rates, header residual life, and plant operating schedule.

In general, the guidelines follow the testing method described in this paper for monitoring known cracks. For example, a header section with the most critical cracking is chosen for AE monitoring. The waveguide/sensor array and location algorithm are selected to differentiate AE events near the known cracks from others away from the cracks. As well as, filtering out AE hits not locatable and likely associated with flow or other types of background noise. The plant operating history is reviewed to determine enveloping operating conditions. Dividing them into plant start-up, shut-down, on-line steady state, and on-line load cycling to provide representative stressing of each type. Thermocouples are added as needed to header tubes and the header OD, to identify temperature differentials and correlation to the operating modes. Temperatures, pressures and AE are monitored together during periods representative of the different operating modes. Extremes in temperature differentials and ramp rates are then correlated to the AE generated for identification of operating modes to determine levels above which substantial AE activity is generated. These levels can then be utilized to provide warnings of possible damage.

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References

1. **Morgan, B.C., Foster, C.L.** 'Acoustic Emission Monitoring of High-Energy Steam Piping Volume 1: Acoustic Emission Monitoring Guidelines for Hot Reheat Piping', *Electric Power Research Institute Report, TR-105265-V1*, 1995.

2. **Coulter, J.E., Stevens, D.M., Gehl, S., Scheibel, J.R.**, 'Acoustic Emission Monitoring of Fossil-Fuel Power Plants', *Materials Evaluation*, **46**, 1988, pp 230-237.
3. **Morgan, B.C., Rodgers, J.M.**, 'Acoustic Emission Monitoring of High-Energy Headers Volume 1: Acoustic Emission Monitoring Guidelines for Superheater Outlet Headers', *Electric Power Research Institute Report*, **TR-107839-V1**, 1997.
4. **Grunloh, H.J., et al**, 'Life Assessment of Boiler Pressure Parts, Volume 3: Heavy Section Crack Initiation and Propagation', *Electric Power Research Institute Report*, **TR-103377-V3**, 1993, Sections 2 & 7.
5. **Shirmohamadi, M.**, 'Developing Stress-Time Histories at Selected Locations of a Boiler Header Field and Lab Testing Events for Support of Acoustic Emission Research', *Material Integrity Solutions Inc. Report*, Project EPRI-96-1, 1996.