Technical Publication

Investigation of Radiant Superheater Crossover Pipe Weld Cracking at Big Cajun II Station

by

James P. King
BABCOCK POWER INC.
(formerly Babcock Borsig Power, Inc.)

Robert D. Hendrix
NRG LOUISIANA GENERATING, LLC
New Roads, Louisiana

Presented at
ASME Pressure Vessels and Piping Conference
Vancouver, B.C., Canada
August 4-8, 2000

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INVESTIGATION OF RADIANT SUPERHEATER CROSSOVER PIPE WELD CRACKING AT BIG CAJUN II STATION

by

James P. King
Babcock Borsig Power, Inc.
Worcester, Massachusetts

and

Robert D. Hendrix
NRG Louisiana Generating, LLC
New Roads, Louisiana

ABSTRACT

This paper describes the many features of a detailed investigation into the determination of a root cause for internal cracking found in the circumferential welds of radiant superheater crossover piping lines in Units No. 1 and 2 boilers at Big Cajun II Station in New Roads, Louisiana.

The history of inside diameter, circumferential cracks dates back to 1992. The cracking had been recorded during several outages for both units. It was discovered by use of ultrasonic shear wave testing, and verified by ultrasonic time of flight diffraction methods. During each of the ensuing unit outages, the crack depths were recorded and mapped. Repairs were undertaken by machining out the complete girth weld followed by re-welding. During the interim years cracking did re-occur at many of the weld locations.

In 2000, a detailed investigation into the cause of the cracking was initiated, which resulted in recommendations for resolving the ongoing problem. This detailed study included; nondestructive testing and metallurgy of removed metal samples, boiler performance testing and analysis and stress, fatigue and fracture mechanics evaluations.

The detailed background, applications, and results of the many and varied testing and analytical tasks are fully described herein. The main conclusion to the root cause of the cracking is identified as fatigue caused by the combined effects of thermal and pressure cycles. Recommendations are given which address the actions needed to limit or prevent re-occurrence of the cracking, including revised boiler operating procedures. In addition, a series of fatigue crack growth curves is presented as a monitoring tool for evaluating existing cracks in the welds.

"Investigation of Radiant Superheater Crossover Pipe Weld Cracking at Big Cajun II Station" originally published in PVP-Vol. 442, Fitness for Service Evaluations and Non-Linear Analysis, Proceedings of the ASME Pressure Vessels and Piping Conference (2002). Reprinted with permission of the publisher, ASME

INTRODUCTION AND BACKGROUND

In September of 2000, an investigation was initiated to determine the root cause of cracking in the radiant superheater crossover piping on the Unit No. 1 boiler at the Louisiana Generating Big Cajun II Station. The results of this investigation were presented in the Reference 1 report from Babcock Borsig Power Inc. to NRG Louisiana Generating LLC. The boiler is a Riley Stoker coal fired TURBO® Furnace unit, with a 580 MW net output rating. The unit was designed to operate at 2,620 psig, 1,005/1,005°F, with a steam flow capacity of 4.3 million lbs/hour. The unit was placed into commercial operation in 1980. Since then Unit 1 has logged approximately 150,000 hours of operation, with over 260 starts. The unit was originally designed to be base loaded. As with many such designed boilers, however, the unit is subjected to typical daily load cycling from 35 to 100 percent of full load capacity.

There are four leads of crossover piping, which run from two radiant superheater outlet headers to two high temperature superheater inlet headers. Each of the crossover piping leads contain an attemperator (water spray station) for cooling the radiant outlet superheat steam. The upstream piping is specified as 20" O.D. by 2.875" minimum wall, SA 335, P22 (2.25Cr - 1Mo) material, and the downstream piping is specified as 20" O.D by 2.500" minimum wall, SA 335, P22 material. The material of the long radius elbows is SA 182, F22. There are a total of ten girth butt welds in each piping lead, typically three upstream and seven downstream of the spray station. Historically, cracking has been detected in all of the upstream welds and in many of the downstream welds on each lead. The estimated depths of the circumferential crack indications, from the ultrasonic testing, has been recorded with a range of values from 0.025" to 0.700", for the upstream minimum specified pipe thickness of 2.875".

The analytical and testing tasks performed included an elastic, finite element stress analysis, crack initiation and fatigue crack growth calculations, nondestructive testing and metallurgical evaluations, and a boiler performance testing and analysis program. From the results of the study, recommendations were developed and options provided to limit or prevent re-occurrence of the cracking. Subsequent recommendations considered possible replacement of the piping, as well as a review of boiler operational procedures and practices.

Historically, there have been a number of on-site inspection and nondestructive testing programs. These have revealed inside diameter initiated cracks at many welds of the radiant superheater crossover piping. During each unit outage, the crack depths were recorded and mapped. The cracked welds were repaired by machining out the complete girth weld followed by re-welding, using the proper pre- and post-weld heat treatment procedures. The re-work was checked either by dye penetrant or magnetic particle testing for cracks.

Additionally, there has been "star" shaped cracking noted at locations in the piping such as radiographic plugs and thermowells, with repairs and/or replacements being made. In the earlier years of the inspection process, thermal fatigue cracking in the radiant superheater outlet header nozzles was detected, and then repaired. For the crossover piping welds, ultrasonic shear wave testing results noted inside surface cracks in many circumferential welds. On two separate occasions, independent testing companies were brought in to corroborate the findings at suspect locations. Both ultrasonic shear wave and time of flight diffraction testing methods were used to confirm the findings. Each time the findings were the same as the initial indications, and repairs and/or replacement were recommended.

NONDESTRUCTIVE TESTING AND METALLURGY

In 1996, an initial metallurgical evaluation was conducted on a removed section of a representative pipe to elbow weldment from the upstream region of the radiant superheater crossover lines. The section had been removed with the circumferential weld intact. The section contained some portion of pipe and a portion of elbow metal. The original backing ring was present. It should be noted that the installed elbows have a larger thickness than that of the adjoining pipe, resulting in a tapered transition joint at the inside surface of the elbows.

Ultrasonic shear wave testing revealed indications in the pipe to elbow weld area. The metallurgical investigation of the weldment identified and confirmed the presence of cracking, as noted during the nondestructive testing. The results revealed the presence of circumferential cracks up to 50 mils in depth. The cracks were attributed to thermally assisted fatigue. There was no evidence of creep damage or microstructural overheating in the metal specimens. The depths of the cracks in the sample were found to be less than originally estimated by the ultrasonic testing. In the laboratory, some locations on the weld were found to have bands of stringer inclusions, which were present in the original material. These are not detrimental, but could have been the cause of false indications in the field ultrasonic testing. Figure 1 gives a view of the cut cross sectioned surface of the weldment, showing the location of a crack at the taper transition at the inside of the elbow. Figure 2 shows an enlarged view of the oxide filled, circumferential crack at the inside surface.

In 2000, concurrent with the other analytical and testing tasks, metallurgical re-evaluation, nondestructive testing, and geometric assessment of two sections of the weldment, removed from the same elbow of the upstream (of attemperator) crossover piping, were conducted. The intent of the re-evaluation was to duplicate the findings from the original analysis of the weldment, and provide another assessment of the circumferential weld and adjacent piping and elbow metal.

Figure 1 The cut cross-sectioned surface of the sample weldment, showing the location of a circumferential crack at the taper transition at the inside of the elbow to pipe junction.

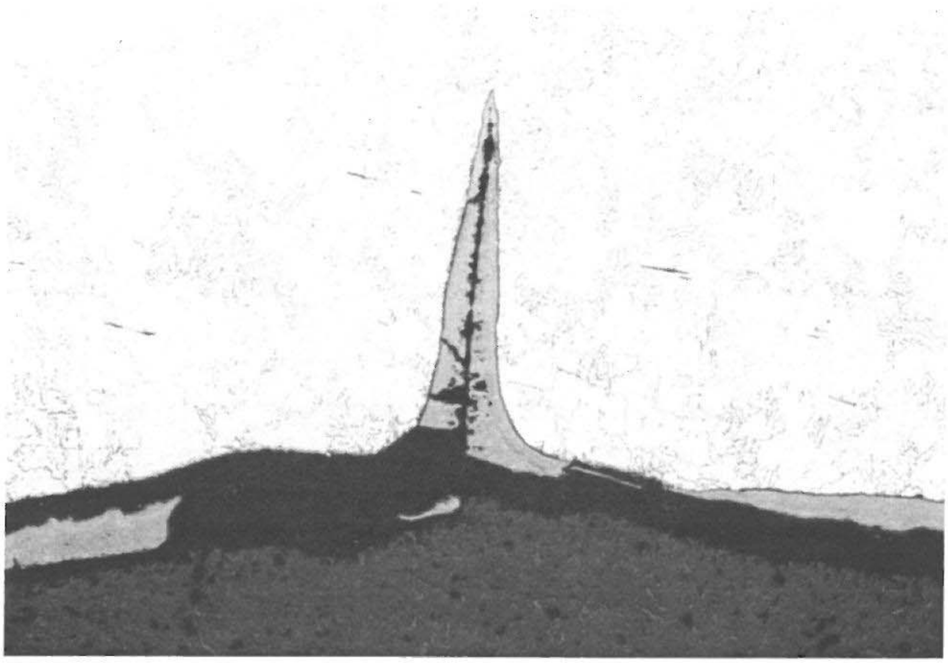


Figure 2 An enlarged view of the oxide filled crack at the inside surface of the taper transition junction. Stringer inclusions can also be seen adjacent to the crack.

The microstructure of the sample material revealed no signs of overheating, and no evidence of creep damage. The matrix was consistent with that of ferrite and pearlite. The pearlite was both lamellar and slightly spheroidized. Dispersion of the alloy carbides was also present. Hardness testing results were consistent with those expected for time in service for the SA-335, P22 and SA-182, F22 materials. In the metallurgical evaluation, side wall lack of fusion was identified in one sample. In other samples there were numerous small, inside surface, circumferential thermal fatigue cracks noted in the same location as was identified in the 1996 analysis. A typical depth of the thermal fatigue cracks identified was 30 mils.

PERFORMANCE TESTING AND ANALYSIS

A baseline boiler performance testing program for the radiant superheater crossover piping system of Unit No. 1 at Big Cajun II station was completed on-site, on November 1 to 3 and December 14 to 16, 2000. The testing was done for a total of nine normal boiler operating conditions including unit start-up, shutdown, load ramping, and load shedding. Due to the power demands of the unit at the times of testing, it was not possible to simulate boiler and/or turbine trip upset events. The results from the testing program, in the form of steam and water temperature, pressure and flow rate values versus time, for the different normal operating conditions were documented for evaluation.

In January of 2001, additional transient data from the operating records for boiler trip, with turbine rundown, for upset events of July 14, 2000 and January 1, 2001 were provided for evaluation. Since 1996, about one such transient event per year has occurred. In addition, eight-boiler trip followed by turbine trip events were identified for the unit, which had occurred since 1996, or approximately two events per year. Unfortunately, there was no transient data available for these latter trip events.

The performance analysis focused on the steam temperature and pressure variations in the radiant crossover piping, which is between the secondary (radiant) superheater and the high temperature (final) superheater. Also included in the analysis was an evaluation of the spray system operation.

The test data was analyzed in order to identify the most severe temperature gradients. These gradient values were later input into stress analysis calculations. The temperature gradient charts show the general temperature reading volatility of all four radiant crossover leads for the November testing, the December shutdown and startup, and the July 2000 and January 2001 unit trips.

In addition to the thermal stresses imposed on the crossover piping by the changes in steam temperature, corresponding changes in pressure also contribute to the stresses in the crossover piping. Because of this, pressure gradients were also evaluated for the transient tests and trips. The temperature and pressure transient profiles for the July 14, 2000, boiler only trip event are shown on Figures 3 and 4.

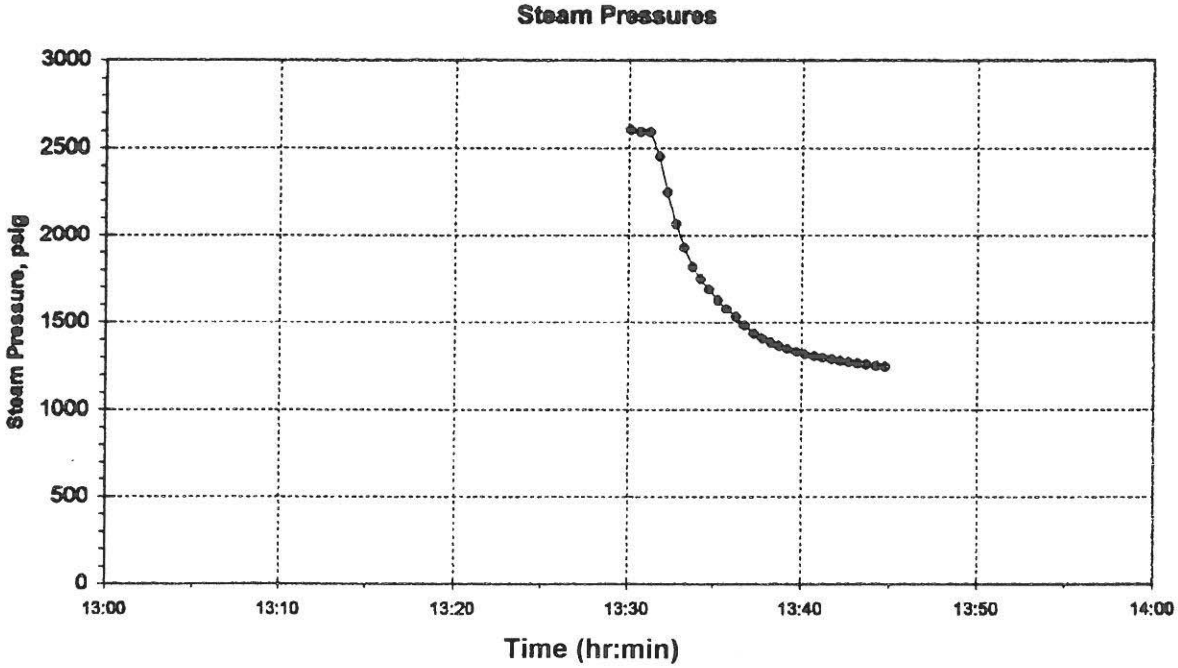
STRESS, FATIGUE, AND FRACTURE MECHANICS ANALYSIS

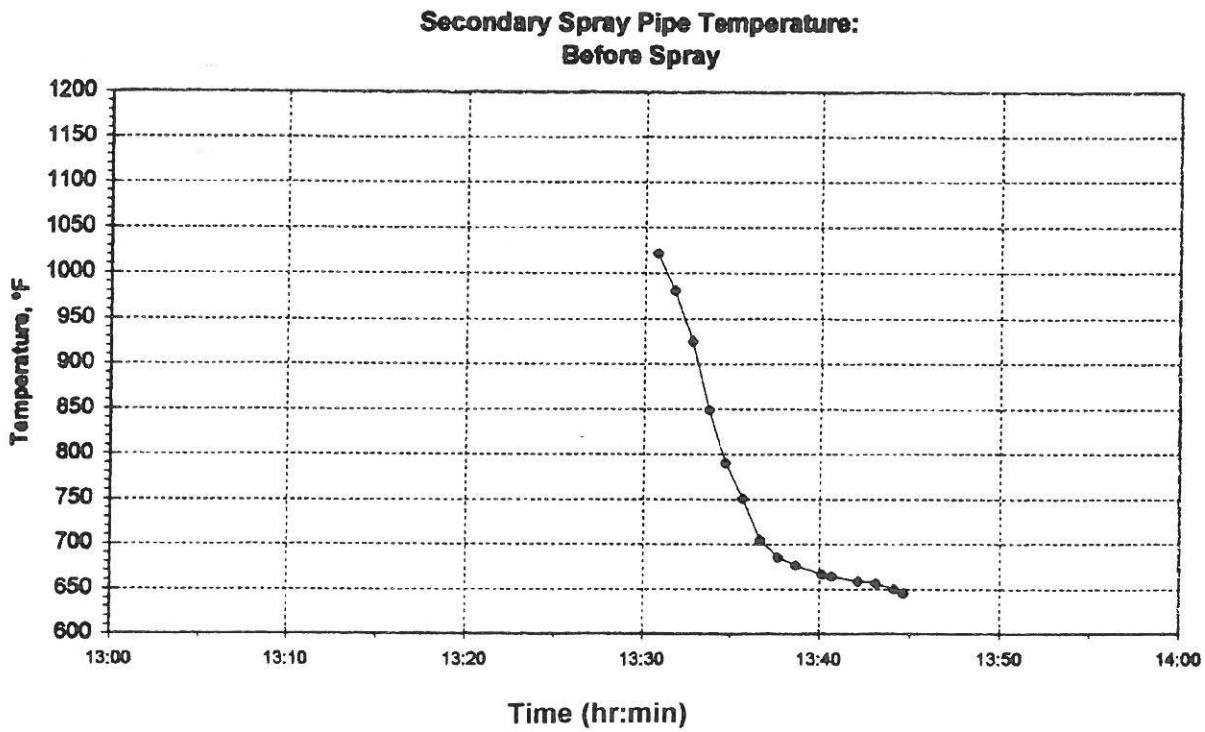
A comprehensive analytical program was performed for the Unit No. 1 boiler to determine the root cause and to provide insights into the prevention of further cracking in the girth butt welds of the radiant superheater crossover piping. The evaluations consisted of elastic, finite element stress analysis, assessment of the potential for crack initiation using literature S-N data, and fatigue crack growth calculations. Since the metallurgical evaluation of removed weldment samples revealed no signs of overheating and no evidence of creep damage, the effects of creep on the crack initiation and growth analyses were discounted at this time.

STRESS ANALYSIS

Two separate finite element models were generated for a typical crossover pipe to elbow, circumferential weld junction. The ANSYS general purpose finite element analysis code[2] was utilized for the stress analyses. The first model represents the original "as built" girth butt welded junction with a backing ring. The second model represents a "shortened" version, due to a loss of component metal in the previous weld repairs. There is no backing ring in the repair model. The geometry models are depicted in Figures 5 and 6. The finite element model for the shortened, repair version is depicted on Figures 7 and 8. Note that the "as installed" elbows have a larger thickness than the adjoining pipe, and consequently there is an internal tapered transition geometry at the weld junctions as shown in the figures. The nominal thickness of the elbows is 3.75" compared to the minimum specified value of the upstream piping of 2.875". To capture the effects of the wall thickness transition and backing ring (as-built model) on stresses in the weld, three-dimensional solid models were required. Through the application of symmetry, only one half of the section is modeled. Terminal points for the models were established at the mid-point of the elbow and one pipe diameter upstream of the weld. For the finite element evaluation, analysis sections were taken on each side of the weld, for both models.

A representative weld junction at the top of the riser from the radiant superheater outlet header, on one of the four piping leads, was selected for analysis. This location is upstream of the attemperator, and thus exposed to the higher inlet steam temperatures.





Figures 3 and 4 Temperature and pressure plots versus time from the Transient No. 3, boiler only trip event of July 14, 2000.

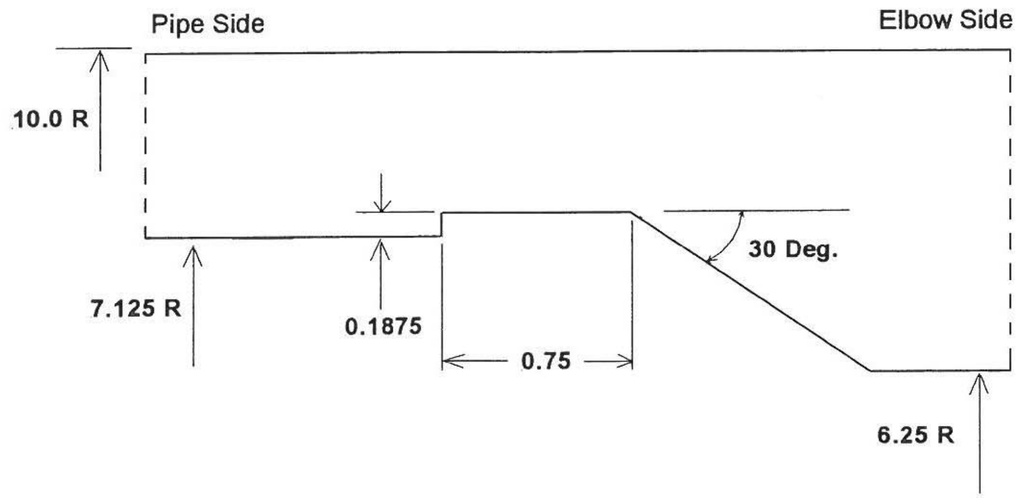


Figure 5 Geometric sketch of the "as built" pipe to elbow girth butt weld junction.

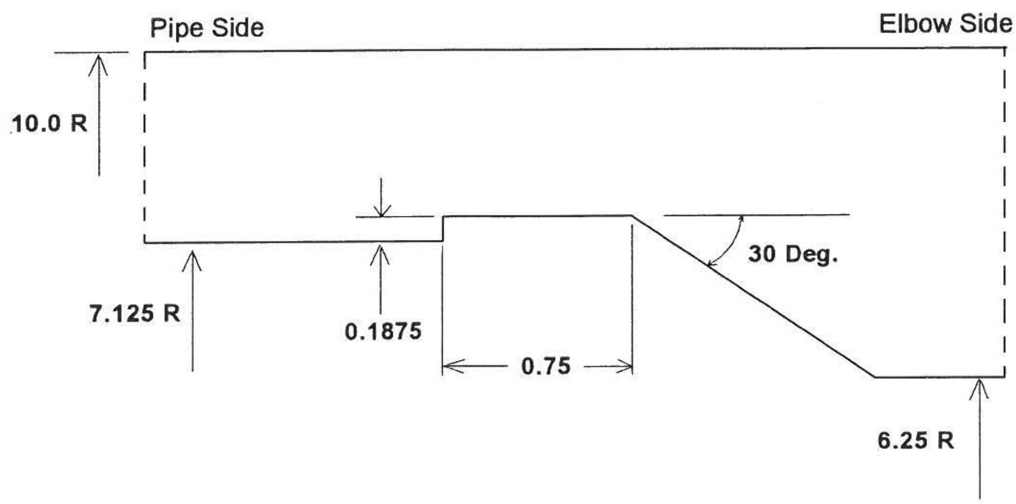


Figure 6 Geometric sketch of the "repaired" pipe to elbow girth butt weld junction.

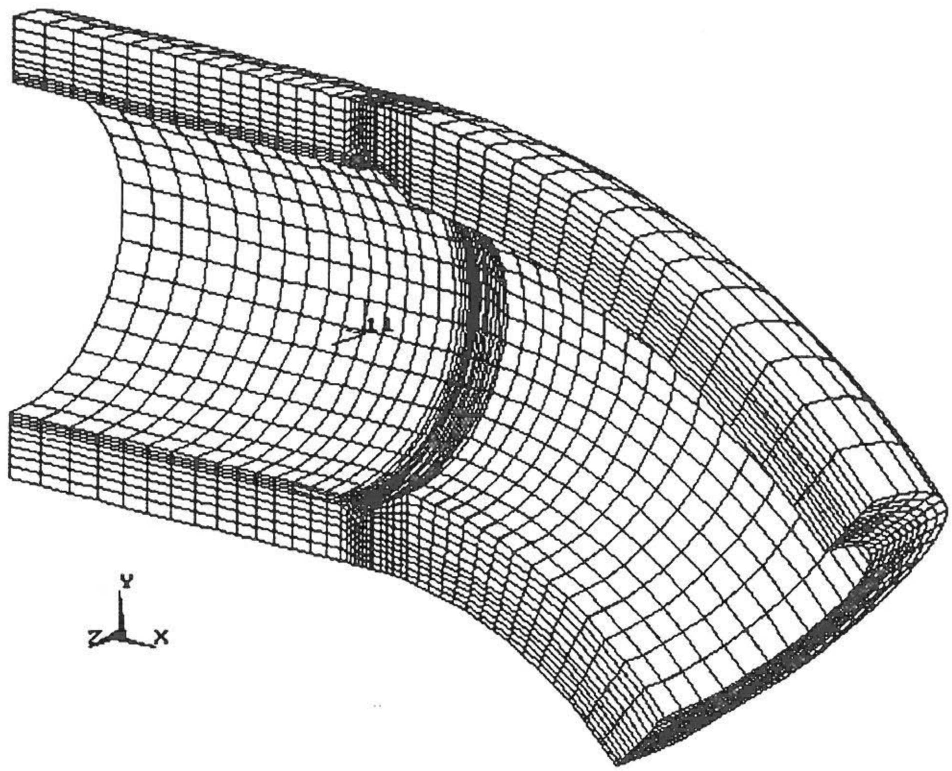


Figure 7 Overall view of the finite element model for the "repaired" weld.

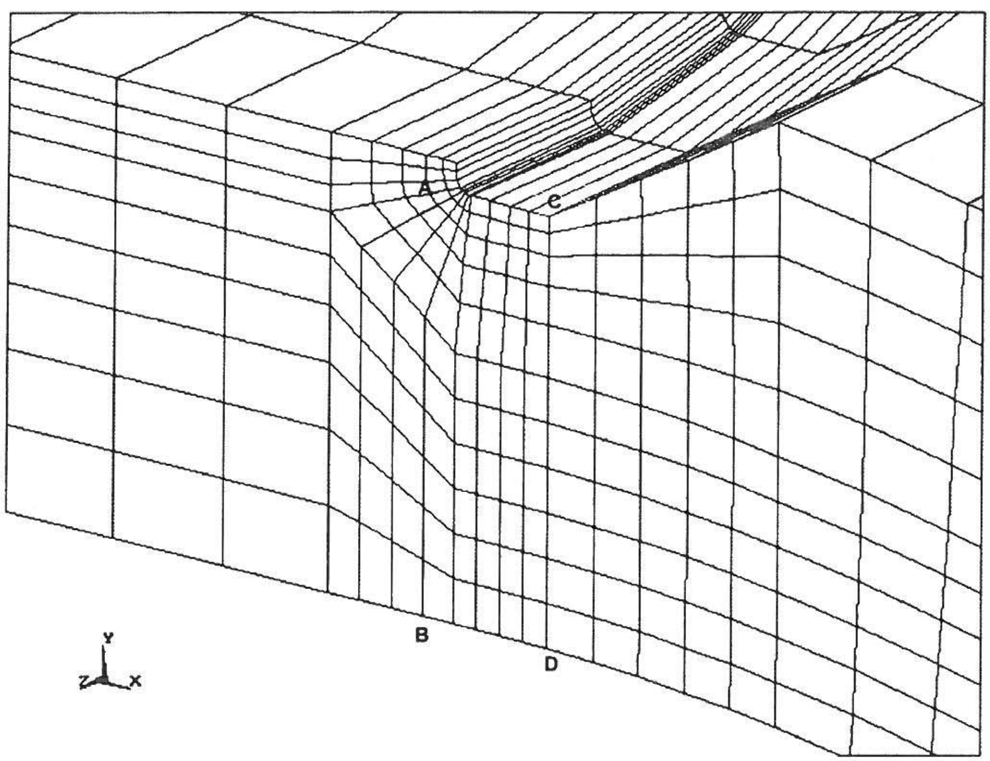


Figure 8 Close-up of the weld region in the repaired configuration at the 180-degree position, indicating the potential crack planes AB and CD.

LOAD CONDITIONS

Loads were applied to each finite element model to bound the operating stresses experienced. Since the evaluations performed assume elastic material behavior, separate load cases were run to allow ready identification of the stress contribution of each load type. The three specific load cases evaluated are described as follows.

Load Case 1: Pressure

Pressure loading at the nominal operating value of 2,700 psi.

Load Case 2: Thermal Expansion

Thermal expansion loading at the design temperature values of 990°F and 960°F for the upstream and downstream of spray portions of the system.

For this case, the applicable thermal bending moment values were obtained from the results of a thermal flexibility analysis performed in the spring of 2000, for the entire radiant superheater crossover piping system. This piping analysis was done utilizing the ADLPIPE computer program[3]. The applicable moment values, from the representative weld junction, for the "as-built" and "shortened" geometry conditions were utilized as input to the finite element analysis. It should be noted that the thermal bending moments from the "shortened" model are significantly higher (by a factor of approximately three), than those generated for the "as-built" model. However, these higher values still meet the requirements of Equation 13A, paragraph 104.8.4, of the ASME B31.1 Power Piping Code[4].

Load Case 3: Thermal Transients

Temperatures with pressure transients were evaluated for both the "as-built" and "shortened" models. Initially, two transients were selected from the results of the Unit No. 1 boiler testing program. The transients represent the normal operating conditions with the highest change in temperature (gradient) values from the testing results. Specifically, they are from the semi-controlled cool down data from December 13 (Transient No. 1), and from the daily load shedding condition testing results from November 2, 2000 (Transient No. 2). Later, a third transient, (Transient No. 3), from operating data depicting a boiler only trip of July 14, 2000, was evaluated for the shortened model only. This severe temperature and pressure transient is from a boiler trip with turbine rundown event, which occurs approximately one time per year. For this transient, which is depicted in Figures 3 and 4, the temperature gradient is equal to a loss of 76 degrees per minute, and the concurrent pressure drop is 410 psi per minute.

For Transients No. 1 and 2, the piping was assumed to be at an initial temperature of 1000°F, and for Transient No. 3 the piping was assumed to be at a steady state temperature of 1025°F. Metal temperatures throughout each model were calculated at 15-second intervals over a span of ten minutes. Nodal temperatures obtained from the thermal analysis at selected times were input to structural models of the joints to calculate the thermal strains and stresses. The bulk steam temperature reductions simulated in these transients resulted in tensile stresses at the pipe inside surfaces. During cooling of the inside and near surfaces, these layers tend to contract but are restrained by the outer, hotter layers. Stress values are at a maximum at the inside surface, and decrease rapidly in the through-thickness direction. At the outside surface of the pipe, compressive stresses result.

HEAT TRANSFER FILM COEFFICIENTS

Thermal stresses are produced by the development of temperature gradients in a component. The magnitude of the gradient, and thus stress, is dependent on the convective heat transfer between the fluid and the component, and the conductive heat transfer within the component. The convection heat transfer between the fluid and component is characterized by the film coefficient. The conduction heat transfer within a component is determined by the parent material's thermal conductivity and specific heat values. For both analytical models, film coefficients were applied to all internal surfaces. For Transients Nos. 1 and 2, film coefficient values were determined using a full load steam flow rate. During Transient No. 3 the indicated reduction in pressure resulted in a corresponding reduction in flow rate, with decreasing values of film coefficients applied.

TRANSIENT ANALYSIS STRESSES

The maximum axial thermal stress predicted during the simulated transients was 72.2 ksi, located in the pipe side of the repair weld model, for Transient No. 3. For Transient No. 1, the maximum stress predicted was 10.6 ksi, and for Transient No. 2 the maximum stress predicted was 24 ksi. The thermal transient stresses are shown in the Figure 9 plots.

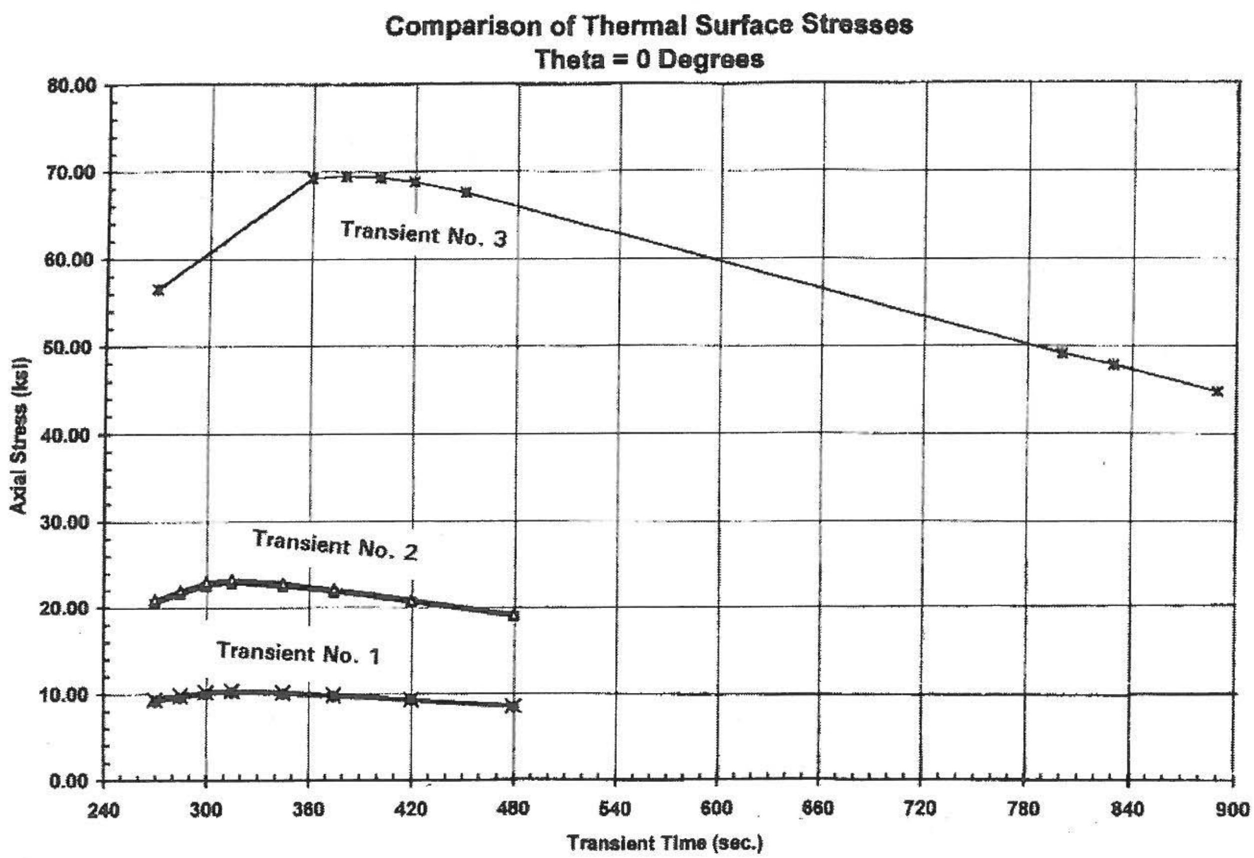


Figure 9 Plots of the predicated axial thermal surface (elastically equivalent) stresses resulting from the three defined temperature transients.

FATIGUE ANALYSIS

The combined, elastically equivalent, axial stress results from the pressure, thermal expansion, and thermal transient load cases, together with the specified number of cycles for each thermal transient event, were evaluated to determine crack initiation in the shortened, repair model only. This model was selected since it experiences the much higher thermal expansion stresses, and the operational data for the most severe, Transient No. 3 boiler trip, is from July 14, 2000, and would be experienced by a typical repaired weld junction.

To predict crack initiation, the damage contributions per month of operation were determined using a linear damage rule from the ASME Boiler and Pressure Vessel Code, Code Case N-47[5]. Essentially, it involves the use of S-N data at elevated temperatures along with a cumulative damage rule to evaluate the fraction of life consumed by cyclic loading. For fatigue damage, design S-N data from the ASME Code, Section VIII, Division 2[6] and Code Case N-47[5], were used. This data represents the combination of cyclic strain and frequency of occurrence required to initiate a defect.

Monthly damage calculations for fatigue were performed for the weld repair model. The operating cases considered in the fatigue evaluations included normal unit startup and shutdown, and those for the three defined thermal transients, plus cycles of the boiler trip followed by turbine trip event. For this latter case, an assumed, ratioed value of thermal stress, from the boiler only trip (Transient No. 3) event was utilized. Once the damage per month was determined, the total time required to predict crack initiation was obtained when the cumulative damage equaled a value of 1.0. The results of the fatigue analysis for the repair model showed that weld cracking would be postulated to initiate after a period of 40.5 months of boiler operation.

FRACTURE MECHANICS ANALYSIS

To provide an estimate of propagation time for a weld that contain cracks, fracture mechanics based fatigue crack growth calculations were performed using the PC-Crack code[7]. For these calculations, upper bound fatigue crack propagation rate data for 2.25Cr - 1Mo material was applied, as obtained from the ASME Code, Section XI[8].

Based on the results of the calculations, crack propagation values are depicted on the curves shown in Figure 10. The resulting crack growth curve values show good correlation with the recorded ultrasonic testing measured depths at typical upstream weld locations. Also, these curves can conservatively be applied to the downstream (of spray) weld components, which are normally exposed to lesser temperature effects. It should be noted that the total combined axial stresses from all the load cases are greater on the upstream (pipe) side, rather than the downstream (tapered elbow) side of the representative repaired weld junction.

SUMMARY

The many and varied features of the detailed investigation to determine the cause of the continued cracking in the welds of the radiant superheater crossover piping leads have been described herein.

The conclusion to the study is that the main contributors to the occurrences of internal surface circumferential cracking in the girth butt weld components are the severe tempera-

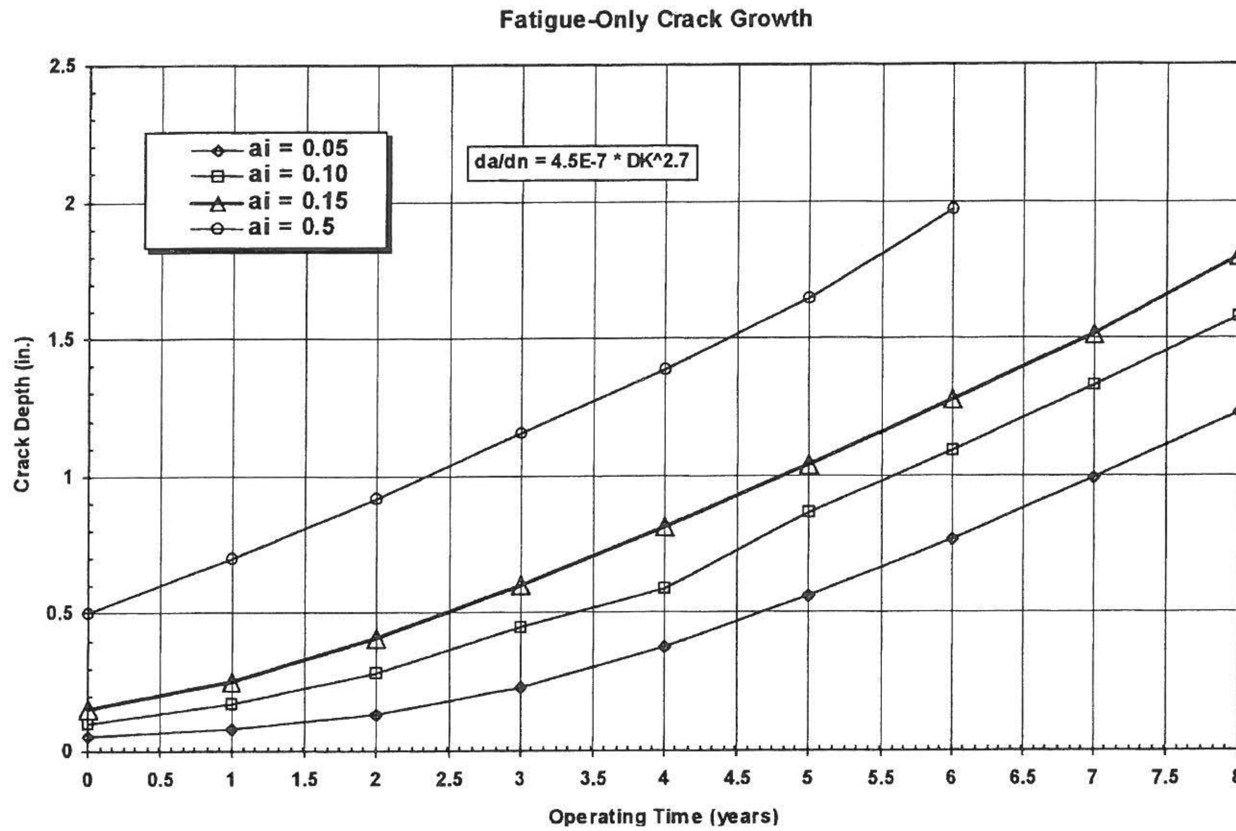


Figure 10 Curves showing the predicated crack depths versus operating time as a function of initial crack size, considering fatigue crack propagation.

ture and pressure transient effects from the boiler trip, with turbine rundown, and boiler followed by turbine trip events, respectively.

In addition to the transient effects of temperature and pressure, the ongoing repairs to the welded joints within the crossover system have effectively shortened the individual segments of the piping. The shortened sections have resulted in a reduction in piping flexibility, with a significant increase in the thermal bending stress levels from the originally installed piping. This secondary effect further aggravates the previously described transient effects.

The transient profiles for the before spray piping of the system show temperature values in excess of 1000°F for some periods of time for several of the normal and upset boiler operating events, but the component microstructures from the metallurgical analysis of the removed weldments and field replication at surface locations show no evidence of severe overheating or creep damage. However, the temperatures of the crossover piping leads should be monitored, since any prolonged exposure to values in excess of 1,000° F could lead to creep damage, resulting in a decrease in the time for crack initiation, and a corresponding increase in the rate of crack propagation.

A significant result of the comprehensive investigation of the cracking is represented by the fatigue crack growth curves, depicted on Figure 10. The crack depths from the curves show good correlation with the recorded ultrasonic testing measured values.

The fatigue crack growth curves, together with current crack depth measurements and ASME Code[4] minimum wall thickness values, can be used in any component repair and/or replacement decisions. The curves were established based on data from a representative boiler only trip transient, and the reported number of boiler/turbine trips experienced by the crossover piping. Some conservative methods were employed in the evaluations, but assumptions were also made as to the severity of the boiler followed by turbine trip thermal transients.

Due to the severe temperature gradient effects from the boiler only trip events, it has been recommended that the operational practice of keeping the turbine on line after a boiler trip be discontinued.

It has been recommended that the owner continue to collect transient data from both the Unit No. 1 and 2 (identical) boilers, including the thermal and pressure gradients from the typical boiler only, and boiler followed by turbine trip events.

It has also been recommended that for future weld repairs, new pipe spool pieces be utilized in the process in order to avoid the "shortening" effects at the pipe weld joints that have occurred during past repairs.

Recommendations have been described herein, which will alleviate the effects of the two main contributors to the cracking. However, there is currently some residual fatigue damage present in the welds of the crossover piping lines due to previous operational trips and shortening effects. Therefore there will be some future iterations of crack identification, with decisions on monitor or repair. Eventually, a decision will be made relative to total pipe replacement. Because of this, a recommendation is given that a cost evaluation be performed on repairs versus total replacement, as a guide to future planning. Part of this evaluation could be an option for replacement using SA 335 P91 (9Cr - 1Mo - V) pipe material instead of the existing SA 335 P22 material. The P91 material has improved creep properties and increased strength, which results in thinner components and subsequent increased resistance to fatigue.

ACKNOWLEDGEMENTS

The authors would like to recognize the contributions of Craig Gillum, Brian Ryder, and Brian Vitalis of Babcock Borsig Power, Inc., Gary Wood of AEP Pro Serv, Inc. and Scott Rau of Structural Integrity Associates, Inc., to the analytical and testing tasks described herein.

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