Technical Publication

Recent Experience in Boiler Header Tube Nipple Failures

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ABSTRACT *A very common location for boiler tube failures is at the junction of a tube nipple and header. Cracking, often leading to failure, has been found to exist at several different locations including; the tube nipple, the nipple to header weld and the header bore hole.*

The cracking is often associated with, but not restricted to, high temperature components. Instances of cracking have been discovered in nipples attached to waterwall, economizer and primary superheater headers. In general, the failure mechanisms associated with header nipple cracking are; stress rupture, fatigue and water-side corrosion. A common failure mode is fatigue induced by differential thermal expansion.

Case studies of typical header nipple cracking are presented herein. These studies address the applicable crack detection techniques, metallurgical findings and failure analysis methods; together with the appropriate design and operational considerations required to eliminate or minimize further header tube nipple cracking.

INTRODUCTION

The subject of tube failures, in fossil fired boilers, with the corresponding loss of unit availability, has been a continuing industry problem, which is currently receiving much attention. Recent publications on this subject, by the Canadian Electrical Association [1] and the Electric Power Research Institute [2] have presented detailed information on boiler tube failures as applied to the entire boiler. This paper focuses on the specific area of the boiler tube nipple to header junctions, and presents recent experience with indications and failures in such regions. This experience shows that problems can occur in nipples attached to virtually any header in a boiler. Most failures have been documented for boilers in service for a period of more than 15 years.

The case studies presented herein are categorized as, failures occurring in high temperature steam tubes and in lower temperature water carrying tubes. Two factors which greatly influence the propensity for tube nipple cracking are, the presence of a corrosive medium, and a cyclic mode of boiler operation. Another important consideration is that tube nipple cracking can be accompanied with, and can be a precursor to, cracking in a header component.

During a scheduled or forced outage, obvious examples of cracking can be detected by visual inspection. However, for more subtle or minor indications nondestructive examination techniques such as, fiberoptics, dye penetrant, magnetic particle, ultrasonics and replication are utilized to locate and determine the extent of damage.

BACKGROUND

A typical boiler tube nipple to header intersection is shown in Figure 1. The relative difference in size of the two components tends to make this connection a highly stressed location, particularly at the attachment weld which acts as a stress intensifier. In many instances, cracking has been found to have initiated in or adjacent to the weld, including locations of weld undercut. Boiler tube nipple cracking or swelling, as described in the case studies herein, is mostly associated with the failure mechanisms of fatigue, stress rupture and waterside corrosion. Many times a component failure is attributed to the interaction of two of the mechanisms, such as corrosion-fatigue or creep-fatigue.

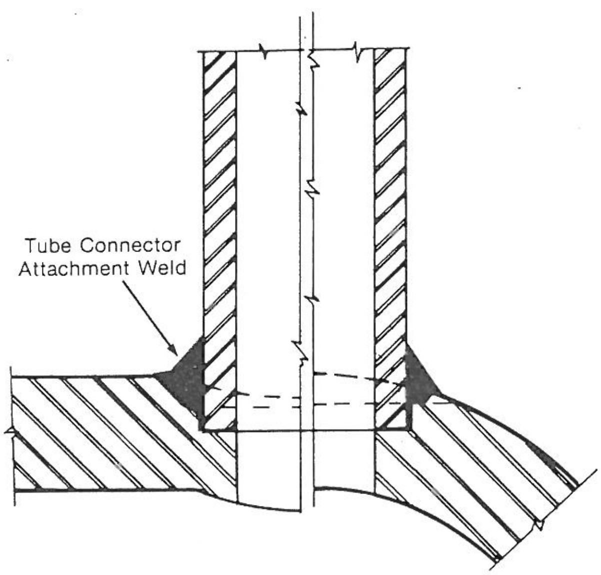

Figure 1. Typical tube connector to header junction

Fatigue

Fatigue cracking leading to component failure results from cyclic type loadings. Fatigue damage in tube nipples can be caused by differential, or restraint of, thermal expansion; and by the internal temperature transient effects of the flowing water or steam. This latter cause, which is often described as thermal shocking for severe transients, can be initiated or aggravated by a corrosive condition.

In the design of tube routing for a boiler, thermal flexibility analysis may be performed in accordance with the rules of ANSI/ASME B31.1 Power Piping Code [3]. Compliance with the requirements of Equation 13A, Paragraph 104.8.3, of the Code, for thermal expansion stress range, assures that tubing and piping components are satisfactory for a designed number of temperature cycles. However, if a boiler designed for base loaded duty has been utilized in a cyclic or two-shift mode of operation for a number of years, then some thermal expansion fatigue failures could be postulated to occur. These type of failures are likely to occur at a tube nipple to header junction, due to the different thermal expansion rates of the tube and header, and dependent on the amount of flexibility in the tube routing.

In examining fatigue type failures of boiler pressure parts, the simplified rules of ASME Boiler and Pressure Vessel Code, Section III [4], can be used as a guidance. Use of Equation 11 (NB-3653.2) of the Code, provides values of peak stress intensity range, for every significant load set pair, experienced by a component. This equation includes evaluation of pressure, thermal expansion, thermal gradient and thermal discontinuity stress range values, as applicable. The thermal gradient (through the wall) and thermal discontinuity stresses are acting during a temperature transient event. The peak stress range values are input to a fatigue evaluation using a cumulative damage concept.

A boiler tube nipple to header junction is subjected to temperature excursions due to plant events such as load change, startup and shutdown. A typical daily two-shift mode of operation involves shutting the boiler off overnight, for a six to eight hour bottle-up period, followed by a hot restart each morning, to meet system demands. The increased number of temperature excursions due to such operation, can lead to component cracking and eventual failure. The tube nipple to header region is most susceptible to this type of boiler duty because of differential thermal expansion effects, and the added presence of thermal discontinuity stresses, caused by such transients.

Stress-Rupture

It is our experience that most stress-rupture type failures in boiler tube nipples at headers are caused by high temperature creep. Such failures, occurring in superheater and reheater tube connectors are primarily due to operation above the specified component design conditions for extended periods of time.

The presence of internal scale in a tube connector can also cause an overtemperature condition, by affecting the heat transfer characteristics of the metal, and leading to eventual deformation or cracking in the component.

In performing remaining life calculations for a component, or in evaluating failures due to high temperature creep, two of the simplified analytical tools available are; the Larson-Miller parameter [5], which correlates time, temperature, and stress for a given material; and the Life Fraction Rule, where incremental creep damage values are summed for a component, for periods of operation at different temperatures or stresses.

Three of the case studies presented herein, detail tube nipple failures due in part to creep-fatigue interaction.

CASE STUDIES

Case 1

This case involves internal circumferential cracking found in tube nipples attached to an economizer inlet header. In addition to the cracking, extensive internal pitting and corrosion were present, as depicted in Figure 2. The nipples and tubes are specified as, 2″ O.D. by 0.200″ wall, SA-210 Grade A-1, carbon steel material.

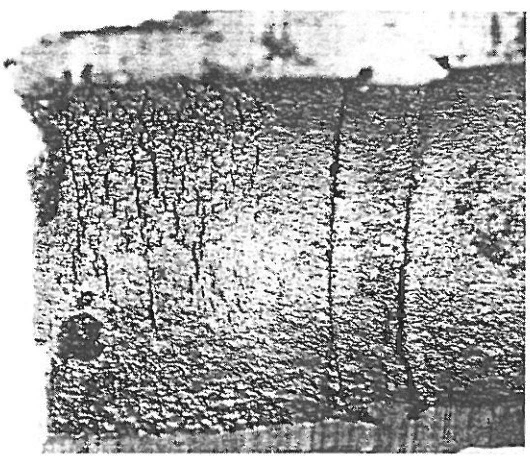

Figure 2. Internal circumferential cracking in a tube connector attached to an economizer inlet header

Metallurgical examination of a stub sample revealed that the cracks were nearly straight, transgranular in nature and deposit filled. Figure 3 shows one of the many cracks originating at pits on the inside surface. Some of the cracks were found to have nearly penetrated through to the outside surface of the nipple. The material structure was found to be normal lamellar pearlite in ferrite, indicating no exposure to excessive or long-term overtemperatures.

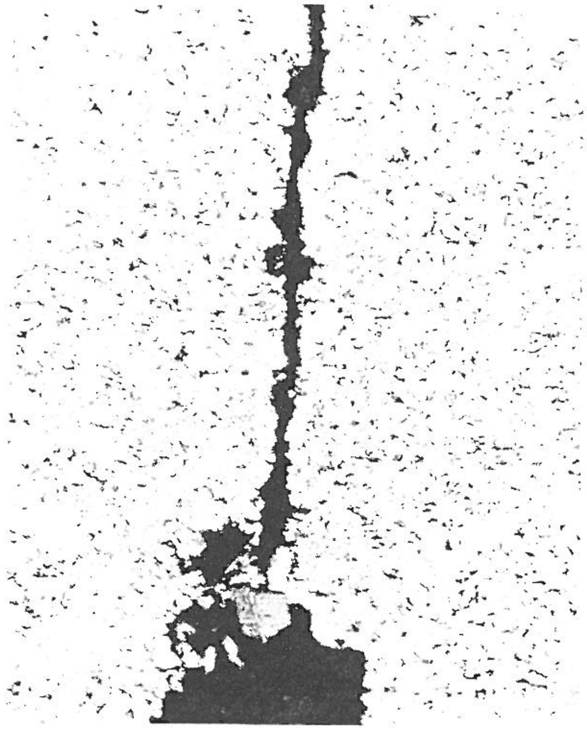

Figure 3. Photomicrograph of a crack from the Figure 2 sample, originating at a corrosion filled internal pit (100X)

The massive internal pitting and circumferential cracking, observed for this case study are attributed to a corrosion fatigue process. The cause was determined to be thermal stresses, induced by many cycles of sudden component cooling, in a corrosive environment. The fracture surface of a corrosion fatigue crack is typically thick-edged, and is oriented perpendicular to the direction of the maximum tensile stress.

The subject of economizer inlet header/tubing cracking is topical and is receiving increased industry concern and attention. The Reference 6 paper, and EPRI Project No. RP-1890-6, in process, address this subject in detail.

Case 2

This example addresses internal circumferential cracking in tube connectors at a superheater outlet header. The cracking was found to exist just below the attachment weld to the header. The tubes and connectors are specified as, 2″ O.D. by 0.320″ wall, SA-213 Grade T-22, low alloy material.

Visual examination of the tube connector samples confirmed the cracking, as shown in Figure 4. Also, both the inside and outside surfaces were thickly coated with a blue-black scale.

Figure 4. Internal circumferential cracking in a tube connector specimen at a superheater outlet header (2×)

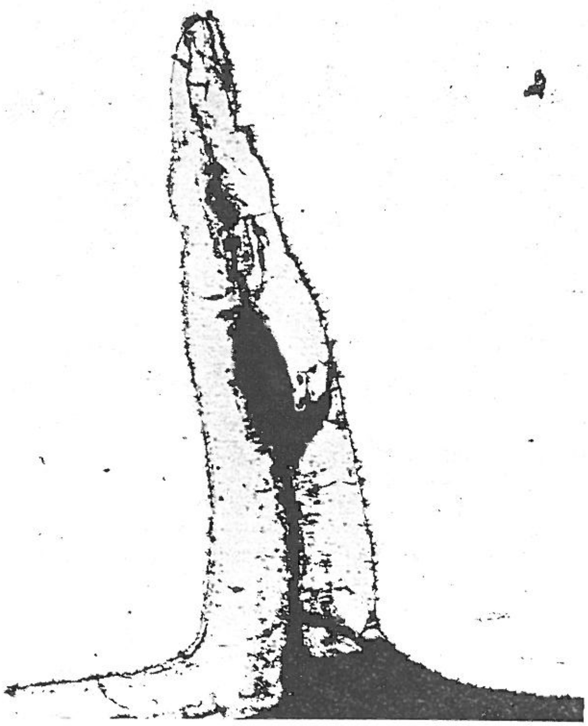

Figure 5. Photomicrograph of a typical transgranular crack from the Figure 4 sample, showing thick oxide deposits (100×)

Metallurgical evaluation of the samples showed many transgranular, oxide filled cracks, up to 0.120″ deep. A photomicrograph of a typical crack is shown on Figure 5. The structure was found to be completely spheroidized, with evidence of a slight temperature gradient through the wall. This indicates that the metal has been exposed to high temperatures for an extended period of time. This condition has been aggravated by the presence of the thick (0.020″) internal scale.

The internal circumferential cracking described for this example is typical of a thermal fatigue condition, caused by many cycles of heating and cooling temperature excursions. This condition was enhanced by the presence of a weakened structure, due to long-term overheating, leading to the interaction of creep and fatigue.

Case 3

This case describes a failure in the form of external circumferential cracking in the weld attaching a tube nipple to a high temperature superheater outlet header. Several instances of failure were found, typically in the furnace side shorter leg inlet tubes. The tube material is specified as, 1¾″ O.D. by 0.320″ wall, SA-213 Grade T-22.

Specimens were cut from the tube sample, transverse to the crack, in preparation for microscopical examination. The results of the investigation showed that the crack had originated at a slag inclusion near the toe of the weld. It had propagated outward, and inward through the weld and into the tube along the weld interface, and through the tube wall. Figure 6 shows part of the crack, together with the heavy oxide scale built up between the crack and the large void existing between the tube and the weld metal.

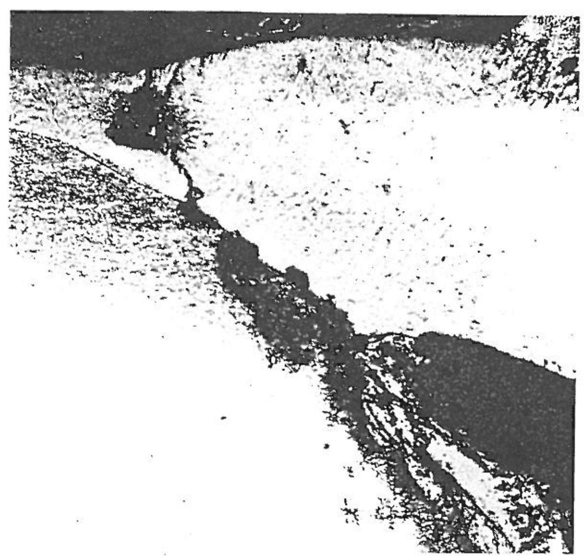

Figure 6. Close-up of an external circumferential crack originating in a void near the toe of the attachment weld at a superheater header (75×)

Examination of a tube specimen taken several inches away from the cracked weld revealed a complete coalescence, and agglomeration of the carbides in ferrite, indicating exposure to elevated temperatures, but considered normal for the 20 plus years of service.

The failure is attributed to thermal fatigue, induced by thermal expansion cycling, with the crack initiating at a stress raiser. The crack had existed for some time as evidenced by the thick oxide scale. The oxide deposit assists in the crack propagation because the volume occupied by the oxide is greater than the volume of the metal from which it is formed. The oxide product prevents the crack from closing during the compression portion of the stress cycle, and increases the stress at the crack tip. The crack then propagates faster due to the formation of the wedge.

Case 4

This example concerns a radiant superheater outlet header inlet tube connector, that contained a circumferential crack at the toe of the attachment weld. Also, the tube connector portion was found to be swollen. Refer to Figure 7. The tube material is specified as 1¾″ O.D. by 0.240″ wall, SA-213 Grade T-22.

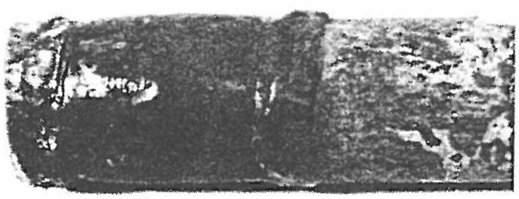

Figure 7. As received superheater tube connector sample with an external circumferential crack and swollen diameter

A visual and dimensional examination showed the crack starting at the toe of the weld and extending well towards the inside surface. Much internal and external blue-black scale was noted. The stub portion was found to be swollen to 1.844″ O.D. compared to the normal 1.750″. This portion also showed minor thinning (0.220″) on one side.

Several specimens were taken through the circumferential crack and prepared for microscopical examination. This investigation confirmed the crack

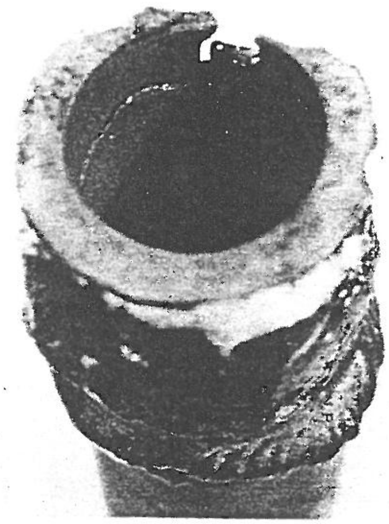

Figure 8. Superheater tube nipple sample with circumferential and longitudinal cracking

origination and path, which was found to be transgranular. A tenacious scale deposit, which measured 0.010″ thick, was found on the walls of the crack. Several other O.D. transgranular cracks were noted. The structure of the tube connector is spheroidized carbides in ferrite, indicating exposure to high temperatures.

The conclusion for this case, is that the cracks at the toe of the weld are indicative of fatigue by thermal expansion. An earlier modification to the boiler roof seals had shortened the length of the inlet superheater tubes, thus increasing thermal expansion stresses. In addition, the swollen stub, the spheroidized structure and the thick blue-black scale all confirm high metal temperature exposure, leading to the interaction of creep and fatigue.

Case 5

This example involves both externally originating circumferential cracking and internal longitudinal cracking, in tube connectors attached to a high temperature superheater outlet header. See Figure 8. For this particular case, the longitudinal cracking was found to exist in the tube nipple, the header bore hole and the header ligament field. The header cracking was located by fiberoptics and confirmed by ultrasonic techniques. The tube material is specified as, 1¾″ O.D. by 0.250″ wall, SA-213 Grade TP321H stainless steel.

A visual examination of the as-received connectors confirmed the circumferential and longitudinal cracking indicating the possibility of two separate modes of failure.

For the longitudinal cracking, specimens were removed and examined at different magnifications. The results showed a large, intergranular oxide filled crack, together with many more smaller similar cracks. The structure was found to be essentially a matrix of austenite, with a possible carbide precipitate. Some creep voids were observed at the grain boundary triple points in the form of wedge shaped cracks. See Figures 9 and 10.

Figure 9. Photomicrograph from the Figure 8 specimen of a longitudinal, intergranular crack (100×)

The circumferential crack in the attachment weld was obviously due to thermal expansion fatigue, as described for several other cases. The cracks had originated on the outside surface and propagated through to the inside surface.

The longitudinal cracks were concluded to be thermal and creep related. Cycling duty, together with high metal temperatures were the major contributors to this failure.

Figure 10. Enlargement of the structure from the Figure 9 photomicrograph, showing creep voids at grain boundary triple points (500×)

SUMMARY

The five case studies described herein, provide very typical examples of potential and actual failures in boiler tube nipples attached to water carrying and high temperature steam headers.

Circumferential and longitudinally oriented cracks have been found to exist at internal and external tube surfaces, and in attachment welds. Fatigue, stress rupture and water-side corrosion, acting separately or interacting, are the failure modes most responsible for tube nipple cracking.

Fatigue failures are typically caused by thermal expansion or temperature transient effects. Fatigue cracking can be accelerated by the presence of corrosion or high temperature creep.

High temperature creep is the most common cause of stress rupture failures in tube nipples. The presence of internal scale directly affects the heat transfer characteristics, causing tube metal overtemperatures leading to deterioration of the material structure, and eventual deformation and/or cracking.

RECOMMENDATIONS

In order to eliminate or minimize the potential for header tube nipple cracking, the following recommendations are presented as design, operational or maintenance items.

1. Allow for sufficient flexibility, with consideration given to location of restraints, in order to minimize thermal expansion stresses, in the design of inlet and outlet tubing to a header.

2. Allow for the specified number of thermal expansion cycles in the design of supports, attachments and seals for such tubing.
3. Utilize upgraded materials, to accommodate higher temperatures, and temperature differentials and excursions, in the design of such components.
4. Require that tube connector welds be made with smooth contours, to minimize the effects of stress concentrations.
5. Implement strict water chemistry requirements to inhibit the formation of internal scale.
6. Perform scheduled chemical cleaning to eliminate existing scale.
7. Perform visual external, fiberoptic internal and dimensional inspections of tube nipples, with nondestrutive examination of the attachment welds during annual outages.
8. Operate within the specified operational guidelines for ramping rates and temperature limits, during startup, shutdown and other boiler transient events.
9. Alleviate thermal shocking to components such as economizer inlet header tube connectors during boiler startups, by such methods as trickle feed operation or installation of an economizer recirculation system.

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