Hawaiian Steam Engineering Co.
P. O. Box 2711
Honolulu, Hawaii 96803

Analysis of Boiler Tube Failures
Union Pacific RR Steam Locomotive #844
June 24, 1999
Sacramento, California

Summary

While sitting at rest with a boiler pressure of approximately 225 psi, a spontaneous boiler tube failure occurred allowing the uncontrolled release of boiler water. The water flashed into steam, escaping the boiler mostly from the smokestack, however some steam did access the cab causing minor 1st degree burns to several occupants, requiring only Firstaid treatment. The event occurred at about 10:30 am on June 24, 1999 at Sacramento, California.

Investigation

Inspection of the boiler revealed 10 failed 2-1/4" tubes. According to UPRR records, the tubes conform to ASME SA-178 Gr.A specification with a tube wall thickness of 0.120" (No. 11 BWG).

All tube failures were located at the waterside of the rear tube sheet. Four tubes were completely sheared from the tube sheet while six other tubes showed partial tears in the tube wall. Failed tubes were located on the exterior rim of the tube bundle and for the most part, failed tubes were separated by several non-failed tubes.

Waterside inspection of the tube to tube sheet surfaces showed unusual contours. After needle gun descaling, non-failed tubes and flues indicated excessive grooving. Removal of the scale to solid metal on the 2-1/4" tubes left a groove approximately 1/8"-3/16" from the tube sheet and to a depth of approximately 1/8" from the external tube surface. Grooving on the flues was identical except for magnitude of corrosion which was less. Depth and length of grooving on the flues was about 1/16".

Fireside inspection included removal by grinding of several tube and seal welds flush with the tube sheet. Typically the interior tube wall was found on the order of 1/16" thick surrounded by a layer of black iron oxide (magnetite Fe_3O_4) about 1/8" in thickness.

There was no evidence of over-rolling during tube installation visible from the fireside. Corrosion precluded any reliable determination of over-rolling from the waterside.

Failure Sequence

Inservice failure of one tube in a firetube boiler is rather common, mostly caused by thinning of the tube wall in the tube sheet due to over-rolling due to poor workmanship or repeated rolling to stop tube leaks. Simultaneous failure of 10 non-adjacent fire tubes is most uncommon if not unprecedented.

No attempt was made to determine the single tube that precipitated the failure event as finding the proverbial straw is irrelevant when the camel has 300 cracked vertebrate. All of the tubes were very uniformly corroded.

Failure of the first tube in the event caused the opening of a 2-1/4" hole to atmosphere. Because the opening was below the water line, the water contents of the boiler began moving at near sonic velocity toward the opening. Failure of the tubes on the exterior of the tube bundle can be attributed to the momentum of the water in the throat sheet water leg flowing upward and impacting the tube bundle. Also contributing to the failure would be impact of water in the shell of the boiler flowing rearward until contacting the rear tube sheet, diverting its momentum at right angles to the tubes. Time from initial tube failure to total or partial failure of the other nine tubes would be on the order 10 to 20 thousandths of a second.

Analysis

1. Corrosion Reaction

Tube and flue attachment to the rear tube sheet was found to be excessively and uniformly corroded. Oxidation products are black rust (magnetite Fe_3O_4) which evidence indicates was preferentially formed from the tube wall vice the tube sheet. The mechanism of corrosion is determined to be *Crevice Corrosion*. This is a derivative of basic oxygen cell corrosion.

Corrosion and Oxidation

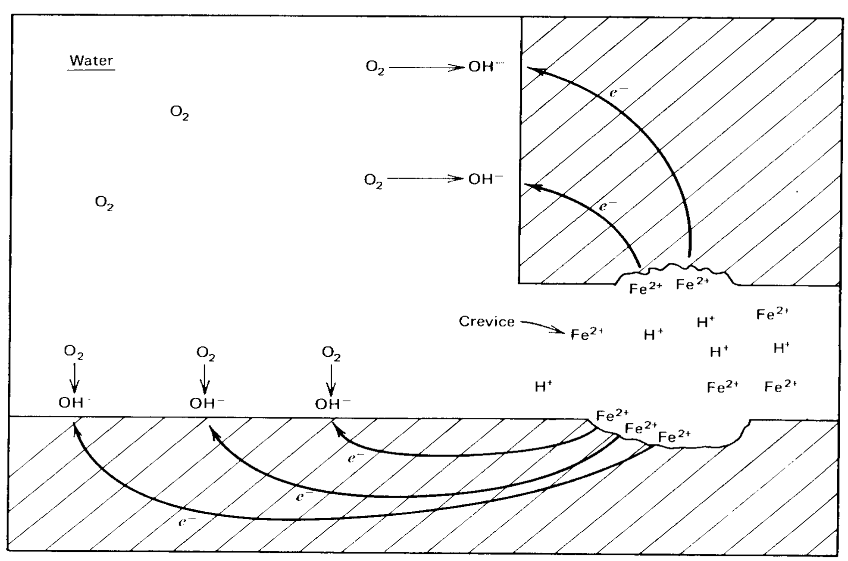

FIGURE 15.1 Crevice corrosion of iron. Because the oxygen is depleted rapidly in the crevice, an oxygen concentration cell is set up between the crevice and the more exposed areas adjacent to it. The crevice region is anodic, with the corrosion half-cell reaction $Fe \rightarrow Fe^{2+} + 2e^-$. Reproduced from Material Science and Engineering (Wiley).

Anyone experienced with firetube boilers of any style has seen black blisters on the waterside of firetubes. This is oxygen cell corrosion. In the presence of oxygenated water, once the corrosion has started, the pit begins to act as an anode to the surrounding metal surface area (acting as cathode). As the surface area of the pit grows larger, the electrical potential increases thereby accelerating the corrosion rate.

Corrosion and Oxidation

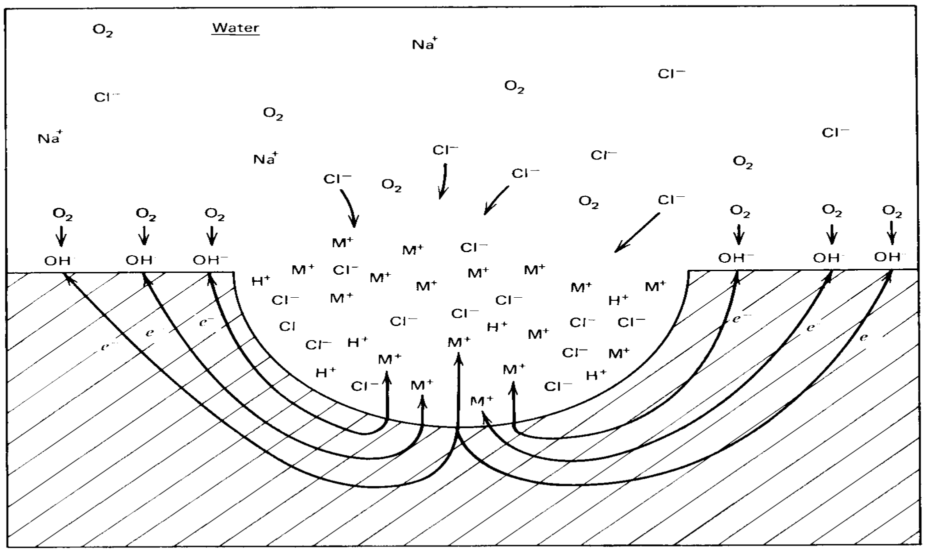

FIGURE 15.2 Pitting corrosion of a metal in a salt solution. The oxygen concentration cell in pitting is similar to that associated with a crevice (Fig. 15.1). The pitting process tends to be autocatalytic in nature because, as the pit grows, the region formed is depleted of oxygen, leading to an increasing corrosion rate. (Adapted from *Corrosion Engineering* by M. G. Fontana and N. D. Greene. Copyright 1967 by McGraw-Hill Book Co. Used with permission of McGraw-Hill Book Co.) Reproduced from Material Science and Engineering (Wiley).

Crevice Corrosion acts identically except that instead of a small pit, when oxygenated water finds access to a crevice such as the area between the tube and tube sheet, the crevice imitates an artificially large anode in the oxygen cell reaction. Consequently, the corrosion rate is accelerated, induced to an even higher rate by the high metal temperature due to high combustion gas temperatures.

2. Tube Attachment

Current set of tubes in the 844 were installed during the winter of 1995-96. Although installed for 3-1/2 years, only about 120 service days were accrued. The tubes and flues were attached to the rear tube sheet in accordance with the Union Pacific RR Standard Practice which called for roller expanding the tubes in the tube sheet then seal welding the exposed tube end to the tube sheet. The ASME Boiler Code requires that after seal welding tubes, the tubes be lightly re-rolled to reset the tube wall to tube sheet as the heat input from seal welding tends to distort the tube, pulling it away from the tube sheet. The post seal welding re-roll was not a practical problem during the days of UP Standard Practice since all water for steam locomotive boiler use was very closely chemistry controlled such that no free oxygen was present. Without free oxygen available in the boiler water, crevice corrosion could not occur even with the presence of a crevice created by seal welding distortion.

3. Water Chemistry

Municipal water supplies typically come from two principal sources, well water or river water. Well water supplies mostly are high in mineral content but low in dissolved oxygen whereas river water is high in dissolved oxygen but low in minerals. This makes a standard water chemistry program nearly impossible to maintain for the UP Steam Program as mineral and/or oxygen content could vary as much as ten to one hundred times from one water stop to the next. No commercial boiler water treatment company has an established program to meet these conditions. Furthermore, no such company desires to establish a program for a sole consumer.

Current boiler layup procedure is to remove the washout plugs and allow the boiler to dry by natural circulation of air. This is a proven method for over 140 years. However, with active crevice corrosion as existed in the 844 rear tube sheet, the powdery products of corrosion retained moisture in the crevice, allowing the corrosion process to continue even with the rest of the boiler dry. Presence of free circulating air providing unlimited oxygen supply. In essence, even though the boiler saw only 120 days of service, as far as the corrosion reaction of the tubes in the rear tube sheet were concerned, the boiler was filled with water since the tubes were installed 3-1/2 years earlier.

Findings

1. Union Pacific Steam Locomotive #844 was retubed during the winter of 1995-96 using the UP Standard Practice for boiler repairs.
2. UP Standard Practice for boiler repairs as written during the steam era expects boiler water supply from UPRR treated watering facilities.
3. Current Steam Program Operational commitments dictate UP system-wide operation and therefore consistent water supply is impossible to maintain.
4. Crevice corrosion occurred at the rear tube sheet due to the installation technique used ***and*** the presence of free oxygen in the boiler feed water.
5. The failure event was precipitated by one tube failing and the momentum of the boiler water hammering the other uniformly corroded tubes caused three more tubes to completely fail and 6 other tubes to partially tear open.
6. A catastrophic boiler failure scenario is impossible given the type, location and magnitude of the defects found.

Recommendations

1. Modify the UP Standard tube and flue installation technique to conform to the ASME Boiler code requirements for re-rolling tubes and flues after seal welding.
2. Create a water treatment program to test each water supply and medicate the water accordingly.
3. Change the boiler lay-up procedure to more positively control corrosion. Suggested methods include heated air supplied to boiler or desiccant placed in boiler and monitored.

Conclusions

Having known of the phenomenon of crevice corrosion for over 20 years, which includes 11 years as a National Board Commissioned Boiler Inspector, this is the first instance that I have seen this type of corrosion and therefore, obviously have never witnessed a failure because of it. The fact the 10 tubes simultaneously failed due to crevice corrosion is a testament to the superior quality of workmanship by the UP boilermakers. All tubes were installed in a consistent manner causing the corrosion to be extremely uniform. Had one or two tubes been over or under rolled, those would have failed prematurely to the rest and the corrosion problem identified.

In simplest terms, this tube failure event has two contributing causes: tube installation technique and water chemistry. The tube installation technique can be modified to eliminate the crevice in the tube sheet thereby removing the most prominent element in the crevice corrosion equation. Secondly, in the last 10 to 15 years, municipal water systems, to accommodate increasing population, have increasingly chlorinated, fluoridated, etc. their water supplies that makes the water increasingly unsuitable for steam locomotive consumption. The old locomotive adage "don't put water in the boiler you wouldn't drink yourself" takes on new meaning when compared to the per capita consumption of bottled water in the US.

The operating crew can mitigate the water chemistry problem to a large degree with a custom prepared treatment program and acquired chemistry expertise. This should be instituted for no other reason than to insure reliable boiler life well into the next century.

Finally, if this failure event had occurred in an industrial plant on a Thursday morning, the tubes would have been removed on Friday, new tubes installed and the boiler back online Monday morning. Also to reiterate, due to the type, location and magnitude of the corrosion, catastrophic failure (explosion) was a physical impossibility.

Matt Austin
President
Hawaiian Steam Engineering Co.
July 8, 1999

Photo "A"
Tube in upper quadrant on engineer's side that failed completely.

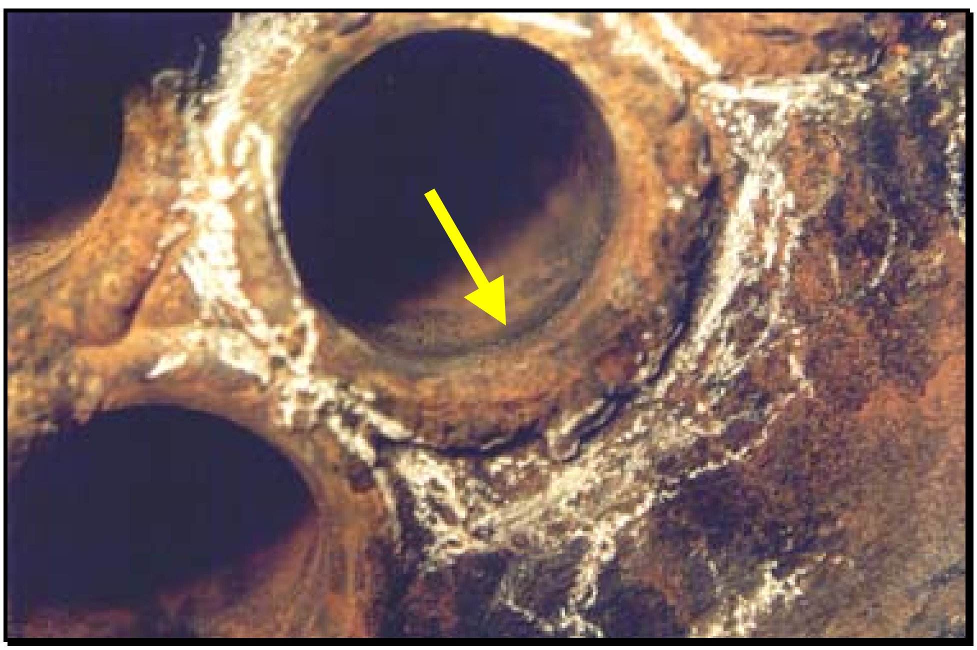

Photo "B"
Tube in lower quadrant engineer's side that partially failed. Arrow indicates opening in tube wall, circumferential crack.

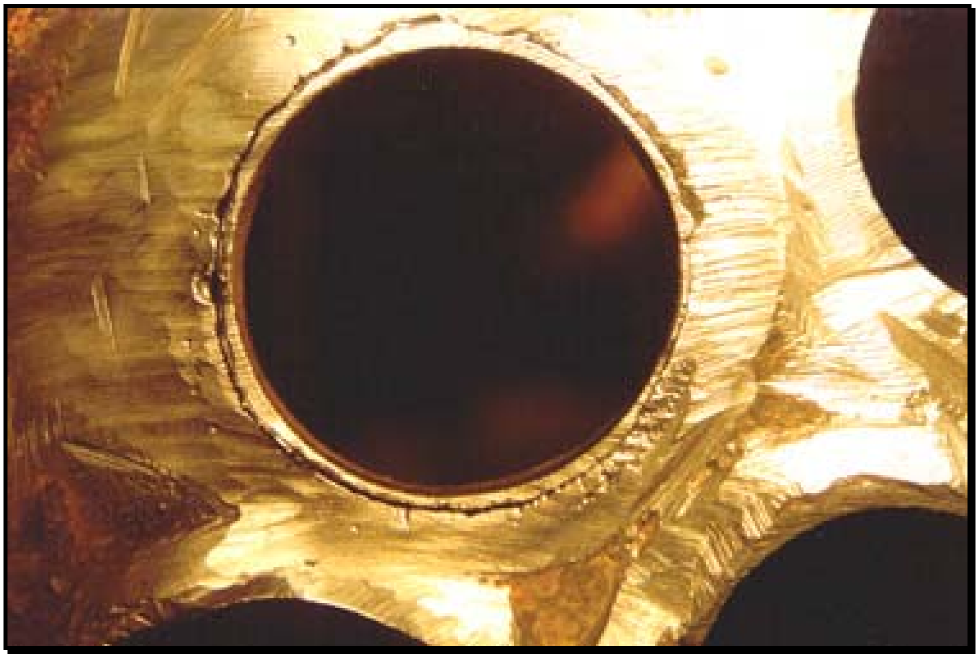

Photo "C"

Completely failed tube lower fireman's side. Seal weld was ground off flush with tube sheet to provide indication of extent of crevice corrosion.

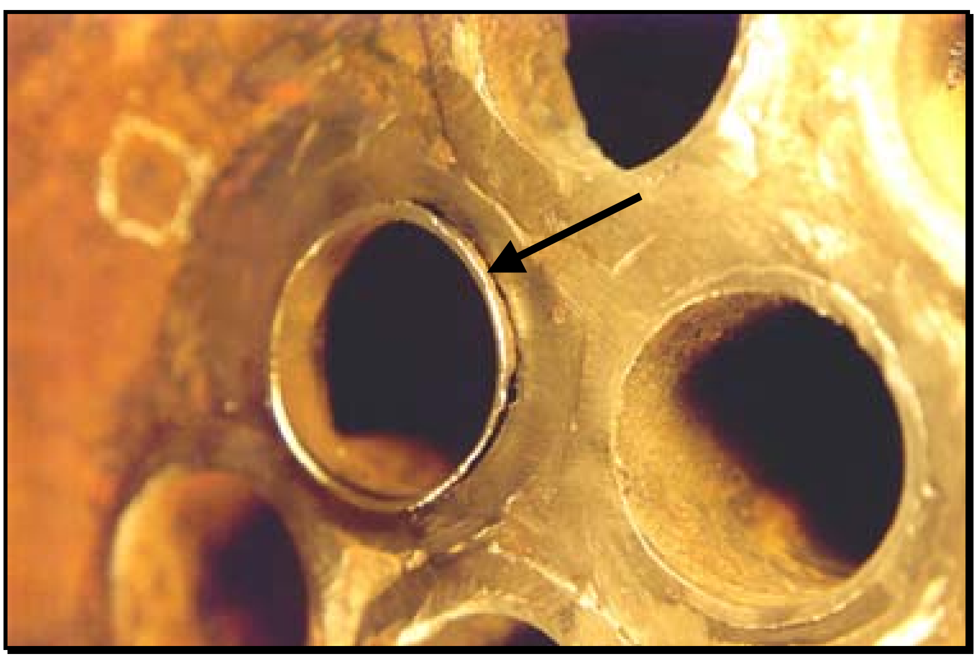

Photo "D"

Usually tight in tube sheet, rolled stubs are typically removed with torch or air tool. This was less than finger tight.

Photo "E"
Tube stub end removed from tube sheet.

Photo "F"
Mating tube to that of stub shown in Photo "E".

Photo "G"
Mating stub end to tube end.

Photo "H"
Note black iron oxide on portion of stub end.

Photo "I"

Extensive thinning of tube wall adjacent to tube sheet and in tube sheet area is visibly noticeable.

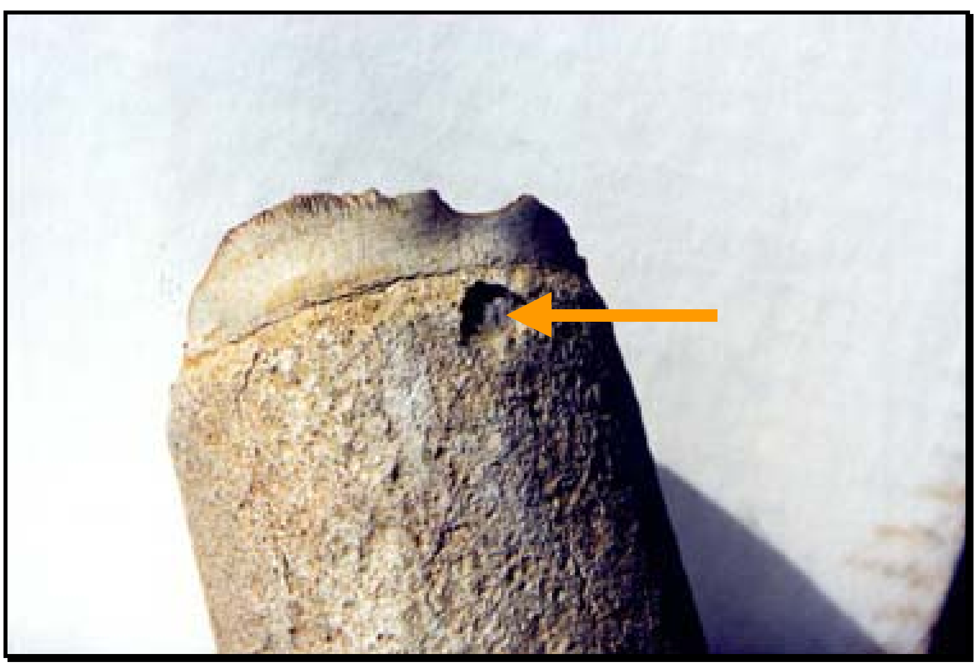

Photo "J"

Classic oxygen cell corrosion approximately ¼" diameter. Tube has been descaled by chemical cleaning.

Photo “K”

Electric resistance welded (ERW) seam beginning to degrade due to corrosion.

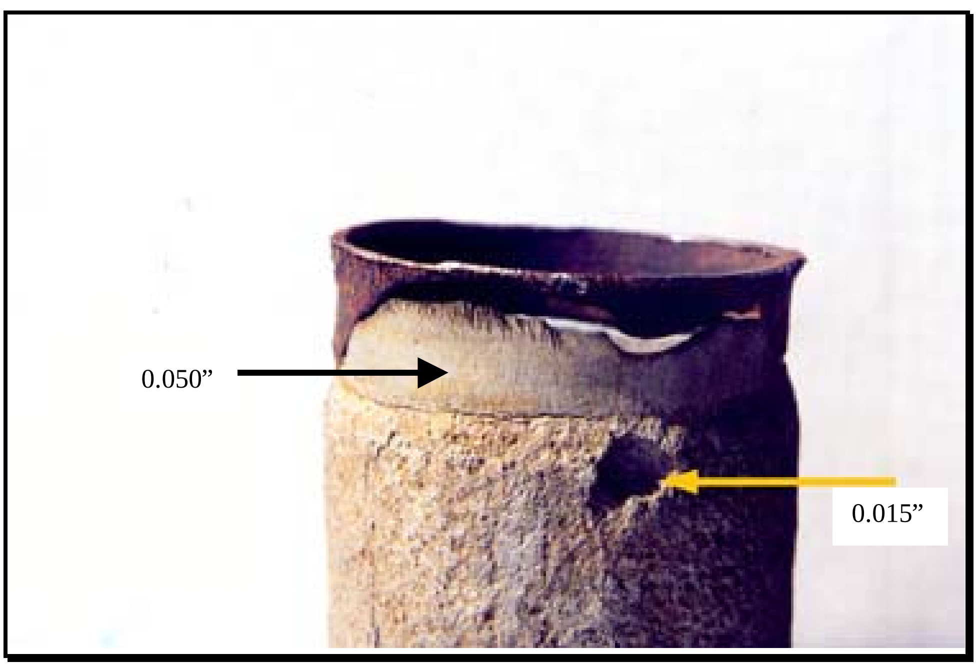

Photo “L”

Thickness at bottom of pit is 0.015”. Thickness at tube seat still attached to tube average is 0.050”. Average thickness of tube wall for 3” from tube sheet is approximately 0.120”.