FAILURE ANALYSIS OF CRACKED BOILER TUBE

EXAMPLE REPORT

*Modified from Original Report*

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FAILURE ANALYSIS OF CRACKED BOILER TUBE

SUMMARY

Cracking of the boiler tube had occurred by thermal fatigue. The difference in thermal heating/expansion of the surrounding wall plates versus the water-filled boiler tube had applied high thermal strains onto the tube during rapid temperature changes (i.e. starts/stops, TRIPS, operating issues, etc.). Repeated thermal cycling had resulted in the formation of thermal-based corrosion fatigue cracks.

This design would be inherently susceptible to thermal fatigue and efforts to minimize rapid thermal changes are recommended. The other two boilers of this design are at risk of similar failures.

1.0 INTRODUCTION

A failed wall tube had been removed from a boiler. The leak site itself had been destroyed during tube removal. The provided tube sections comprised of several cut sections taken adjacent the failure site, labeled A through E. The tube comprised of ASME SA 178 Grade A carbon steel.

It was reported that the adjacent/mirror tube had been repaired in August 2006 due to a leak at the same elbow location. It was also reported that the boiler had undergone non-ideal operating conditions such as lack of consistent fuel supply, reduced steam conditions during soot blowing and issues with refractory at several locations.

The client had three identical boilers. Steel Image was requested to determine the nature and cause of tube cracking.

2.0 EXAMINATION

2.1 Visual/Macroscopic Examination

Figure 1a displays the external location where the failure had occurred on the boiler, made apparent from the corresponding replacement tube. It was reported that the adjacent/mirror tube had been repaired several years before due to a leak at the same location.

Figure 1b displays the samples submitted for evaluation. Cracking of the internal surfaces was observed at numerous locations around the tube perimeter (Figures 2 and 3). The largest cracks were located adjacent the wall plate welds, corresponding to restraining points on the tube. Further examination would find these cracks to be corrosion fatigue cracks.

Tube Section B (the tube elbow) exhibited significant deformation, with the wall plate having pulled the tube into an oval shape (Figure 3a). This deformation indicated that
the tube had been subject to loading above its yield strength. The high thermal strains causing this deformation, associated with boiler start/stops and excursions, was deemed to have been the primary contributor to corrosion fatigue cracking.

Examination of Tube Section E, at the end of the removed tube, found cracks which extended beyond the sample end (Figure 4). Therefore, the vertical tube section above the repaired region would also comprise of cracks (the repairs had not removed the full length of the damage).

2.2 Optical Examination

Metallurgical cross-sections were taken from regions that exhibited the most severe internal cracking, including Tube Sections B, C and D (Figure 5). The cross-sections were prepared for examination in accordance with ASTM E3.

Optical examination found the tube material to be in good condition. The core microstructure comprised of ferrite and fine lamellar pearlite, expected for ASME SA 178 carbon steel (Figure 6). No thermal degradation was observed on any of the examined cross-sections.

Optical examination found the cracking to have occurred by corrosion fatigue (Figure 7). The majority of the cracks exhibited a wedge-shape morphology filled with oxidation product. The cracks tended to have started from surface pits. The largest crack observed on the three planes cross-sectioned extended ~2.5mm into the tube.

2.3 SEM/EDS Examination

Energy dispersive spectroscopy (EDS) was conducted on the corrosion product within several of the corrosion fatigue cracks. EDS analysis found the corrosion product in all examined cracks to comprise of iron oxide (Figure 8). No trace elements were found to suggest that corrosion had been enhanced by any water impurities (i.e. chlorine, calcium, etc.).

3.0 CONCLUSIONS

Cracking of the boiler tube had occurred by thermal fatigue. The difference in thermal heating/expansion of the surrounding wall plates versus the water-filled boiler tube had applied high thermal strains onto the tube during rapid temperature changes (i.e. start-ups, operating issues, etc.). Repeated thermal cycling had resulted in the formation of thermal-based corrosion fatigue cracks.

Thermal fatigue occurs when cyclic thermal strains repeatedly crack the protective Fe₃O₄ (magnetite) oxide layer that has formed on the tube. The re-formation of an oxide layer on the freshly exposed metal repeatedly consumes some of the tube material. As this process repeats, pits are initially formed and then cracking occurs. The thermal cycles
typically correspond to significant temperature changes such as boiler start-up, operational events or shutdown. Note that this boiler was reported to have experienced several start-ups and shutdowns in past years. Such cracking tends to occur at locations physically restrained (supported/welded tubes, elbows, etc.) causing high thermal stresses during metal thermal expansion.

Water chemistry can sometimes play a secondary role in thermal fatigue. Yet in this case, water chemistry was not suspected as having been a significant contributor. EDS analysis found the corrosion product within the cracks to comprise of iron oxide. No trace elements were found to suggest that corrosion had been assisted by inappropriate water chemistry. Thus, the primary contributor to cracking was due to thermal strains, not issues with the water chemistry.

The design of the boiler would inherently cause high thermal strains/stresses at the cracked location. In addition to these inherent strains, based upon the design/geometry of the boiler, it was reported that the boiler had historical operating conditions which may have applied elevated thermal strains on parts (i.e. inconsistent fuel supply, reduced steam from soot blowing, etc.). It was unclear whether these operating conditions had applied (a) more thermal strains than boiler starts/stops and/or (b) enough thermal strain to have contributed to crack initiation. At minimum, rapid thermal changes during service would have contributed to crack growth once the crack had initiated. Until proven otherwise, a conservative perspective would assume that any thermal shocks during operation may have contributed to crack initiation and/or growth.

Ultimately, between the design and likely its operating conditions, the tube had experienced cyclic loading above which it could sustain. This was further supported by the mirrored tube also having cracked/leaked several years before at the same location. Assuming the other two boilers had similar (a) starts/stops and (b) operating conditions, the same locations on these boilers may also be at risk of cracking.

The cracking had extended past the submitted tube section. Therefore, the vertical tube material above the removed section would also exhibit some degree of thermal fatigue cracking.

The tube core material was in good condition. No significant thermal degradation had been observed to indicate the tubes had been subject to either short-term or long-term overheating.
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Figure 1: Photographs displaying (a) the site of failure (replacement tube welded in) and (b) submitted portions of the failed tube. The failure had been cut up into pieces prior to submission.

The adjacent, mirrored tube had leaked and been replaced several years before. This suggested that cracking/damage may have been systematic due to design and/or operating conditions.
Figure 2: Photographs displaying the cracking on internal surfaces of Tube Sections (a,c) C and (b,d) D. The other tube sections exhibited similar damage. The damage was observed around the full tube perimeter. Further evaluation would identify these as corrosion fatigue cracks.
Failure Analysis of Cracked Boiler Tube

Figure 3: Photographs displaying the (a) deformation and (b) internal cracking observed on Tube Section B (tube elbow). Deformation indicated that the strains applied by the wall plates had exceeded the yield strength of the tube. Repeated thermal cycling had resulted in corrosion fatigue cracks.
Figure 4: Photographs displaying the end of Tube Section E (the end of the removed tube). Cracking spanned beyond the tube end and had continued onto tube material still present within the boiler (i.e. not all of the tube damage had been removed by the repair).
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Figure 5: Photographs displaying the three cross-sections taken from the boiler tube. Cross-sections were taken from regions that visually exhibited the most damage.

Figure 6: Micrographs displaying the tube’s core microstructure on the fire-side. No significant thermal degradation was observed. The core was representative of the as-manufactured tube condition for ASME SA 178 steel. Etched using 3% nital.
Figure 7: Micrographs displaying three of the largest cracks observed on the cross-sectioned boiler tube. Cracking had occurred by corrosion fatigue. The largest observed crack measured ~2.5mm. The corrosion product within the cracks was later found to comprise of iron oxide. Etched using 3% nital.
Figure 8: EDS spectra of a crack on Section C found the corrosion product within to comprise predominantly of iron oxide. This crack was representative of other cracks examined by EDS. No water contaminants were suspected as having contributed to cracking.