Ramifications Of Cracks At The Fillet Welds Of High Temperature Steam Headers

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ABSTRACT: During a major statutory inspection of a 150MW steam raising boiler, cracks were found at the stub tube-to-header fillet weld of both the secondary superheater outlet header and the reheater outlet header. These cracks extended in some instances up to halfway through the tube wall thickness. The extent of the cracking precluded immediate and widespread repair and so an engineering solution was devised to identify the most critical cracks and repair these while leaving less critically cracked stubs in service.

While the unit was returned to service, the long-term life of the boiler was in question. The expected life of these headers was compared with the required life of the unit and the economic issues of repairing stubs compared to replacing with a new header and stubs, the result being a new for old replacement.

This paper will describe the extent of the cracking found, the engineering calculations undertaken to ensure the safe return of these headers to service and the longer-term life issues.

1 INTRODUCTION

The Battle River Generating Station consists of 3 black-coal fired unitized boilers that feed three steam turbines. Of these units Boiler 3 is the oldest, being commissioned in 1969 and having operated up to December 2003 for a total of approximately 265,000 hours and undergone more than 600 starts. The station expects to operate Boiler 3 until around 2021, which equates to a life expectation of almost 400,000 hours.

A statutory inspection of Boiler 3 in 2001 looked at emerging life issues and identified cracking at the superheater and reheater header stub welds, at dissimilar metal welds (DMWs), and deterioration of the superheater and reheater banks as issues expected to limit the future reliability and life of this boiler. This paper describes only the actions taken to manage cracking at the reheater and secondary superheater outlet header stub welds of Boiler 3.

2 SECONDARY SUPERHEATER AND REHEATER OUTLET HEADERS

2.1 Secondary superheater outlet header, SH4

The superheat circuit for Boiler 3 consists of three banks of primary superheater tubes in the rear furnace pass and a secondary superheater in the front furnace pass immediately above the furnace. Steam passes from the primary superheater via cross-over pipes into the secondary superheater inlet header, travels through the secondary superheater tube banks to the secondary superheater outlet header, SH4. The steam then passes to the steam turbine via a main steam line.

The secondary superheater outlet header, identified as SH4, has a design metal temperature of 557°C for a pressure of 12.8 MPa and is fabricated from SA 387 D which is a plate steel specification indicating that this header is seam welded. The central-T is also manufactured from SA 387 D material. The header is supported by a centrally located steam outlet branch and four brackets connected to the four downcomers emanating from the steam drum. The SH4 header has sixty six rows of tubes across the header with two tubes per row. The upper row is labeled row “A” and the lower row “B”. The SA213 T22 SH4 stub tubes are 50.8mm OD x 8.6mm MWT and these stub tubes join the SA213 T347H secondary superheater outlet tubes via a transition piece approximately 457mm from the header.
The creep life of SH4, based on the operating temperature of 541°C (rather than the design temperature of 557°C), a nominal wall thickness of 65.2 mm and creep-rupture properties reported in the literature, ranges from a lower bound life of 162,000 hours to a mean life of >500,000 hours. The header microstructure (Figure 1) shows bainite in a ferrite matrix with no signs of significant thermal deterioration nor was there creep cavitation on grain boundaries or triple points. Consequently it was considered reasonable to assume that the header material exhibited at least mean creep-rupture properties.

![Microstructure of the SH4 header parent steel in the vicinity of a seam weld.](image)

**Figure 1**: Microstructure of the SH4 header parent steel in the vicinity of a seam weld.

### 2.2 Reheater outlet header, RH2

Exhaust steam from the high pressure turbine travels via the cold reheat line to the reheater inlet header, through the reheater banks to the reheater outlet header, from where the superheated steam travels via the hot reheat line to the intermediate pressure turbine.

The reheater outlet header, designated RH2, has a design metal temperature of 557°C for a pressure of 4.1 MPa. The header is fabricated from SA 335 P22 material, a pipe specification indicating that this header does not have a seam weld. The central-T is, however, manufactured from SA 387 D material. The header is supported by a centrally located steam outlet branch and four brackets connected to the four downcomers.

The RH2 header has sixty six rows of tubes across the header with three tubes per row. The upper row is labeled row “A”, the middle Row “B” and the lower row “C”. The SA213 T22 stub tubes are 54.0 mm OD x 4.6 mm MWT and these stub tubes join the SA213 T347H reheater outlet tubes via a transition piece approximately 457 mm from the header.

The design metal temperature of 557°C is well within the creep range for 2¼Cr1Mo steel. The creep life for this header was calculated to be > 500,000 hours and so quite adequate for the maximum proposed life for this boiler.
3 ENGINEERING ASSESSMENT OF THE SUPERHEATER OUTLET HEADER

From a review of the inspection records it was found that in July 1993 all stub to header fillet welds were intact but several tube weld toes were cracked between the 1:00 to 2:30 o’clock position and other tubes were cracked between the 9:30 to 11:00 o’clock position. All cracked tube welds were repaired at that stage. The SH4 header had also experienced cracking at the support brackets which has been managed successfully with remedial grinding to remove these defects.

The inspection in 2001 found some weld profiles to be quite poor as shown in Figure 2. Inspection of the SH4 stub tube to header weld toes and stub tube weld toes found extensive cracking at the tube weld toe, however, no cracking was found at the stub tube to header weld toes. This cracking was removed by pencil grinding as shown in Figure 3. Figures 4 and 5 plot the crack depths against tube number. Clearly the deepest and largest number of cracks were located at the ends of the header. Figure 6 plots the total number of cracks against the position of these cracks around the tube. Again a clear trend emerged with the majority of cracking at between the 9:00 to 3:00 positions, i.e. at the top of the tube. This was similar to that found in the survey undertaken in July 1993.

The location of cracking suggests an imbalance between the vertical movement of the furnace and the SH4 header during startup and shutdown. SH4 is supported through attachment to the downcomers which will expand downwards from the steam drum. The movement of the stub tubes where they penetrate the furnace wall is governed by the expansion of the furnace. It is therefore suggested that this cracking may develop as a result of differential expansion between the downward movement of the header and the movement of the furnace.

To prevent further failures of these stub tube welds this imbalance in movement must be addressed. If this is not possible, the profile of the welds needs to be significantly improved to provide the smallest stress concentrations possible.

Figure 2: SH4 header and stubs. Approximately 18 inches from the header the transition welds between the 2½CrMo stubs and the 347H superheater tubes can be seen.

Figure 3: Example of the excavation at the stub weld toe on the SH4 header. Where the remaining tube wall thickness was equal to or greater than the minimum design thickness, the excavation was left without the need for weld repair.
Figure 4: Row A. The cracks at the stub tube, tube to weld toes were separated into the four clock locations given above. The depth of each crack was then plotted against tube number. The crack distribution and severity in shown in this graph.

Figure 5: Row B. The depth of each crack at the SH4 header stub tube weld toe was plotted against tube number. The crack distribution and severity in shown in this graph indicating that the most cracking occurs at the ends of the header.

Figure 6: The total number of crack-like indications at the SH4 header stub tube to weld toes is plotted against crack position. Clearly, most cracking occurs between the 9:00 to 3:00 o’clock position. i.e. at the top of the tube.

4 ENGINEERING ASSESSMENT OF THE REHEATER OUTLET HEADER

The history for the RH2 header showed that an inspection in July 1993 of 198 stub/header welds found that 36 were cracked and these were weld repaired. In August 1995 186 DMWs were repaired using orbital weld overlays, and the remaining 12 DMWs were replaced with new transition pieces. The RH2 header has also experienced cracking at the support brackets and these have been successfully managed through remedial grinding.

During the 2001 inspection, reheater header stub tube 1C and 2C (south end) were found to have pin hole leaks that had eroded the header body.

Magnetic particle inspection found extensive cracking at the stub tube to header weld toes. Examples of this cracking are shown in Figures 7 and 8.

The distribution of the RH2 stub tube to header cracking was collected from NDT reports and is shown in Fig. 9. For Row A tubes the cracks were predominantly located between the 9:00 to 3:00 o’clock positions and in elements 1 to 40. Row B tubes had more cracked tubes than Row A and C with the cracks again predominantly between the 9:00 to 3:00 o’clock positions. For the Row B stub tubes the cracking was found largely between elements 10 to 55. The least amount of cracking was found in Row C stub tubes with the cracking predominating in elements 10 to 29 and 39 to 60.
For Row C tubes, cracking was evenly distributed around the tubes. As for the SH4 header, the location of cracking was predominantly at the top of the tubes.

Figure 7: Cracking at the toe of the stub tube to header weld of reheater outlet header, RH2.  
Figure 8: Close up of the cracking at the toe of the stub to header weld of RH2.

Figure 9: The distribution of cracks in the stub tube to header welds for Rows A, B and C are shown for each element across the RH2 outlet header. Clearly, the majority of cracking has occurred between elements 10 to 61. The majority of cracking for Row A is between elements 1 and 45, for Row B, between elements 10 and 61 and for Row C, between elements 10 and 29 and 39 and 60.

5 DISCUSSION

5.1 Stub Tube Weld Cracking

There was extensive and widespread cracking found at the toe of the stub tube welds on the SH4 and RH2 outlet headers. Once any cracking was identified it was removed by pencil grinding. Dye penetrant inspection was used to determine when the cracks had been removed and once the cracks were removed the crack depths were recorded. As the depth of the cracks varied considerably and time and resources were scarce it was necessary to determine those tubes that must be repaired and those that could be safely left. It was then necessary to determine the critical excavation depth, below which weld repair was required.

During this inspection and the development of an engineering solution to manage this cracking, the root cause of cracking was not identified. However, the location of cracking suggested that there was an imbalance in the vertical movement of the stub tubes between the furnace wall penetrations and the SH4 header or restraint to the longitudinal expansion of the tubing. Either could induce considerable strain on the stub tubes when the header was heating during startup.
5.2 Minimum Thickness Calculations for the SH4 and RH2 Stub Tubes

To satisfy the statutory authority, the excavations to remove the cracking at stub tube weld toes must leave a remaining wall thickness equal to or greater than the ASME Section I minimum design thickness. This thickness is calculated using Equation 1, and any excavations greater than this depth were to be weld repaired.

\[
t = \frac{PD}{2S + P} + 0.005D + e \quad \text{.......................... Equation 1}
\]

The minimum tube thickness based on ASME Section I was calculated from Eqn. 1 for the design conditions listed below:

<table>
<thead>
<tr>
<th>Tube material</th>
<th>SH4 Header</th>
<th>RH2 Header</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SA213 T22</td>
<td>SA213 T22</td>
</tr>
<tr>
<td>( P = )</td>
<td>13.0 MPa</td>
<td>4.1 MPa</td>
</tr>
<tr>
<td>( T = )</td>
<td>541 °C</td>
<td>541 °C</td>
</tr>
<tr>
<td>( D = )</td>
<td>50.8 mm</td>
<td>54 mm</td>
</tr>
<tr>
<td>( S = )</td>
<td>53.8 MPa</td>
<td>53.8 MPa</td>
</tr>
<tr>
<td>( e = )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( t = )</td>
<td>5.7 mm</td>
<td>2.25 mm</td>
</tr>
</tbody>
</table>

Thus, provided the stub tube wall thickness remaining after the removal of the crack was greater than the ASME minimum thickness, weld repair would not be necessary. Hence, an excavation depth of 2.9 mm for the SH4 header or 2.3 mm for the RH2 header would be acceptable. If, however, the excavation was deeper than these limits, the defect would require weld repaired. This is shown in Fig. 10 below.

![Crack at weld toe](image1)

Example of the crack at the weld toe. Recommended repair profile, SH4. Recommended repair profile, RH2.

Figure 10: Acceptable maximum excavation depth.

5.3 Creep Life of the SH4 and RH2 Stub Tubes including an Excavation

This repair procedure has provided a safe means to return the SH4 and RH2 headers to service, however, those cracks ground out to the maximum allowable depth now have a stress concentration built into the weld that could decrease the creep life of these welds.
The creep-rupture life of the stub tubes was calculated assuming removal of all evidence of cracking through excavation to the minimum design thickness. The stress in the stub tube before any effective wall loss through cracking and excavation was 32.35 MPa and 22.55 MPa for SH4 and RH2 stub tubes respectively, and the maximum stress level after excavation was 51.4 MPa and 47.2 MPa for SH4 and RH2 stub tubes respectively. However, the excavation has introduced a stress concentration to the stub tube weld toe that is assumed to be 1.5.

The last partial inspection of the SH4 and RH2 stub fillet welds was in 1998 and no cracking was detected. Hence it can be expected that the stub tube fillet welds had operated under operating conditions up to this period without cracking. Hence the life fraction consumed can be assumed to be the life fraction exhausted in the 200,000 hours to 1998 plus the life fraction exhausted once the cracking had developed, and this cracking is assumed (conservatively) to have existed from 1998 to 2001. The total possible creep lives for each period are shown in Table 2 including the remaining life.

<table>
<thead>
<tr>
<th>SH4 Header Creep Life</th>
<th>RH2 Header Creep Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>To 1998</td>
<td>1998-2001</td>
</tr>
<tr>
<td>Min &gt;500,000 h</td>
<td>440,000 h</td>
</tr>
<tr>
<td>Mean &gt;500,000 h</td>
<td>&gt;500,000 h</td>
</tr>
</tbody>
</table>

| Min >500,000 h        | >500,000 h            | 60,000     | 7 years   |
| Mean >500,000 h       | >500,000 h            | 315,000    | 36 years  |

**β** - life assuming 541°C, stress at excavation x 1.5SCF & operating pressure

Thus the SH4 header stub tubes that have been excavated to the maximum depth and not repaired have a remaining life of between 2 to 13 years, and will need to be repaired or replaced to achieve the 2021 planned life.

The RH2 header stub tubes have a remaining creep life of between 7 to 36 years and will probably need to be replaced or repaired to operate satisfactorily until 2021.

### 5.4 DMWs between Outlet Header Stubs and Superheater and Reheater Tubing

The DMWs between the stub tubes and the secondary superheater tube bank and reheater tube bank should have significant remaining life as the metal temperatures under which these joints operate are relatively low. However, these stub tubes are clearly experiencing significant external strains due to some restraint of movement during startup and shutdown and so the life of these joints must also be in question. In fact the wholesale replacement of the RH2 DMWs in 1996 suggests that the system stresses on these joints are significant.

### 6 CONCLUSIONS

This investigation has shown that the superheater outlet header and reheater outlet header have significant issues with cracking at the header stub to tube weld toes and with creep life limitations for tubes that had cracks removed but that were not weld repaired. These issues would seriously limit the life of the headers unless major repairs are implemented.

The reheater outlet header also had significant issues with cracking at the header stub tube DMWs and until the root cause of the cracking is determined and corrected this will continue to threaten the integrity of the headers.

In the cost benefit analysis undertaken by the station, the cost of repair of the stubs in situ was compared to the cost of new headers and stubs. The superheater was to be replaced which provided
a window for major works. Furthermore, the access for repair was tight and fitup with the new superheater was also an issue. Thus considering the difficulty of repair and the ensuing costs, replacement of the each header with a new header and factory fitted stubs was found to be the most economic.

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