Failure of a Riser Transition Assembly on a Primary Reformer

A failure occurred on the Riser Transition Cone (RTC) section of the Primary Reformer Riser Transition Assembly (RTA) in a top-fired KBR reformer. Cracking extended around the circumference of the part and was visible around the external surface. The failed RTC section was found to meet all the mechanical, chemical and physical requirements specified. Cracking progressed predominantly from the inner surface towards the outer surface as a result of stress relaxation cracking. This paper reviews the incident, failure analysis, root cause investigation, lessons learned and recommendations to prevent a re-occurrence.

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Introduction

The Primary Reformer located at the Ammonia Urea Melamine (AUM) Plant located in the Point Lisas Industrial Estate, Trinidad and Tobago, West Indies, experienced a failure to the Riser Transition Cone (RTC) on 6th August 2016. The failure occurred in a 1,850 MTPD (2,040 STPD) top-fired reformer designed by Kellogg Brown and Root (KBR) which was commissioned in 2009. This paper describes the failure that occurred, the investigations and the lessons learned.

Plant Background

The AUM Facility is owned by Methanol Holdings Trinidad Limited (MHTL) and is managed and operated by Industrial Plant Services Limited (IPSL). The AUM plant complex is comprised of seven (7) plants which produce urea, melamine and UAN solution (Figure 1. In addition to the AUM Plant Complex, IPSL manages and operates five (5) methanol plants and two (2) ammonia plants. MHTL’s AUM complex began operation in 2010 and produces 647,500 metric tons per year of Ammonia for use as feedstock for its downstream operations which comprise a UAN plant producing 1,483,500 metric tons per year of UAN (32%) solution and two (2) Melamine plants with a combined annual capacity of 60,000 metric tons of melamine.

Incident Description

On 6th August 2016, the AUM Ammonia Plant was operating steadily at a plant rate of 90%. While taking routine readings at 5:00 AM, the area operator reported a fire at Riser C cone area within the Primary Reformer Penthouse. Flames were also localized to the Riser area away from personnel with little to no damage to surrounding reformer tubes and auxiliaries.
The AUM Ammonia Plant was taken offline with process gas being removed from the Primary Reformer soon after. The condition of the RTA is shown in Figure 2.

**Process and Mechanical Design**

**Process Design and Technology**

The AUM Plant Primary Reformer is a top-fired 2,040 STPD KBR design, which was constructed by MAN Ferrostaal AG and Proman (Trinidad) AG, the EPC contractors for the AUM Complex. The AUM Ammonia plant commenced production in April 2009. The AUM Plant Primary Reformer is shown in Figure 3.
former tubes is transferred through a riser, returning up the center of each row to the effluent chamber at the top of the furnace. The furnace comprises of two-hundred and eighty (280) tubes with five (5) risers. Each row (A to E) consists of fifty-six (56) tubes with a single riser. The arrangement is shown schematically in Figure 4.

The riser tube takes the reformed gas from the center of the collection manifold and transports it back up through the furnace where it is transferred to the effluent chamber which directs the process stream to the secondary reformer. The effluent chamber and the riser tube as it exits through the furnace roof are refractory lined and cooled by a water jacket. The riser tube operates at a temperature controlled by the combustion environment within the furnace and the process stream within the tube. The metal temperature is approximately 1500-1675°F (816 – 913°C). On leaving the furnace through the roof, the external metal temperature will reduce rapidly, over a short length, to that of the water jacket.

**Mechanical Design**

The Riser Transition Assembly (RTA) connects the Riser Tube to the water-cooled effluent chamber. The RTA as shown in Figure 5, is comprised of two (2) Incoloy 800HT pieces which are internally lined with castable refractory. The top piece, the Riser Transition Cone (RTC), was formed from plate and fabricated with a longitudinal fillet weld. The bottom of the RTC is connected by a round seam fillet weld to the Riser Transition Fitting (RTF). It is assumed that the longitudinal seam weld of the RTC used ERNiCr-3, the same weld filler specified for connecting the RTC to the RTF. The top of the RTC was connected with a round seam fillet weld to the Riser Transition Pipe (RTP) which was made from seamless carbon steel piping (ASTM A106 Grade B). An internal liner runs inside of the RTA to protect and contain the castable refractory. The internal liner is manufactured from Incoloy 800HT plate and is sealed to the RTF using ceramic fiber blanket material.

Operating conditions of the RTA were as follows:
- Internal pressure: 590 psia (40.7 bara)
- Nominal Process Temperature: 1473°F -1500°F (800°C – 816°C)
The external surface temperature of the RTC (with process gas isolated and during cool down of the reformer) was measured to be 600°F (316°C) which is consistent with being internally insulated. Further investigation in operation found that typical external temperature measurements outside the firebox on the RTC were 500°F – 560°F (260°C – 293°C).

Failure Analysis

Industrial Plant Services Limited (IPSL) on behalf of Methanol Holdings Trinidad Limited (MHTL) contracted with Quest Integrity USA, LLC (Quest Integrity) to conduct a failure analysis on the Riser Transition Cone (RTC) section of the Primary Reformer Riser Transition Assembly (RTA) removed from the AUM Ammonia Plant (Figure 6). The failure analysis was performed on the Riser C RTC. The objective was to identify the damage mechanism(s) and associated root causes that resulted in the RTC failure.

The RTC was visually examined and measured before sectioning to perform alloy verification, tensile testing, metallography, fractography, scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS).

Cracking extended about 75% around the circumference (Figure 7). In the piece examined by Quest Integrity, the cracking extended around the
circumference of the part approximately 17 in (44 cm) on the external surface and was located roughly 2 in (5 cm) below the round seam weld connecting the IN800HT RTA to the carbon steel riser transition pipe above. About 10 in (25 cm) of the crack was visible on the internal surface.

Identification of Damage Mechanism

The results of the testing for alloy verification and material tensile testing found the chemical composition of the RTA sample and the average tensile testing property values to be consistent with and meeting the minimum values for yield strength (YS), ultimate tensile strength (UTS), and elongation specified by ASTM B409 for alloy UNS 08811. The materials used for the construction of the RTC met the mechanical, chemical, and physical requirements and the RTC was not defective or otherwise out of specification.

Stress Relaxation Cracking

Further failure analysis and investigation of the crack surfaces by fractography, examination of the microstructure at the failure location, scanning electron microscopy (SEM), and microhardness testing were used to identify and confirm stress relaxation cracking as the failure mechanism. No evidence of creep (creep voids, etc.) or stress corrosion cracking (chlorides or a wet environment) were found in testing.

This ‘stress relaxation cracking’ damage mechanism is also known by several other names including reheat cracking, strain age cracking and stress assisted grain boundary oxidation. This mechanism is observed in austenitic alloys in which cracking occurs along grain boundaries rather than by plastic deformation within the grains. It is caused by the formation of chromium carbides which leave the edges of grains weakened as a result of chromium depletion. This results in intergranular cracking and oxidation along the compromised grain boundaries.

Signatures of stress relaxation cracking include:

1. Intergranular cracks, often accompanied by isolated voids along grain boundaries in front of the crack tip.
2. Brittle cracking with no associated deformation.
3. Thin metallic filaments rich in nickel and iron and depleted of chromium by the surrounding oxide lining the adjacent grain boundaries.
4. Fractures located in area with hardness levels above 200 HV (e.g., the heat affected zone of welds or heavily cold-worked sections).
5. Process fluid temperatures in the range of 930°F - 1380°F (500°C – 750°C), and metal temperatures between 1110°F - 1200°F. (600°C – 650°C)
6. Cracking which occurs in relatively short time frames, often in less than two years of service or within one year or less of a repair or modification.

Supporting Evidence for Stress Relaxation Cracking

The etched metallographic cross sections revealed intergranular cracking along boundaries of the large grains typical of IN800HT. (See Figure 8 and Figure 9).
Precipitation and void formation was observed along grain boundaries ahead of the progressing crack fronts. Voids and precipitates along grain boundaries ahead of cracks are shown more clearly in Figure 9.

EDS readings were taken of the filament and at the middle of a grain in the bulk material. The results in Table 1 show the filament to be enriched with iron and nickel and depleted of chromium as compared to the bulk material and specification for IN800HT.

The SEM image in Figure 10 shows a subsurface crack with a pronounced metallic filament within the oxide-lined crack surface. Semi-quantitative microhardness and wall thickness measurements were taken from a longitudinal cross section (Figure 11). The results of from the longitudinal cross section are provided in Table 2. All the Vickers (500 g) hardness measurements are above 200 HV. The plane of cracking in the longitudinal cross section, identified as Points 5 and 6, are the locations at which the hardness is highest and the wall thickness is lowest, although it is still above the minimum 0.53 in (13.5 mm) specified. No trend of note was observed for hardness of wall thickness in the transverse cross section.

Figure 8. The cross-sectioned fracture revealed intergranular cracking and more degradation at the inner surface (a, b) compared to the outer surface (c, d). Subcritical cracking initiated at the inner surface exhibited metal filament running along the crack path lined with oxide. Precipitates were observed along the grain boundaries and within grains to a lesser extent.

Figure 9. At mid-thickness, cracks branched in opposing directions indicating changing stress states (a, b). Precipitation and void formation was observed along grain boundaries ahead of progressing crack fronts in the cross-sectioned fracture (c).

Figure 10. SEM images of the mounted sample showed metallic filaments within oxide-lined cracks. Voids and precipitates were observed along grain boundaries ahead of cracks. Image taken at 500X in BSE mode.
Table 1. Semi-quantitative EDS readings of metallic filament and bulk material shown in Figure 10.

<table>
<thead>
<tr>
<th>ELEMENT (wt. %)</th>
<th>Filament</th>
<th>Bulk</th>
<th>IN 800HT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al aluminum</td>
<td>0.24</td>
<td>0.78</td>
<td>0.15-0.60</td>
</tr>
<tr>
<td>Si silicon</td>
<td>0.32</td>
<td>1.05</td>
<td>1.0 max</td>
</tr>
<tr>
<td>Cr chromium</td>
<td>2.20</td>
<td>20.89</td>
<td>19.0-23.0</td>
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<tr>
<td>Mn manganese</td>
<td>0.30</td>
<td>0.86</td>
<td>1.5 max</td>
</tr>
<tr>
<td>Fe iron</td>
<td>60.97</td>
<td>45.42</td>
<td>39.5 min</td>
</tr>
<tr>
<td>Ni nickel</td>
<td>35.97</td>
<td>31.00</td>
<td>30.0-35.0</td>
</tr>
</tbody>
</table>

Figure 11. Longitudinal cross section taken at the edge of where the through-wall fracture ended. The round seam weld and associated HAZ and cracks extending from the outer surface are faintly visible.

The microhardness and wall thickness findings suggest that stress relaxation cracking occurred in the plane just above the knuckle as a result of two factors: high hardness caused by strain-hardening during fabrication and increased tensile stress caused by a lowered cross-sectional area at the point of minimal wall thickness.

The failure analysis conducted by Quest Integrity concluded that the intergranular cracking in the RTC progressed predominantly from the inner surface towards the outer surface in the knuckle region of RTC as a result of stress relaxation cracking. This conclusion is based on multiple physical observations which are consistent with the signatures of the mechanism.

Process Safety Analysis

The RTC, as discussed earlier in this paper, connects the riser tube to the water jacketed effluent chamber. The metal temperature will reduce rapidly, over a short length, to that of the water jacket. The RTA is refractory lined to reduce the metal temperature of the 800HT RTA as well as the temperature of the Riser Transition Pipe (RTP) which was made of seamless carbon steel piping (ASTM A106 Grade B). The exterior of the RTA is designed to be uninsulated to allow cooling by air. A decreasing temperature gradient therefore exists from the internal process fluid, through the refractory, to the external metal surface.

A metal temperature in the range of 1110°F - 1200°F (600ºC – 650ºC) is necessary for stress relaxation cracking. Evidence suggests the RTC metal temperature reached a temperature range of 1020°F -1380°F (550-750ºC). IPSL observed damage to the refractory lining (Figure 12).

Following the failure analysis performed by Quest Integrity, IPSL reported that the RTA was externally insulated at the time of failure. The original construction drawing provided by MAN Ferrostaal and checked by KBR, do not show this section to be externally insulated. Drawings of similar KBR furnaces include a note stating “Do Not Add External Insulation on the Riser Transition Assembly” but there was no such instruction found on the drawings for this project. It was also noted that at IPSL’s two (2) other managed Ammonia Plants of similar Reformer design, the RTCs were not externally insulated.
This observed damage to the internal refractory lining shown in Figure 12, combined with the presence of external insulation likely allowed a localized increase in temperature, concentrated at the inner surface of the RTC. Severe degradation observed along the inner wall and the adjacent crack faces is consistent with such localized heating. As cracking progressed, the temperature of the external surface would have increased, eventually reaching the critical zone allowing stress relaxation cracking to occur in the opposing direction.

Figure 12. After the damaged RTA section was removed, the underlying alumina refractory displayed a longitudinal crack running down the length of component, marked with a yellow box. The height where the crack occurred is marked with red arrows, above which cracks are evident at the top of the alumina, marked with a blue box. Photo provided by IPSL.

**Design for Insulation / As-Built**

The insulation specification for the AUM Ammonia RTA does not indicate that the RTC is to be insulated. Whilst insulation was conceivably installed to reduce heat exposure at the Penthouse area, the installation of the insulation at this area was incorrect. Stricter adherence to specifications is required to ensure as-built condition is in conformance with design.

Also, based on the consequence of failure in this component, there should be a specific instruction to avoid external insulation of the RTA on the drawings.

### MOC / HAZOP Review

Insulation of the RTC represented a deviation from the specifications and required a proper analysis to be conducted to avoid any unintended consequences due to the change.

### Lessons Learned

During the outage to repair Riser C RTC, the opportunity was taken to inspect all of the four (4) remaining RTCs. UT Flaw, Dye Penetrant Testing (100% on all parent material and welds), Replica Metallography (taken at the riser transition pipe-to-cone weld interface, on the transition pipe side and at riser transition pipe-to-cone weld interface on the cone side) were performed. These inspections were all subsequently included in future TAR/Outage inspection plans for the RTCs. All insulation was removed from the remaining RTCs and stricter adherence to insulation specifications, especially for high temperature service equipment, has been implemented. Additionally, for any changes to insulation specifications, IPSL’s policies have been updated to ensure that a proper Management of Change (MOC) evaluation is completed. Also for future installations, closer attention to QA/QC for heat treatment would be implemented.

### Recommendations

To avoid similar failures in the future, the following actions are recommended:

1) **Apply Heat Treatments to Susceptible Components**

Austenitic alloy components that have the potential for exposure to temperatures in the range of 1020-1380°F (550-750°C), should undergo heat treatment at 1800°F (980°C) applied before or after cold-forming to reduce the susceptibility to cracking during service. Welds in these components should receive stress-relief heat treatment at a minimum temperature of 1625°F (885°C). Heat treatments of 1.5 h are required for sections
up to 1 in (25 mm) thick with an additional hour added for each additional inch of thickness.

[Note: No documentation of heat treatment of the RTC during fabrication was provided/located. The material test report for the plate noted that the sample submitted for testing was solution annealed.]

2) Avoid Critical Temperature Range
Components made of cold-formed austenitic alloys that did not receive the aforementioned heat treatment prior to service must be kept out of the critical temperature range between 1020°F - 1380°F (550°C - 750°C) to avoid stress relaxation cracking. Even short periods of time at these temperatures can lead to sudden failure by stress relaxation cracking. The use of external insulation around an RTC must be avoided so that heat can pass through the metal wall.

3) Non-destructive Evaluation
To detect subcritical stress relaxation cracking in components at risk of stress relaxation cracking, UT or X-ray inspection is recommended. Inspection should be focused in the areas of cold-working (e.g., bends and curves) and heat affected zones of welds.

4) Adherence to MOC Procedures
During maintenance installations, stricter QA/QC measures have been implemented to ensure that insulation is installed as per design specifications and that a proper MOC evaluation is completed for any changes to insulation specifications.

5) Review of As-Built Drawings and Vendor Drawings
Since the RTCs contain refractory and are to not be insulated, RTC drawings were updated to include the note “Do Not Insulate”. QA/QC plans were subsequently updated to ensure that during future insulation works, all specifications would be adhered to.

References