Reformer Component Management after an Overheating Incident that resulted in Tube Failures

A significant overheating incident occurred in CSBP’s reformer in May 2011, after 12 years of operation. Prior to the incident, the reformer was restarted after a hot trip and the furnace was inadvertently restarted using a cold restart procedure. Seven reformer tubes failed as a result of gross overheating and pressure. A prior overheating incident occurred in 2009, and although no tubes failed at that time, three were replaced based on inspection findings.

After the 2011 failure, the only damage found was to the reformer tubes and the outlet bull tee to transfer line welds. During normal operation a relatively slow rate of creep strain was measured. In the tubes that had not failed strains of 0.5-1% occurred as a result of each incident. After the 2011 incident the tubes were inspected with an external crawler which measured the strain and performed eddy current testing. The eddy current testing indicated nearly all of the tubes were cracked, with up to 40% through-wall and as a result, all the reformer tubes should be replaced. Subsequent metallographic examination revealed that no cracking was present in the area defined by eddy current testing, as having the highest level cracking and the level of creep voiding damage was lower than expected for the measured strain. This indicated that the damage that occurred in the incident occurred as a result of short-term deformation rather than long-term creep. Strain-based life assessment, assuming all the strain occurred as a result of creep damage, was carried out by Quest Integrity using proprietary LifeQuest™ reformer solution. It demonstrated that the reformer could confidently be restarted and operated for six months without changing any tubes. In addition, a tube harvesting programme was defined. The reformer operated without incident for six months leading up to the next planned shutdown. During this time, a number of tubes with higher strains were replaced ensuring that no further failures will occur before the next planned shutdown. Over half of the original tubes remain in service.

The outlet bull tee to transfer line welds had a low to moderate level of cracking after the incident in 2011. This cracking had previously been observed but to a lesser extent and was probably stress relief cracking. It was decided to repair the bull tees in the November 2011 shutdown. A repair procedure was developed to orbitally machine out the damage and weld repair using orbital TIG without a preheat treatment, which is known to be successful especially in methanol plants. Unfortunately cracking occurred in the HAZ of the welds. A high temperature solution anneal was carried out and the welding was then successfully completed without any cracking occurring. A temper bead procedure was used in the capping layer to minimize the risk of stress relief cracking while the reformer is in service.
Introduction

A significant overheating incident occurred in the primary reformer at CSBP’s ammonia production facility in May 2011 that resulted in tube failures. The failure occurred when the plant was being restarted after a hot trip and the furnace was inadvertently restarted using a cold restart procedure. The plant was immediately shutdown to identify the damage caused and ensure it was fit-for-service before the plant was restarted.

In 2009 a similar overheating incident occurred to the reformer and although no tubes failed at the time, three were replaced based on inspection findings.

The CSBP ammonia plant was designed by Haldor Topsoe and commissioned in 1999. It has been operating at the design capacity of 650 tonne per day. CSBP also have two nitric acid plants, ammonium nitrate plant and two sodium cyanide plants. The reformer in the ammonia plant is shown in Figure 1.

This paper outlines the cause of the overheating, the resulting damage and the actions taken to ensure the plant was fit for operation while minimising the downtime.

The Furnace Operation

The reformer was installed in 1999 and had operated for 12 years at the time of the incident in 2011. The furnace has two cells with 36 tubes, four rows of eight burners on either-side and top flue gas exit.
The following materials are used in the radiant and convection sections:

Reformer Tube: Modified HP 50 (134 mm (5.3 in) OD)
Outlet pigtails: Inco 800H
Outlet manifolds (4): Cast PG 20/32Nb-16
Bull tees (2): Cast PG 20/32Nb-16
Transfer line: Carbon steel refractory lined
1st coil Mixed feed: 321 +P22 (finned)
2nd coil Process Air: 321H + P22 (finned)
3rd coil Steam Super: 321H+ P22 (finned)
4th coil Natural Gas: P11
5th coil HP Steam: P11 (finned)
6th coil Air: A106 GrB (finned)
7th coil Natural Gas: A106 GrB (finned)
8th coil BFW: A106 GrB (finned)

Normal operation of the reformer

The reformer normally operates at a very steady rate with the following conditions:
- Reformer outlet temperature 760°C to 770°C (1400°F to 1418°F)
- Outlet pressure of 3070 kPa (445 psi)
- Flue gas temperature at the first coil in the convection section is 1023°C (1873°F)
- Tube metal temperature measured by pyrometer 850° to 900°C (1562°F to 1652°F) (Pyrometer emissivity set at 1)
- Steam /Feed NG ratio 2.2-2.35

These conditions are typical of many ammonia plants where a secondary reformer is also part of the process path. Given the relatively modest operating condition in many ammonia plants compared to methanol for example, the catalyst tubes and outlet components would be expected to have relatively long lives.

Overheating in 2009

A tube overheating incident occurred on 20th November 2009 during start up of the reformer after a trip. At the time steam was not initially mixed with the natural gas supplied to the reformer tubes (Figure 2). This resulted in carbon build up on the catalyst in tubes, restriction of flow in the tubes and as a result overheating of the tubes.

Overheating in 2011

On the 23rd May 2011 the plant tripped as a result of a low gas supply prior to the restart. Approximately 1¾ hours after lighting the burners steam was injected in to the tubes. Failures occurred 18 minutes later and a fire occurred in the furnace when the natural gas feed was applied 30 minutes after the steam was injected.

During the incident the following temperatures were recorded:
- Reformer outlet temperature.
  - Normally 760°C to 770°C (1400°F to 1418°F)
  - Maximum detected 939°C (1722°F) at bull tee and 868°C (1594°F) in the transfer line
- Convection section temperature (prior to first coil)
  - Normal 1023°C (1873°F)
  - Maximum of 1030°C (1886°F)
  - The convection section temperature was probably low as cold air was sucked into the air damper
- Natural gas 1st feed coil inside the convection section
  - Normal 551°C (1023°F)
  - Maximum of 575°C (1067°F)
Figure 2: Overheat in 2009. Showing the steam flow rates, process gas exit temperature and natural gas feed process exit pressure and natural gas fuel flow rate.

Figure 3: Overheat in 2011. Showing the mixed feed gas and steam flow rates, process gas exit temperature and process gas pressure.

The timing of the change in feed to the reformer tubes and the measured process gas exit temperatures is shown in Figure 3. The data from the temperature excursion suggests that it is probable that apart from the reformer tubes, it is unlikely that any other components would have been significantly affected. The convection section was probably not significantly overheated as the air damper was open. It is possible that the pigtails and outlet manifold were overheated after the fire.
Mitigations in place to prevent overheating

- Insulated the bottom part of the tubes with higher creep up to five meters height
- Maintained the maximum flow through the tubes sacrificing the exit temperature
- Increased the process steam/gas ratio to max (Steam/Gas 2.35)
- Continuously monitoring the tube skin temperature and turning off the burners where the hot tubes are identified

Damage Found

Damage predicted and damage found during normal shutdown inspections

A risk based assessment/inspections planning (RBA/RBI) of the pressure equipment in the ammonia plant was completed in 2004. This indicated that there were no significant high risk items in the reformer or the convections section. The key issues identified were high temperature creep cracking of the following:

- Reformer tubes especially if the reformer was unevenly balanced
- The outlet pigtails
- The outlet manifolds
- The bull tees

As result of these risks, the components had been inspected on a regular basis at up to a four yearly intervals. The following detailed inspections had not been carried out:

- Comprehensive measurement of the strain in the pigtails as the calculated life indicated that a low life fraction was used
- Extensive dye penetrant testing of the welds on the bull tees
- Measurement of the movement of the outlet headers during start up/shutdown

After two-years in service, due to a catalyst change the reformer was inspected by Quest Integrity using their proprietary LOTIS™ tube inspection method. This showed that the strain was very low and was effectively a baseline. It also showed the highest strain was at the bottom of the tubes. Manual pi tape measurement of strain in the tubes was carried out at the bottom and 1m from the floor of the reformer in 1999, 2001, 2004, 2006, 2008, 2009 (after the first overheating incident) and 2011 (after the second overheating incident). The results are summarised in Figure 4.

Damage observed after the 2009 incident

Following the overheating incident in 2009 the only damage found was as follows:

**Reformer tubes**

The reformer tubes were inspected in 2009 using an external crawler to measure the tube strain and inspect the tubes using an eddy current technique. This showed one tube had an OD strain >3% and four tubes with OD strain 2-2.5%. The inspection also indicated 14 tubes had over 30% wall cracking. Three tubes were replaced. Following the removal of the tubes no metallurgical assessment was carried out to confirm the results of the inspection and quantify the degree of creep damage.
Figure 4: Strain measurement in the bottom of the reformer tubes. The data directly prior to the incidents in 2009 and 2011 and in 2015 were estimated.

**Bull tee**
Dye penetrant testing was carried in 2009 around the welds connecting the manifold arms and the outlet cone to the two bull tees. This showed some fine isolated random indications of fine cracking up to 3.5 mm long adjacent to the tee to outlet cone weld. Replication showed that creep voids were present next to the cracking. No crack indications were present in the bull tee to header welds.

After the cracking was detected, the movement of the ends of the outlet headers and the movement of the bull tee was surveyed to determine if there was any measurable bending load applied to the bull tees. No difference in movement was detected between the bull tee and the ends of the outlet header.

**Other items**
No other damage was observed in 2009.
Damage observed in 2011

Reformer tubes
Seven reformer tubes were found to have failed after the incident in 2011. The following was observed:

- The failures were all typical of overload due to short term overheating. They ranged from 330 mm to 1200 mm (13 in to 47 in) long with fracture openings of 40 mm to 350 mm (1.5 in to 13.8 in). A typical failure is shown in Figure 5
- The reformer tubes were bulged at the failures. The highest OD strain in the tubes 200 mm (7.8 in) from a failure was measured to be 3%
- Tube failures occurred in both cells
- Three failures had occurred level with the lower burners (1.7m (67 in) from the bottom of the tube) or about 1.2m (48 in) above the floor of the furnace
- Four failures had occurred level with the second row of burners (3m from the bottom of the tube) or about 2.5m above the floor of the furnace
- The outer surface of the reformer tubes was more heavily oxidised in the bottom 3m than the top of the tubes

![Figure 5: Typical reformer tube failure.](image)

The reformer tubes which had not failed were inspected using an external crawler to measure the tube strain and inspect using an eddy current technique. This showed 21 tubes had an OD strain >3% and over 90% of the tubes had >30% wall cracking with 10 tubes with >45% wall cracking. The results also showed that the maximum strains were all located near the bottom of the tubes. The company that provide the diameter and eddy current assessment on the tubes recommended, at the time of the inspection, that all the tubes were damaged and should be replaced as soon as possible.

Manual strain measurements were also repeated at the bottom of the reformer tubes after the incident, see Figure 3. These manual measurements correlated well with the highest measurement made by the external crawler on each tube as position of the highest strain was in the same locations.

Bull Tee
Dye penetrant testing was carried out on the bull tee welds after the overheating incident. This showed that the extent of cracking at the bull tee to transfer line weld had increased from 2009. The cracking present was primarily at edge of the weld beads either in the weld HAZ or in the middle of the weld. The cracks ran in a range of directions. Typical cracking is shown in Figure 6.

Microstructural examination revealed that the creep voiding was present in the weld adjacent to the cracking and that the cracks were typical of creep voiding.

It was considered that the cracking probably occurred as a result of stress relief cracking that could have been enhanced by the overheating. Stress relief cracks in high nickel/chromium such as PG 20/32Nb alloys is known to occur [1].
Life Assessment and Management of Reformer Tubes

A tube was removed from the reformer that had been identified as having 45% wall cracking following inspection by the eddy current. The areas of highest wall cracking and highest strain (3.95%) were removed from the tube. Macrographic examination of a polished ring and microscopic examination showed that there was no evidence of any cracking present but creep voiding was present (Figure 7).

Other components

Extensive inspection of the coils and refractory in the convection section was carried out after the 2011 overheating incident. No significant damage was detected.

Examination of the outlet pigtails after the 2011 overheating incident revealed that they were about 1 mm (1%) larger in circumference at the reformer end than at the manifold end due to creep strain. It was not known as to what proportion of this strain occurred as a result of normal service or the over-heating incidents. No evidence of any creep damage or cracking at the pigtail to manifold welds or pigtail to reformer tube bottom cone welds was detected. The pigtails have a very flexible design and as a result cracking at the welds was not expected.

Figure 6: Cracking in the bull tee welds.

Figure 7: Microstructure of the worst tube identified by eddy current testing of the tubes showing the typical level of creep voiding.

Eddy current testing was carried out in the laboratory using a single point probe over a range of frequencies from 2 to 100 HZ. This showed a different response for samples from overheated tubes to samples from the top of reformer tubes which had not seen any significant overheating even though no cracks were present in either case. This indicates that the response difference was probably due to the different microstructure caused by the effects of overheating.

The typical microstructure of a tube removed from “normal “service after over
10 years service life typically consists of modified primary carbides, coarsened secondary carbides and fine creep voids depending on the loading (Figure 8). The microstructure of the failed tubes had been modified from the “normal” structure as a result of overheating by dissolving secondary carbides and spherodising primary carbides (Figure 9). It was estimated from the results of short term heat treatment trials intended to reproduce those observed in the overheated tubes that the tubes had experienced temperatures in excess of 1200°C (2192°F) in the areas of the failures. Nevertheless no evidence of melting was seen and it was shown that the tubes had not been heated to 1400°C (2552°F).

The remaining life of the surviving CSBP reformer tubes was estimated using the Quest Integrity LifeQuest™ Reformer method [2]. This life assessment methodology has been developed specifically to process data obtained from tube inspections based on tube diameter measurement.

A number of “virtual” tubes were created each having a different amount of strain. This was arranged to be close to the bottom of the tube where it is understood, the greatest measured strain was located in the CSBP tubes. The past history, tube geometry and operating pressure applicable to the CSBP tubes was entered into the LifeQuest™ Reformer model. This model assumes that the tube material ages with time and that the overheated material in the tubes will have a future creep strain rate equivalent to heavily aged material in “normal” operation. Assessment of other overheated material by creep testing has shown this to be case. The results obtained are listed in Table 1.

<table>
<thead>
<tr>
<th>Maximum OD strain in 2011 (%)</th>
<th>Total Rupture time from 2000 hrs</th>
<th>Predicted Failure Date</th>
<th>80% Damage</th>
<th>Recommended Retirement Date</th>
<th>Creep Effective Temp °C (°F)</th>
<th>Number of tubes above the strain figure</th>
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<tbody>
<tr>
<td>1</td>
<td>367091</td>
<td>Nov 2041</td>
<td>July 2033</td>
<td>813 (1495)</td>
<td>0</td>
<td></td>
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<tr>
<td>1.5</td>
<td>263575</td>
<td>Jan 2030</td>
<td>Jan 2024</td>
<td>823 (1513)</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>210846</td>
<td>Jan 2024</td>
<td>March 2019</td>
<td>828 (1524)</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>182646</td>
<td>Nov 2020</td>
<td>Sept 2016</td>
<td>833 (1531)</td>
<td>22</td>
<td></td>
</tr>
<tr>
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<td>159023</td>
<td>Feb 2018</td>
<td>July 2014</td>
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<td></td>
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<tr>
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<td>March 2015</td>
<td>March 2012</td>
<td>842 (1548)</td>
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</tr>
</tbody>
</table>

*number of tubes in 0.5 mm strain range above the strain figure i.e. for 2% strain it is the number of tubes with 2-2.5% strain

Table 1. Summary of LifeQuest™ Reformer results.

Figure 8: Typical ex-services modified HP50 showing minor creep voiding.

Figure 9: Typical microstucture adjacent to a failure in a tube.
It is believed that the overheat incidents have in fact contributed to the strain. The analysis of tube diameter data has suggested that there was a step jump in the mean measured tube strain (Figure 3). This means that the “normal operation creep strain” would have been a little less than that used in the assessment. It may appear inappropriate to assume that any strain that occurred during overheat incidents is non-damaging. At high strain rates under load, the damage mechanism is more like tensile deformation. This leads to bulk deformation of the material. Normal operation at relatively low strain rates is an intergranular creep process. These different damage mechanisms are not directly additive. This results in conservatism in the data given in Table 1, it is considered non-conservative to assume the addition strain caused by the overheating incidents did not contribute to damage as far as the life assessment was concerned.

The LifeQuest™ Reformer method does not have inbuilt safety factors. In accordance with the recommendation in API 579, the recommended retirement date is set at the date at 80% of the predicted failure date (Table 1).

As no tubes remained in service after the incident in 2011 had strains >4% it was recommended to limit the installation of new tubes to the seven failed tubes. Based on the results obtained, it was recommended that the 14 tubes measured to have more than 3% OD strain in June 2011 should be replaced at the planned outage for late 2011 if they are confidently to survive operation until June 2014. A total of 20 tubes were replaced in the next planned outage, during October 2011.

**Repair of Bull Tees**

After the 2011 incident it was recommended that the bull tees should be repaired. It was decided that these repairs should be done in the October 2011 shutdown. Bull Tees are known to be difficult to repair as a result of poor weldability and liquation cracking in the HAZ [1]. As a result of this it is common practice to carry out a high temperature (1150°C) (2103°F) solution treatment prior to welding. It is also known that bull tees in operation within Methanol plants with a typically higher operating temperature than ammonia plants can be successfully repaired by orbital machining and orbital pulsed TIG welding.

A repair procedure was developed to orbitally machine out the damage and weld repair using orbital TIG without a preheat treatment. Unfortunately cracking occurred in the HAZ of the welds probably due to liquation cracking [1]. A high temperature solution anneal was carried out with the aim of heat treating at 1150°C (2102°F) for a short period with a rapid fan cool. Regretfully the maximum achieved temperatures were 1088°C (1990°F) and 1097°C (2006°F) due to heating elements failures but welding was then successfully completed without any cracking occurring. A temper bead procedure was used in the capping layer to minimize the risk of stress relief cracking while the reformer is in service.
Conclusions

1. The 2011 overheat in the CSBP occurred as a result of accidentally using a cold start up procedure for a hot trip.

2. Seven tubes failed as a result of overload at high temperatures over 1200°C (2192°F).

3. Eddy current inspection of reformer tubes indicated that the majority of tubes in the reformer were badly cracked. However laboratory examination showed that no cracking was present and indicated that the eddy current response was probably due to microstructural changes that had occurred due to the overheat.

4. LifeQuest™ Reformer, reformer tube life assessment indicated that a large proportion of the tubes in service had long live expectancy and the at the plant could be operated immediately after the seven failed tubes were replaced. In addition only 14 tubes were recommended to be replaced at the next shutdown.

5. Cracking was detected in the Bull Tees that may have been exacerbated by the overheating incidents. This was probably stress relief cracking.

6. Liquation cracking in the HAZ occurred during the weld repair of the Bull tees without a prior heat temperature solution anneal. However welding after a solution anneal at 1090°C (1994°F) was successful.

7. A temper bead weld procedure was used to try to minimise the risk of stress relief cracking of the repaired Bull Tees.

References


2. Charles Thomas Reformer Life Assessment - Development of a Materials Database, AICHE 2008