Metallurgical Investigation of a Methanol Furnace Tubing Failure

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ABSTRACT

Rupture of fifteen HP40-1% Nb methanol reformer radiant tubes was investigated. The ruptures occurred during restart of the furnace following a unit shutdown due to a low steam-to-carbon ratio trip. The ruptures were evidenced by both circumferential and longitudinal fractures with three tubes being completely separated. Subsequent investigation indicated that all of the ruptured, catalyst-filled tubes failed by tensile overload caused by overheating. This paper describes the events preceding the failure, the failure investigation, methods used to determine the integrity of the remaining tubes, and techniques employed to repair useable sections of the failed tubes.

Introduction

Fifteen radiant tubes in a top-fired methanol reforming furnace ruptured following a unit shutdown caused by a low steam-to-carbon ratio trip. The failures occurred after relight of the burners while the furnace was on hot steam standby awaiting natural gas feed. Reforming is accomplished in vertical, internally bored, catalyst-filled tubes of HP40-1% Nb metallurgy. Design inlet and outlet process temperatures are 1000°F and 1616°F respectively.
Visual inspection of the furnace tubes revealed several fracture orientations: longitudinal ruptures, complete circumferential tube separations, and circular holes blown from tubes, Figures 1-3. All failures occurred in the northeast quadrant of the furnace approximately three meters (10 feet) from the ceiling at a level coinciding with the burner flame front. Partial, non-through-wall, ID cracks not associated with the fracture surfaces of the failed tubes were also observed. Of primary concern was the integrity of the remaining tubes not obviously damaged. This paper describes the failure investigation conducted on the ruptured tubes, details the methods used to assess the integrity of the remaining tubes, and describes procedures used to weld repair useable sections of the failed tubes.

Metallurgical Analysis

Samples from the fifteen tubes containing examples of each of the three observed fracture types were selected for laboratory examination. The samples received for analysis are shown in Figure 4. All samples exhibited macroscopic ductility in the form of bulging at the fracture. One sample exhibited an ID crack partially through the wall and not associated with the primary fracture. The fracture surfaces on all tube samples showed a dual morphology of columnar grains from the OD to midwall with equiaxed grains from the midwall to ID typical of the centrifugal casting, Figure 5. No heavy oxide buildup was observed on any sample.

Laboratory analysis concentrated on assessing the extent of high temperature damage suffered, including creep damage. One tube section was subjected to mechanical properties and chemistry verification. Mechanical property test results are shown in Table I. Noticeable is the increase in yield strength and decrease in percent elongation compared to as-cast values. These results are attributed to the precipitation of secondary carbides during service. Chemical analysis showed the composition of the tube sample selected for chemistry verification to be within specification.

Samples were taken for metallographic examination from all received failed sections to determine service temperature profiles and to check for creep damage. A photomicrograph of a typical fracture surface cross-section is shown in Figure 6. The fracture originated from the tube ID and followed primary carbide networks. A secondary crack runs perpendicular to the main fracture. The majority of the secondary carbides have redissolved in the matrix indicating exposure to very high temperatures, on the order of 2250°F for the approximately one hour duration of the upset. The presence of oxide on the fracture surface suggests that the overheating continued for some time following rupture. Figures 7 and 8 are photomicrographs of another failed tube section at the fracture and 180 degrees opposite the fracture, respectively. The lack of secondary carbides and slightly coarsened primary carbides indicate exposure to temperatures somewhat higher than that shown in Figure 6, on the order of 2350°F. Examination of the samples shown in Figures 6-8 in the unetched condition revealed no void formation at carbide-matrix interfaces, the occurrence of which would indicate damage from creep processes.
In-situ metallographic examination of selected tubes throughout the remainder of the furnace was performed to determine service temperature profiles and identify areas of the furnace in which tubes had been overheated. Results indicated that tube metal temperatures were highest in the quadrant where the ruptures had occurred. A more thorough laboratory examination of one of the unfailed, in-situ inspected tubes removed from the furnace confirmed the in-situ metallographic findings.

Figure 9 shows the tube and furnace geometry and the locations of metallographic samples taken from each tube. Figures 11-14 show the microstructures along the length of a failed tube at the locations shown in Figure 9. Figures 15-18 show the microstructures at corresponding locations along the length of an unfailed tube previously selected for in-situ investigation. The microstructure of a tube from an area outside the firebox at the top flange is shown in Figure 10 for comparison with the microstructures shown in Figures 11-18. This microstructure should be representative of all furnace tubes outside the firebox. The absence of secondary carbide precipitation and unaltered primary carbides represents an "as-cast" structure and indicates exposure to temperatures less than 900°F.

Figure 11 shows the microstructure of a failed tube at the area of failure (and maximum heat input from the burners). The almost completely dissolved carbides indicate exposure to temperatures approximately 2200-2250°F during the one hour upset. The microstructures in Figures 12-13 indicate exposures to slightly lower temperatures, 2000-2100°F, than those experienced at the failure area. Even lower temperatures were experienced at the bottom of the tube, Figure 14, because the tube was insulated from the firebox. An upset exposure time of eight hours was estimated for the tube sections represented in Figures 13 and 14 compared to one hour for the upper portion of the tube due to the heat retaining properties of the firebrick adjacent to the tube in the bottom section of the furnace.

The microstructure of the tube removed from the unfailed section of the furnace at the burner flame front-height, Figure 15, indicates that it was exposed to lower temperatures than was the failed tube at the same location, shown in Figure 11. The microstructures along the remaining length of the unfailed tube, Figures 16-18, follow a pattern similar to that of the failed tube in the same locations except for indicating exposure to lower temperatures. These findings would seem to indicate that the extreme heat flux causing the tube failures was confined to an area of the furnace banded by the failures.

To further assess the possibility of ID cracking in apparently unfailed tubes, an unfailed tube located next to two failed tubes was removed for inspection. A three meter section of the tube located at the burner flame front was split open and liquid penetrant examined, revealing no evidence of cracks.

Non-Destructive Examination

Based on encouraging results from the laboratory examination, it was decided to test only a random sampling of the remaining tubes non-destructively. Test techniques consisted of ultrasonics, eddy current, and radiographic methods.
Longitudinal wave, ultrasonic inspection was initially selected due to its rapid inspection ability. This particular inspection method used a loss of sound transmission between two sets of transmitting and receiving probes to indicate ID cracking. A UJ Reflectoscope from Automation Industries with a 1MHz probe was used for the inspection.

A one meter tube section was split open and two longitudinal notches machined by EDM (Electrical Discharge Machined) on the ID for instrument calibration. One notch was machined to ten percent of the wall thickness at one end of the tube sample and another notch machined to twenty percent of the wall thickness at the opposite end, both notches being approximately three centimeters in length. Trial measurements on the calibration sample indicated that detection of the twenty-percent notch was possible with good repeatability.

Tubes in the failure area were initially inspected by manual scanning. The Reflectoscope was gated to alarm at the twenty percent notch depth. Radiographs were taken in areas showing indications of cracks to verify the ultrasonic results. The crack verification radiographs failed to reveal any cracks. Based on this experience, ultrasonic inspection was dropped.

An ID eddy current inspection was then initiated to take advantage of the sensitivity of eddy currents to surface interruptions. This inspection became possible when de-activated catalyst was removed from the top portion of the tubes. An Automation Industries 3300 eddy current instrument with a Brush No. 220 strip chart recorder was used for the inspection. A differential wound, saturation probe was constructed with fifteen meters of cable for lowering into the tubes. Instrument calibration was accomplished with the EDM machined sample tube used previously. Again, trial measurements indicated that the twenty percent notch could repeatedly be detected. However, it was found that internal oxide scale (formed during the upset) created sufficient noise to mask any real indications. Efforts to power brush the tube bores proved unsuccessful, so the eddy current inspection was abandoned.

The only remaining inspection technique available at this point was radiographic inspection. Initial attempts to radiograph tubes filled with catalyst had indicated that the waviness on the film associated with catalyst geometry precluded positive identification of cracks without cutting open the tubes to verify the radiographic results. Radiography had become feasible following catalyst removal from the tubes. Approximately forty-two tubes were chosen for inspection in the failure area along a 1.5 meter length at the location of the fractures. If no cracks were found the furnace would be considered safe to start up. A panoramic ID exposure technique was chosen to minimize the number of exposures necessary to complete the inspection. Radiographic results showed no evidence of cracks in the tubes inspected.
Tube Repairs

Tubes were repaired by replacing the failed sections with stubs cut from the existing spare tubes. The failed tubes were square cut back from the fractured area and both ends dye penetrant inspected approximately thirty-centimeters into the bore as a final check for cracks. No cracks were found.

The top halves of the tubes were removed from the furnace to facilitate shop machining of the weld bevel and to allow welding the replacement stubs in a controlled environment. In this manner only one field bevel and weld were made. Welding was accomplished with a semi-automatic TIG process using matching filler metal and pure Argon for both the shield gas and ID purge. Both the weld root pass and cover pass were dye penetrant inspected for cracks. The field weld was made in a similar manner. One-hundred percent of the completed welds were inspected by radiography using a single wall exposure technique.

Some weld repairs were necessary as indicated by the radiographic inspection due in part to the difficulty in field welding plus the strict defect level requirements adhered to in the original fabrication specification. The majority of the repairs were made due to lack of penetration caused in part from the uneven field weld bevel. Following acceptance of all repaired tubes, catalyst was loaded and pressure drop tests conducted. No hydrostatic or pneumatic tests were performed on the repaired tubes.

Summary and Conclusions

Important conclusions and observations gained from this experience include:

- All tubes failed due to tensile overload during the high temperature upset. The tensile stresses resulting in failure were from internal tube pressures from the steam injected into the tubes during the standby.
- Tubes that did not fail are not expected to have a significant reduction in stress-rupture life because of a lack of evidence of creep damage.
- Inspection of catalyst-filled, cast, reformer tubes for ID damage is difficult. Catalyst must be removed to achieve an accurate assessment of furnace tube integrity. Further development of an automated ultrasonic inspection technique designed specifically for detection of ID indications may eliminate the need for catalyst removal.
- Successful field weld repairs can be made on aged tubes without the need for expensive and time consuming solution annealing treatments.

REFERENCE

TABLE I

Mechanical Properties of a Typical Service Aged HP-40 1% Nb Failed Reformer Tube

<table>
<thead>
<tr>
<th></th>
<th>T.S. MPa (psi)</th>
<th>Y.S. MPa (psi)</th>
<th>Elongation % (2 in Gage)</th>
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<tbody>
<tr>
<td>Design Minimum</td>
<td>448 (65,000)</td>
<td>220 (32,000)</td>
<td></td>
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<tr>
<td>Typical As-Cast</td>
<td>517 (75,000)</td>
<td>248 (36,000)</td>
<td></td>
</tr>
<tr>
<td>1500 hrs. Service @ 1650°F</td>
<td>450 (65,400)</td>
<td>296 (43,000)</td>
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Figure 1: Photograph of failed tube showing small longitudinal rupture near weld seam.

Figure 2: Photograph of failed tubes showing longitudinal rupture and hole blown out from tube.
Figure 3:
Photograph of failed tube showing longitudinal ruptures with catalyst on tube ID.

Figure 4:
Photograph of failed tube samples received for analysis.

Figure 5:
Photograph of typical fracture surface from a failed tube showing both columnar and equiaxed structures formed during cooling of the centrifugally cast tube. 3X

Figure 6:
Photomicrograph of the fracture surface of a typical failed tube sample showing the fracture following primary carbides. Glyceria Etch 125X
Figure 7:
Photomicrograph of a failed sample at the fracture location. Lack of secondary carbides indicates short-term exposure to temperatures of approximately 2250-2350°F. Glyceregia Etch 250X

Figure 8:
Photomicrograph of a failed sample at midwall 180° opposite from the fracture. Same microstructure as in Figure 7 indicating uniform overheating of tube sample to approximately 2250-2350°F. Glyceregia Etch 250X

Figure 9
Reformer Tube Detail
Figure 10:
Photomicrograph showing essentially "as-cast" structure representative of microstructures from tubes at top flange outside the firebox. Structure indicates exposure to temperatures less than 900°F. Glyceregia Etch 250X

Figure 12:
Photomicrograph showing structure indicative of exposure to temperatures of 1650°F for 1500 hours and 2000-2100°F for 1 hour. Glyceregia Etch 250X

Figure 11:
Photomicrograph showing structure indicative of exposure to temperatures of 1650°F for 1500 hours and 2200-2250°F for 1 hour. Glyceregia Etch 250X

Figure 13:
Photomicrograph showing structure indicative of exposure to temperatures of 1650°F for 1500 hours and 2000-2100°F for 8 hours. Glyceregia Etch 250X
Figure 14:
Photomicrograph showing structure indicative of exposure to temperatures of 1650°F for 1500 hours and 1900-2000°F for 8 hours.
Glyceregia Etch 250X

Figure 15:
Photomicrograph showing structure indicative of exposure to temperatures of 1650°F for 1500 hours and 1900-2000°F for 1 hour.
Glyceregia Etch 250X

Figure 16:
Photomicrograph showing structure indicative of exposure to temperatures of 1650°F for 1500 hours and 2000-2100°F for 1 hour.
Glyceregia Etch 250X
Figure 17:
Photomicrograph showing structure indicative of exposure to temperatures of 1650°F for 1500 hours and 2000-2100°F for 8 hours.
Glyceregia Etch 250X

Figure 18:
Photomicrograph showing structure indicative of exposure to temperatures of 1650°F for 1500 hours and 1850-1950°F for 8 hours
Glyceregia Etch 250X