CONVECTION SECTION FAILURE ANALYSIS AND FITNESS-FOR-SERVICE ASSESSMENT

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INTRODUCTION
In-service equipment failures present a considerable challenge to reliability engineers. Since these events are unplanned, the spare parts and resources to quickly and efficiently make repairs may not be readily available. Facility management is faced with decisions to perform short-term repairs to equipment to safely operate until repair parts, equipment, manpower and product supply permit an extended outage and long-term repair. In these instances, the reliability engineer will need to answer many questions, but in the case of a failure of convection tubes in a furnace (as presented in this article), they will need to answer whether the facility can restart the furnace and continue to operate reliably until the next planned shutdown.

TUBE FAILURE ANALYSIS
A large-scale natural gas manufacturing plant in the United States suffered a tube failure in the convection section of a fired heater. The failure occurred in one of the eight passes of finned tubes near the top of the convection section (Figure 1).

Results of the failure analysis indicated that the finned convection tube failed by tensile overload from a through-wall crack near the “hot face” of the tube. A brittle fracture occurred through the circumferential tube weld at the center of the tube located at the middle tube support (Figure 2). The weld was embrittled by sigma phase (σ) formation in the material of construction that results in a loss of fracture toughness in heat resistant castings from elevated temperature exposure.

The tube bundle was supported by three tube sheets (tube supports); two on the ends and one in the middle. Subsequent inspection identified that both end tube supports had dropped down due to failure of the four support bolts (two for each end support). The loss of support at the end tube sheets resulted in the tube coil having a high tensile stress, with a bending and possibly a torsional component, on the top of the tubes at the failure site(s) along the middle support.

REPAIRS AND TESTING
The operator had an inventory of replacement tubes for the convection section to allow for immediate replacement of several tubes. During the removal of the damaged tube, an adjacent tube was found to be cracked on the outside. No additional tubes were found to be cracked by visual inspection. However, the full extent of the tube cracking was unknown from the inspection due to the configuration of the convection section and the use of finned tubes. Visual or NDT testing of the tubes would be difficult or impossible without the removal of a substantial number of tubes. Visual inspection, dye penetrant inspection, or a proof hydrotest would only locate tubes which had through wall cracks or tubes where cracking could be located on the external surface. Existing cracks which were not through wall and initiated from the inside diameter (ID) could not be found with confidence using these conventional methods.

FAILURE ASSESSMENT DIAGRAM (FAD) METHOD
Rather than proceeding with a full repair, a hydrotesting procedure was developed using fracture mechanics and a failure assessment diagram (FAD) analysis to proof test the remaining tubes (see Figure 3). FAD is a fracture mechanics model for assessing crack-like flaws. A series of calculations are performed using the component geometry, crack dimensions, and material properties. These calculations result in an assessment point on the FAD. Failure is predicted if the point falls on or outside of the curve. The crack is considered to be stable if the point falls inside of the curve. The FAD assessment method is implemented in API 579, Part 9, Level 2.
The proof hydrotest was to be performed at a much higher pressure than required by API 530 for testing new tubes during construction. The desired pressure would be high enough that existing crack-like flaws of a critical size or greater in the tubes would propagate to failure under the hydrotest conditions. The maximum pressure would also be limited by the API 560 limitation of 90% of yield strength at ambient temperature for testing (Table 1). In theory, the tubes that survive the hydrotest pressure could then be assumed to have existing crack-like flaws that would not fail in operation.

Table 1. Comparison of Test Pressures.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Pressure</td>
<td>530 psig (3.65 MPa)</td>
</tr>
<tr>
<td>Design Tube Wall Temperature</td>
<td>1,482 °F (806°C)</td>
</tr>
<tr>
<td>Minimum Test Pressure</td>
<td>1,460 psig (10.07 MPa)</td>
</tr>
<tr>
<td>Maximum Test Pressure</td>
<td>6,630 psig (45.7 MPa)</td>
</tr>
<tr>
<td>Proof Test Pressure</td>
<td>3,500 psig (24.1 MPa)</td>
</tr>
</tbody>
</table>

The proof hydrotesting of the furnace tubes was accomplished by testing each of the eight passes in the convection coil at 3,500 psig (24.1 MPa) and holding the pressure for one hour. During the testing, one additional tube failed at 900 psig (6.2 MPa) and was replaced. The tube was removed and the failure location was preserved for failure analysis.

Upon completion of the hydrotesting, the furnace was successfully returned to operation. However, these repairs were considered temporary.

WHEN SHOULD WE PLAN FOR REPLACEMENT OF THE TUBES?

The initial tube failure event likely resulted in additional crack-like flaws in surrounding tubes. Further failure analysis and engineering assessment were planned to fully understand the root cause of the failures and to determine the remaining life of the convection coil tubes.

The desired outcome of the failure analysis and engineering assessment was to determine if the convection tubes were fit to operate until either of two future shutdown opportunities defined by the facility.

MATERIAL TESTING

In order to accurately calculate critical flaw sizes, material properties such as toughness, yield strength, and ultimate tensile strength must be identified. These material properties were obtained by destructive tests from tube samples removed from the heater.

MAXIMUM POSSIBLE EXISTING FLAW SIZES

Maximum possible existing flaw sizes in the tubes were calculated using the material properties data obtained from the ex-service tube. The analysis used commercial software that uses the calculation guidelines contained in the British Standards BS-7910 and API 579/ASME FFS-1.

CRITICAL CRACK SIZE CURVES

The result of this analysis is a plot of flaw depth (a) versus flaw length (2c) for an assumed elliptical surface flaw. Additionally, it is possible for a 360° surface flaw to exist in the tubes. This analysis was also done in order to identify a critical depth for a 360° surface flaw. Figure 4 shows the resulting critical crack size curve. The critical 360° flaw is plotted with a flaw length equal to the outer circumference of the tube. These flaw sizes represent the maximum possible flaw sizes that could withstand hydrotest conditions of 3,500 psig (24.1 MPa) and a temperature of 70°F (21°C).

Any combination of flaw depth and flaw length that falls on or below the curve can exist in the tubes. The actual possible crack configurations could not be narrowed down beyond this due to the limitations of “back-calculating” an existing flaw size from hydrotest conditions.

EXTENT OF EXISTING FLAW SIZE

In theory, it is possible that a long and shallow crack or a 360° surface crack would exist in the tubes that passed the proof test. However, a qualitative conclusion regarding which flaw length/depth combinations are more likely to occur can be reached based upon the axial stress profile of the tubes.

The axial stress due to bending at the top of the pipe cross-section is tensile, while the axial stress due to bending at the bottom of the pipe cross section is compressive. This results in the overall axial stress that tends to grow a crack being higher at the top of...
the pipe cross-section than at the bottom, leading to the identification of the likely and unlikely crack growth scenarios shown in Figure 5.

Another factor that supports the idea that the existing flaws in the tubes are more likely to be shorter and deeper can be drawn from the probable cause of the crack formation. The existing flaws were probably initiated and propagated significantly when a tube sheet support failed and overloaded the welds in the tubes. Alternatively, the crack may have grown after the tube sheet failure due to tube vibration. Such a scenario would cause the crack to break through at the 12 o’clock position rather than grow as a circumferential surface crack. The cracks observed in the sampled tubes that failed the hydrotest at 900 psig supports the hypothesis that cracks will be shorter and deeper rather than longer and shallower.

CONCLUSION
A fractured finned convection tube from a convection coil failed down the center of a circumferential tube weld which suffered sigma phase (σ) embrittlement. In order to safely resume operations and avoid a potentially long repair timeframe, hydrotesting at a proof pressure was used to provide reasonable assurance that tubes in the convection section would not fail upon restart or in the near term operation.

Further failure analysis and engineering assessment were performed to fully understand the root cause of the failures and to determine the remaining life of the convection coil tubes. The failure analysis and engineering assessment results were successfully used to evaluate if the convection tubes were fit to operate until either of two future shutdown opportunities.

These methods exemplify how failure analysis and fitness-for-service provided the operator a sound basis to evaluate the business and safety risks of continued operation until long-term repairs and system improvements could be implemented.

“We had a failure. Can we restart and continue to operate reliably until our next planned shutdown?” Failure analysis and fitness-for-service are valuable tools that you can use to answer these questions. ■

For more information on this subject or the author, please email us at inquiries@inspectioneering.com.

REFERENCES
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James (Jim) Widrig has worked on Petrochemical plants and Refineries for 30+ years and has been employed by Quest Integrity since 2007. Mr. Widrig is a Principal Consulting Engineer and currently holds the position of Manager, Advanced Engineering. Throughout his career, he has held various positions of responsibility including Health and Safety Program Manager, Operations Manager, Project Team Manager, Senior Operations Engineer, and Process Engineer. He has extensive experience in risk-based inspection, failure investigations, fitness-for-service, process plant operations, process safety, risk management, incident investigation, loss control, and process design.