Heat Exchanger Threat Assessment Methodology

Wednesday May 21, 2014
AFPM Reliability and Maintenance Conference
San Antonio, TX

Philip A. Henry, P.E.
Principal Engineer

The Equity Engineering Group, Inc.
Shaker Heights, OH USA
Presentation Overview

- Introduction/Background
- Overview of Risk Based Methodology
- TAR Project Work Process
- TAR Deliverable
- Study Summary
- Critical Components Based on Risk
- Major Findings
- Conclusions
- Questions and Answers
Introduction/Background

- Owner/User operates 3 production platforms and land-based Oil/Gas Processing facilities in middle east
- In operation for approximately 25 -30 years
- Significant high profile heat exchanger failures, increasing as time went on
- Equipment nearing end of life?
- Needed to establish a documentation system (e.g. material, operating, inspection, design code etc.) for technical assessment, identify risk levels and provide mitigation measures and recommendations
Introduction/Background

• Heat Exchanger Threat Assessment Project
  – Past detailed heat exchanger studies were performed **REACTIONILY**, resulted in unplanned shutdowns and downtime
  – Not much learning going on
  – Exchanger historical inspection and maintenance data was scattered between several corporate and site databases, including hard copy files at the sites
  – PFDs were not updated, heat & material balances were from original design, operating conditions including fluid properties and capacities much different than original
Introduction/Background

• Goals
  – Risk identification, reduction and mitigation strategy for each exchanger over the long haul
  – Improve heat exchanger reliability, reduce downtime and save money
  – Target increase turnaround frequency to 7 years
  – intended to create a single archive (central database) for each asset at the plant/equipment level and to retain current and historic information
  – More importantly, develop a sustainable tool that could be used PROACTIVELY going out into the future
Introduction/Background

• 468 heat transfer equipment items (1069 components)
  – Welded (Compabloc) Plate & Frame Exchangers
  – Gasketed Plate & Frame Exchangers
  – Shell & Tubes
  – Air Coolers
  – Fired Tube Boilers
  – Electric heaters
Introduction/Background

- Methodology
  - Need a proven risk-based methodology, Owner/Operator chose to use the quantitative risk based inspection methodology presented in the 2nd Edition of API 581, “Risk-based Inspection technology”
  - Necessary to supplement API 581 method to go beyond inspection recommendations only
  - Provide a solution to the short and long term risks associated with heat exchanger pressure boundary and tube bundle failures
Introduction/Background

• Methodology
  – Results are risk mitigation recommendations whose goal is to improve reliability of each heat exchanger and to extend runtimes to 7 years between interruptions.
  – Recommendations to mitigate risk are made where the calculated risk is determined to be above acceptable levels.
  – The risk level, before and after risk mitigations have been implemented are displayed in a risk matrix.
Introduction/Background

• Deliverables
  – Threat Assessment Report (TAR) - a two or three page summary “Threat Assessment Report (TAR)” for each exchanger that
    * documents the results of a materials/corrosion damage assessment
    * documents a review of exchanger past inspection history and current operating environment
    * Provides results of a threat assessment
    * Provides risk analysis results
    * Provides short and long term risk mitigation strategies required to meet stated goals
  – Sustainable Database
    * Keep data/analysis alive going into future
    * Evergreen/update as more information is learned
    * Transfer knowledge between sites
Introduction/Background

- Owner/Operator decided to use the quantitative API 581 risk methodology
- Industry recognized methodology through ANSI approved balloting process within the API Inspection Subcommittee
- Compliant with API 580 and fully documented in the 2nd edition of 581
- API RBI V9.0 software was used, enhanced for this project by creating a plugin (add-on feature) to populate the TARs directly from API RBI SW
Overview of Risk Based Methodology

Risk Target

- Actual Risk is calculated quantitatively for each component ($/yr)
- In API RBI, Risk is the product of the probability of failure and consequence of failure
- Risk Mitigation required if target exceeded

\[ R(t) = P_f(t) \cdot C_f \]
Overview of Risk Based Methodology

Risk Matrix

- API 581 risk matrix can be used to show results qualitatively
- Provide on Threat Assessment Report before and after recommended mitigation
Overview of Risk Based Methodology

Definition of Failure

• Pressure Boundary Components
  – Shell (SS) and Channel (TS) cylinders
  – Air cooler header boxes and tubes
  – Plate and Frame nozzles and gaskets
  – failure is defined as loss of containment

• For Heat Exchanger Bundles
  – Internal tubes
  – failure is defined as a tube leak which causes loss of usage
Overview of Risk Based Methodology
Probability of Failure

• POF Factors
  – Required thorough review of each exchanger service from the E²G metallurgical/corrosion engineer.
  – Assess the susceptibility of each potential damage mechanism, including thinning (local or general), external damage (e.g. CUI or cracking), environmentally assisted cracking, etc.
  – For pressure boundary components, damage factors are calculated for each applicable damage mechanism, the total of which is then used as a multiplier on the POF of an undamaged vessel (Generic Failure Frequency) to determine the actual POF for the in-service heat exchanger.
  – For bundles, POF is based on failure library
Overview of Risk Based Methodology

Probability of Failure

- For Pressure Boundary components, Probability of Failure is defined as:

\[ P_f(t) = gff \cdot D_f(t) \cdot F_{MS} \]

where:

- \( P_f(t) \) – probability of failure as a function of time
- \( gff \) – equipment specific generic failure frequency
- \( D_f(t) \) – damage factor based on the applicable damage mechanisms as a function of time
- \( F_{MS} \) – management systems factor, may be plant or unit specific
Overview of Risk Based Methodology
Probability of Failure

- **Generic Failure Frequency** – A probability of failure developed for specific component types based on a large population of component data that does not include the effects of specific damage mechanisms. The population of component data may include data from all plants within a company or from various plants within an industry, from literature sources, past reports, and commercial data bases.

- **Management Systems Factor** – Adjusts the generic failure frequencies for differences in process safety management systems. The factor is derived from the results of an evaluation of a facility or operating unit’s management systems that affect plant risk.
Overview of Risk Based Methodology

Probability of Failure

- The damage factor, \( D_{f-total}(t) \)
  - Adjusts the generic failure frequency based on the active damage mechanisms the component is subject to and considers the susceptibility to the damage mechanism and/or the rate at which the damage accumulates
  - Is a function of time
  - Takes into consideration historical inspection data and the effectiveness of both past and future inspections
  - Applied on a component and damage mechanism specific basis


Probability of Failure (POF) 

**Damage Factors**

- The damage factors in API 581 are summarized in Table 4.2
- The damage factors be segregated into the following general categories
  - Thinning and Lining Damage
  - Stress Corrosion Cracking (SCC) Damage
  - External Damage
  - HTHA Damage
  - Brittle Fracture Damage
  - Piping Mechanical Fatigue Damage

---

<table>
<thead>
<tr>
<th>Damage Factor Variable</th>
<th>Damage Factor Description</th>
<th>Paragraph</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{th}^T$</td>
<td>Damage factor for general and localized thinning</td>
<td>5.0</td>
</tr>
<tr>
<td>$D_{in}^T$</td>
<td>Damage factor of inorganic and organic linings for all component types</td>
<td>6.0</td>
</tr>
<tr>
<td>$D_{relative}^T$</td>
<td>Damage factor for caustic cracking</td>
<td>7.0</td>
</tr>
<tr>
<td>$D_{amine}^T$</td>
<td>Damage factor for amine cracking</td>
<td>8.0</td>
</tr>
<tr>
<td>$D_{sulphate}^T$</td>
<td>Damage factor for sulfide stress corrosion cracking</td>
<td>9.0</td>
</tr>
<tr>
<td>$D_{HIC-SOHC-M}^T$</td>
<td>Damage factor for HIC/SOHIC cracking in $H_2S$ environments</td>
<td>10.0</td>
</tr>
<tr>
<td>$D_{carbonate}^T$</td>
<td>Damage factor for carbonate cracking</td>
<td>11.0</td>
</tr>
<tr>
<td>$D_{PGA}^T$</td>
<td>Damage factor for polythionic acid cracking in austenitic stainless steel and nonferrous alloy components</td>
<td>12.0</td>
</tr>
<tr>
<td>$D_{cl-cc}^T$</td>
<td>Damage factor for chloride stress corrosion cracking</td>
<td>13.0</td>
</tr>
<tr>
<td>$D_{HHC-HT}^T$</td>
<td>Damage factor for hydrogen stress cracking in HF environments</td>
<td>14.0</td>
</tr>
<tr>
<td>$D_{HIC-SOHC-HF}^T$</td>
<td>Damage factor for HIC/SOHIC cracking in HF environments</td>
<td>15.0</td>
</tr>
<tr>
<td>$D_{CUI-fer}^T$</td>
<td>Damage factor for external corrosion on ferrous components</td>
<td>16.0</td>
</tr>
<tr>
<td>$D_{CUI-F}^T$</td>
<td>Damage factor for CUI on insulated ferritic components</td>
<td>17.0</td>
</tr>
<tr>
<td>$D_{cl-cc}^T$</td>
<td>Damage factor for external chloride stress corrosion cracking on austenitic stainless steel components</td>
<td>18.0</td>
</tr>
<tr>
<td>$D_{cl-cc}^T$</td>
<td>Damage factor for external chloride stress corrosion cracking on austenitic stainless steel insulated components</td>
<td>19.0</td>
</tr>
<tr>
<td>$D_{htha}^T$</td>
<td>Damage factor for high temperature hydrogen attack</td>
<td>20.0</td>
</tr>
<tr>
<td>$D_{brittle}^T$</td>
<td>Damage factor for brittle fracture of carbon steel and low alloy components</td>
<td>21.0</td>
</tr>
<tr>
<td>$D_{temper}^T$</td>
<td>Damage factor for temper embrittlement of Cr-Mo low alloy components</td>
<td>22.0</td>
</tr>
<tr>
<td>$D_{885}^T$</td>
<td>Damage factor for 885 embrittlement</td>
<td>23.0</td>
</tr>
<tr>
<td>$D_{sigma}^T$</td>
<td>Damage factor for sigma phase embrittlement</td>
<td>24.0</td>
</tr>
<tr>
<td>$D_{mech}^T$</td>
<td>Damage factor for mechanical fatigue</td>
<td>25.0</td>
</tr>
</tbody>
</table>
Overview of Risk Based Methodology
Consequence of Failure

- For pressure boundary components, consequence of Failure in API RBI is defined as the loss of containment of hazardous fluids from pressurized processing equipment that may result in damage to surrounding equipment, serious injury to personnel, production losses, and undesirable environmental impacts
  - The consequences of loss of containment are determined using well established consequence analysis techniques and are expressed as an affected impact area or in financial terms
  - Impact areas from such event outcomes as pool fires, flash fires, fireballs, jet fires and Vapor Cloud Explosion (VCEs) are quantified based on the effects of thermal radiation and overpressure on surrounding equipment and personnel
Overview of Risk Based Methodology

Consequence of Failure

Toxic Area

Flammable Area

Personnel Injury

Equipment Damage
Overview of Risk Based Methodology

Consequence of Failure

- A single release can have several outcomes
- Event trees are used to determine the possible outcomes for a release
- Each event outcome determines a probability of ignition or safe dispersion
Overview of Risk Based Methodology
Consequence of Failure

- Potential Event Outcomes
  - Jet Fires
  - Pool Fires
  - Flash Fires
  - Fireballs
  - Vapor Cloud Explosions
  - Non-Flammable Ruptures
    * Physical Explosions (Energy Release)
    * BLEVEs
  - Steam Leaks/Burns
  - Chemical Splashes (Amine/Caustic)
  - Toxic Release
Overview of Risk Based Methodology
Consequence of Failure
Event Tree – Vapor Leakage Case

Vapor Release

\( \begin{align*}
\text{Ignition} & : \quad p_{oi_{vl}} \\
\text{Immediate Ignition} & : \quad \left(1 - p_{oi_{vl}}\right) \\
\text{No Ignition} & : \quad \left(1 - p_{oi_{vl}}\right)
\end{align*} \)

\( p_{oi_{vl}} \)

\( \begin{align*}
\text{Delayed Ignition} & : \quad \left(1 - p_{oi_{vl}}\right) \\
\text{Flame Front Fast} & : \quad p_{vcedi_{vl}} \\
\text{Flash Fire} & : \quad \left(1 - p_{vcedi_{vl}}\right) \\
\text{Flame Front Slow} & : \quad \text{Jet Fire, if continuous} \\
\text{Fireball, if instantaneous} & : \quad \text{VCE}
\end{align*} \)

\( p_{vcedi_{vl}} \)

\( \text{Safe Dispersion} \)
Overview of Risk Based Methodology

Consequence of Failure

Event Tree – Liquid Leakage Case

Liquid Release

\[ (1 - \text{poi}_{ll}) \]

\[ \text{Ignition} \]

\[ \text{Delayed Ignition} \]

\[ (1 - \text{poii}_{ll}) \]

\[ \text{Immediate Ignition} \]

\[ (1 - \text{poii}_{ll}) \]

\[ \text{No Ignition} \]

\[ \text{Safe Dispersion} \]

\[ \text{Flash Fire} \]

\[ \text{Pool Fire} \]

\[ \text{Flame Front Fast} \]

\[ \text{Flame Front Slow} \]

\[ \text{Fireball} \]

\[ \max(\text{Jet Fire, Pool Fire}) \]

\[ \text{VCE} \]

\[ \text{Copyright © 2014 E²G | The Equity Engineering Group, Inc. All Rights Reserved.} \]
Overview of Risk Based Methodology
Determination of Risk

• In API RBI, Risk is the product of the probability of failure and consequence of failure

\[ R(t) = P_f(t) \cdot CA \quad \text{for Area–Based Risk} \]
\[ R(t) = P_f(t) \cdot FC \quad \text{for Financial–Based Risk} \]

• In these equations, CA is the consequence impact area expressed in units of area and FC is the financial consequence expressed in economic terms
Overview of Risk Based Methodology
Determination of Risk

- For area-based risk, CA is determined for:
  - Equipment Damage (ft$^2$/yr)
  - Personnel Injury (ft$^2$/yr)
  - Toxic Injury (ft$^2$/yr)
  - Financial ($/yr)
Overview of Risk Based Methodology
Determination of Risk

• For financial-based risk ($), FC is as follows

\[ FC = FC_{cmd} + FC_{affa} + FC_{prod} + FC_{inj} + FC_{environ} \]

where

- \( FC_{cmd} \) - Component Repair Cost \cdot Material Cost Factor
- \( FC_{affa} \) - Equipment Damage Area \cdot Equipment Replacement Cost
- \( FC_{prod} \) - Production Cost/day \cdot Outage time (days)
- \( FC_{inj} \) - Personnel Injury Area \cdot Population Density \times Injury Cost
- \( FC_{environ} \) - Environmental Cleanup Cost

• The Cost Factors are determined at unit level
  - Cost factors only used in Financial Risk calculation
  - Area based risk calculation will use the largest of equipment, personnel and toxic consequence areas
  - No financial or reliability impact on area risk calculation
Overview of Risk Based Methodology

Heat Exchanger Bundles - POF

- Bundle failure definition – Tube Leak
- For bundles, POF is calculated filtering on a failure library database and applying Weibull statistics to failed bundles meeting a suitable set of matching criteria.
- Condition based inspection programs are limited since failure data for a particular bundle usually does not exist, not enough data to be statistically significant
- API RBI relies on failure database with matching criteria to obtain statistical “cut-set”
- Differs from fixed equipment or pressure boundary “damage factor” approach
Overview of Risk Based Methodology
Heat Exchanger Bundles - POF

- Probability of Failure (POF) is determined either of several ways
  - Estimated Weibull Parameters based on Filtering/matching existing bundle design and service in bundle failure libraries
    \[
    POF(t) = F(t) = 1 - R(t) = 1 - \exp\left(-\left(\frac{t}{\eta}\right)^\beta\right)
    \]
  - Estimated MTTF of Weibull parameters based on past history of the bundle being evaluated, recommended default value for BETA is 3.0
  - Expert Opinion is required, if no failure data or insufficient amount of data is available either locally or from seed
Overview of Risk Based Methodology
Heat Exchanger Bundles - POF

- Obtain a matching set of bundles by filtering on failure libraries
  - Exchanger Type
  - Tube Metallurgy
  - TS and SS Fluid Categories
  - Operating conditions (temperatures, pressures, velocities, etc.)
  - Process Unit
  - Controlling Damage Mechanism
  - Damage Severity
  - Fluid Damage Modifiers (H₂S, sulfidation, caustic, etc.)
  - Many, many others
Overview of Risk Based Methodology
Heat Exchanger Bundles - POF

- Weibull plot based on filtered set of similar bundles
  - Goodness of fit test
  - If poor fit, redo filter/cut set
  - Ability to review matching bundle set
  - Eliminate outlier bundles as necessary to make the fit more appropriate
- Previous inspections effect amount of uncertainty (shift to the left)
Overview of Risk Based Methodology
Heat Exchanger Bundles - POF

• When sufficient inspection information exists for a bundle such that a Mean Time To Failure (MTTF) may be determined, the analyst can specify the bundle MTTF.

• A Weibull distribution can be determined from the specified MTTF. If the $\beta$ parameter (slope) is known (API RBI assumes it to be 3.0), the $\eta$ parameter (characteristic life) can be determined from the gamma function

\[
MTTF = \eta \cdot \Gamma \left[ 1 + \frac{1}{\beta} \right]
\]
Overview of Risk Based Methodology
Heat Exchanger Bundles - COF

- Bundle COF can only be expressed in financial terms
  - Lost Production/ Business interruption
  - Maintenance and Inspection Costs
  - Environmental Cost (e.g. leaks to cooling tower)

\[
COF = Cost_{prod} + Cost_{env} + Cost_{bundle} + Cost_{maint}
\]
Overview of Risk Based Methodology

Risk Mitigation

- Calculate Target Date – date at which risk target is reached
- Calculate Remaining Life – i.e. time and date minimum required thickness \( t_{\text{min}} \) reached
- Identify other potential damage mechanisms that can not directly be linked to a remaining life (e.g. cracking, tube end thinning, gasket failure)
- Recommend mitigation techniques to increase life and reduce risk
TAR Project Work Process

• Data Gathering and Uploading into SW
  - Data scattered in various electronic databases and local files, various formats and locations, not conveniently accessible. MAXIMO, EABOX, individual SME files
  - Required touching many areas of the organization, on-site Interviews, operations reviews
  - On-site data gathering including trips to production facilities
  - Some missing/unavailable Data had to be assumed
TAR Project Work Process

• Data Gathering and Uploading into SW
  – All data required validation by Owner Operator, very difficult, added complexity to delivery schedule
  – Required teamwork using Owner personnel
  – Goal: Key informational elements of each heat exchanger available in one document/form
  – An accessible database of information
TAR Project Work Process

• Data Validation
  - Required data validation from Owner/operator prior to threat analysis and risk assessment
  - Key Step in the process was getting Owner sign-off for data validation including missing data and assumptions
TAR Project Work Process

- **Materials Review and Threat Assessment**
  - Critical step in work process
  - Corrosion SMEs conducted process overview, corrosion analysis and assessment of treating (CW, Glycol, Amine) procedures
  - Past inspection and failure history review
  - Determine acceptability of materials
  - Identify potential threats and quantify damage mechanisms (corrosion rates, cracking susceptibilities, etc.)
TAR Project Work Process

• Risk Assessment, Reduction and Mitigation Strategy
  - Risk Specialist and Corrosion Engineers
  - Perform quantitative risk assessment per API 581
  - High risk items identified and addressed
  - Insight into risk drivers, POF and COF to improve causal understanding and risk mitigation strategies
  - Insight into the overall health (true damage state) of the equipment
  - Mitigation recommendations target risk driver, with goal to reduce risk to acceptable level
TAR Project Work Process

- Risk Assessment, Reduction and Mitigation Strategy
  
  - Short Term Mitigations - address issues that need immediate attention, e.g. upgrade metallurgy, FFS and repair of damage, cracking inspections, seawater filtering and biocide control, exchanger re-design, coating and liner applications, tube ferrule installation, purchase of replacement shells, purchasing a spare, etc. These should only be to fix problems.

  - Long Term Mitigations (after short terms things fixed) - include continuous monitoring glycol and seawater systems, long term risk-based inspections frequencies and techniques, spare bundle rotation program, monitoring heat transfer performance, injection of chemical inhibitors
TAR Deliverable

- **Final Heat Exchanger Threat Assessment Report (TAR)**
  - Exchanger Mechanical and Operation Details
  - Calculated Risk Results for API RBI
  - Materials Review
  - Threats Analysis
  - Short and Long Term Mitigation Recommendations
  - Equipment Sketches
  - Bundle Failure Curves
  - Inspection History Summary
  - Process Overview Summary
Heat Exchanger Threat Assessment Project

TAR Deliverable

Example Bundle TAR
Waste Gas Cooler Bundle, Item 177-C-2003-T01

Risk Mitigation

Material Review:

- The exchanger is in poor form, exchange, and failure heat transfer plates. It is overwound to cool the waste gas from the reflux condenser.
- The exchanger contains and exchanges waste heat in the process of being recycled.
- The exchanger and water/steam control panel is outlined in "U.S. Water Quality Report" dated July 2011, and has been thoroughly reviewed and is effective in controlling corrosion and water/steam activity in the exchanger system.

History:

- Process: Unchanged
- Days: 524.0
- Days: 524.0
- Rate Reduction: 0.0%

Threats:

- The exchanger membranes are considered fully resistant to corrosion.

Inspection History Summary:

- Since commissioning in June 2002, the cooler has given satisfactory service and no major problems highlighted. Inspections in 2004, 2006, 2010, 2012 and no significant defects were observed.
- In June 2012, the internal Titanium Plates were mostly inspected, as accessible through the nozzle opening and found in good order.

Failure Probability Curve:

Process Summary:

The cooler is used to cool down the Hot waste gas going to the Knott Out Drum, in which the gas from the top will be flowing into the exchanger and then into the Knott Cooler and collected water at the bottom floor to the upper drain to the use. Hot waste gas from the Process Exchanger is cooled heat before entering Waste KO Drum [177-C-2003] with Cold water from RPR which goes overhead.

Commissioned in 2009, based on the maximum operating level, and the performance test in March 2011, the performance of the exchanger is within the specification in terms of heat transfer efficiency and service. Monitoring the service efficiency and freezing resistance are recommended as this affects the heat transfer efficiency over time.

The fluid quality is monitored from fluid sampling analysis in April 2011 which indicated the glycol pH, percentage of water and glycol volume percentage. The corrosion rate monitoring is taken only by thickness measurement. The corrosion rate of the equipment increases with the decrease in glycol pH. The glycol pH should be checked periodically and kept on the basic side to be realized the point at 7 to 8.0. A glycol solution that is too alkaline tends to foam and emulsify.

The gas production profile will vary based on gas demand rate from ASDAS. The rate of glycol circulation and absorbed water is expected to set to very significantly on the gas production and is expected to be consistent at the way through the facility, and throughout the design cases. The heat transfer coefficient is expected to increase gradually and the freezing resistance is expected to linearly increase over time.
Risk Mitigation

Material Review Comments

This exchanger is a plate frame exchanger with titanium heat transfer plates. It uses seawater to cool the waste gas from the reflux condenser. A thorough review of the materials and process shows that the plate pack is fit for continued service. The seawater corrosion and water quality control program as outlined in "US Water Quality Report" dated July 2011 has been thoroughly reviewed and is effective for controlling corrosion and microbiological activity in the seawater system.

Threats

The titanium plates are considered fully resistant to corrosion.

Panel gasket failure and internal welded plate failure are the major threats to these Compabloc exchangers and may control life. There have been 4 documented gasket failures at Umm Shaif. The cooler cannot be bypassed and requires 30 days to repair.

Fouling is a threat that may degrade cooler performance and may force cleaning at intervals less than the desired 7 year inspection interval target. Past inspection indicates very little fouling/scaling has occurred since commissioning in 2002, therefore, unplanned shutdowns as a result of fouling are not expected.
Since commissioning in June, 2002 the cooler has given satisfactory service and no major problems highlighted. Inspected in 2004, 2008, 2010, 2012 and no significant defects were observed.

In June 2012, the internal Titanium Plates were visually inspected, as accessible through the nozzle opening and found in good order.
TAR Deliverable

Example Bundle TAR
Waste Gas Cooler Bundle, Item 177-C-2003-T01

Risk Mitigation Recommendations

Short Term:
None.

Long Term:
Required before May-2017, rotate spare exchanger into service and send current exchanger off-site to be thoroughly cleaned and inspected. Replace panel gaskets and refurbish the exchanger during this period.

If performance driven shutdown for cleaning occurs at less than the desired inspection interval, then seawater scale treatment and filtration must be improved.
## Study Summary

- **TAR Statistics**

<table>
<thead>
<tr>
<th>Site</th>
<th>TS Comps</th>
<th>SS Comps</th>
<th>Bundles</th>
<th>Air Coolers</th>
<th>Total Comps</th>
<th>Short Term Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>81 (24%)</td>
<td>116 (35%)</td>
<td>92 (27%)</td>
<td>47 (14%)</td>
<td>336</td>
<td>50 (15%)</td>
</tr>
<tr>
<td>Site 2</td>
<td>65 (30%)</td>
<td>67 (31%)</td>
<td>67 (31%)</td>
<td>15 (8%)</td>
<td>214</td>
<td>83 (39%)</td>
</tr>
<tr>
<td>Site 3</td>
<td>19 (20%)</td>
<td>31 (32%)</td>
<td>33 (34%)</td>
<td>14 (14%)</td>
<td>97</td>
<td>51 (53%)</td>
</tr>
<tr>
<td>Site 4</td>
<td>122 (29%)</td>
<td>122 (29%)</td>
<td>122 (29%)</td>
<td>56 (13%)</td>
<td>422</td>
<td>208 (49%)</td>
</tr>
<tr>
<td>Totals</td>
<td>287</td>
<td>336</td>
<td>314</td>
<td>132</td>
<td>1069</td>
<td>392 (37%)</td>
</tr>
</tbody>
</table>
Study Summary

- Initial Risk Target of $100,000 per year was chosen
- Only 8% of components High and Med-High risk
- Initial TAR delivery basis
Study Summary

- Risk Target of $10,000 per year
- Increased High and Med-High risk items to 15%
- Final TAR delivery basis
Study Summary

- Mitigation recommendations were primarily based on a risk target ($/yr)

- However, during project, Owner also wanted the following criteria used as well
  - Movement on risk matrix from RED (High Risk) or ORANGE to YELLOW (Medium Risk)
  - Tmin Remaining Life Criteria, in which case short term recommendations were made at half-life
Example TARs

Critical Components

• Site 1: GTP 177-E-2010-SS, Start-Up Fuel Gas Heater
  - **Unmitigated Risk** - $1,023,400/yr
  - **Background** – Electrically Heated SS exchanger with dry gas on the shell side, no corrosion threats
  - **Risk Drivers** – High COF, no bypass available, 30 days to repair, $54,000/day production impact, High POF, SCC of SS shell, no evidence of cracking inspection.

![Diagram of heat exchanger](image-url)
Example TARs

**Critical Components**

- **GTP 177-E-2010-SS, Start-Up Fuel Gas Heater**
  - **Short Term Mitigation** – By Dec-2014, **purchase spare to have available**, inspect for external cracking of 316 stainless covering 60-94% of the total surface area using Dye penetrant or Eddy current test with UT follow-up of relevant indications
  - **Long Term Mitigation** – Perform 100% visual external examination with dye penetrant or eddy current crack inspection before May-2017.
Example TARs
177-E-2010-SS Start-Up Fuel Gas Heater

- Results – Mitigated Risk of $5815/yr

<table>
<thead>
<tr>
<th>Probability of Failure</th>
<th>Consequence of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 POF &lt;= 0.0001</td>
<td>A COF &lt;= 10000</td>
</tr>
<tr>
<td>2 0.0001 &lt; POF &lt;= 0.001</td>
<td>B 10000 &lt; COF &lt;= 100000</td>
</tr>
<tr>
<td>3 0.001 &lt; POF &lt;= 0.01</td>
<td>C 100000 &lt; COF &lt;= 1000000</td>
</tr>
<tr>
<td>4 0.01 &lt; POF &lt;= 0.1</td>
<td>D 1000000 &lt; COF &lt;= 100000000</td>
</tr>
<tr>
<td>5 POF &gt; 0.1</td>
<td>E COF &gt; 100000000</td>
</tr>
</tbody>
</table>
Example TARs

Critical Components

- NGTP 427-E-304-CSN2, Glycol Exchanger-Rich Cold
  - **Unmitigated Risk** - $207,520/yr
  - **Background** – Titanium clad plate and frame exchanger (Compabloc) with titanium heat transfer plates
  - **Risk Drivers** – High production value, 7 days SD, fully resistant to Rich TEG, CUI is predicted (crate of 0.027 mm/yr)
  - **Short Term Mitigation** – Strip insulation and perform 100% on-stream visual inspection followed by spot UT at CML locations on the cold nozzles. Repair/replace coating as necessary. Required to be completed by Aug-2013
**Example TARs**

*Critical Components*

- **NGTP 427-E-304-CSN2, Glycol Exchanger-Rich Cold**
  - **Long Term Mitigation** – Keep glycol pH between 7.0 and 8.0 to minimize corrosion and scaling. Monitor pH monthly. If performance deteriorate and cleaning more frequent than inspection interval, glycol filtration must be improved to remove sludge. Perform 100% visual on-stream inspection followed by spot UT at CML locations again before Aug-2020.
Example TARs
427-E-304-CSN2 Glycol Exchanger-Rich Cold

- Results - Mitigated Risk of $9191/yr
Example TARs

Critical Components

- GSU 08.2HSR3-C-1003-SS, DEA Reboiler

  - **Background** – CS fixed T/S regenerator reboiler using 40 psig steam to strip off steam from the hot lean DEA on the shellside
  - **Unmitigated Risk** - $202,760/yr
  - **Risk Drivers** - High COF due to H₂S content, Non-PWHT CS Shell, High susceptibility to Amine cracking (ASCC), Lean Amine corrosion (0.4 mm/yr est. corrosion rate), hazardous fluid
  - **Short Term Mitigations** - Due to shell dent from mis-handling, perform L2 or L3 FFS or purchase new shell by Mar-2014. If excessive corrosion, consider 304L SS clad shell
Example TARs

Critical Components

• GSU 08.2HSR3-C-1003-SS, DEA Reboiler
  
  - Short Term Mitigations (Con’t):
    - Monitor Lean DEA envelope (quarterly confirmation of HSAS wt.% levels <3 wt.% and weekly monitoring of residual H\textsubscript{2}S content of Lean DEA of >0.003 mole/mole). This should be completed before Aug-2013
  
  - Long Term Mitigations:
    - By Mar-2021, perform internal visual inspection followed with CML placement at bottom of shell and vapor outlet for UT measurements for potential erosion/corrosion
    - Perform internal WFMT for amine cracking of shell welds. Consider PWHT of CS shell and use of B7M studs for FHC (subject to mechanical design confirmation) or ensure shell is water washed rather than steamed out at downtimes
Example TARs

08.2HSR3-C-1003-SS DEA Reboiler Heat Exchanger

• Results - Mitigated Risk of $9427/yr
Example TARs
Critical Components

- **60.4PU8-E-01-SS, Degasser Vent Condenser**
  - **Unmitigated Risk** - $23,183/yr
  - **Background** – This 316L SS heat exchanger is used for heat exchange between hot steam (Shellside) and cold seawater (tubeside) within Potable Water Production unit
  - **Risk Drivers** – Major threat is chloride SCC. Past histories of the similar condensers indicate frequent through-wall cracking particularly at the hot (102°C) inlet. This vent gas condensate should have low corrosivity to SS with some minor pitting potential due to residual chlorides
Example TARs

Critical Components

- 60.4PU8-E-01-SS, Degasser Vent Condenser
  - **Short Term Mitigation** – Purchase replacement shell upgrading to 254SMO (high alloy austenitic), should be available for installation at next shutdown. Next required inspection Oct-2016
  - **Long Term Mitigation** – Perform LPI inspection of hot inlet area to confirm no Chloride SCC every other shutdown. Next required inspection is Oct-2026
Example TARs
60.4PU8-E-01-SS Degasser Vent Condenser

- Results - Mitigated Risk of $439/yr

<table>
<thead>
<tr>
<th>Probability of Failure</th>
<th>Consequence of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>POF &lt;= 0.0001</td>
</tr>
<tr>
<td>2</td>
<td>0.0001 &lt; POF &lt;= 0.001</td>
</tr>
<tr>
<td>3</td>
<td>0.001 &lt; POF &lt;= 0.01</td>
</tr>
<tr>
<td>4</td>
<td>0.01 &lt; POF &lt;= 0.1</td>
</tr>
<tr>
<td>5</td>
<td>POF &gt; 0.1</td>
</tr>
</tbody>
</table>

Long Term Predicted Risk

Risk Results

Risk After Mitigation

X - Mitigation is implemented

POF (Failures/yr) 0.256
COF($) 9.056E+4
Risk($)/yr 2.3183E+4

POF (Failures/yr) 0.0048
COF($) 9.1266E+4
Risk($)/yr 439.2946
Example TARs

Critical Components

- **PGP 20-XT11C-E3-HEST-TS, Control Oil Cooler**
  
  - **Unmitigated Risk** - $223,270/yr
  
  - **Background** – CS fixed tubesheet exchanger used to exchange heat between shellside Hydraulic Oil and the cool tubeside gearbox (Turbine Oil)
  
  - **Risk Drivers** – High COF, production loss, external corrosion bare CS, no inspection thickness readings documented since 1978
Example TARs

Critical Components

- PGP 20-XT11C-E3-HEST-TS, Control Oil Cooler
  - **Short Term Mitigation** – None Required
  - **Long Term Mitigation** – By Jan-2015, perform 100% visual external inspection followed by UT measurements at any externally damaged areas
Example Passports
20-XT11C-E3-HEST-TS Control Oil Cooler

- **Results - Mitigated Risk of $2840/yr**

<table>
<thead>
<tr>
<th>Probability of Failure</th>
<th>Consequence of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\text{POF} \leq 0.0001$</td>
</tr>
<tr>
<td>2</td>
<td>$0.0001 &lt; \text{POF} \leq 0.001$</td>
</tr>
<tr>
<td>3</td>
<td>$0.001 &lt; \text{POF} \leq 0.01$</td>
</tr>
<tr>
<td>4</td>
<td>$0.01 &lt; \text{POF} \leq 0.1$</td>
</tr>
<tr>
<td>5</td>
<td>$\text{POF} &gt; 0.1$</td>
</tr>
</tbody>
</table>

**Risk Results**

- Long Term Predicted Risk
- Risk After Mitigation

<table>
<thead>
<tr>
<th>POF(Failures/yr)</th>
<th>COF($)</th>
<th>Risk($/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0401</td>
<td>5.5678E+6</td>
<td>2840.0</td>
</tr>
<tr>
<td>0.0005</td>
<td>1.261E+7</td>
<td>2840.0</td>
</tr>
</tbody>
</table>

Copyright © 2014 E²G | The Equity Engineering Group, Inc. All Rights Reserved.
• 353-T-114-HEST-TS, Glycol Regen. Condenser
  - **Unmitigated Risk** - $21,488,000/yr
  - **Background** - The purpose of this vertical condenser is to recover/condense valuable glycol (tubside) leaving the glycol reboiler, using cool rich glycol (shellside). CS channel and 304SS shell and bundle
  - **Risk Drivers** – Major threat of sour water corrosion to CS (Est. crate of 0.2 mm/yr). Limited inspection data collected. Also, minor threat to external corrosion. Moderate threat of Wet H$_2$S damage as this is a hot sour water exposure with non-PWHT 60 grade material
Example TARs

Critical Components

- **353-T-114-HEST-TS, Glycol Regen. Condenser**
  - **Short Term Mitigation** – By Jun-2015, perform 100% visual internal and external inspections for corrosion followed by UT thickness measurements. Perform WFMT of 50% of internal weldments
  - **Long Term Mitigation** – By Jun-2022, perform 100% visual internal and external inspections for corrosion followed by UT thickness measurements. Perform WFMT of 50% of internal weldments. Repeat every shutdown.
Example TARs
353-T-114-Hest-TS Glycol Regen. Condenser

- Results - Mitigated Risk of $8187/yr

<table>
<thead>
<tr>
<th>Long Term Predicted Risk</th>
<th>Risk Results</th>
<th>Risk After Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>POF(Failures/yr)</th>
<th>COF($)</th>
<th>Risk($)/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0803</td>
<td>2.6754E+8</td>
<td>2.1488E+7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Probability of Failure</th>
<th>Consequence of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>POF &lt;= 0.0001</td>
</tr>
<tr>
<td>2</td>
<td>0.0001 &lt; POF &lt;= 0.001</td>
</tr>
<tr>
<td>3</td>
<td>0.001 &lt; POF &lt;= 0.01</td>
</tr>
<tr>
<td>4</td>
<td>0.01 &lt; POF &lt;= 0.1</td>
</tr>
<tr>
<td>5</td>
<td>POF &gt; 0.1</td>
</tr>
</tbody>
</table>

Copyright © 2014 E²G | The Equity Engineering Group, Inc. All Rights Reserved.
• 353-T-110-HEST-SS, Sour Gas Cooler
  - Unmitigated Risk - $6,000,500/yr
  - Background - This exchanger is used to cool down overhead sour gas from Glycol Regenerator Reflux Condenser before going to the Sour Gas liquid Separator. Uses unfiltered seawater to cool (tubeside). 304 SS shell with AL Bronze channel and 90/10 CuNi Bundle.
  - Risk Driver – High COF due to 8% H$_2$S in vapor, estimated low susceptibility to Cl SCC in process sour water, however, no credit for past cracking inspection. Minor threat to sour water corrosion (Est. crate of 0.01 mm/yr)
Example TARs

Critical Components

- **353-T-110-HEST-SS, Sour Gas Cooler**
  - **Short Term Mitigation** – By Mar-2014, perform WFMT inspection of 50-100% of internal shell welds
  - **Long Term Mitigation** - By Mar-2019, perform WFMT inspection of 50-100% of internal shell welds. By Mar-2021, perform internal visual inspections followed by pit depth measurement for potential water corrosion pitting. Weld repair as necessary
Example TARs
353-T-110-HEST-SS Sour Gas Cooler

• Results - Mitigated Risk of $2811/yr
Example TARs

Critical Components

- **353-T-101B2-T02, 1\textsuperscript{st} Stage After Cooler Bundle**
  - **Unmitigated Risk** - $139,800/yr
  - **Background** - 70/30 CuNi bundle used to cool down the 1\textsuperscript{st} stage compressed process gas (shellside) using unfiltered seawater (tubside) from cooling water system outlet, which then goes into primary gas. Bundle replacements were required at < 3 year intervals due to combination of plugging, external fouling/corrosion and leaks

• 353-T-101B2-T02, 1\textsuperscript{st} Stage After Cooler Bundle
  
  - Risk Drivers – Two Major Threats
    
    ▪ Unfiltered aerated seawater corrosion on the tubeside caused by either erosion of tube ends due to high velocities or plugging of tubes with marine debris or MIC pitting of the tubes due to poor biocide or high temperature causing salt deposition and plugging
    
    ▪ Second major threat is tube OD fouling and corrosion under deposits due to condensed produced water (chlorides and $\text{H}_2\text{S}$) from the raw gas
Example TARs

Critical Components

- 353-T-101B2-T02, 1\textsuperscript{st} Stage After Cooler Bundle

  - **Short Term Mitigation**
    - Unfiltered Option - By Dec 2013, upgrade bundle for both OD and ID corrosion to Titanium Grade 2. Upgrade FHC to 254SMO. Seawater requires rigorous filtering to prevent marine debris plugging tubes and seawater biocide control to prevent MIC corrosion.
    - Filtered Option – By Dec 2013, upgrade bundle for both OD and ID corrosion. As compressor discharge temperature is 102 C, 254SMO (or super duplex) would be satisfactory for both seawater and process side corrosion.

  - **Long Term Mitigation**
    - By Dec 2019, perform visual inspection of tube bundle for tube end erosion and OD and ID pitting. If visual ID pitting found then perform EC testing to quantify depth. OD pitting to be externally visually inspected after cleaning. Note that if 254SMO is selected with unfiltered seawater, then more frequent inspections and shorter life is expected.
Example TARs
GG2 353-T-101B2-T02, 1st Stage After Cooler Bundle

• Results - Mitigated Risk of $6484/yr

<table>
<thead>
<tr>
<th>Probability of Failure</th>
<th>Consequence of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>COF &lt;= 10000</td>
</tr>
<tr>
<td>2</td>
<td>10000 &lt; COF &lt;= 100000</td>
</tr>
<tr>
<td>3</td>
<td>100000 &lt; COF &lt;= 1000000</td>
</tr>
<tr>
<td>4</td>
<td>1000000 &lt; COF &lt;= 1000000</td>
</tr>
<tr>
<td>5</td>
<td>COF &gt; 10000000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>POF (Failures/yr)</th>
<th>COF ($)</th>
<th>Risk ($/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9978</td>
<td>4.7E+4</td>
<td>4.6896E+4</td>
</tr>
</tbody>
</table>
• **353-T-110-HEST-SS, Seal Oil Cooler Bundle**
  
  - **Unmitigated Risk** - $2455/yr
  
  - **Background** - This S&T exchanger is used to cool the shellside seal oil using filtered seawater on the tubeside. CS shell with 316SS channel and 70/30 CuNi Bundle.
  
  - **Risk Driver** - There was little indication of plugging or issues in the histories but bundles (B1/B2) were replaced in 2007, no reason given. Calculated MTTF is 30 years.
• 353-T-110-HEST-SS, Seal Oil Cooler Bundle
  
  - Risk Driver (Con’t.) - The major threat to the 70/30 CuNi bundle is aerated seawater corrosion on the tubeside caused by either:
    
    ▪ A. Erosion/corrosion of tube ends due to high velocities or more likely plugging of tubes with marine debris,
    
    ▪ B. MIC pitting of the tubes due to poor biocide management of the seawater. There is little indication of plugging or issues in the histories for this or similar bundle with limited ID inspections.
• **353-T-110-HEST-SS, Seal Oil Cooler Bundle**
  
  - **Short Term Mitigation** – None

  - **Long Term Mitigation** - By Jan-2018 (half-life), perform visual inspection of tube bundle for tube end erosion and ID pitting. If visual ID pitting found then perform EC testing to quantify depth or hydrotect bundles to detect leaks. Seawater requires rigorous filtering to prevent marine debris plugging tubes and seawater biocide control to prevent MIC corrosion.
Example TARs
353-T-110-HEST-SS, Seal Oil Cooler Bundle

- Results - Mitigated Risk of $2595/yr

<table>
<thead>
<tr>
<th>Probability of Failure</th>
<th>Consequence of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>COF &lt;= 1000</td>
</tr>
<tr>
<td>2</td>
<td>10000 &lt; COF &lt;= 100000</td>
</tr>
<tr>
<td>3</td>
<td>100000 &lt; COF &lt;= 1000000</td>
</tr>
<tr>
<td>4</td>
<td>1000000 &lt; COF &lt;= 10000000</td>
</tr>
<tr>
<td>5</td>
<td>COF &gt; 10000000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>POF (Failures/yr)</th>
<th>COF ($)</th>
<th>Risk ($/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0522</td>
<td>4.7E+4</td>
<td>2455.2157</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>POF (Failures/yr)</th>
<th>COF ($)</th>
<th>Risk ($/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0552</td>
<td>4.7E+4</td>
<td>2595.2087</td>
</tr>
</tbody>
</table>
Major Findings

- Structured approach/work process was needed to get a handle on heat exchanger reliability issues
- Focus needed to be proactive, not reactive
- Application of risk-based approach with 15 year look-ahead seemed reasonable to meet 7 year turnaround cycle
- Final Risk Target used was $10,000/year, a $100,000/yr risk target was too high
Major Findings

- Seawater corrosion control program needed to be improved to minimize any pitting threat.
- IOWs (e.g. residual oxygen < 10 ppb, SO$_3$ of 1 - 2 ppm, residual chlorine) were specified with monthly monitoring and reporting.
- Glycol system pH needed to be controlled between 7.0 and 8.0 to minimize corrosion and scaling. Monitor pH monthly.
- Monitor lubes oil outlet temperature monthly to assess the presence of scales or marine growth in the tubes. If temperature exceeds 70 C, bypass the exchanger for cleaning.
Major Findings

• Ensure compliance to filtering, biocide control and scale inhibition requirements to minimize deposits and corrosively of the hot seawater. Periodic flushing cleaning of deposits as recommended by manufacturer.

• Buy spare exchangers / bundles depend of specific component recommendations

• Upgrade metallurgy depend of specific component recommendations.

• Revamp maintenance practice for plugging Ti tubes. Non Ti plugs will lead to galvanic corrosion and hydriding in seawater.

• Periodic bundle removal and cleaning specific to components
Conclusions

- Consider applying Risk Based principle programs to better focus mechanical integrity
- API 581 quantitative methods provide a proven structured and consistent approach across a wide range of equipment
- Thorough review of damage mechanisms by a corrosion engineer is critical to success of program
- Program needs to be Sustainable (kept alive)
  - can continue to look into the future with upkeep
  - Updating of Inspection from on-line and turnaround inspection activities
  - Addition or modifications of equipment and changes to business operations needs to be managed
Questions
Philip A. Henry
email: pahenry@equityeng.com

20600 Chagrin Blvd. • Suite 1200
Shaker Heights, OH 44122  USA
Phone: 216-283-9519 • Fax: 216-283-6022
www.equityeng.com