Implementation of Code Case N-838 for Flaw Tolerance Evaluation of CASS Piping
Introduction

- Background of thermal aging concerns for CASS piping
- Identifying components susceptible to aging
- Recent developments and ASME Code activities for aging management of susceptible CASS components
- How to fulfill License Renewal commitments and develop an aging management program for CASS piping using flaw tolerance methods
- How to take actions now for managing thermal aging concerns for CASS piping
Background

- CASS materials have been used in many RCS piping system components in PWRs
- Thermal aging is known to occur in CASS materials such that high delta ferrite materials have greater amounts of aging (i.e., reduction in toughness and increase in strength)
- The GALL Report, Rev. 2, (XI.M12) requires that all CASS piping components be screened and the aging effects of the “susceptible” components must be managed by either enhanced volumetric examination or plant- or component-specific flaw tolerance evaluation
- Since there are currently no qualified volumetric inspection techniques for CASS, a flaw tolerance evaluation is needed for those plants with license renewal commitments
Non-Uniform Grain Structure in CASS Materials

Highly non-uniform grain structure due to austenite and ferrite segregation
Which CASS Components are Susceptible per the GALL Report?

- Susceptibility to thermal aging of CASS components is determined from casting method, molybdenum (Mo) content, and ferrite content.
- For low Mo content (0.5 wt% max), only static-cast steels with >20% ferrite are susceptible to thermal embrittlement.
- For high Mo content (2.0 to 3.0 wt%) steels, static-cast steels with >14% ferrite and centrifugal-cast steels with >20% ferrite are potentially susceptible to thermal embrittlement.
- In the susceptibility screening method, ferrite content is calculated using the Hull’s equivalent factors*:
  \[
  \begin{align*}
  Cr_{eq} &= (Cr) + 1.21(Mo) + 0.48(Si) - 4.99 \\
  Ni_{eq} &= (Ni) + 0.11(Mn) - 0.0086(Mn)^2 + 18.4(N) + 24.5(C) + 2.77 \\
  \text{ferrite content} &= 100.3(Cr_{eq}/Ni_{eq})^2 - 170.72(Cr_{eq}/Ni_{eq}) + 74.22
  \end{align*}
  \]

  * Source: NUREG/CR-4513, Rev. 1
Piping and Components Made from CASS Materials in PWRs

- Cold Leg Piping (Westinghouse-designed plants)
- Hot Leg Piping (Westinghouse-designed plants)
- RCS Piping Components (Elbows and Safe Ends)
- Surge Line Piping (straight sections and elbows)
- Surge Line Nozzles
- Accumulator Injection Nozzles in the Cold Leg
- Other CASS Components (e.g., Reactor Coolant Pump Casings)
Flaw Tolerance Evaluation
What’s the Problem?

- CASS piping exhibits a wide range of material behavior, the worst of the aged material properties are for type CF-8M with high delta ferrite content.

- The traditional method of performing a deterministic fracture mechanics evaluation may not be adequate for these components:
  - Large scatter and variability in materials, in addition to the thermal aging effects, means that material properties are not well defined.
  - Prior to Code Case N-838, no Code approved method was available for evaluating flaws (or flaw tolerance) of CASS piping with high delta ferrite.
  - Assuming worst case loads, aged material properties and Code structural factors was too conservative for this application.

- Code-approved alternative method using a probabilistic fracture mechanics (PFM) approach is required for these components.
Sample EPFM Results (Deterministic)

Typical Cold Leg Pipe in a PWR

EPFM Solution for \( \sigma_m = 8 \text{ ksi} \) and \( \sigma_b = 10 \text{ ksi} \)

- Critical Flaw Sizes (S.F. = 1.0)
- Below the limits of detectability for current volumetric inspection techniques for CASS
- Maximum Allowable Flaw Size

\[
\begin{align*}
\text{Depth of Flaw, Fraction of Thickness (a/t)} & \quad \text{Length of Flaw, Fraction of Circumference (l/2\pi)} \\
0 & \quad 0 \\
0.2 & \quad 0.2 \\
0.4 & \quad 0.4 \\
0.6 & \quad 0.6 \\
0.8 & \quad 0.8 \\
1 & \quad 1
\end{align*}
\]

- 20% DFN (S\( \text{Fm=Sfb=1.0} \))
- 30% DFN (S\( \text{Fm=Sfb=1.0} \))
- 20% DFN (S\( \text{Fm=2.7, Sfb=2.3} \))
- 30% DFN (S\( \text{Fm=2.7, Sfb=2.3} \))

\( a \) = flaw depth, \( t \) = pipe thickness

S.F. = Code Structural Factor
Recent Developments for CASS Piping Aging Management

- ASME Section XI Code Case N-838 was developed for CASS piping flaw tolerance evaluation
- Under an EPRI-funded project, SI developed a flaw tolerance methodology for CASS piping using a probabilistic fracture mechanics approach to determine maximum tolerable flaw sizes
  - EPRI published this as Technical Basis Document (MRP-362) to be used in support for Code Case N-838
- Code Case N-838 is approved by Section XI Standards Committee in Feb 2015 and will be published in the next supplement of the Boiler and Pressure Vessel Code
- The Code Case method has already been used by a number of utilities to complete license renewal commitments for managing aging of CASS piping
Probabilistic Fracture Mechanics (PFM) Method for CASS Piping

- Define inputs
  - Loads
  - Pipe size
  - Material Composition/Delta Ferrite Content

- Employ distributions from CASSPAR software
  - Fracture toughness (J-R Curves)
  - Stress-strain curve
    - From experimental data and predictive models

- Software employs PFM method to evaluate distribution of critical crack depth (for a given surface length)

- Establish a safety goal
  - e.g., conditional probability < $1 \times 10^{-6}$ per reactor year
  - Failure criteria consistent with other safety issues
    - e.g., Pressurized Thermal Shock (10CFR50.61a)
CASSPAR PFM Analysis Method

**INPUT**
- Composition (delta ferrite)
- Distribution of J-K Curve ($J=\sigma \Delta \epsilon$)
- Stress-Strain Curves
- J-solution-tension-bending
- Service Loads, pipe size

**OUTPUT**
- Applied Value of J
- Critical Crack Sizes at Selected Probabilities
- Tearing Instability Analysis
## Proposed Failure Probability for Each Service Level Using PFM Method

<table>
<thead>
<tr>
<th>Service Level</th>
<th>Prob. of Occurrence</th>
<th>Conditional Failure Probability</th>
<th>Combined Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.0</td>
<td>$10^{-6}$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>B</td>
<td>~ 0.1</td>
<td>$10^{-5}$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>C</td>
<td>&lt; $10^{-2}$</td>
<td>$10^{-4}$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>D</td>
<td>&lt;&lt; $10^{-2}$</td>
<td>$10^{-4}$</td>
<td>$10^{-6}$</td>
</tr>
</tbody>
</table>
Step I of Flaw Tolerance Evaluation of CASS

Steps to generate inputs for the plant-specific evaluation:

1. Screening for susceptible CASS components
   a) Locations with delta ferrite content > 20%
   b) Postulate flaws at those locations

2. Determine stresses (for each service level)
   a) Axial stresses for postulated circumferential flaws
   b) Hoop stress for postulated axial flaws
Step II of Flaw Tolerance Evaluation of CASS

Allowable Flaw Size Determination:

1. Determine allowable flaw sizes as a function of the Stress Ratio
   a) \( (\sigma_m + \sigma_b + \sigma_e)/\sigma_f \) for axial stress
   b) \( (\sigma_h/\sigma_m) \) for hoop stress

2. Calculate allowable flaw depth vs. flaw length from tables in Code Case N-838 for different service levels
## Maximum Allowable Flaw Depth-to-Thickness, a/t, for Circumferential Flaws (Service Level A)

*Table reproduced from Code Case N-838*

<table>
<thead>
<tr>
<th>Stress Ratio</th>
<th>0.0</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>&gt; 0.75</th>
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<td>0.60</td>
<td>0.75</td>
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<td></td>
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<td></td>
<td></td>
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<tr>
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<td></td>
</tr>
<tr>
<td>0.50</td>
<td>0.75</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.45</td>
<td>0.75</td>
<td>0.30</td>
<td>0.27</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>0.40</td>
<td>0.75</td>
<td>0.43</td>
<td>0.35</td>
<td>0.32</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>0.35</td>
<td>0.75</td>
<td>0.67</td>
<td>0.49</td>
<td>0.44</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
<td>0.39</td>
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<td>0.60</td>
<td>0.54</td>
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<td>0.47</td>
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<td>0.61</td>
<td>0.58</td>
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<td>0.75</td>
<td>0.76</td>
<td>0.70</td>
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<td>0.75</td>
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<td>0.10</td>
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<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
</tr>
</tbody>
</table>
### Maximum Allowable Flaw Depth-to-Thickness, a/t, for Axial Flaws (Service Level A)

The following table reproduces data from Code Case N-838 for the maximum allowable flaw depth-to-thickness, $a/t$, for axial flaws (Service Level A). The table outlines the relationship between stress ratio and nondimensional flaw length, $a/(R_e t)^{0.3}$.

<table>
<thead>
<tr>
<th>Stress Ratio</th>
<th>0.0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
<th>1.2</th>
<th>1.4</th>
<th>1.6</th>
<th>1.8</th>
<th>2.0</th>
<th>2.2</th>
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<tr>
<td>1.20</td>
<td>0.75</td>
<td>0.59</td>
<td>0.28</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>1.15</td>
<td>0.75</td>
<td>0.61</td>
<td>0.46</td>
<td>0.32</td>
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</tr>
<tr>
<td>1.10</td>
<td>0.75</td>
<td>0.63</td>
<td>0.52</td>
<td>0.40</td>
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<td></td>
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<tr>
<td>1.05</td>
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<td>0.56</td>
<td>0.47</td>
<td>0.37</td>
<td>0.29</td>
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<td>1.00</td>
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<td>0.71</td>
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<td>0.45</td>
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<td>0.85</td>
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<td>0.50</td>
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<td>0.75</td>
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<td>0.74</td>
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<td>0.73</td>
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<tr>
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<td>0.75</td>
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<td>0.74</td>
</tr>
<tr>
<td>&lt; 0.40</td>
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<td>0.75</td>
<td>0.75</td>
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<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
</tr>
</tbody>
</table>

*CC N-838 does not apply in this region*
Step III of Flaw Tolerance Evaluation of CASS

Perform Fatigue Crack Growth evaluation:

1. Technical basis for assumptions given in MRP-362
   a) Hypothetical initial reference flaw depth = 25% thickness
   b) Flaw depth vs. length ratio = 1:6

2. Perform fatigue crack growth (FCG) calculation
   a) Using cyclic operating loads during operating period
   b) Calculate final depth of initial 1/4t reference flaw at the end of plant evaluation period

3. Compare FCG final crack size results to allowable flaw sizes
Example FCG Results

\[ a = \text{flaw depth} \]
\[ t = \text{pipe wall thickness} \]
Example PFM Analysis Results

<table>
<thead>
<tr>
<th>Component</th>
<th>Service Level</th>
<th>Probability of Failure</th>
<th>Allowable Flaw Size</th>
<th>Final Flaw Depth at End of Operating Period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Depth, a (inch)</td>
<td>a/t</td>
</tr>
<tr>
<td>Hot Leg</td>
<td>A</td>
<td>$10^{-5}$</td>
<td>1.35</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>$10^{-5}$</td>
<td>1.18</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>$10^{-4}$</td>
<td>0.95</td>
<td>0.38</td>
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<tr>
<td>Cold Leg</td>
<td>A</td>
<td>$10^{-6}$</td>
<td>2.61</td>
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<td></td>
<td>B</td>
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<td></td>
<td>D</td>
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<tr>
<td>Crossover Leg</td>
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<tr>
<td></td>
<td>B</td>
<td>$10^{-5}$</td>
<td>1.53</td>
<td>0.57</td>
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<tr>
<td></td>
<td>D</td>
<td>$10^{-4}$</td>
<td>0.78</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Values shown are from real plant data

Limiting case is service level D for this particular plant
Conclusions

- Identify License Renewal (LR) commitments and implementation dates for CASS piping aging management
- Start planning now to develop an Aging Management Program
- Make use of available industry resources, MRP-362 and Code Case N-838

⇒ Three plants have used this approach for RCS piping and three other plants for Surge Line piping to meet the LR commitments for managing thermal aging of CASS