Development of Target Flaw Sizes for CANDU Pressure Vessel Welds for use in Inspection Qualification

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Layout of Presentation

- Target Flaw Size (TFS) and Acceptance Flaw Size (AFS) in performance demonstration of NDE system and disposition of detected flaws
- Current TFS revisit. Rationales, scope and purpose of developing new TFS and AFS
- Development of new TFS and AFS
Background

- Inspection Specification (IS) defines inspection requirements
  - CSA N285.4
  - IS provides sufficient info for ISP to design, operate and qualify inspection system (technology, equipment, procedure and personnel)

- Target Flaw Sizes (TFS)
  - The size of a flaw (character, shape and dimension) used to qualify inspection system. Qualification requires demonstration of high accuracy in sizing and high probability of detecting of flaws ≥ TFS. Missed indications smaller than TAFS would not challenge the structural integrity of the component.

- Acceptance (Allowable) Flaw Size (AFS)
  - A screening criterion to separate inspected flaws to either Acceptable (fitness for service) or Un-acceptable (requires further analysis)
Comply with ENIQ Recommendations

- European Network for Inspection Qualification (ENIQ)
  - European Methodology for Qualification of Non-Destructive Testing (3rd issue), EUR 22906 EN, ISSN 1018-5593

- Inspection Qualification Input Information (ENIQ Sec. 4.2)
  - 3. types, dimensions, orientations, locations and morphologies of defects to be detected and/or sized, depending on the defect situation considered
  - Defects are determined from applicable codes and standards, or by metallurgy and fracture mechanics calculations

- TFS and AFS are defects obtained from upfront, preemptive fracture mechanics analysis
  - Follow Elastic-Plastic Fracture Mechanics method
  - Under bounding loading conditions and material properties
  - Current looking, unconditionally stable until next inspection
  - TFS are used for qualification, AFS are for screening
Target Flaw Size (TFS)

- To demonstrate performance of NDE process
- Smallest of all AFS, therefore unconditionally stable until next inspection
- Requires high confidence in detection and sizing by NDE
Table IWB-3510-1
Allowable Planar Flaws

Material: Ferritic steels that meet the requirements of NB-2331 and G-2110(b) of Section III

<table>
<thead>
<tr>
<th>Aspect Ratio, [Note (1)] a/t</th>
<th>Volumetric Examination Method, Nominal Wall Thickness, [Note (1)], [Note (2)] t, in. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2½ (65) and less</td>
</tr>
<tr>
<td></td>
<td>Surface Flaw, [Note (3)], [Note (4)]</td>
</tr>
<tr>
<td>0.0</td>
<td>3.1</td>
</tr>
<tr>
<td>0.05</td>
<td>3.3</td>
</tr>
<tr>
<td>0.10</td>
<td>3.6</td>
</tr>
<tr>
<td>0.15</td>
<td>4.1</td>
</tr>
<tr>
<td>0.20</td>
<td>4.7</td>
</tr>
<tr>
<td>0.25</td>
<td>5.5</td>
</tr>
<tr>
<td>0.30</td>
<td>6.4</td>
</tr>
<tr>
<td>0.35</td>
<td>7.4</td>
</tr>
<tr>
<td>0.40</td>
<td>8.3</td>
</tr>
<tr>
<td>0.45</td>
<td>8.5</td>
</tr>
<tr>
<td>0.50</td>
<td>8.7</td>
</tr>
</tbody>
</table>
ASME Code Section XI Table IWB-3510-1 or Table IWB-35120-1 Could be Potential TFS

**IWB-3512-1, Nozzle-to-Shell Welds**

<table>
<thead>
<tr>
<th>Aspect Ratio, $\frac{a}{t}$</th>
<th>Surface Flaw, [Note (1)] $a/t$, %</th>
<th>Subsurface Flaw, [Note (2)] $a/t$, %</th>
<th>Surface Flaw, [Note (2)] $a/t$, %</th>
<th>Subsurface Flaw, [Note (4)] $a/t$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>3.1</td>
<td>3.4$Y^{1.00}$</td>
<td>1.9</td>
<td>2.0</td>
</tr>
<tr>
<td>0.05</td>
<td>3.3</td>
<td>3.8$Y^{0.96}$</td>
<td>2.0</td>
<td>2.2</td>
</tr>
<tr>
<td>0.10</td>
<td>3.6</td>
<td>4.3$Y^{0.72}$</td>
<td>2.2</td>
<td>2.5$Y^{0.69}$</td>
</tr>
<tr>
<td>0.15</td>
<td>4.1</td>
<td>4.9$Y^{0.48}$</td>
<td>2.5</td>
<td>2.9$Y^{0.47}$</td>
</tr>
<tr>
<td>0.20</td>
<td>4.7</td>
<td>5.7$Y^{0.50}$</td>
<td>2.8</td>
<td>3.3$Y^{0.47}$</td>
</tr>
<tr>
<td>0.25</td>
<td>5.5</td>
<td>6.6$Y^{0.65}$</td>
<td>3.3</td>
<td>3.8$Y^{0.61}$</td>
</tr>
<tr>
<td>0.30</td>
<td>6.4</td>
<td>7.8$Y^{0.84}$</td>
<td>3.8</td>
<td>4.4$Y^{0.77}$</td>
</tr>
<tr>
<td>0.35</td>
<td>7.4</td>
<td>9.0$Y^{0.99}$</td>
<td>4.4</td>
<td>5.1$Y^{0.93}$</td>
</tr>
<tr>
<td>0.40</td>
<td>8.3</td>
<td>10.5$Y^{1.00}$</td>
<td>5.0</td>
<td>5.8$Y^{1.00}$</td>
</tr>
<tr>
<td>0.45</td>
<td>8.5</td>
<td>12.3$Y^{1.00}$</td>
<td>5.1</td>
<td>6.7$Y^{1.00}$</td>
</tr>
<tr>
<td>0.50</td>
<td>8.7</td>
<td>14.3$Y^{1.00}$</td>
<td>5.2</td>
<td>7.6$Y^{1.00}$</td>
</tr>
<tr>
<td>Inside corner region</td>
<td>2.5</td>
<td>Not applicable</td>
<td>2.5</td>
<td>Not applicable</td>
</tr>
</tbody>
</table>
Acceptance Flaw Sizes (AFS)

➢ To safeguard the structural integrity when flaws are left without repair until next inspection

➢ Obtained from Critical Flaw Sizes (CFS) by considering subcritical crack growth between two consecutive inspections

Continued service without repair, structural integrity will be maintained

For common components

For a group of components sharing similar characteristics

For a specific component

Flaw size

small

large

AFS for common components under all loading conditions; ASME Section XI IWB-3500 Tables

AFS for a group of components under all loading condition. New AFS

AFS for a specific component under a specified and known loading condition. Flaw disposition
Critical Flaw Sizes (CFS)

- From fracture mechanics calculations
  - Demarcation between stable (safe) and unstable (failure)
  - Forward looking, focus on next inspection
  - Margins factorized in calculations

- CFS and AFS
  - AFS are obtained from CFS by considering subcritical crack growth between two consecutive inspections
  - CFS is forward looking, AFS is current looking
  - AFS are dependent on inspection interval
TFS, AFS, CFS and Inspection Limit Size (ILS)

For a given pipe size with different flaw aspect ratios

TFS

AFS

CFS

small

large
CANDU Pressure Vessel Welds

- Shell-to-Shell and Nozzle-to-Shell welds of CANDU Pressure Vessels from owner survey
  - Nuclear Class, Full penetration, ferritic steel welds subject to PIP as per CAS285.0
- Vessel nominal wall thickness from 12.7 mm to 108 mm

<table>
<thead>
<tr>
<th>Component</th>
<th>Bruce A</th>
<th>Bruce B</th>
<th>Darlington</th>
<th>Pickering A</th>
<th>Pickering B</th>
<th>Pt Lepreau (CANDU 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressurizer</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Bleed Condenser</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>N/A</td>
</tr>
<tr>
<td>Degasser</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>✓</td>
</tr>
<tr>
<td>Maintenance</td>
<td>✓</td>
<td>✓</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Steam Generator</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Preheater</td>
<td>✓</td>
<td>✓</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Shutdown</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

1 Currently installed components (original, refurbished, or replaced)
Representative Basic Weld Configurations

- Defects are idealized as Surface Planar Flaws (ASME B&PV Code Section XI IWA-3310)
  - Having sharp edges, most dangerous flaws
- Flaw Aspect Ratio 1:6 (depth to length) as per ASME B&PV Code Section XI Appendix L

<table>
<thead>
<tr>
<th>Case #</th>
<th>Weld Configuration</th>
<th>Loading</th>
<th>Flaw Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>longitudinal seam welds in cylindrical shell</td>
<td>internal pressure</td>
<td>axial</td>
</tr>
<tr>
<td>2</td>
<td>cylindrical shell-to-spherical head girth welds</td>
<td>internal pressure</td>
<td>circumferential</td>
</tr>
<tr>
<td>3</td>
<td>flange-to-cylindrical shell welds of reinforced openings (e.g., manway)</td>
<td>internal pressure</td>
<td>circumferential</td>
</tr>
<tr>
<td>4</td>
<td>nozzle-to-cylindrical shell welds</td>
<td>internal pressure nozzle loads</td>
<td>circumferential</td>
</tr>
<tr>
<td>5</td>
<td>nozzle-to-spherical head welds</td>
<td>internal pressure nozzle loads</td>
<td>circumferential</td>
</tr>
</tbody>
</table>
Longitudinal Seam Welds in Cylindrical Shell

Internal pressure = 28 MPa

axial surface crack

uniform tension on x-y end face due to internal pressure = 133.33 MPa

3a

a

crack front

28 MPa

crack face pressure

Longitudinal Seam Welds in Cylindrical Shell
Cylindrical Shell-to-Spherical Head Girth Butt Welds

Internal pressure = 28 MPa

Y-displacement = 0 on x-z end face

Crack face pressure = 28 MPa

Crack front

 Inner surface

Page 14
Flange-to-Cylindrical Shell Welds of Reinforced Openings (e.g. Manway)
**Nozzle-to-Cylindrical Shell Welds**

- Uniform tension on x-y end face due to internal pressure
  - 109.271 MPa for Case D
  - 109.033 MPa for Case D2
- Internal pressure
  - 22.947 MPa for Case D
  - 22.897 MPa for Case D2
- y-displacement = 0 on x-z end face of nozzle for Case D (axial reaction due to internal pressure)
- z-displacement = 0 on x-y end face
- y-displacement = -5.0 mm on x-z end face of nozzle for Case D2

**Notation:**
- δa
- crack pressure
- crack front

**Ontario Power Generation**
Nozzle-to-Spherical Head Welds

Internal pressure = 27.354 MPa for Case E
19.791 MPa for Case E2

uniform tension on x-z end face of nozzle
63.797 MPa for Case E
144.705 MPa for Case E2

y-displacement = 0 on x-z bottom face

inner surface

6a

crack front
Highlights of Fracture Mechanics Analysis

- Fracture Tolerance Analysis to determine CFS
  - Elastic Plastic Fracture Mechanics method of J-integral ductile tearing (J-T)
  - Under largest design limit loads (ASME Section III Level D)
  - Finite element for J-integral, lower bound resistant curve

- Fatigue Crack Growth Analysis to determine AFS
  - Paris formulation (ASME Code Section XI Appendix A)
  - 12 year Inspection interval: given CFS, inverse calculate AFS, i.e. FCGA from initial size= AFS to final size= CFS
  - Under 200 full pressure cycles ($\Delta \sigma = 2\sigma_y$) and 2200 significant thermal transients ($\Delta \sigma = \sigma_y / 3$)

- TFS is smallest AFS
Results of $t=108$ mm, $R_i=1080$ mm

- J-R Curve A is for Charpy V-Notch (CVN) energy of 50 ft-lbs, Curve B is for CVN of 90 ft-lbs
- Lower bound tensile is for SA-350 Gr. LF1 at $350^\circ C$, for Pickering A bleed condenser nozzles
- Tensile properties of SA-516 Gr. 70 represents most vessel and nozzle materials
- Aspect ratio 1:6 (depth:length)
- Case A (axial flaw in longitudinal seam welds in cylindrical shell) result is bounding

<table>
<thead>
<tr>
<th>Case</th>
<th>Tensile Properties</th>
<th>J-R curve</th>
<th>Crack depth at failure (mm)</th>
<th>CFS (mm)</th>
<th>AFS (mm)</th>
<th>AFS/wall thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Lower Bound</td>
<td>A</td>
<td>4.570</td>
<td>3.341</td>
<td>2.961</td>
<td>0.027</td>
</tr>
<tr>
<td>A</td>
<td>SA-516 Gr. 70</td>
<td>B</td>
<td>9.720</td>
<td>6.758</td>
<td>4.740</td>
<td>0.044</td>
</tr>
<tr>
<td>B</td>
<td>Lower Bound</td>
<td>A</td>
<td>32.95</td>
<td>28.14</td>
<td>22.207</td>
<td>0.206</td>
</tr>
<tr>
<td>C</td>
<td>Lower Bound</td>
<td>A</td>
<td>50.56</td>
<td>44.89</td>
<td>36.142</td>
<td>0.335</td>
</tr>
</tbody>
</table>
Bounding Case A: Finite element J-integral Calculations Agrees With handbook

Comparison of J-integral calculations

- Case A (516 Gr 70), internal pressure=28 MPag
- Handbook (hoop stress= 295 Mpa)
- Handbook (hoop stress=280 MPa)
- Poly. (Case A (516 Gr 70), internal pressure=28 MPag)

Axial surface crack
R_i= 1080 mm
t= 108 mm

y = 0.0142x^3 - 0.3094x^2 + 26.822x - 12.409
R^2 = 0.9999
Bounding Case A: Nonlinear Dependence of J-Integral on Internal Pressure

- Small decrease in internal pressure (i.e. -4.97%) results in large decrease (about -22%) in J-integrals

![Graph showing the difference in J-integrals vs. axial crack depth.]

**Graph Details:**
- Axial surface crack
- Ri = 1080 mm
- t = 108 mm
- Under two pressures
  - p₁ = 28 MPag
  - p₂ = 26.61 MPag

**Equations:**
- Difference in pressure = \( \frac{p₂ - p₁}{p₁} = -4.96\% \)
- Difference in J-integrals = \( \frac{J₂ - J₁}{J₁} \)
Bounding Case A: Nonlinear Dependence of CFS on Internal Pressure

- Small decrease in internal pressure (i.e. -4.97%) results in large increase (5%-45%) in CFS
- Nonlinearity is more significant for large wall thickness

![Graph showing differences in crack depths vs. wall thickness with labels and data points]

Axial surface crack
$R_i/t = 10$
Under two pressures
$p_1 = 28 \text{ MPag}$
$p_2 = 26.61 \text{ MPag}$

ASME lower bound J-R curve
Handbook J-integral solution

Post tearing crack depth at failure
Critical crack depths
Comparison of J-R Curves

- The JR curve corresponds to CVN=90 ft-lbs is about 6% (at JR at about 300 kJ/m²) lower than ASME lower bound JR curve (ASME B&PV Code Section XI Appendix C-8321).
- A slightly increase of CNV value from 90 ft-lbs to 95 ft-lbs would equate the two JR values at or beyond 300 kJ/m².
Bounding Case A: Nonlinear Dependence of CFS on J-R Curves

- A small increase of JR curve would result in larger CFS, i.e. a 6% increase of JR curve would increase CFS by 15-20%.

![Graph showing differences in crack depths vs. wall thickness (mm). The graph includes two J-R curves: one for ASME lower bound and another for CVN = 90 ft-lbs at 662 °F. There is also a Handbook J-integral solution with critical crack depths highlighted.]

Axial surface crack
Ri/t = 10
p = 26.61 MPa

- Post tearing crack depth at failure
- Critical crack depths

Wall thickness (mm)
Bounding Case A: J-Integral at failure Barely Change with J-R Curves

- The post-tearing crack depth and J-integral at failure barely changes with the increase of JR curve.

![Graph showing J-integral at failure vs. wall thickness](image)

- Axial surface crack
- \( R_i/t = 10 \)
- \( p = 26.61 \) MPag

ASME lower bound J-R
Curve B of COG-JP-4431-V04R0

Handbook J-integral solution
Two J-R curves
1. ASME lower bound
2. CVN = 90 ft-lbs at 662 oF
Calculation of CFS as a Function of Wall Thickness

- Calculations are for Case A (axial flaw in longitudinal seam welds in cylindrical shell)
  - Results applicable to other cases of vessel/nozzle welds
- OD range [279.4, 2376.0] mm, thickness [12.7, 108] mm, ID axial flaw, flaw aspect ratio 1:6 (depth:length)
- EPFM method of J-T to calculate CFS
  - J-integral is from Ductile Fracture Handbook (EPRI NP-6301)
  - J-Resistance curve is ASME lower bound (ASME B&PV Code Section XI Appendix C-8321).
  - Internal pressure=26.61 MPa(g), hoop stress= 306.6 Mpa, 0.7*Su=280 MPa
Calculation of AFS and TFS as a Function of Wall Thickness

- AFS as calculated from CFS
- Fatigue Crack Growth Analysis
  - Paris formulation
  - Initial size = AFS, final size = CFS
  - Under cyclic Stress (hoop stress)
    1. 200 cycles, from -150 MPa to 150 MPa (-σ_y to σ_y)
    2. 2200 cycles, from -25 MPa to 25 MPa (-σ_y/6 to σ_y/6)
- TFS are equal to AFS (for a given aspect ratio of 6)
TFS as a Function of Vessel Wall Thickness (in mm)

Target Flaw Sizes for CANDU Ferritic Vessels/Nozzles

- Polynomial regression:
  \[ y = 7 \times 10^{-8}x^4 - 1 \times 10^{-6}x^3 - 0.0023x^2 + 0.2724x + 0.8571 \]
  \[ R^2 = 0.9931 \]
- Logarithmic regression:
  \[ y = 3.2025 \ln(x) - 3.9542 \]
  \[ R^2 = 0.977 \]

Target Flaw Length is 6 times of Target Flaw Depth

Conditions of Applicability
- Outer diameter: 279.4 mm (11") to 2376 mm (93.5")
- Wall thickness: 12.7 mm to 108 mm
- Inner radius over thickness ratio ≤ 10
TFS as a Function of Vessel Wall Thickness (in % of thickness)

**Target Flaw Sizes for CANDU Ferritic Vessels/Nozzles**

**Conditions of Applicability**
- Outer diameter: 279.4 mm (11") to 2376 mm (93.5")
- Wall thickness: 12.7 mm to 108 mm
- Innerradius over thickness ratio ≤ 10

\[ y = 6E-07x^4 - 0.0002x^3 + 0.0165x^2 - 0.9677x + 41.046 \]
\[ R^2 = 0.9916 \]

\[ y = -10.26\ln(x) + 57.779 \]
\[ R^2 = 0.9908 \]

Target Flaw Length is 6 times of Target Flaw Depth
Comparison of new TFS with Section XI Table IWB-3510-1 of ASME B&PV Code

Comparison of TFS with IWB-3510-1 Allowables

- Polynomial regression:
  \[ y = 7 \times 10^{-8}x^4 - 1 \times 10^{-6}x^3 - 0.0023x^2 + 0.2724x + 0.8571 \]
  \[ R^2 = 0.9931 \]

- Logarithmic regression:
  \[ y = 3.2025 \ln(x) - 3.9542 \]
  \[ R^2 = 0.977 \]

Flaw Length is 6 times of Flaw Depth

Target or IWB-3510-1 flaw Depth (mm)

Vessel wall thickness, \( t \) (mm)
Comparison of new TFS with Section XI Table IWB-3510-1 of ASME B&PV Code (cont’d)

Comparison of TFS with IWB-3510-1 Allowables

- Polynomial regression:
  \[ y = 6 \times 10^{-7}x^4 - 0.0002x^3 + 0.0165x^2 - 0.9677x + 41.046 \]
  \[ R^2 = 0.9916 \]

- Logarithmic regression:
  \[ y = -10.26\ln(x) + 57.779 \]
  \[ R^2 = 0.9908 \]

Flaw Length is 6 times of Flaw Depth

Target Flaw Sizes
- IWB-3510-1
- Polynomial regression
- Logarithmic regression

Vessel wall thickness, \( t \) (mm)

Target or IWB-3510-1 Flaw Depth (% \( t \))
Q&A and Discussion