MRP/BWRVIP
Evaluation of BTP 5-3

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Objectives of the MRP/BWRVIP Project

- Conduct survey regarding use of BTP 5-3 in PWR and BWR fleets
- Evaluate the BTP 5-3 procedures which had previously been identified as potentially non-conservative
  - B1.1(3)(a) and (b), B1.1(4), and B1.2
- Determine if application of BTP 5-3 B1.1(3) (a) and (b) for defining RPV pressure-temperature (P-T) limits provides adequate margins against RPV failure through 60 year license period (EOLE, End of License Extended)
- If needed, recommend alternative procedures to ensure that adequate margins against RPV failure are maintained through EOLE
A survey was conducted to understand which BTP 5-3 procedures have been used in the PWR and BWR fleets.

A database of transverse-longitudinal (T-L, or weak direction) and longitudinal-transverse (L-T, or strong direction) Charpy data and dropweight data was assembled.

By comparing the predictions of the BTP 5-3 procedures with measured data, the accuracy and uncertainties of the procedures were assessed.
Overview and Overall Conclusions of MRP/BWRVIP Project (2/2)

- Probabilistic fracture mechanics (PFM) analyses using FAVOR revealed that the BTP issue has negligible risk significance for vessel shell P-T curves, and therefore no change to application of B1.1(3) for development of P-T limits is recommended.

- Regression analyses of data relevant to the specific BTP 5-3 procedure used to determine Initial RT$_{NDT}$ of a PWR beltline plate showed the 10CFR50.61 PTS screening criteria is not exceeded during 60 year license.

- B1.2 guidance for conversion of USE(L-T) to USE(T-L) is reasonably conservative and adequate.

- Use of BTP 5-3 for PWR nozzles is addressed separately by the ongoing PWROG project to demonstrate beltline P-T curves bound nozzles (RIS 2014-11).
MRP/BWRVIP Survey Findings (1/2)

- Survey was successful in establishing trends regarding use of BTP 5-3
- Many source documents: Generic Letter 92-01 responses and related RAI responses; Reactor Vessel Integrity Database (RVID2) verification requests; FSARs; surveillance program documents
- Plants built to a Code edition earlier than Summer 1972 Addenda to ASME III 1971 were required to qualify materials using L-T Charpy specimens and all vessel components will have L-T data
- Supplemental testing of T-L specimens was often conducted to permit determination of Initial $RT_{NDT}$ per ASME III NB-2331
  - Supplemental testing was generally limited to the beltline materials
MRP/BWRVIP Survey Findings (2/2)

- Discrepancies noted between survey responses and RVID2
  - Several instances where RVID2 identifies use of BTP 5-3 even though plant had docketed information to the contrary in the 1990s
  - BTP 5-3 has been used for some materials not tagged as “MTEB 5-2” in RVID2

- Several plants identified T-L Charpy data in NSSS vendor archives not documented in RVID2

- Where BTP 5-3 was used to determine Initial RT_{NDT} for beltline shell plates and forgings, B1.1(3) (a) or (b) was used

- With a few exceptions, when T-L Charpy data is not available, BWRs have used the GE procedure (NEDC-32399P) for determination of Initial RT_{NDT} and BTP 5-3 for determination of Initial USE
  - Evaluation of the NRC-approved GE procedure was not in the scope of the MRP/ BWRVIP project
Evaluation of BTP 5-3 Procedures
Evaluation of BTP 5-3 B1.1(3)

- **BTP 5-3 B1.1(3):** "If transversely-oriented Charpy V-notch specimens were not tested, the temperature at which 68 J (50 ft-lbs) and 0.89 mm (35 mils) LE [lateral expansion] would have been obtained on transverse specimens may be estimated by one of the following criteria:
  - (a) Test results from longitudinally-oriented specimens reduced to 65% of their value to provide conservative estimates of values expected from transversely oriented specimens.
  - (b) Temperatures at which 68 J (50 ft-lbs) and 0.89 mm (35 mils) LE were obtained on longitudinally-oriented specimens increased 11°C (20°F) to provide a conservative estimate of the temperature that would have been necessary to obtain the same values on transversely-oriented specimens.”

- **Sources of data (CVN data for T-L and L-T orientations)**
  - Reactor Embrittlement Archive Project (REAP) database of surveillance materials
  - EPRI NP-933, *Nuclear Pressure Vessel Steel Data Base*, industry tests of over 50 heats of RPV steels in the late 1970s
  - Industry data supplied during the survey process
  - Literature survey results
Analysis of BTP 5-3 B1.1(3) – SA533B-1 Plates

(a) and (b) Combined

B1.1(3) exhibits characteristics of a mean relationship.
Two different populations of data

Preliminary evaluation suggests populations may be differentiated by L-T orientation upper shelf energy (USE)

- Black (SA508-2 material) and blue (SA508-3 material) data are for USE ≥ 140 ft-lb
  - These exhibit similar relationship as plates and can be grouped with the plates
- Red (SA508-2 material) data are for USE < 140 ft-lb and exhibit different relationship
Preliminary Results for BTP 5-3 B1.1(3)

- All plates, and SA508-2 and SA508-3 forgings with USE ≥ 140 ft-lb: standard error about the BTP 5-3 B1.1(3) method was determined and used in PFM analyses as an effective $\sigma_i$ term for probabilistic analyses; $\sigma_i = 19.9^\circ F$
  - Regression analyses of B1.1(3)(a) and (b) individually were also conducted for use in refined analyses

- SA508-2 forgings with USE < 140 ft-lb (no figure): standard error about the BTP 5-3 B1.1(3) method was determined and used in PFM analyses as an effective $\sigma_i$ term for probabilistic analyses; $\sigma_i = 40.7^\circ F$
Evaluation of BTP 5-3 B1.1(4)

- **BTP 5-3 B1.1(4):** “If limited Charpy V-notch tests were performed at a single temperature to confirm that at least 41 J (30 ft-lbs) was obtained, that temperature may be used as an estimate of the RT_{NDT} provided that at least 61 J (45 ft-lbs) was obtained if the specimens were longitudinally oriented. If the minimum value obtained was less than 61 J (45 ft-lbs), the RT_{NDT} may be estimated as 11°C (20°F) above the test temperature.”

- **Sources of data (RT_{NDT} and L-T Charpy data)**
  - EPRI NP-933 database of over 50 heats of RPV steels developed by industry in the late 1970s (plates, forgings and welds)
  - Industry data from AREVA study of SA508-2 forgings
  - Industry data on SA533B-1 plate material from survey
  - REAP database does not contain RT_{NDT} values
Preliminary Results for BTP 5-3 B1.1(4)

- **Plates**: The criteria of achieving at least 45 ft-lb at 10°F is not meaningful; assessment of RT\textsubscript{NDT} data shown at right
  - 95% confidence level for RT\textsubscript{NDT} for plates is 40°F

- **Forgings**: Similar to plate evaluation, RT\textsubscript{NDT} best estimate at 90-95% probability level is 50°F regardless of measured L-T values

- **Welds**: BTP 5-3 B1.1(4) is conservative for all manual metal arc and submerged arc welds evaluated from EPRI NP-933
Evaluation of BTP 5-3 B1.2

- **BTP 5-3 B1.2**: "...Reactor vessel beltline materials must have Charpy upper shelf energy, in the transverse direction for base material and along the weld for weld material according to the ASME Code, of no less than 102 J (75 ft-lbs) initially and must maintain Charpy upper shelf energy throughout the life of the vessel of no less than 68 J (50 ft-lbs). If tests were only made on longitudinal specimens, the upper shelf energy values should be reduced to 65% of the longitudinal values to estimate the transverse properties."

- **Sources of data (T-L and L-T Charpy data)**
  - REAP database of surveillance materials
  - EPRI NP-933 database of over 50 heats of RPV steels developed by industry in the late 1970s
  - Industry data supplied during the survey process
  - Literature survey results including large dataset (Smith and Ayres, 1973) evaluated using simulation process
Preliminary Results for BTP 5-3 B1.2

- Figure compares L-T USE to T-L USE for materials that have both directions measured
  - Blue line represents B1.2
- Current guidance in B1.2 is adequate; 86% of data conservatively estimated, consistent with multiple historical evaluations
- NRC previously evaluated this guidance
  - Found 85% conservatively estimated and concluded “…this information supports the continued use of the “multiplier” approach suggested in MTEB 5-2.”
Assessment of Potential Impact on RPV Integrity
RPV Integrity Assessment Objectives and Methods

- Assess the effect of uncertainty in Initial RT\textsubscript{NDT} (RT\textsubscript{NDT(u)}) estimated from BTP 1.1(3) (a) & (b) on Appendix G P-T Limit curves, RT\textsubscript{PTS} (10CFR50.61) and Conditional Probability of Failure (CPF)

- Determine if BTP 5-3 and its application to Appendix G P-T limit curves should be revised to include the uncertainty in RT\textsubscript{NDT(u)}

- The necessity for revising BTP 5-3 and its application to the Appendix G P-T limits is assessed by using CPF and the change in CPF (\Delta CPF) for RPV cooldown along P-T limit curves with and without the uncertainty in the estimated RT\textsubscript{NDT(u)}

- CPF and \Delta CPF are determined by comparing current BTP application practice ($\sigma_i = 0^\circ F$) using two different methods:
  - Mean RT\textsubscript{NDT(u)} and standard error for RT\textsubscript{NDT(u)} estimated (1) for the BTP guidelines and (2) from data regression analysis
RPV Integrity Assessment

- **PWR Plate Example**
  - RPV wall thickness = 8.6-inch, R/t = 10
  - Mean $RT_{NDT(u)} = BTP$ estimate; $\sigma_i = 0^\circ F$; EOLE ART = 237 $^\circ F$
  - Mean $RT_{NDT(u)} = BTP$ estimate; $\sigma_i = 19.9^\circ F$; EOLE ART = 256 $^\circ F$
  - Mean $RT_{NDT(u)} = data regression estimate; \sigma_i = 15.1^\circ F$; EOLE ART = 243 $^\circ F$

- **LUS Forging Example**
  - Low Upper Shelf (LUS) is defined as < 140 ft-lb in L-T direction
  - RPV wall thickness = 7.75-inch, R/t = 10
  - Mean $RT_{NDT(u)} = BTP$ estimate; $\sigma_i = 0^\circ F$; EOLE ART = 132 $^\circ F$
  - Mean $RT_{NDT(u)} = BTP$ estimate; $\sigma_i = 40.7^\circ F$; EOLE ART = 186 $^\circ F$
  - Mean $RT_{NDT(u)} = data regression estimate; \sigma_i = 32.7^\circ F$; EOLE ART = 184$^\circ F$

- **Postulated circumferential inside surface flaw with depth = 3% wall thickness**
Correlation Lines and Predicted $RT_{NDT(u)}$ for PWR Plate

Initial $RT_{NDT} = \text{Actual Transverse CVN 50 ft-lb Temperature} - 60, ^\circ F$

- $\text{Actual} = \text{Estimated}; \ 1.1(3) \ (a) \ & \ (b); \ \sigma_i = 0^\circ F \ or \ 19.9^\circ F$
- Regression Mean $RT_{NDT(u)}$ for $1.1(3)(b); \ \sigma_i = 15.1^\circ F$
- $\text{IS-P1; Regression mean} = 24^\circ F$
- $\text{IS-P2 \ & \ IS-P3; Regression Mean} = 15.7^\circ F$
- $\text{LS-P4; Regression mean} = 15.1^\circ F$
- $\text{LS-P5; Regression mean} = -10.3^\circ F$

Initial $RT_{NDT} = \text{Estimated Transverse CVN 50 ft-lb Temperature} - 60, ^\circ F$
Appendix G P/T Limit Curves for Estimated $RT_{NDT(u)}$ and $\sigma_i$ for PWR Plate

The P/T Limit Curves are input into the FAVOR software for the PFM CPF and $\Delta$CPF analyses.
The insignificant difference in CPF shows there is negligible safety benefit to changing BTP B1.1(3) or its application.
### RT<sub>PTS</sub> Evaluation for PWR Beltline Plate

<table>
<thead>
<tr>
<th>Variable, °F</th>
<th>Plate: thickness = 8.62-inch, R/t = 10</th>
<th>Mean RT&lt;sub&gt;NDT&lt;/sub&gt; = BTP 1.1(3)</th>
<th>Mean RT&lt;sub&gt;NDT&lt;/sub&gt; = Data regression at BTP 1.1(3)(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemistry Factor, CF</td>
<td>176</td>
<td>176</td>
<td>176</td>
</tr>
<tr>
<td>EOLE ∆RT&lt;sub&gt;NDT&lt;/sub&gt; @ CBMI</td>
<td>204.6</td>
<td>204.6</td>
<td>204.6</td>
</tr>
<tr>
<td>Initial RT&lt;sub&gt;NDT&lt;/sub&gt;</td>
<td>21</td>
<td>21</td>
<td>15.7</td>
</tr>
<tr>
<td>σ&lt;sub&gt;i&lt;/sub&gt;</td>
<td>0</td>
<td>19.9</td>
<td>15.1</td>
</tr>
<tr>
<td>σ&lt;sub&gt;Δ&lt;/sub&gt;</td>
<td>17.0</td>
<td>17.0</td>
<td>17.0</td>
</tr>
<tr>
<td>Margin</td>
<td>34.0</td>
<td>52.3</td>
<td>45.5</td>
</tr>
<tr>
<td>EOLE RT&lt;sub&gt;PTS&lt;/sub&gt;</td>
<td>260</td>
<td>278</td>
<td>266</td>
</tr>
</tbody>
</table>

→ The RT<sub>PTS</sub> calculated from the mean RT<sub>NDT</sub> and associated σ<sub>i</sub> obtained from regression analysis of data specific to BTP B1.1(3)(b) shows this beltline plate does not exceed PTS screening criteria of 10CFR50.61 through EOLE.
Correlation Lines and Predicted $RT_{NDT(u)}$ for LUS Beltline Forging (<140 ft-lb L-T)

$RT_{NDT} = \text{Actual Transverse CVN 50 ft-lb Temperature} - 60, \ ^\circ F$

$RT_{NDT} = \text{Estimated Transverse CVN 50 ft-lb Temperature} - 60, \ ^\circ F$

- Actual = Estimated; 1.1(3)(a)&(b); $\sigma_i = 40.7 ^\circ F$
- Regression Mean $RT_{NDT}$ for 1.1(3)(a); $\sigma_i = 32.7 ^\circ F$
- IS; Regression mean = 47.2 $^\circ F$
- LS; Regression mean = 42.2 $^\circ F$

RPV beltline LUS Forging
Appendix G P-T Limit Curves for Estimated $RT_{NDT(u)}$ and $\sigma_i$ for LUS Forging

RPV beltline - Ring forgings with LUS toughness
Wall thickness = 7.75-inch
R/t = 10
50°F/hr cooldown from 540°F to 60°F

The P/T Limit Curves are input into the FAVOR software for the PFM CPF and $\Delta$CPF analyses

Circ weld: $RT_{NDT(u)} = -53.5^\circ F; \ \sigma_i = 12.8^\circ F; \ \text{Margin} = 61.6^\circ F; \ \text{ART} = 232^\circ F$

$RT_{NDT(u)} = 30^\circ F; \ \sigma = 0^\circ F; \ \text{Margin} = 34^\circ F; \ \text{ART} = 132^\circ F$

$RT_{NDT(u)} = 30^\circ F; \ \sigma = 40.7^\circ F; \ \text{Margin} = 88.2^\circ F; \ \text{ART} = 186^\circ F$

$RT_{NDT(u)} = 42.2^\circ F; \ \sigma = 32.7^\circ F; \ \text{Margin} = 73.7^\circ F; \ \text{ART} = 184^\circ F$
## CPF and ∆CPF Evaluation Summary for the RPV LUS Beltline Ring Forging

<table>
<thead>
<tr>
<th>Variable</th>
<th>Current EOLE Appendix G P-T Curve</th>
<th>Alternate EOLE Appendix G P-T Curve</th>
<th>Current EOLE Appendix G P-T Curve</th>
<th>Alternate EOLE Appendix G P-T Curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Initial RT&lt;sub&gt;NDT&lt;/sub&gt; = BTP 1.1(3) estimate = 30°F, σ&lt;sub&gt;i&lt;/sub&gt; = 40.7°F</td>
<td>Mean Initial RT&lt;sub&gt;NDT&lt;/sub&gt; = Data regression estimate of BTP 1.1(3)(a) = 42.2°F, σ&lt;sub&gt;i&lt;/sub&gt; = 32.7°F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CF, °F</td>
<td>51</td>
<td>51</td>
<td>51</td>
<td>51</td>
</tr>
<tr>
<td>EOLE ΔRT&lt;sub&gt;NDT&lt;/sub&gt; @ t/4, °F</td>
<td>68</td>
<td>68</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>Initial RT&lt;sub&gt;NDT&lt;/sub&gt;, °F</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>42.2</td>
</tr>
<tr>
<td>σ&lt;sub&gt;i&lt;/sub&gt;, °F</td>
<td>0</td>
<td>40.7</td>
<td>0</td>
<td>32.7</td>
</tr>
<tr>
<td>σ&lt;sub&gt;Δ&lt;/sub&gt;, °°F</td>
<td>17</td>
<td>17</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Margin, °F</td>
<td>34</td>
<td>88.2</td>
<td>34</td>
<td>73.7</td>
</tr>
<tr>
<td>ART, P-T limit curve, °F</td>
<td>132</td>
<td>186</td>
<td>132</td>
<td>184</td>
</tr>
<tr>
<td>CPF, EOLE P-T Limit</td>
<td>1.332E-08</td>
<td>2.620E-09</td>
<td>1.330E-08</td>
<td>2.740E-09</td>
</tr>
<tr>
<td>ΔCPF, EOLE P-T Limit</td>
<td>1.07E-08</td>
<td></td>
<td>1.06E-08</td>
<td></td>
</tr>
</tbody>
</table>

→ The insignificant difference in CPF shows there is negligible safety benefit to changing BTP B1.1(3) or its application to LUS forgings
Preliminary Conclusions & Report Schedule
Preliminary Conclusions (1/2)

- Evaluations of the fracture toughness estimation methods provided by BTP 5-3 B1.1(3)(a) and (b), B1.1(4), and B1.2 have been performed.
- Evaluations were based on an enhanced material properties database gathered from the literature and plant material test programs.
- BTP 5-3 B1.2
  - B1.2 guidance for conversion of $\text{USE}_{(L-T)}$ to $\text{USE}_{(T-L)}$ is reasonably conservative and adequate.
    - Consistent with previous (1990) NRC evaluation of B1.2
- BTP 5-3 B1.1(4)
  - B1.1(4) is acceptable for weldments.
  - No use of B1.1(4) for vessel shell plates or forgings was identified; therefore, risk evaluations of potential non-conservatism of B1.1(4) for those product forms were not conducted.
Preliminary Conclusions (2/2)

- **BTP 5-3 B1.1(3)**
  - Plant survey showed that all PWRs that use BTP 5-3 for beltline shell materials use B1.1(3)
  - Appendix G P-T limits, accounting for the uncertainty in the mean fit provided by B1.1(3), were evaluated using FAVOR

- **Based on these evaluations, there is negligible safety benefit to changing BTP 5-3 B1.1(3) or its application**
  - Industry evaluation concludes that BTP 5-3 B1.1(3) is acceptable for continued use as-is
### Summary by Vessel Component of Preliminary Conclusions Regarding BTP 5-3 Procedures for Estimating Initial $RT_{NDT}$

<table>
<thead>
<tr>
<th>Vessel Component</th>
<th>BTP 5-3 Procedure for $IRT_{NDT}$</th>
<th>Used?</th>
<th>P-T Curves</th>
<th>PTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beltline Shell Plates</td>
<td>B1.1(3)(a) or (b)</td>
<td>Yes</td>
<td>PFM analyses using FAVOR show negligible safety benefit from revision of P-T limit curves; no change to B1.1(3) or its application is recommended.</td>
<td>For a high ART beltline plate, regression analyses and associated $\sigma$ specific to B1.1(3)(b) shows PTS limit is not exceeded through EOLE</td>
</tr>
<tr>
<td></td>
<td>B1.1(4)</td>
<td>Note 1</td>
<td>N/A – no use identified</td>
<td>N/A – no use identified</td>
</tr>
<tr>
<td>Forged beltline rings</td>
<td>B1.1(3)(a) or (b)</td>
<td>Yes</td>
<td>PFM analyses using FAVOR show negligible safety benefit from revision of P-T limit curves; no change to B1.1(3) or its application is recommended.</td>
<td>No beltline ring forging exceeds PTS screening criteria through EOLE</td>
</tr>
<tr>
<td></td>
<td>B1.1(4)</td>
<td>Note 1</td>
<td>N/A – no use identified</td>
<td>N/A – no use identified</td>
</tr>
<tr>
<td>Forged nozzles</td>
<td>B1.1(3)(a) or (b)</td>
<td>Yes</td>
<td>PWR issue to be addressed by PWROG study of Appendix G margins for nozzles that alleviates need to use BTP 5-3.</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>B1.1(4)</td>
<td>Yes</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Note 1:** No use identified.
Project Status and Schedule

- Draft report MRP-401/BWRVIP-287 was issued to MRP, BWRVIP, PWROG in December 2014
  - Review comments have been received and are being addressed
- Target completion date for final report: June 2015
- BWRVIP & MRP are considering a study by GEH to evaluate the “GE procedure” for determination of Initial RT\textsubscript{NDT}
  - In December 1994 safety evaluation, NRC previously concluded that the GE RT\textsubscript{NDT} estimation method is an acceptable alternative for determining initial RT\textsubscript{NDT} values
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