Demonstrate Appendix G Margins for PWR RPV Nozzles

PA-MSC-1091R1
Methodology & Progress

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Materials Center of Excellence
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Background

- Multiple RAs have been issued to various licensees with regards to consideration of the reactor vessel nozzle corner in P/T curves.
- Responding to RAs has been costly for utilities.
- RIS 2014-11 states:
  - "All addressees should ensure that P-T limits sufficiently address all ferritic materials of the reactor vessel, including the impact of structural discontinuities, and address the impact of neutron fluence accumulation in accordance with the requirements of 10 CFR Part 50, Appendix G."
- Recent traditional approach uses very conservative 1/4T nozzle flaw.
  - All nozzle P-T curve RAI responses to date have shown that existing plant P/T curves bound the nozzle curves.
RPV Nozzles

Purpose

• Project
  – Identify the magnitude of the various ASME Appendix G margins related to assessment of the PWR inlet/outlet nozzles
  – Develop a basis for generically addressing nozzles supporting P-T curve submittals
  – Justify the use of the RPV beltline region as the limiting region to be used for P-T curves thereby demonstrating that current approved methodologies comply with Appendix G

• Presentation
  – Make NRC aware of the approach being used to achieve project purpose
Approach

• Document the following conservatisms for the PWR inlet/outlet nozzles
  – Establish acceptable smaller postulated flaws
  – Generic near surface alternate RT\textsubscript{NDT} (RTT\textsubscript{0})
    – Previously approved Code Case N-629
      » Now incorporated into Appendices A and G
    – Avoids BTP 5-3 uncertainties
  – Constraint condition
PWR Exams

RPV Nozzles

- RG 1.150 stimulated significant improvements in exams of the clad to base metal region.
- These same techniques have been used since at least 1989 industry-wide for nozzle inner radius and beltline exams.
- No changes in those techniques were made to complete successful PDI qualifications.
- No individual, even if he failed the overall test, has failed to find cracks larger than 0.25 inch in the PDI.
  - Bamford, Bishop, Stevens, Becker and Ranganath, “Technical Basis for Elimination of RV Nozzle Inner Radius Inspections,” ASME PVP, 2001
- Over 2000 reactor years of PWR service, in the USA have been experienced.
- ASME Code Case N-648-1, which replaces volumetric NDE with visual, has been approved by ASME and NRC.
PWR Exams (Continued)

• Exams done using Appendix VIII technology have been completed on every operating PWR, per the requirements of Section XI.
• Total exams using Appendix VIII technology in USA (as of fall 2000):
  
    Westinghouse: 210  
    IHI Southwest: 196  
    AREVA: 148  
    TOTAL: 554  

(The total exceeds 615 at the end of 2014)
• No ID indications have been found to date.
Probability of Correct Rejection

Postulated Flaws

- It is not necessary to postulate large flaws
  - Small flaws are detectable with high probability
  - No indications have been found in over 2000 reactor years in nozzle ID exams
  - ASME Section XI Appendix G allows use of smaller postulated flaws in regions of discontinuity
Generic RTT<sub>0</sub>

- Most US PWR Nozzles are SA-508 Class 2 or ASTM A-508 Class 2
- Master Curve RTT<sub>0</sub>
  - Previous work shows significant margin between RTT<sub>0</sub> and RT<sub>NDT</sub> in most cases
  - True measure of fracture toughness transition temperature
  - Accepted via ASME CC N-629 via RG 1.147R13 (Now in Appendix G)
  - RT<sub>NDT</sub> not always well characterized

- Kirk, PVP2014-28540
- NUREG-1807, 2006
Generic RTT₀

- Most US PWR Inlet/Outlet Nozzles are A-508 Class 2
- Master Curve reference temperature data gathered on the following equivalent grades:
  - SA-508 Class 2 (also ASTM A-508 Class 2)
  - 22NiMoCr37 which is a DIN comparable
  - SFVQ2A which is Japanese equivalent
- Data collected from
  - Open Literature
  - Special Technical meetings
  - EPRI database
  - Westinghouse documents
- Only valid specimen geometry/data per ASTM E1921, “Test Method for the Determination of Reference Temperature, \( T_o \), for Ferritic Steels in the Transition Range”
  - Cited by ASME Section XI Appendix G-2110 (formerly Code Case N-629)
Generic RTT₀

- 22 heats found
  - Forgings are in most cases the same as were used in commercial PWR or BWRs
  - In all cases the heats selected are representative
    - Japanese RPVs,
    - Swedish RPVs,
    - German first through fourth generation RPVs
    - U.S. older RPVs
  - The references were checked to ensure no duplication (each is a different forging heat)
- Most are T-L orientation (weak direction) and removed from 1/4T location
- Conservative values used:
  - Some irradiated data
  - T-L orientation (weak direction)
  - Precrack Charpy (PCC) size specimens increased by 10°C (18°F) to compensate for low constraint bias (per ASTM E1921)

<table>
<thead>
<tr>
<th>Material Identity</th>
<th>Specification</th>
<th>Geometry</th>
<th>T₀ (°C) PCC adjusted</th>
<th>Thickness Location</th>
<th>Orientation</th>
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Near Surface Toughness

- Small flaw enables use of near surface toughness data
  - Surface properties are better due to faster cooling rate during quenching
    - Produces a finer microstructure, smaller carbide phases, reduced length of linear phase boundaries, and some tempered martensite
    - Results in better Charpy properties and fracture toughness
  - Fortunately for the high $T_0$ values found in the German nozzle forging ring, near surface measurements were made
    - $T_0$ at the postulated flaw depth is used
Near Surface Toughness

RPV Nozzles

Graphs showing impact energy vs. temperature for different locations on the reactor vessel (ID surface, 1/4T, OD surface, 3/4T) at various temperatures (in °F).
Near Surface Toughness

RPV Nozzles

BWR Nozzle

16MND5
Near Surface Toughness

- Data mostly confined to A-508 Class 2
  - Other product forms show same trend
- 12 forgings with 14 surface or near surface transition temperature measurements were found
  - $T_0$ or CVN 30ft-lb transition temperature
  - Mostly T-L (weak) orientation data
  - Ranged from 14°C (25°F) to 45°C (81°F) improvement relative to 1/4T
  - 14°C (25°F) Minimum
  - 29°C (52°F) Average

![Graph showing near surface toughness data](image-url)
RTT\textsubscript{0} at Surface

- Combine
  - Surface master curve T\textsubscript{0} measurements where available
  - Benefit 14\degree C (25\degree F) where only 1/4T T\textsubscript{0} data available
- Yields alternate generic mean A-508 Class 2 (RT\textsubscript{NDT})
  - RTT\textsubscript{0} significantly lower than a generic RT\textsubscript{NDT}
  - $\sigma$ = standard deviation

<table>
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<th>Specification</th>
<th>T\textsubscript{0} (C) PCC &amp; Surface corrected</th>
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<td>BMWi</td>
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</table>
Nozzle Corner Embrittlement

- RIS 2014-11 “all ferritic components within the entire reactor vessel must be considered in the development of P-T limits, and the effects of neutron radiation must be considered for any locations that are predicted to experience a neutron fluence exposure greater than $1 \times 10^{17}$ n/cm$^2$ ($E > 1$ MeV) at the end of the licensed operating period.”

- Maximum fluence projected near nozzle inside corner surface $\sim 1.5 \times 10^{17}$ n/cm$^2$ at 60 years for some plants
  - Cu = 0.18% and Ni = 0.91% (Upper bound values per ORNL/TM-2006/530)
Stress Intensity Factor Calculation

• Through wall time history stresses
  – Inlet & Outlet nozzle corner cuts
  – W - 2, 3, 4 loops, B&W & CE design
  – Primary (pressure) & Secondary (cooldown transient) stresses
Stress Intensity Factor Calculation

- Stress intensity factor based on ORNL/TM-2010/246, Rev. 1
  - Magnification factor equation for a 1/4T flaw at deepest point
  - Conservative for postulated smaller flaw
    - 0.1T
    - Nozzle corner flaw: 6:1 and 2:1

![Stress Intensity Factor (K) Along the Crack Front for 1,000 psig Pressure Loading for the PWR Inlet Nozzle](chart.png)
Limiting ART

- Back calculate allowable ART from P-T curve using allowable pressure near room temperature where nozzle curve would intersect beltline P-T curve
  - Example: ART = 55°F
Constraint

- Negative T-stress reduces the triaxialicity of the stress state along the crack front. This loss of constraint leads to a reduction of the crack opening stress and, as a result, to a reduction of the failure probability.
  - T-stress is the second order term in the crack front stress field equation
- Several papers show significant increase in toughness at nozzle due to loss of constraint
  - Siegele, et.al., PVP2010-25615, *Integrity Assessment of a German PWR RPV Considering Loss of Constraint*
  - Generic semielliptical corner crack increased toughness
Summary of Approach

- Small postulated flaw
  - Basis and precedent set with Code Case N-648-1 and BWRVIP-108
- Generic near surface alternate $RT_{NDT}$ ($RTT_0$)
  - Conservative values used
  - Code Case N-629 (ASME XI Appendix G)
  - Avoids BTP 5-3 uncertainties
- Conservative fluence and chemistry to account for embrittlement
- Standard SIF solution
- Published constraint papers show additional conservatism
The Materials Committee is established to provide a forum for the identification and resolution of materials issues including their development, modification and implementation to enhance the safe, efficient operation of PWR plants.
BTP 5-3 Focus Group
Conclusions / Summary

-Tim Wells, Focus Group Chair
Summary of Preliminary Results and Conclusions

- MRP/BWRVIP study concludes that the BTP 5-3 procedures that have been used for P-T curves, PTS evaluations, and Upper Shelf Energy evaluations are acceptable for continued use without revision.
- Using a separate technical approach, the PWROG MOTA study also shows BTP 5-3 is acceptable for continued use without revision.
- The PWROG technical approach for demonstrating Appendix G margins for PWR nozzles will address both RIS 2014-11 and the impact of BTP 5-3 for nozzles.