Potential Non-Conservatism in EPRI Report, BWRVIP-100, Rev. 1-A, and EPRI Software, BWRVIP-235

(CLOSED SESSION)

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Agenda (Closed Session)

- Background
- Project Objectives
- Reevaluation of Fracture Toughness Data – Preliminary Conclusions
- Evaluation Procedure in BWRVIP-100, Rev. 1-A
- Discussion of Relevant Data and Results
- Actions Taken by EPRI/BWRVIP to Address Part 21 TOI
- BWR Fleet Impact for the Part 21 TOI
- Summary
- List of Data Sources Used in this Project

Background (1 of 3)

- BWRVIP-100, Rev. 1-A contains fracture toughness (FT) vs. fluence criteria for evaluation of flaws in irradiated stainless steel core shroud materials (not prepared under EPRI's 10 CFR Appendix B nuclear quality assurance (NQA) program)
- BWRVIP-235 is a structural analysis software code for evaluating flaws in BWR internals (prepared under EPRI's NQA)
  - The code incorporates the methodologies specified in BWRVIP-100 for the evaluation of flaws in irradiated core shroud materials

Background (2 of 3)

- The NRC Safety Evaluation (April 12, 2016) for BWRVIP-100, Rev. 1 contained a number of recommendations regarding future testing
  - Develop an estimate of the initial as-welded toughness of core shroud welds
  - Seek additional stainless steel weld and HAZ materials to better characterize their toughness affected by irradiation and thermal aging
  - The ferrite content should be characterized
  - Revise the fracture toughness correlation as appropriate based on results of testing additional specimens (exposed in operating BWRs, test reactor or PWRs), or should ensure that measured J-R curves for the additional specimens are bounded by the predictions of the existing model

Background (3 of 3)

- Several testing activities, funded by BWRVIP, were carried out from 2016 to 2020 to obtain additional FT data with emphasis on weld metal
  - Primary focus was to conduct FT and crack growth testing of core internals material removed from José Cabrera located in Spain (also known as Zorita)
  - For comparison to the Zorita weld material, weld specimens from the core shroud of Barsebäck Unit 2 nuclear power plant were also tested
- The EPRI Materials Reliability Program (MRP) and Argonne National Labs also conducted various FT (and CGR) testing on Zorita materials during this time period

Project Objectives

- To compile additional relevant FT data for irradiated stainless steels applicable to the estimated fluence for BWRs through an 80-year operating period
- To evaluate the impact of FT data made available since the publication of BWRVIP-100, Rev. 1-A
- To develop recommendations for updating the BWRVIP FT correlations

Reevaluation of Fracture Toughness Data – Preliminary Conclusions (1 of 2)

- The initial evaluation indicates that the analysis procedures published in BWRVIP-100 are non-conservative in the fluence range from 5E20 n/cm^2 to 3E21 n/cm^2 when considering the newly acquired weld metal data
  - Specifically, the lower bound FT of 50 ksi-√in specified in BWRVIP-100 may be reached at a fluence of 5E20 n/cm^2 as opposed to the previously defined threshold of 3E21 n/cm^2
- This non-conservatism extends to the analysis methods contained in BWRVIP-235 for evaluating flaws in irradiated core shroud materials thus necessitating the issuance of a 10 CFR Part 21 – Transfer of Information to all known recipients on February 19, 2021

Reevaluation of Fracture Toughness Data – Preliminary Conclusions (2 of 2)

- Current BWRVIP assessment conservatively assumes that weld metal toughness controls the failure mode although the vast majority of flaws are located in heat-affect zone (HAZ) and/or base metal
- Several of the base metal and weld FT tests had unstable crack extension and the toughness was conservatively estimated using the linear elastic parameter K_{Ic}, as defined by ASTM E-1820
  - Fractographs and load-COD data indicate ductile crack growth
  - Additional evaluations of load-COD data are ongoing to determine if J-R curves can be developed per ASTM E-1820
- BWRVIP is maintaining a conservative approach until this work has been completed and independently reviewed by experts

Brief Summary of Evaluation Procedures in BWRVIP-100

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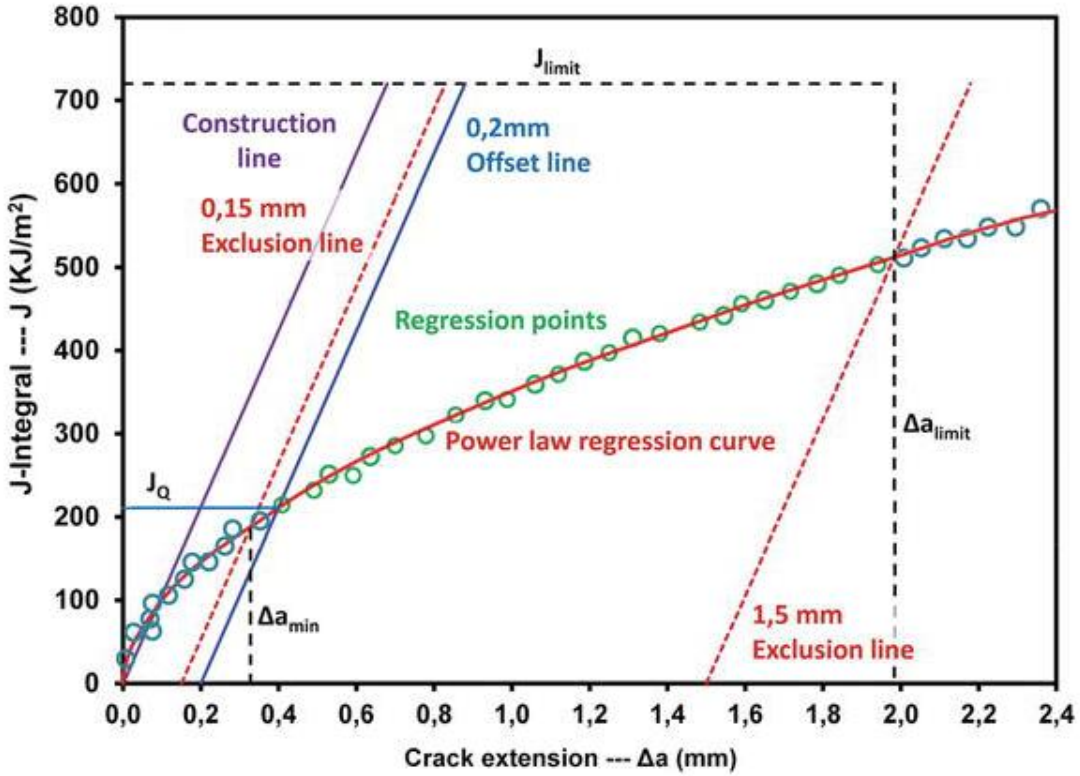
Example J-R curve where $J=C(\Delta a)^n$



https://www.intechopen.com/books/contact-and-fracture-mechanics/fracture-toughness-determination-with-the-use-of-miniaturized-specimens

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Brief Summary of Evaluation Procedures in BWRVIP-100

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Discussion of Relevant Data and Results

Chemical Analysis of Zorita Weld and Base Metal (1 of 2)

- Analyzed compositions of Weld 2 (vertical weld) and Plate B (Piece B3) to confirm that the materials are consistent with Type 304/308 SS
- Development of ICP-OES method for analyses of:
  - Fe, Ni, Cr, Mn, Mo, Ti, Al, Cu, Co, V and Si
- Analysis of C and S in a dedicated instrument (LECO CS-200)

Chemical Analysis of Zorita Weld and Base Metal (2 of 2)

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Ferrite Content

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Stress-Strain Curves for Weld, HAZ and Base Metal as Function of Dose

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Tensile Data – Comparison of YS and UTS for Weld Metal

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Power Law Coefficient C Correlation and Experimental Data for Welds, HAZ and Base Metal from BWRVIP-100, R1-A

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Comparison of C Coefficient for Weld Metal

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Reevaluation of Weld Testing

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Reevaluation of W2WFT08

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Comparison of C Coefficient for HAZ and Base Metal

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BWRVIP-100, Rev. 1-A vs Preliminary Assessment

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Actions Taken by EPRI/BWRVIP to Address Part 21 (1 of 3)

- Evaluations, recommendations, and guidance provided to utilities to assess the impact of the Part 21 TOI

1. BWRVIP conducted a structural margins assessment of potentially impacted internals
   - Conclusion that there is a reasonable expectation that a structural margin to unstable crack extension of at least 1.0 exists for flaws in irradiated BWR internals components in the operating fleet

Actions Taken by EPRI/BWRVIP to Address Part 21 (2 of 3)

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Actions Taken by EPRI/BWRVIP to Address Part 21 (3 of 3)

2. Acceptance and screening criteria in BWRVIP-76, Rev. 1-A revised for determining impact on inspection intervals for both horizontal and vertical core shroud welds (repaired and non-repaired shrouds)
3. Workarounds developed for continued use of BWRVIP-235 structural analysis software
4. Criteria in BWRVIP Letter 2016-030 clarified for evaluation of off-axis flaws where fluence is ≥ 5E20 n/cm^2
5. Conduct test data re-evaluations of linear-elastic interpreted load-COD data to determine if J-R curves can be developed

(Items 2 through 4 were communicated in an update to the Part 21 TOI Notice issued on March 19, 2021)

BWR Fleet Impact for the Part 21 TOI

- Utilities are updating core shroud flaw evaluations as a result of the changes to the fluence threshold of 5E20 n/cm^2 (for a FT of 50 ksi-√in)
  - Some changes to inspection intervals might result, but the BWRVIP is not aware of any plants that have concluded that they have "missed" an examination
  - The BWRVIP expects that all plants will be able to satisfy the structural margins specified in BWRVIP-76, Rev. 1-A and BWRVIP Letter 2016-030

Summary

- Preliminary evaluation of irradiated stainless steel weld data acquired since publication of BWRVIP-100, R1-A indicate that the FT of 50 ksi-√in is reached at a fluence of 5E20 n/cm^2 as opposed to the previously defined threshold of 3E21 n/cm^2
- EPRI/BWRVIP has issued guidance to utilities for updating flaw evaluations and associated inspection intervals where necessary
- Structural margins are expected to be maintained
- Additional evaluations are ongoing to evaluate the low toughness weld tests to determine if J-R curves can be developed
- Updates to BWRVIP-100, R1-A on hold until data has been reevaluated and correlations revised, if required
- Updates regarding current FT evaluations will be communicated to the NRC when complete

List of Data Sources Used in the Project

1. NUREG/CR-6960, ANL-06/58, “Crack Growth Rate and Fracture Toughness of Irradiated Austenitic Stainless Steels in BWR Environment,” March 2008.
2. NUREG/CR-7207, “Degradation of LWR Core Internal Materials Due to Neutron Irradiation,” December 31, 2010.
3. Materials Reliability Program: PWR Internals Age-Related Material Properties, Degradation Mechanisms, Models, and Basis Data—State of Knowledge (MRP-211). EPRI, Palo Alto, CA: 2007. 1015013.
4. BWRVIP-302: BWR Vessel and Internals Project, Examination of a Boat Sample Removed from the Core Shroud at Hatch Unit 1. EPRI, Palo Alto, CA: 2016. 3002008370.
5. BWRVIP-294, Revision 2: BWR Vessel and Internals Project, Fracture Toughness of Zorita RPV Core Internals Applicable to BWRs: Final Report 2019. EPRI, Palo Alto, CA: 2019. 3002015929.
6. Materials Reliability Program: Zorita Internals Research Project (MRP-440), Testing of Highly-Irradiated Baffle Plate Material. EPRI, Palo Alto, CA: 2019. 3002016015.
7. Materials Reliability Program: Fluence Effects on Stainless Steel Welds (MRP-451): Crack Growth Rate and Fracture Toughness Testing of Zorita Weld and HAZ Materials. EPRI, Palo Alto, CA: 2020. 3002018250.
8. Chen,Y., Alexandreanu, B., Natesan, K., “Crack Growth Rate and Fracture Toughness Tests on Irradiated Ex-Plant Materials,” ANL 19-45. Argonne National Laboratory. July 2020.