BWRVIP-100, Rev. 2: Updated Assessment of the Fracture Toughness of Irradiated Stainless Steel for BWR Internal Components

NRC – EPRI Closed Meeting

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Via Webcast

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Outline

- Background
- Overview of Fracture Toughness Evaluations for BWR Internals
- Fracture Toughness Testing Results and Proposed Correlations for Weld and Base Metal
- Summary of Fracture Toughness Evaluations in BWRVIP-100, Rev. 2
- EPRI/BWRVIP Actions Going Forward in 2023-2024

Background (1 of 3)

- Beginning in the mid-to-late 1990’s, data from experiments conducted on irradiated stainless steels were collected and evaluated by EPRI to determine the relationship between fracture toughness and neutron fluence for conditions representative of BWR operating conditions
  - These relationships were essential for dispositioning flaws in irradiated core shroud welds
- Several EPRI reports published
  - BWRVIP-85 (EPRI report 1000887, 2000)
  - BWRVIP-100 (EPRI report 1003016, 2001)
  - BWRVIP-100-A (EPRI report 1013396, 2006)
  - BWRVIP-100, Revision 1 (EPRI report 1021001, 2010)
  - BWRVIP-100, Revision 1-A (EPRI report 3002008388, 2016)

Background (2 of 3)

- Analytical approaches used in BWRVIP-100, Rev. 1-A include:
  - Limit Load (LL)
    - Net section collapse, i.e., extensive plastic deformation
  - Elastic-plastic fracture mechanics (EPFM)
    - Takes into account stable ductile crack extension of an existing flaw as a function of applied load
  - Linear-elastic fracture mechanics (LEFM)
    - Essentially no plastic deformation prior to failure
    - Conservative for ductile materials

Background (3 of 3)

- Additional experimental data have become available since the publication of BWRVIP-100, Revision 1-A
  - Some as a result of testing contracted by EPRI
- EPRI testing based, in part, on NRC Safety Evaluation for BWRVIP-100, Rev. 1 which recommended additional testing of irradiated stainless steels
  - Emphasis on heat affected zone (HAZ) and weld metal
- Harvested materials from Zorita and Barsebäck showed lower than anticipated fracture toughness for weld metal, and indicated a potential non-conservatism in the BWR fracture toughness correlations published in BWRVIP-100, R1-A
- The experimental results were used to reassess the relationship between fracture toughness and neutron fluence for BWR internal components
- The following slides summarize the methodology and revisions to BWRVIP-100

New Irradiated SS Data Introduced in BWRVIP-100, Rev. 2

- Most of the new irradiated data comes from Zorita core barrel and baffle plate (weld, base metal and HAZ) and Barsebäck Unit 2 core shroud weld is documented in:
  - 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.
  - Materials Reliability Program: Zorita Internals Research Project (MRP-440), Testing of Highly-Irradiated Baffle Plate Material. EPRI, Palo Alto, CA: 2019. 3002016015.
  - 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.
  - 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.
  - NUREG/CR-7027, ANL-10/11, “Degradation of LWR Core Internal Materials Due to Neutron Irradiation,” December 31, 2010.
- Additional data:
  - 37 weld data points
  - 8 HAZ data points

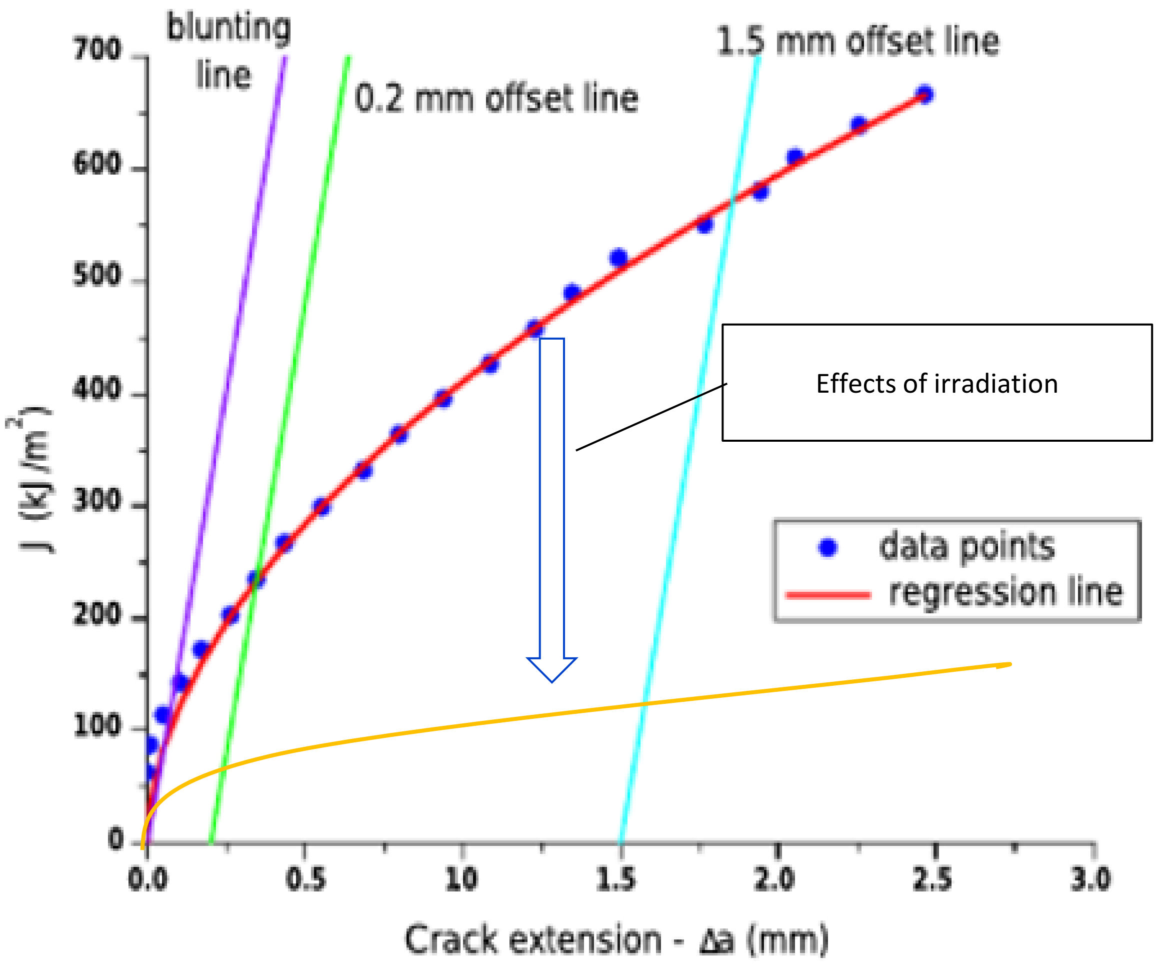
Unirradiated SS Data Introduced in BWRVIP-100, Rev. 2

- Unirradiated data for weld and base metal was also included in the updated correlations to address fracture toughness at low fluence conditions
- The references are:
  - NUREG/CR-6004, “Probabilistic Pipe Fracture Evaluations for Leak-Rate-Detection Applications,” April 1995.
  - D.J. Gavenda, et. al., Effects of Thermal Aging on Fracture Toughness and Charpy-Impact Strength of Stainless Steel Pipe Welds, NUREG/CR-6428, ANL-95/47, May 1966.
  - J.D. Landes and D.M. McCabe, Toughness of Austenitic Stainless Steel Pipe Welds, NP-4768, EPRI, Palo Alto, CA., October 1986.
- Additional data:
  - 34 weld data points
  - 28 base metal and 2 HAZ data points

Fracture Toughness Testing

- Testing was performed using a range of compact tension specimen sizes
- The aim was to determine the degree of ductility (and load carrying capacity) of the material for both weld and base metal/HAZ applicable to BWR internals

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



Effects of irradiation will typically result in lower toughness and hence lower J-Δa curves but this can also be the result of the material that is being tested (weld vs base metal)

BWRVIP-100, Overview of Data Collection and Procedure

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Example Plot of Predicted vs Experimental J-T Curves

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Observations Comparing Stainless Steel Weld and Base Metal

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Commentary on Westinghouse and Studsvik Re-evaluation of SS Weld FT Tests

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Fracture Toughness Testing Results for SS Weld (1 of 2)

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Fracture Toughness Testing Results for SS Weld (2 of 2)

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Revised Flow Stress for SS Weld Metal

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Predicted J-R Curves as a Function of Fluence for Weld Metal

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J-T Curves as a Function of Fluence for Weld Metal

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Fracture Toughness Testing Results for SS Base Metal (1 of 2)

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Fracture Toughness Testing Results for SS Base Metal (2 of 2)

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Commentary on C and n Data for the Low Fluence Zorita SS Base Material Tested by ANL

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Revised Flow Stress for SS Base Metal

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J-R Curves as a Function of Fluence for Base Metal

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J-T Curves as a Function of Fluence for Base Metal

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K_{IC} vs Fluence for Highly Irradiated SS Materials

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Comparison of BWRVIP-100, R1-A and BWRVIP-100, R2 Evaluation Procedures

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BWRVIP-100, Rev. 1-A vs BWRVIP-100, Rev. 2

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Summary of Fracture Toughness Evaluations in BWRVIP-100, Rev. 2

- Revised fracture toughness vs fluence correlations for weld and base metal have been developed primarily based on harvested materials from a decommissioned reactor and other industry testing

- BWRVIP-100, Rev. 2 proposes two categories. i.e., one for weld (the default case) and the other for base metal, with each having slightly different criteria related to fluence thresholds

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BWRVIP Actions Going Forward in 2023-2024

1. Publish BWRVIP-100, Rev. 2 by end of June 2023
2. Submit BWRVIP-100, Rev. 2 to NRC in July 2023 for review (BWRVIP will request a fee waiver)
3. Respond to RAIs as necessary
4. Goal is to obtain SER by December 2024