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Thermal Aging and Neutron Embrittlement Assessment of CASS and SS Welds in PWR Internals

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MRP-276 Acknowledgements

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Main Discussion Points

- Background and purpose
- MRP-276 report structure
- MRP-175 screening criteria technical basis
- Recently acquired data and assessments
- Conclusions
- Recommendations

Background and Purpose

- Report prepared to address two IMT gaps:
  - IMT Gap: P-AS-13 Thermal & Irradiation Embrittlement Synergistic Effects on CASS and Stainless Steel Welds
  - IMT Gap: I&E-06 (I&E Guidelines for Reactor Internals)
- Purpose of review and evaluations:
  - Summarize results of assessments and testing on synergistic effects of thermal aging and irradiation on fracture properties of CASS and austenitic stainless steel welds
  - Assess requirements for fracture property results to analyze reactor internals components
  - Identify additional test data or structural analyses needed to fill existing gaps in available information

MRP-276 Report Structure

- Summarizes technical basis behind MRP-175 screening criteria for thermal and irradiation embrittlement
- Summarizes recently available fracture toughness data and assessments on potential synergistic effects
- Assesses fracture property requirements needed to analyze component items in B&W, CE, and W PWR designs
- Summarizes results and conclusions from this effort and provides recommendations for future efforts

MRP-175 Thermal Aging Embrittlement Screening Criteria

- Temperature, time, and material composition are overriding parameters controlling thermal aging embrittlement (TE)
- Material undergoes microstructural changes (e.g., precipitation of phases)
  - Leads to decreased ductility, toughness, and impact properties
  - Leads to increased yield strength, ultimate tensile strength, and hardness
- MRP-80 summarizes available TE data

MRP-175 Thermal Aging Embrittlement Screening Criteria

Cast Austenitic Stainless Steel (CASS)

- Criteria based on recognized industry efforts approved by NRC

Austenitic stainless steel weld metal

- Microstructure and aging susceptibility superior to statically-cast CASS due to lower Mo, Cr, and delta-ferrite
- Same criteria as statically-cast CASS used
- Therefore, no weld metal falls above screening level (>20%) because of lower ferrite contents

FOLLOWING TABLE PROVIDES SCREENING CRITERIA UTILIZED

MRP-175 Irradiation Embrittlement Screening Criteria

- Exposure to high-energy neutrons (E > 1 MeV) is the overriding parameter controlling irradiation embrittlement (IE)
- Creation of lattice defects from neutron bombardment of the material (e.g., interstitial atoms and vacant lattice sites [or, point defects])
  - Leads to decreased ductility, toughness, and impact properties
  - Leads to increased yield strength, ultimate tensile strength, and hardness
- MRP-79, Rev. 1 summarizes available IE data

MRP-175 Irradiation Embrittlement Screening Criteria

Cast Austenitic Stainless Steel (CASS)

- Criterion based on available fast reactor data
- No PWR or BWR data available at time of publication

Austenitic stainless steel weld metal

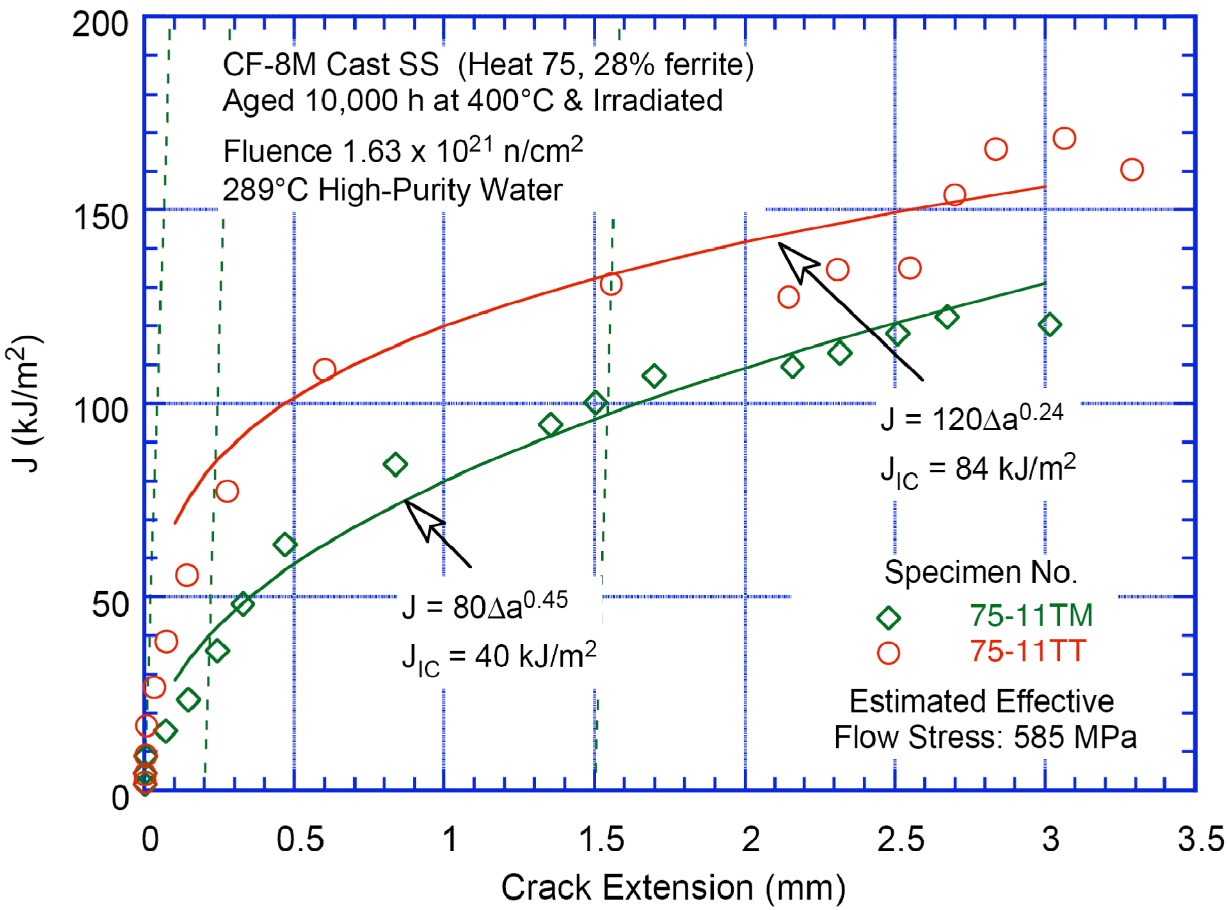
- Criterion based on available data from fast reactor and PWR/BWR
- Data appears to be consistent, except for a few data points between 2-18 dpa where PWR/BWR data falls below lower bound of fast reactor data

FOLLOWING TABLE PROVIDES SCREENING CRITERIA UTILIZED

Recently Acquired Data and Assessments

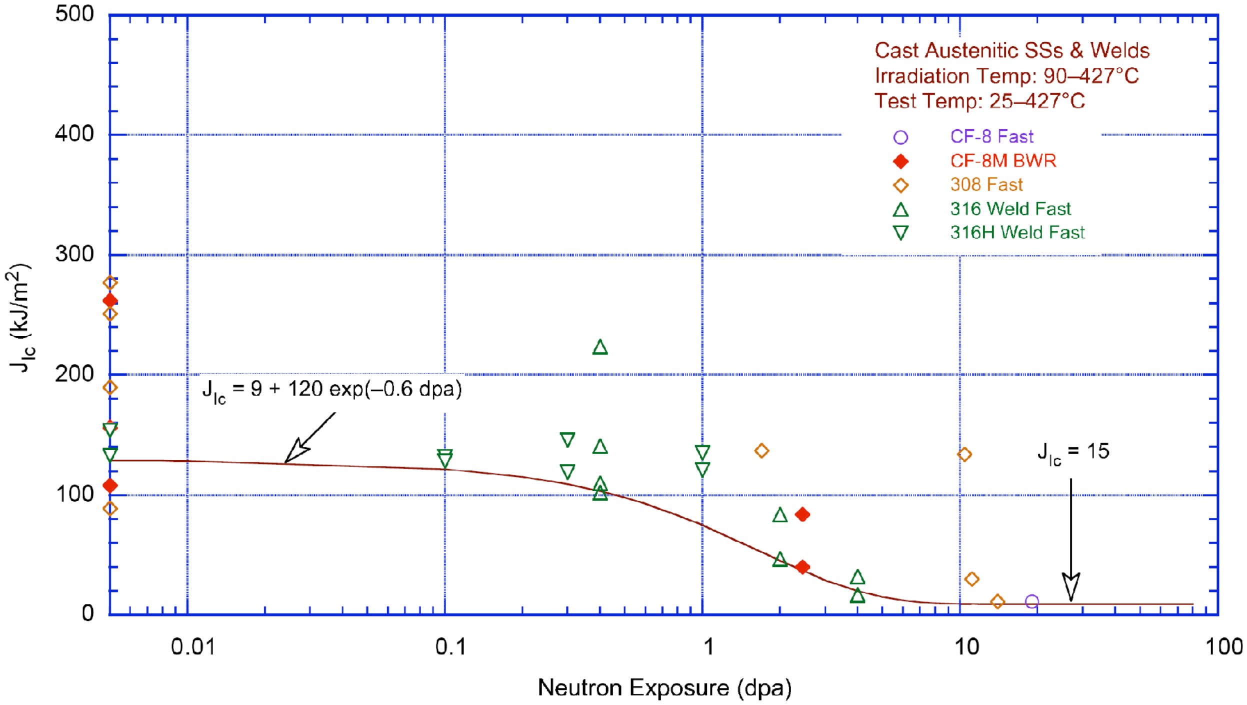
- Three sources of data
  - Work by Chopra et al. of thermally aged CASS irradiated in Halden heavy water BWR
  - Work by Horsten and Belcher on stainless steel strip clad deposit material
  - Work by Kim et al. for CASS and SS weld metal (PWROG and MRP-JOBB materials)

Recently Acquired Data and Assessments



J-R curves for thermally-aged and irradiated CF-8M material and tested in simulated BWR water environments

Recently Acquired Data and Assessments



The change in initiation toughness JIc of CASS and austenitic stainless steel weld metals as a function of neutron exposure (Note, the label JIC = 15 should be JIC = 9)

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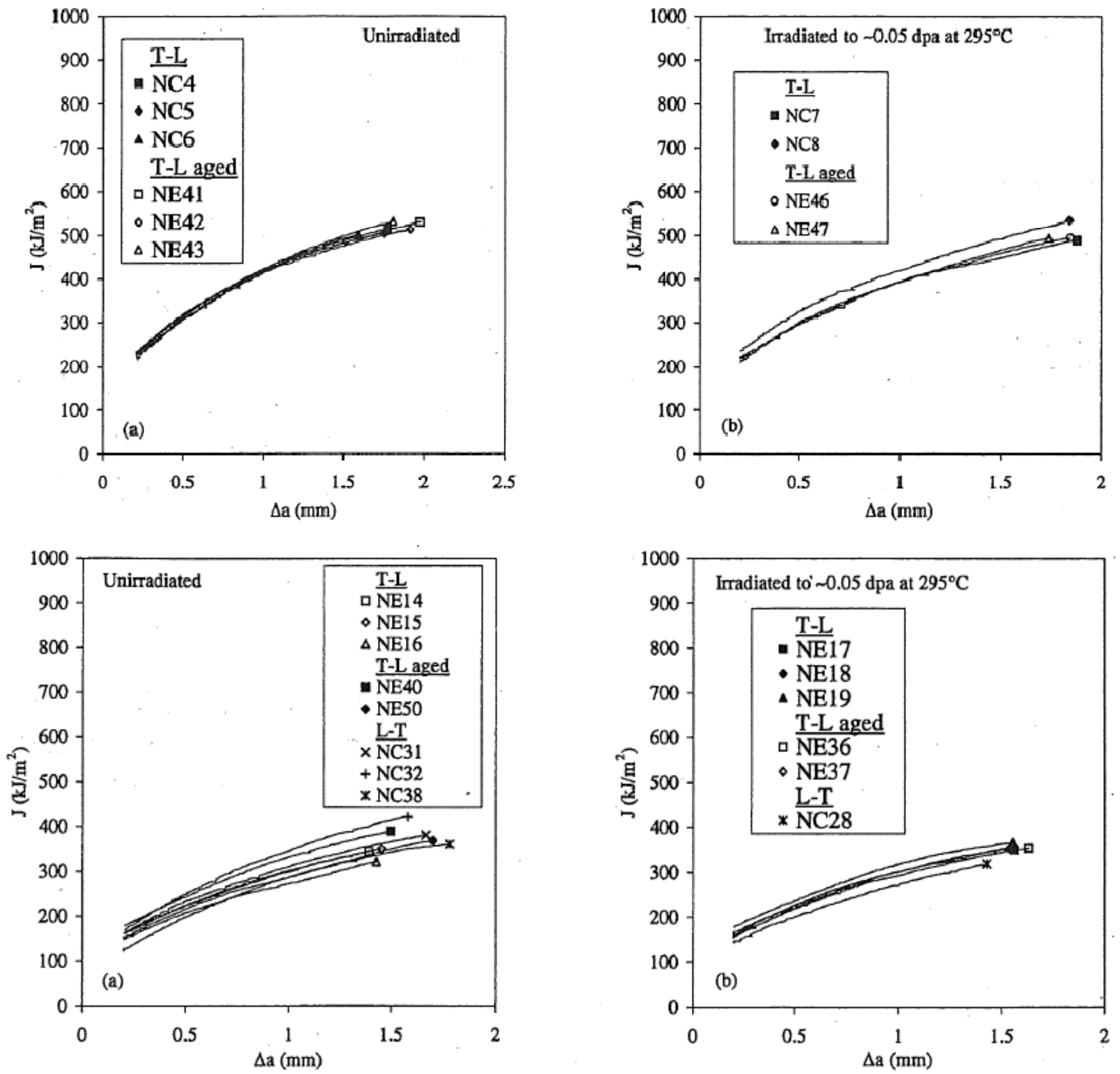
Recently Acquired Data and Assessments



No effect of thermal aging on fracture toughness (J-R) is seen with or without irradiation on Type 308L weld metal. Top, tested at 100°C; bottom tested at 295°C

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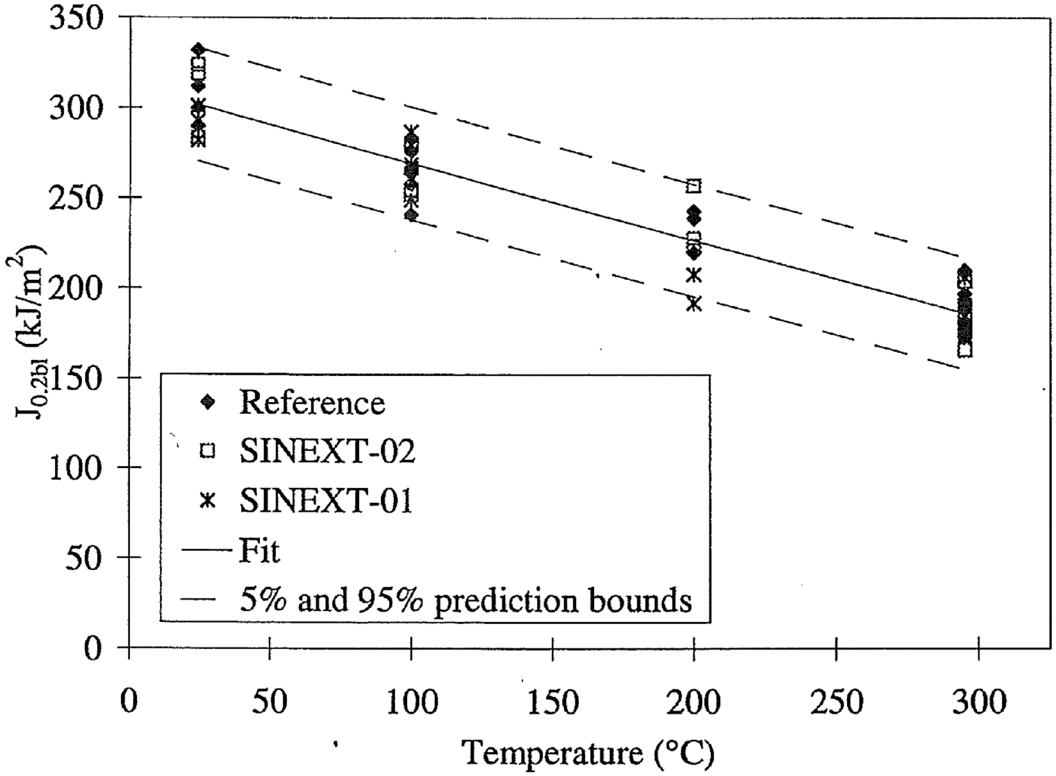
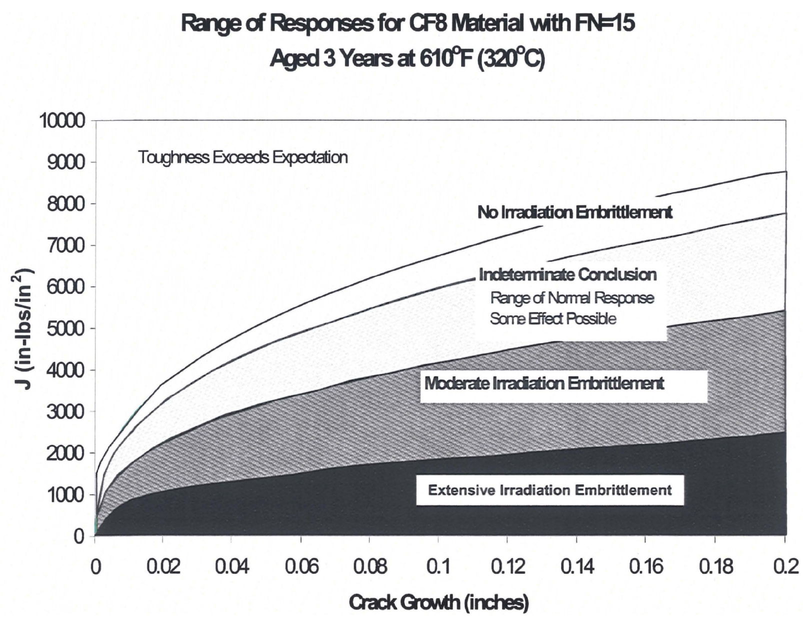
Recently Acquired Data and Assessments

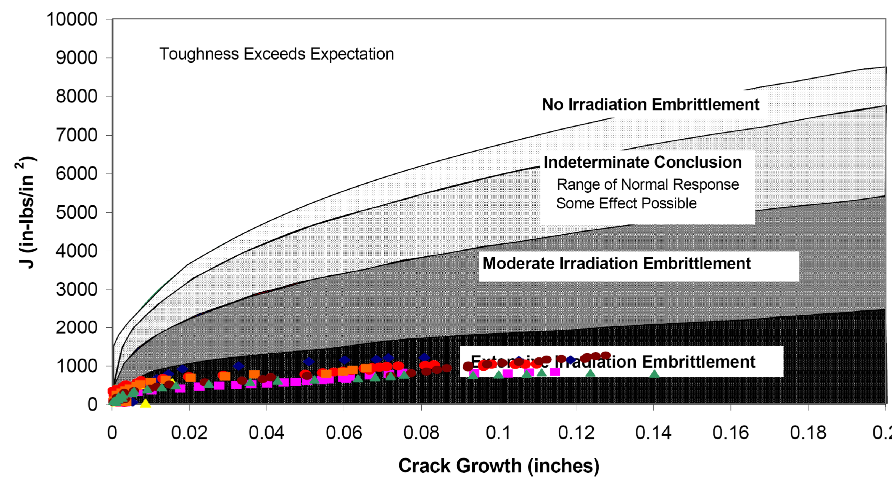


The observed change in initiation toughness (mean, upper, and lower bound) of Type 308L weld metal as a function of temperature

Recently Acquired Data and Assessments



Fracture Response Map for a Typical CF-8 Material Aged at 610°F for 3 Years



Measured J-R Curves for the JOBB CF-8 Material Irradiated to 6 and 12 dpa Compared to the Bands Predicted for Thermal Aging Alone

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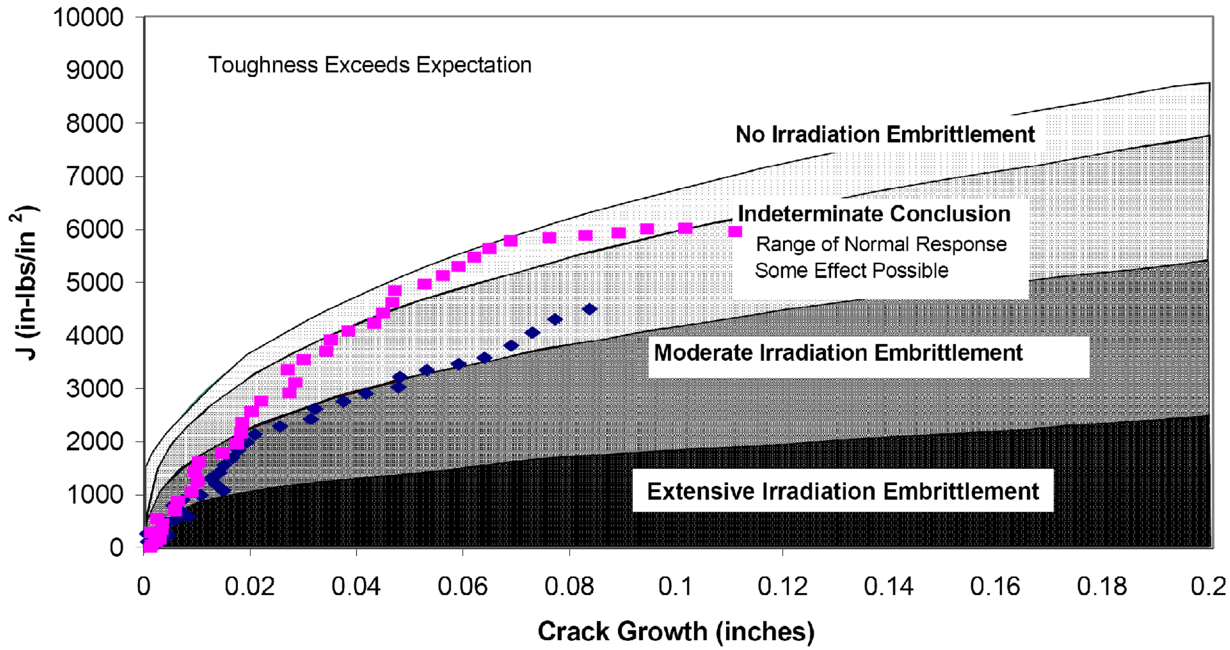
Recently Acquired Data and Assessments



Measured J-R Curves for the CF-3 Fuel Nozzle Material Irradiated to 0.08 dpa Compared to the Bands Predicted for Thermal Aging Alone

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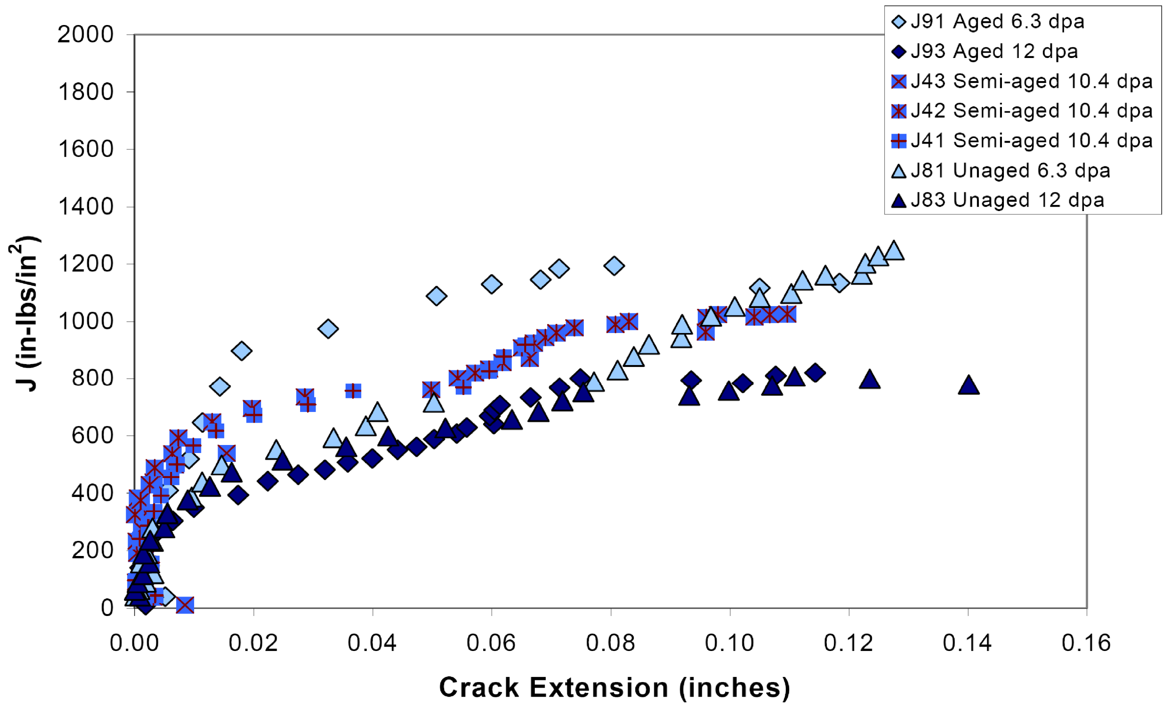
Recently Acquired Data and Assessments



Measured J-R Curves for the JOBB CF-8

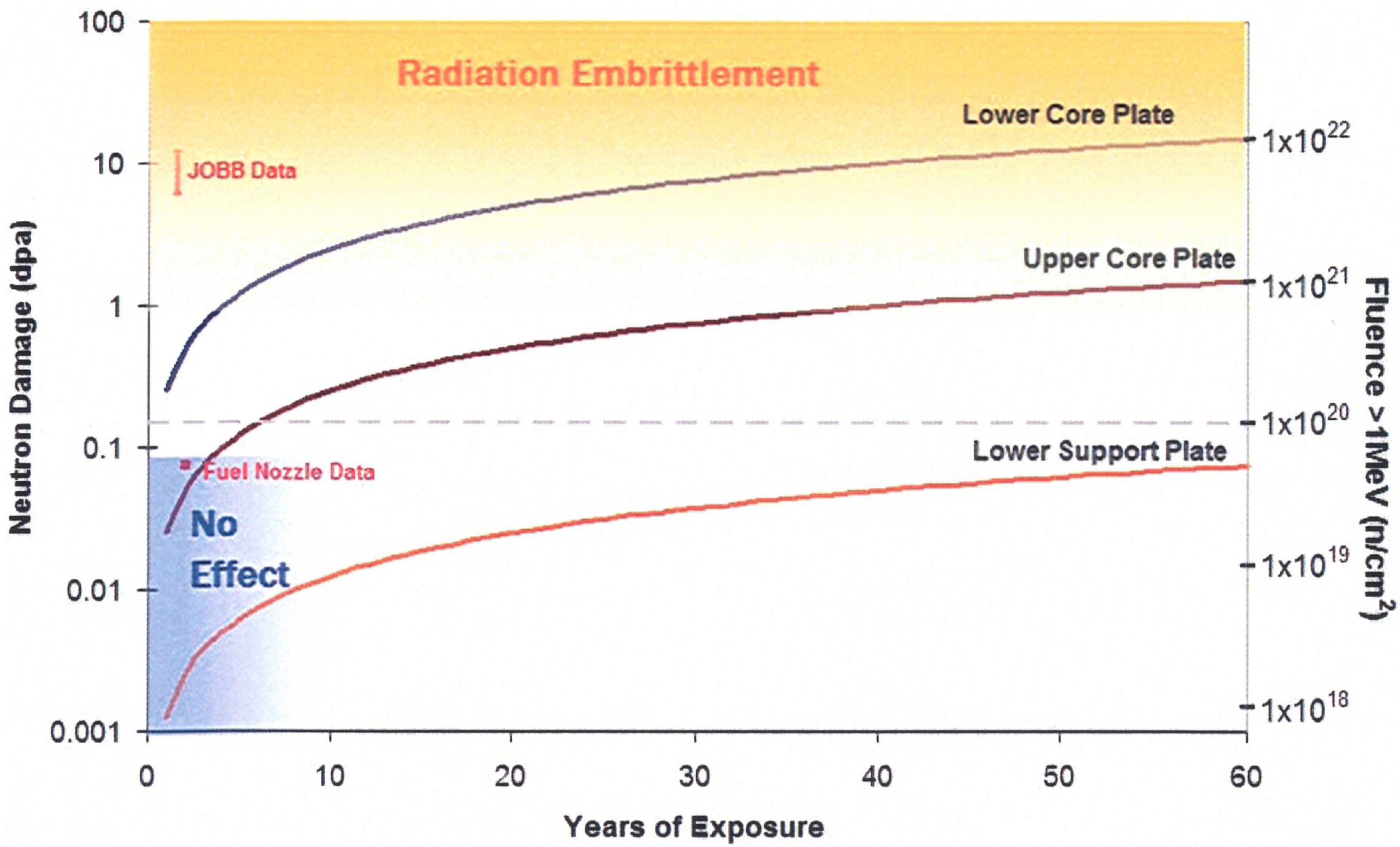
Recently Acquired Data and Assessments

- Available data clearly indicate:
  - Neutron dose level of $1x10^{17}$ n/cm^2, E > 1 MeV does not change fracture toughness of CASS or SS welds that have been completely thermally aged
  - Minimum fluence level for detectable fracture toughness loss due to IE is well established at > 0.5 dpa ($3.3x10^{20}$ n/cm^2, E > 1 MeV) for stainless steels
- No evidence in available data to indicate a synergistic effect of thermal aging and irradiation
- Nevertheless, there currently is insufficient testing to disprove a synergistic potential under all possible combinations of thermal aging and irradiation conditions

Recently Acquired Data and Assessments

- Most significant gap in test data is lack of data from specimens exposed to low (< 1 dpa) radiation doses and long thermal aging times
- Represented graphically in following figure

Implications of Data for PWR Internals Applications



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Recently Acquired Data and Assessments

- Gaps in data:
  - The proposed NRC approach extends to lower neutron fluences where IE is not normally expected
  - Investigation of long-term, low dose exposure of CASS and SS weld materials in LWRs
  - For extended service lives, no data exist to demonstrate SS welds approach same limiting fracture toughness as SS wrought materials
  - SS weld materials reach higher doses than CASS and thus any synergy over long-term aging and dose is not known

Conclusions

- Available test data clearly indicate neutron dose level of 1×10^{17} n/cm^2, E > 1 MeV does not change fracture toughness for completely thermally embrittled CASS and austenitic SS weld materials
- Available data presented in this report show NRC recommended fluence screening criteria for synergistic effect (i.e., 1×10^{17} n/cm^2, E > 1.0 MeV) is far too conservative and MRP-175 screening criteria (i.e., 6×10^{20} n/cm^2, E > 1.0 MeV) is sufficiently conservative
- Implementation of MRP-227 Guidelines provides appropriate aging management for irradiated CASS

Conclusions

- Conclusions of this study support a recommendation to withdraw GALL AMP XI.M13 to allow establishment of requirements for aging management of CASS internals based on MRP-227 in GALL AMP XI.M16
- Most significant gap in available test data is lack of data from specimens exposed to low (less than ~1 dpa) radiation doses and long thermal aging times at PWR operating temperatures
  - Only way to fill this gap is to test CASS and austenitic stainless steel weld items from decommissioned PWRs

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