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Industry-NRC Meeting CASS Screening Criteria for Thermal and Irradiation Embrittlement for BWR and PWR Internals

July 15, 2014

NRC Offices

Washington, DC

Agenda

8:00	Introductions	NRC
8:15	Meeting Objectives	NRC, Industry
8:30	Industry Position on Thermal and Irradiation Embrittlement Screening Criteria	Industry
9:45	Break	
10:00	Industry Position on Thermal and Irradiation Embrittlement Screening Criteria (cont'd)	Industry
10:30	NRC Position on Thermal and Irradiation Embrittlement Screening Criteria	NRC
11:15	Discussion of Industry Comments on NRC Position	NRC
12:00 P.M.	Lunch	
1:00	Discussion of Industry Comments on NRC Position (Cont)	NRC
2:00	Steps to Move Forward and Obtain SE? on Industry Position on Generic Screening Criteria for PWRs and BWRs Utility Required Actions to Meet Staff Guidance	All
2:45	Break	
3:00	Closure and action item review	
3:30	Adjourn	

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Meeting Objectives

- Review proposed industry and NRC positions regarding thermal and irradiation embrittlement criteria
- Establish a full understanding of each position
  - Discuss responses to industry comments on NRC position
- Discuss issues associated with industry burden to comply with current NRC position
- Identify actions required to obtain a Safety Evaluation and/or final NRC position
- Discuss options and potential actions going forward

Outline of Presentation

- Background
- Formation of Working Group
- Interactions with NRC
- Thermal Embrittlement Criteria
- Irradiation Embrittlement Criteria
- Synergy Effects
- Industry Burden Based on Current NRC Position
- Comments on NRC Screening Position
- Review of Industry Comments
- Summary

Background

- During 2013, NRC issued RAIs on MRP-227-A to several PWR utilities regarding evaluation of CASS components
- In May 2013, NRC issued a 2nd set of RAIs on BWRVIP-234
- The industry determined that some RAIs were common to BWRs and PWRs
- Industry/NRC meeting held in Washington, DC on May 21, 2013 to review issues related to evaluation of CASS
  - Follow-up meetings with NRC in August 2013, November 2013 and December 2013
  - NRC requested a common BWRVIP/MRP screening approach for Thermal Embrittlement (TE) and Irradiation Embrittlement (IE)
- PWR/BWR Industry Working Group formed in June 2013 to address CASS issues
  - Significant work conducted to date to address BWRVIP and MRP issues

MRP/BWRVIP Working Group Approach

- Develop responses to BWRVIP-234 RAIs
- Develop PWR/BWR screening criteria for TE and IE
  - Review the technical bases of the Grimes letter, along with other approaches for evaluating metallurgical effects of thermal aging and irradiation embrittlement of CASS
  - Provides a basis for response to MRP-227-A LAI No. 7

2014 Interactions

- February 3 telecon with NRC
  - Presented updated PWR/BWR CASS screening criteria
- Late February – industry submitted additional information on “Synergy Effects of TE & IE in CASS”
  - Follow up discussion between industry and staff on March 12, 2014
- Staff subsequently forwarded their initial position paper regarding TE and IE on March 13, 2014
- Industry submitted response to BWRVIP-234 RAI which included industry’s proposed generic TE and IE screening criteria to NRC on May 23, 2014 (ML14174A841)
- “NRC Position on Aging Management of CASS Reactor Vessel Internal Component,” provided to industry on June 20, 2014 (ML14174A719)

Industry TE Screening Criteria

- Industry proposal is to screen for TE based on delta ferrite prior to screening for IE – use ferrite limits from current pressure boundary practice (i.e., Grimes Letter)
  – TE relevant for internals when delta ferrite > 20% and, in some cases, delta ferrite >14%
- Thin-section CASS structural internals intentionally have lower delta ferrite than primary pressure boundary components
  – Chemical composition of CASS internals is distinctly different from that of CASS piping, i.e., typical internals have delta ferrite < 20%
    - CASS internals are not as susceptible as thick-section castings (e.g., piping, pump casings, valve bodies) to solidification cracking during cooling
    - High ferrite is not needed in small casting to improve casting process yield
  – Supporting evidence documented in BWRVIP-234

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TE Screening Criteria

- Grimes letter susceptibility based on ferrite content
  - TE relevant for internals when delta ferrite > 20% (in some cases when delta ferrite > 14%)

Molybdenum (wt. %)	Casting Method	Susceptibility	Delta ferrite %
High 2.0-3.0% (CF-8M)	static	TE	> 14%
		No	≤ 14%
	centrifugal	TE	> 20%
		No	≤ 20%
Low 0.5% max (CF-3 and CF-8)	static	TE	> 20%
		No	≤ 20%
	centrifugal	No	All

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Thermal Embrittlement (TE) of CASS

- TE of CASS occurs when aging of ferrite phase results in transition to cleavage fracture
- CASS material is susceptible to TE when ferrite volume fraction and distribution are sufficient to support a cleavage failure path
  - Determination of volume ferrite fraction is inexact
    - Spatial variations within casting
    - Multiple measurement techniques
- NUREG/CR-4513, Rev. 1 provides basis for estimating lower bound fracture toughness
  - Correlations based on composition
  - Utilizes Hull's equivalent factors and material composition
- Resolution of NUREG/CR-4513, Rev. 1 and EPRI TR-106092 provided the basis for the criteria in the Grimes letter

Industry Proposal for TE Screening Criteria

- Retain Grimes letter criteria to determine TE susceptibility
  - Chemical composition, casting method and delta ferrite
  - Screening levels based on prediction of delta ferrite using Hull's equivalent factors
- Consistent with current practice for pressure boundary components

Industry IE Screening Criteria

- When necessary screen for IE using fluence of 1 dpa
  - Industry efforts to date show that IE accelerates but does not enhance embrittlement process, especially for CASS materials with moderate delta ferrite content
    - Industry data support the premise that ≤ 20% delta ferrite CASS embrittlement is controlled by the behavior of the austenite phase
    - The effect of irradiation on austenite phase is well understood
      - Data show onset of embrittlement occurs at 3-5 dpa
      - Screening criteria are conservatively established at 1 dpa
  - Current data are inconclusive with respect to IE and TE for high (> 20%) delta ferrite CASS materials
  - "Accelerates but does not enhance" premise provides the basis for TE screening followed by IE screening

* 1 dpa = 6.7×10^{20} n/cm^2 (E >1MeV)

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Consideration of Synergistic Effects

- Grimes letter states:
  - "For RVI components fabricated from CASS and hence subject to thermal embrittlement, concurrent exposure can result in a synergistic effect wherein the service degraded fracture toughness (that) is reduced from the levels predicted independently for either of the mechanisms."
- Synergistic effects
  - Accelerate the embrittlement?
    - Temperature effects shown to accelerate the rates of attaining the same saturation values of embrittlement
  - Exacerbate the embrittlement?
    - Database is sparse (nonexistent!) to support exacerbation
    - Mechanistic considerations suggest separable effects
  - Mechanistic approach requires that there is no (significant) exacerbation effect in IE

Industry Data Supporting “Accelerating-Only” Effect of Synergy

- NUREG-4513, Rev. 1 demonstrated that fully embrittled ferrite <20% does not significantly embrittle the bulk CASS material
- “Full Thermal Aging” heat treatment was ineffective in embrittling the low ferrite content CF8 → high J_q and very high $J_{2.5mm}$
- “Full Thermal Aging” plus 0.08 dpa irradiation was ineffective in the embrittlement of low ferrite content CF3 fuel nozzle→ very high J_q and $J_{2.5mm}$
- Effect of irradiation becomes significant in the range of 6-10 dpa but for these materials does not appear to saturate until ~12 dpa
- Thermal aging prior to irradiation has no significant effect on post irradiation toughness – full thermal age + irradiation actually exhibited greater remaining toughness than partial thermal age + similar irradiations (6.3 to 12 dpa)

Industry data support the premise that low ferrite content (≤ 20%) CASS embrittlement is controlled by the behavior of the austenite phase

Mechanistic View of Embrittlement of CASS

- Embrittlement of duplex CASS structure depends on controlling phase:
  - If delta ferrite phase is of sufficient volume fraction and distributed to provide a continuous path for brittle fracture, then delta ferrite fraction will be controlling
  - If delta ferrite phase is less than of a sufficient volume fraction or is distributed in an isolating dispersion, then austenite properties will be controlling

Controlling Phase	Thermal Embrittlement Susceptibility	Irradiation Embrittlement Susceptibility
Ferrite	Potentially Susceptible to Thermal Embrittlement	Potentially Susceptible to IE if Fluence > Φ_{crit}^{α}
Austenite	Not Susceptible to Thermal Embrittlement	Potentially Susceptible to IE if Fluence > Φ_{crit}^{γ}

  - Susceptibility to TE can be assessed using Grimes Letter Table 2 criteria (Mo content, casting method, delta ferrite)
  - Delta ferrite is calculated using Hull's equivalent factors consistent with the NUREG/CR-4513 correlations of loss of toughness (Cv_{sat}, J-R) vs. delta ferrite surrogate

"In all cases the ANL predictions of J-R curves were accurate or conservative compared to the measured values"

Methodology for Revised Screening Approach
TE and IE Hierarchy and IE Criterion

"Thermal" Screening Criteria

Molybdenum (Wt%)	Casting Method	Delta-Ferrite %	Susceptibility Determination
High 2.0-3.0	Static	> 14%	Potentially Susceptible to TE
		≤ 14%	Not Susceptible to TE
	Centrifugal	> 20%	Potentially Susceptible to TE
		≤ 20%	Not Susceptible to TE
Low 0.5 max	Static	> 20%	Potentially Susceptible to TE
		≤ 20%	Not Susceptible to TE
	Centrifugal	All	Not Susceptible to TE

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Mechanistic approach

Controlling Phase	Thermal Embrittlement Susceptibility	Irradiation Embrittlement Susceptibility
Ferrite	Potentially Susceptible to TE	Potentially Susceptible to IE if Fluence > Φ_{crit}^{α}
Austenite	Not Susceptible to Thermal Embrittlement	Potentially Susceptible to IE if Fluence > Φ_{crit}^{γ}

Approach for Implementation of Revised Hierarchy Screening

Molybdenum (Wt%)	Casting Method	Delta-Ferrite %	Thermal Embrittlement Susceptibility	Irradiation Embrittlement Susceptibility
High 2.0-3.0	Static	>14%	Potentially Susceptible to TE	*No need for IE screening*
		≤14%	Not Susceptible to TE	Screen for susceptibility to IE if Fluence > Φ_{crit}^{γ}
	Centrifugal	>20%	Potentially Susceptible to TE	*No need for IE screening*
		≤20%	Not Susceptible to TE	Screen for susceptibility to IE if Fluence > Φ_{crit}^{γ}
Low 0.5 max	Static	>20%	Potentially Susceptible to TE	*No need for IE screening*
		≤20%	Not Susceptible to TE	Screen for susceptibility to IE if Fluence > Φ_{crit}^{γ}
	Centrifugal	All	Not Susceptible to TE	Screen for susceptibility to IE if Fluence > Φ_{crit}^{γ}

- Initial screening on “TE Susceptibility” criteria also screens for components/material compositions that will manifest IE at lower irradiation fluences
- Subsequent IE screening can be performed addressing components/material compositions that will manifest IE due to embrittlement of the austenite
- The appropriate IE screening criterion is $\Phi_{crit}^{\gamma} = 1$ dpa

Summary of Revised Screening Process and Criteria

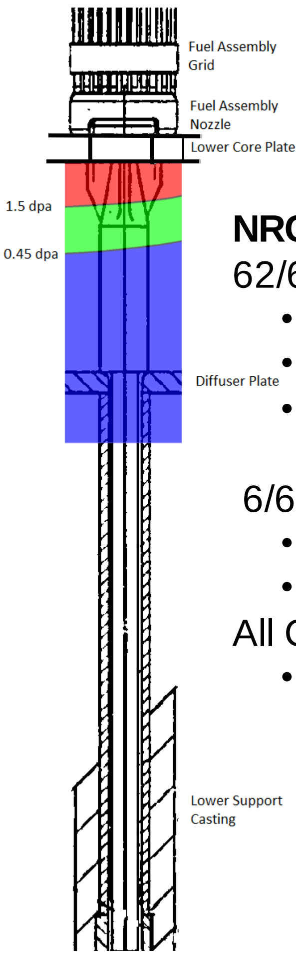
- Screen for TE first
  - No need to further screen for IE when materials already determined to be susceptible to TE
- Screen for IE based on threshold fluence of 1 dpa for embrittlement of austenitic phase

Industry operating experience over 30-40 years supports this approach

Comparison of NRC and industry positions on next slide

Molybdenum (wt. %)	Casting Method	% Ferrite	Position	TE Screening Susceptibility Result Yes or No	IE Screening Susceptibility Result Yes or No
High 2.0-3.0% (CF-3M & CF-8M)	static	0-10	NRC Industry	No No	***Yes, > 1.5 dpa*** ***Yes, > 1 dpa***
		11-14	NRC Industry	No No	**Yes, > 0.45 dpa** **Yes, > 1 dpa**
		≥ 15	NRC Industry	Yes Yes	N/A N/A
	centrifugal	0-15	NRC Industry	No No	***Yes, > 1.5 dpa*** ***Yes, > 1 dpa***
		16-20	NRC Industry	No No	**Yes, > 0.45 dpa** **Yes, > 1 dpa**
		≥ 21	NRC Industry	Yes Yes	N/A N/A
Low 0.5% max (CF-3 & CF-8)	static	0-15	NRC Industry	No No	***Yes, > 1.5 dpa*** ***Yes, > 1 dpa***
		16-20	NRC Industry	No No	**Yes, > 0.45 dpa** **Yes, > 1 dpa**
		≥ 21	NRC Industry	Yes Yes	N/A N/A
	centrifugal	All	NRC Industry	No No	***Yes, > 1.5 dpa*** ***Yes, > 1 dpa***

Example: Embrittlement in Lower Core Support Columns

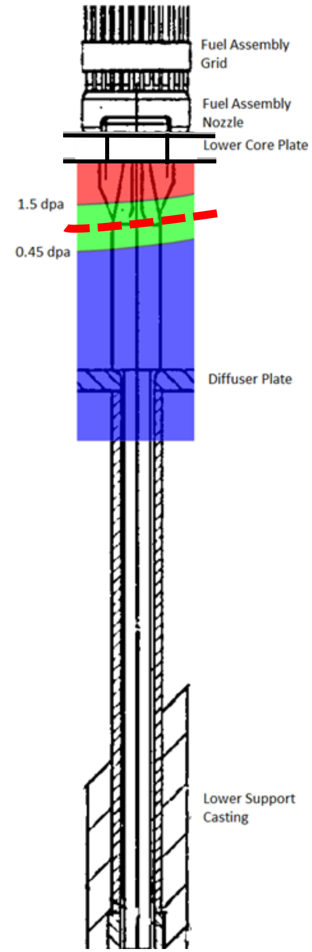


NRC Proposal

62/68 Columns
- Ferrite <15%
- IE in Red
- No Embrittlement - Green, Blue & Below

6/68 Columns
- 15%< Ferrite <20%
- IE + TE in Red & Green

All Columns
- No Embrittlement - Blue & Below



Industry Proposal

68/68 Columns
- Ferrite <20%
- IE Above Dashed Line
- No Embrittlement - Below Dashed Line

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Impact of NRC Proposed Guidance on Thermal and Irradiation Embrittlement of Cast Austenitic Stainless Steel on Lower Support Column Evaluations

Practical Implications of NRC Guidance

- Consider impact of NRC guidance on full range of potential plant-specific Lower Support Column (LSC) evaluations.
  - Six Potential Cases
    - Cases are not intended to represent any existing plant conditions.
    - In all cases the LSC CASS materials are low Mo, statically cast.

Lower Support Column
Case #1: Thermal Embrittlement

- Hull's Ferrite Evaluation: average content calculated for all support columns >20%
  - Material susceptible to thermal embrittlement
  - Top few inches susceptible to irradiation embrittlement (>1.5 dpa)
  - No known examples of this case
- A/LAI 7 Response: Require either
  - Functionality Analysis
  - Flaw Tolerance Analysis

No impact of NRC proposed screening guidance

Lower Support Column
Case #2: Partial Thermal Embrittlement

- Hull's Ferrite Evaluation: Content calculated for 10% (e.g. 6/60) of support columns >20%
  - Limited number of columns subject to thermal embrittlement
  - Top few inches susceptible to irradiation embrittlement (>1.5 dpa)
  - No known examples of this case
- A/LAI 7 Response: Require either
  - Functionality Analysis
    - Demonstrate ability to lose 10% of LSCs?
  - Flaw Tolerance Analysis

No impact of NRC proposed screening guidance

Lower Support Column
Case #3: No Thermal Embrittlement

- Hull's Ferrite Evaluation: Content calculated for all support columns <15%, or support columns not CASS
  - No columns subject to thermal embrittlement
  - Large fraction of known cases
- A/LAI 7 Response
  - Not susceptible to thermal embrittlement (or synergistic effect)
  - Top few inches susceptible to irradiation embrittlement (>1.5 dpa)
  - Are Functionality or Flaw Tolerance Assessments required?
- Remaining Issues
  - Include in Functionality Analysis?
    - IASCC unlikely due to higher stress and dose threshold
  - CRGT flange weld fluence lower not appropriate primary link (below IE threshold)

No impact of NRC proposed screening guidance

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Lower Support Column
Case #4: Incomplete Data

- Hull's Ferrite Evaluation: Content calculated ferrite content for 85% of support columns <15%, remaining columns undocumented
  - Limited number of columns might be subject to thermal embrittlement
  - Several known cases
- A/LAI 7 Response
  - 85% of columns not susceptible to thermal embrittlement (or synergistic effect)
  - 15% of columns might be subject to thermal and/or irradiation embrittlement
    - Statistical analysis suggests high probability that ferrite < 15%
  - Top few inches of all columns susceptible to irradiation embrittlement (>1.5 dpa)
- Remaining Issues
  - Are Functionality or Flaw Tolerance Assessments required?
    - Between Case 2 (Partial TE) and Case 3 (No TE)

Lower Support Column
Case #4: Incomplete Data (Continued)

- Hull's Ferrite Evaluation: Content calculated ferrite content for 85% of support columns <15%, remaining columns undocumented
  - Limited number of columns might be subject to thermal embrittlement
  - Several known cases
- Remaining Issues
  - How many observations are required from Westinghouse/CE fleet to demonstrate following:
    - Reasonable assurance that all lower support columns <20% ferrite
    - Basis for assuming that limited fraction of undocumented columns are between 15% and 20% ferrite.

Statistical analysis suggests that a small number of undocumented columns may have ferrite content between 15% and 20% and would be impacted by NRC guidance. However worst case assumptions on CASS composition predict ferrite content >20%.

Lower Support Column
Case #5: “Synergistic” Embrittlement

- Hull’s Ferrite Evaluation: Content calculated ferrite content for all support columns >15%, but <20%
  - Fluence threshold for irradiation/thermal embrittlement lowered to 0.45 dpa
  - No known cases
- A/LAI 7 Response:
  - 100% of columns not susceptible to thermal embrittlement
  - Top few inches of all columns susceptible to “synergistic” irradiation/thermal embrittlement (>0.45 dpa)
  - Are Functionality or Flaw Tolerance Assessments required?
    - Same as Case 3 (No TE), except volume of LSC over threshold fluence slightly expanded
- Remaining Issues
  - Include in Functionality Analysis?
    - IASCC unlikely due to higher stress and dose threshold
  - CRGT flange weld fluence lower not appropriate primary link (below IE threshold)

NRC proposed screening guidance would increase volume of lower support column material considered to be susceptible to irradiation embrittlement.

Lower Support Column
Case #6: Partial “Synergistic” Embrittlement

- Hull’s Ferrite Evaluation: Content calculated ferrite content for 80% support columns <15%, remaining 20% are between 15 and 20% ferrite
  - Fluence threshold:
    - 80% @ 1.5 dpa (irradiation embrittlement)
    - 20% @ 0.45 dpa (synergistic effect)
  - Realistic situation
- A/LAI 7 Response:
  - 80% of columns not susceptible to thermal embrittlement
  - Top few inches of all columns susceptible to irradiation embrittlement (>1.5 dpa)
  - 20% of columns with embrittlement range extended 0.45 dpa
  - Are Functionality or Flaw Tolerance Assessments required?
    - Same as Case 3 (No TE) except 20% of columns with volume of LSC over threshold fluence slightly expanded
- Remaining Issues
  - Include in Functionality Analysis?
    - IASCC unlikely due to higher stress and dose threshold
  - CRGT flange weld fluence lower not appropriate primary link (below IE threshold)

NRC proposed screening guidance would increase volume of lower support column material considered to be susceptible to irradiation embrittlement.

Impact of NRC CASS Screening Proposal Lower Support Columns

Lower Support Columns

- Impact of “Synergistic” embrittlement range between 15% and 20% Ferrite (Case 5 and Case 6)
  - A/LAI 7 Response (Modified Case 3):
    - Not susceptible to thermal embrittlement
    - Top few inches susceptible to irradiation embrittlement (>1.5 dpa or >0.45 dpa)
- Remaining Questions:
  - If Cases 3, 5 and 6 are not susceptible to thermal embrittlement, is functionality or flaw assessment required?*
  - Include in functionality analysis?
    - IASCC unlikely due to higher stress and dose threshold
  - CRGT flange weld fluence lower not appropriate Primary link (Below IE threshold)

* If Case 3 does not require functionality/flaw assessment and Cases 5 & 6 do, then the plants with ferrite contents between 15% and 20% carry an extra burden. It is not clear that there are any clear safety benefits to be gained from this additional effort.

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Impact of NRC CASS Screening Proposal

- Other Reactor Internals Components
  - Top surface of upper core plate near 1 dpa
    - Decreasing Fluence threshold to 0.45 dpa may increase volume of CASS material subject to irradiation embrittlement in upper internals.
  - A/LAI 7: “The requirement may not apply to components that were previously evaluated as not requiring aging management during development of MRP-227.”

NRC Position on TE and IE

Comments on NRC Proposed CASS Screening Criteria for Thermal and Irradiation Embrittlement

Industry Comment #1

Components with Adequate Toughness are Screened-in by NRC Position

The screening differences between the NRC revised position and the industry position (BWRVIP Letter 2014-086, ML14174A841) may seem to be small from a technical perspective. However, the two positions are very different when implementation and demonstration required by licensees is taken into consideration because of component locations screened in (current NRC position) versus those same locations screened out (industry position). For a CASS component internals location with delta ferrite content of 16% and neutron exposure of 0.5 dpa, the NRC revised position seems to recognize that existing data implies that the fracture toughness remains adequate to maintain component functionality. However, where the industry position relied on these existing data to screen out this particular component location, the NRC revised position will require demonstration of that adequacy, with all of the attendant difficulties for each licensee to provide actual – as opposed to implied – data to support the demonstration. It seems likely that a fairly significant number of component locations will involve delta ferrite content between 16 and 20%, with neutron exposures in the 0.2 dpa to 0.75 dpa range, which will eventually lead to extensive functionality demonstration costs, and where the NRC revised position appears to recognize that – while the fracture toughness has been reduced considerably – the component functionality is not threatened.

NRC Staff Response:

No comment provided.

Industry Comment #2

Lower Screening Criteria Not Required for Conservative Fracture Analysis of Assumptions Applied to Reactor Internals.

The current NRC position observes correctly that the 255 kJ/m^2 J value at 2.5 mm of crack extension was based on elastic-plastic fracture toughness assessment of simplified CASS piping components. This is likely overly conservative for RVI CASS components that are largely subjected to compressive stresses, which may be configured within a redundant structural system, and whose functionality does not include pressure boundary functions. From this observation, one might have expected a slightly less conservative set of screening criteria, more along the lines of the industry position. That is not the case. The level of required technical demonstration for CASS RVI component locations will be substantial.

NRC Staff Response

Staff and industry agree in principle that 255 kJ/m^2 is probably too conservative, but this needs to be demonstrated via generic flaw tolerance evaluations of RVI components justifying a lower toughness to be used as a basis for the revised screening levels. Industry needs to perform this work not NRC instead of asking NRC to rely on engineering judgment with regard to an appropriate toughness level. (EPRI TR-112718 appears to show that this type of work has already been done for certain cases.)

Industry Comment #3
J value at 2.5 mm (for 20% or lower ferrite) is >255 kJ/m^2

For the BWRs, the critical concern is to maintain the 20% ferrite level with the preferred position being 1 dpa as the screening criteria. There must be agreement that the J value at 2.5 mm (for 20% or lower ferrite) is >255 kJ/m^2 as supported by the BWRVIP response to the RAI-9a. This is consistent with BWRVIP-234 Table 6-1 which built a series logic for the acceptability of the CASS components.

NRC Staff Response:

No comment provided.

Industry Comment #4

BWR components listed in Table 6-1 of BWRVIP-234 do not require any augmented inspections.

Given the original arguments put forth supporting the 255 kJ/m^2 toughness arguments presented in BWRVIP-234 and supported in detail by the latest RAI-9a response, it is important to affirm that the BWR components listed in Table 6-1 of BWRVIP-234 do not require any augmented inspections. We believe that these data provide sufficient technical bases to allow the NRC to accept this position. The discussion that the toughness requirement is very likely conservative and was generated for piping further supports this position. If the NRC position is that inspections are required with the current data, it would be beneficial to understand the safety benefit of inspections when the expected variation in toughness is small. Further, it will be necessary to understand whether and what type of generic calculations can be used to justify a lower required value of J that will still demonstrate adequate fracture toughness for a component.

NRC Staff Response:

See staff response to Comment 2. Also, the staff observes there are only a couple of components in BWRVIP-234 Table 6-1 that would exceed 0.45 dpa. A component-specific fracture toughness basis could be developed for these components (fleet generic flaw tolerance evaluation for specific components).

Industry Comment #5
Request NRC Comment on Austenite vs. Ferrite Control

The "TE" section of the current NRC position notes that NUREG/CR-4513, Rev. 1 provides lower-bound fracture toughness J-R curves for aged CASS materials in three categories (<10%, 10-15%, and >15% delta ferrite contents) and that it also correlates with molybdenum contents and casting method (centrifugal vs. static). It also notes that the Grimes letter provides screening criteria correlated with J-R curves exhibiting a minimum J value at 2.5 mm crack extension of 255 kJ/m^2. However, it does not provide any discussion of the industry's approach for addressing TE relative to austenite control versus ferrite control.

NRC Staff Response:

Addressing TE via "austenite control" requires acceptance of the mechanistic theory that if the ferrite volume fraction is 20% or less, the toughness of the ferrite phase does not affect the bulk toughness. The NRC staff does not believe there is no effect on bulk toughness no matter how brittle the ferrite becomes, and is not aware of data that support the industry's position.

Industry Comment #6

Request NRC Comments on MRP-175 and MRP-276

The "IE" section of the current NRC position notes that fracture toughness for CASS materials decreased due to neutron irradiation above about 0.3 dpa, and considers this level as a threshold for changes in the measured fracture toughness. But, NRC notes also that embrittlement becomes significant at slightly higher fluence levels, 0.5-2 dpa, depending on the material. However, there is no discussion of the industry's evaluation of data that was reported in MRP-276 or the screening criterion and its basis developed in MRP-175.

NRC Staff Response:

Dated evaluated in MRP-276 was the Kim et. al data. The staff feels this data is of limited value because it was tested at room temperature, used small specimens, and lacks data in the transition fluence range of 0.5-2 dpa.

Industry Comment #7

Fluence Range for Fracture Toughness Curve in NUREG/CR-7207

The "NRC staff's position" section notes that the 0.45 dpa fluence selection correlates to a fracture toughness of 255 kJ/m^2 when toughness is predicted with Equation 25 from NUREG/CR-7027. It is not clear how 0.45 dpa is chosen since, as is stated in NUREG/CR-7027 (page 78, paragraph below Figure 64), "the lower bound curve indicates that for cast SSs and welds irradiated **<u>up to 1.0 dpa</u>**, the predicted J at 2.5 mm is above the screening value of 255 kJ/m^2 (1456 in.-lb/in.^{2})." (Note: bolded text and underline added for emphasis)

<u>NRC Staff Response:</u>

The statement in the NUREG text is not accurate. When J@2.5 is calculated using 1 dpa in equation 25, the actual value is 208 kJ/m^2.

Industry Comment #8

Request Technical Basis for Lower Ferrite Screening Levels in Proposed NRC Guidance

The "NRC staff's position" section also notes that the staff applies criteria to two different ferrite screening levels depending on neutron "exposure". The staff suggests changing the ferrite screening to the levels described in NUREG/CR-4513, Rev. 1 (10% and 15% ferrite) from the current ferrite screening levels (14% and 20%) accepted both by the staff and industry for license renewal (e.g., the Grimes letter, MRP-175, and MRP-227-A) without a described technical basis. The basis data for the 14% and 20% screening levels of ferrite are established in industry documentation that clearly states the conservatism used in determining these values and thus it is not clear why additional conservatism (i.e., decreasing the ferrite screening levels to 10% and 15%) is required.

See following slide for NRC Staff response

Industry Comment #8
Request Technical Basis for Lower Ferrite Screening Levels in Proposed NRC Guidance

NRC Staff Response:

Basis for Reduced Ferrite Screening Levels at > 0.45 dpa

- NRC reduced ferrite content
  - Accounts for uncertainty of end state toughness due to IE+TE
  - NUREG/CR-4513 J-R curves for TE alone show significant margin above 255 kJ/m^2 at 2.5 mm crack extension at:
    - 10-15% ferrite for low-moly
    - <10% ferrite for high-moly
- This provides margin for uncertainty wrt additional embrittlement due to fluence

See Figure 1 below for an illustration of the principle. The figure shows there is considerable margin for the lower bound curves for CF-3 and CF-8 above the 255 kJ/m^2 toughness level at 2.5 mm crack extension. However, for the CF-8M with the same ferrite range, the toughness is right around 255 kJ/m^2. Therefore, for the CF-8M there is no additional margin for reductions in toughness due to irradiation effects. Figure 2 shows a similar plot for <10 ferrite, which shows even CF-8M has some margin of toughness above 255 kJ/m^2 at 2.5 mm crack extension.

Industry Comment #8
Request Technical Basis for Lower Ferrite Screening Levels in Proposed NRC Guidance

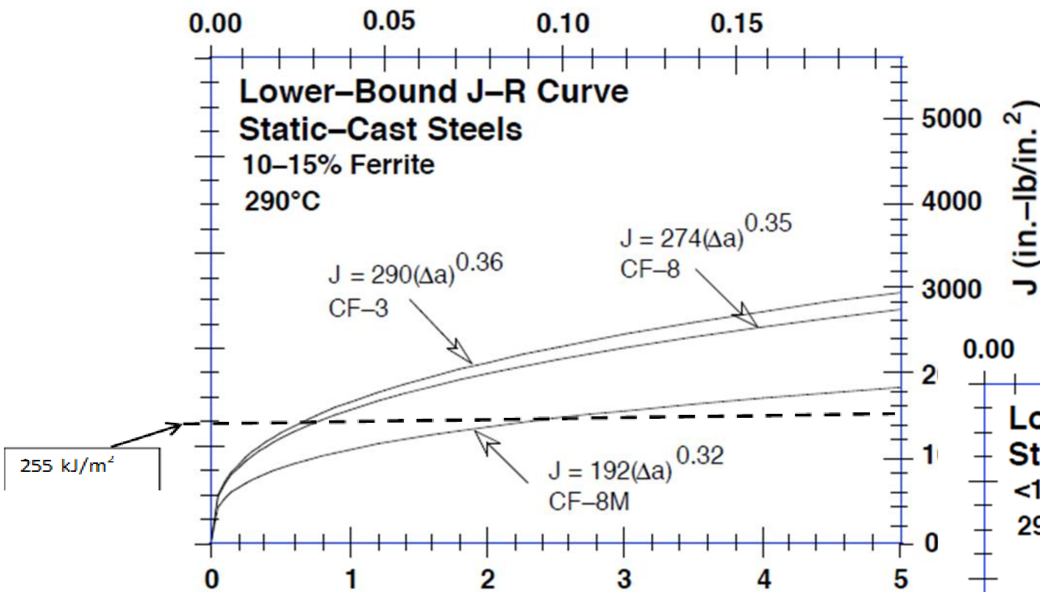

Figure 1 - NUREG/CR-4513 Lower Bound J-R Curves for 10-15% Ferrite Showing Margin Above 255 kJ/m^2 at 2.5 mm for CF-3 and CF-8

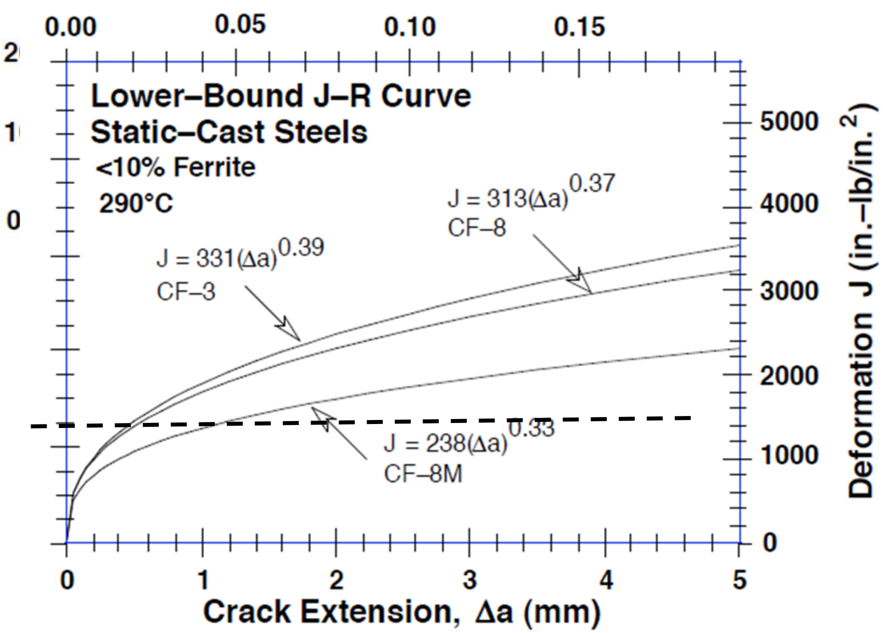

Figure 2 - NUREG/CR-4513 Lower Bound J-R Curves for <10- Ferrite Showing Margin Above 255 kJ/m^2 at 2.5 mm for CF-8M

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Industry Comment #9

Proposed NRC Position Appears to Imply that IE and TE effects re additive

The "NRC staff's position" section of the position also notes in item 3 of its numerical summary that "components may also be susceptible to TE…". It is not clear as to why this statement is necessary. The first sentence ("Above 1.5 dpa, all stainless steel and CASS…") states it clearly that at high fluence levels loss of fracture toughness requires aging management. The second sentence appears to suggest that embrittlement is additive, which it is not; once the material is embrittled, it is embrittled.

NRC Staff Response:

The staff agrees IE and TE may not simply be additive but the potential for a lower end of life toughness should be considered in any evaluation using estimated fracture toughness properties.

Industry Comment #10

Lower Screening Criteria Not Required for Conservative Fracture Analysis of Assumptions Applied to Reactor Internals.

Table D has a column listed as “FN.” This is incorrect; the column should correctly be listed as “Delta Ferrite %.”

NRC Staff Response:

Noted – the staff made this change.

Industry Comment #11
Additional Sources of Conservatism in Analysis

Under the "NRC Staff's Position", it states that the 255 kJ/m^2 may be over-conservative considering non-pressure boundary applications and redundancy of function. It then discounts those conservatisms without providing any discussion as to what the magnitude of the conservatisms might be. The additional information to address the conservatisms is partly available empirically or from structural fundamentals; for example:

- The lack of a credible mechanism that would cause multiple initiations in the PWR environment in a narrow time frame.
- The low probability of any undetected pre-service flaws, and the likely random spatial distribution of their occurrence in an assembly.
- The lack of observed failures or confirmed cracking in any CASS components after many years of operating experience in PWRs and BWRs.
- Consideration that much of the operational stress loading is secondary; i.e., displacement controlled self-relieving stresses, mostly thermal, and that the sizing of the structural members is conservative for safety function primary loads.

See following slide for NRC Staff response

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Industry Comment #11
Additional Sources of Conservatism in Analysis

NRC Staff Response:

The bullets above are describing elements of what the staff would consider a functionality analysis. This would typically be done for components that did not pass the screening criteria, such as for an MRP-227-A Action Item 7 evaluation. Such elements could be considered in a generic industry evaluation justifying a lower fracture toughness value as the basis for the screening criteria. Quantitative demonstrations are typically more compelling.

Industry Comment #12
Impact of NRC Proposed Screening Criteria

As requested, industry will provide comments on Table D of the current NRC position at the July 15, 2014 meeting.

NRC Staff Response:

No staff response necessary.

NRC Summary – General Comments

- There is very little data for CASS subject to both thermal aging and irradiation representative of reactor vessel internals operating conditions.
- There is almost no IE+TE fracture toughness data for CASS in the 0.5 dpa-2 dpa transition range of interest.
- NRC screening criteria are similar, but a little more conservative than industry's.
- The staff feels that erring on the conservative side is appropriate, particularly when there is a lack of data to support either position.
- Industry should develop analyses supporting a lower fracture toughness basis for the screening criteria, such as generic flaw tolerance analyses.
- NRC staff is not convinced that industry's mechanistic argument regarding austenite controlled or ferrite controlled CASS toughness is valid. I.e., staff does not believe ferrite toughness has no effect on bulk toughness just because ferrite is below 20%.
- Some data does show toughness can be lower for CASS with IE+TE, than that caused by IE or TE alone.
- Lower fluence screening criteria and adjustments to ferrite screening criteria above this fluence are intended to make address uncertainties in behavior of CASS under IE+TE.
- See Figure A-2 of 2014-086 (Fig. 60 of NUREG/CR-7027, for Heat 75 – J @ 2.5 for fully aged + irradiated ~ 125 kJ/M^2 vs. same heat, fully aged and unirradiated, from Table 7 of the Supplemental Information in 2014-086, J@ 2.5 is 418 kJ/m^2.

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NRC Staff Interpretation of Industry Position

- Toughness drops due to ferrite embrittlement and austenite embrittlement – **Staff agrees**.
- Screen on thermal, everything with high ferrite is in – **Staff agrees**.
- For high dpa, everything screens in – **Staff agrees**.
- For those things not already in, screen for IE – **Staff agrees**
- Set IE screening level so that (effectively) most things screen out
- Recognize that chosen level is beyond where embrittlement starts, i.e., chosen level is where degradation in toughness is significant – **Staff agrees**
- For those things that are embrittled by IE, but not fully embrittled, screen them out because they have adequate toughness because not much toughness is needed. Even the NRC admits that the 255 kJ/m^2 J value at 2.5 mm is conservative, but NRC has not quantified what the conservatism means, so NRC should just let us screen everything out because these components really don't need to be tough.
- Industry doesn't like the NRC screening because some things might screen in, and then the industry would need to perform analyses to show how much toughness is required, and that is hard and expensive.
- If there is less than 20 volume percent of a microstructural component, changes in material properties of that component has zero effect on the bulk properties.

Summary

- Common (PWR and BWR) approach for screening of TE and IE developed
  - TE before IE
    - Once screened in for TE, no additional screening required for IE
    - If not screened in for TE, then screen for IE
  - IE screening at 1 dpa
    - More conservative in several locations compared to staff
    - Where less conservative, no meaningful impact on safety with less effort/burden in the screening process

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