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2015-025 BWR Vessel & Internals Project (BWRVIP)

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Document Control Desk
U.S. Nuclear Regulatory Commission
11555 Rockville Pike
Rockville, MD 20852

Attention: Joseph Holonich

Subject: Project No. 704 – Summary of Industry Position on Screening Criteria for Thermal and Irradiation Embrittlement for PWR and BWR Reactor Internals Fabricated of Cast Austenitic Stainless Steel

References:
1. Letter from D. Madison (BWRVIP Chairman) and A. McGehee (BWRVIP Program Manager) to J. Holonich (NRC), Project No. 704 – BWRVIP Response to NRC Request for Additional Information on BWRVIP-234, dated May 23, 2014. ADAMS - ML14174A841.
2. Letter from J. Holonich (NRC) to A. Mendiola (NRC), Summary of the July 15, 2014, Meeting with the Electric Power Research Institute on Items Related to Cast Austenitic Stainless Steel and the Materials Reliability Program-227-A, "Pressurized Water Reactor Internals Inspection And Evaluation Guidelines," September 9, 2014. ADAMS - ML14127A077.
3. "NRC Position on Aging Management of CASS Reactor Vessel Internal Components," June 23, 2014, ADAMS - ML14174A719.
4. Email from C. Wirtz (EPRI) to J. Holonich (NRC), October 7, 2014.
5. NUREG/CR-4513, ANL-93/22, Revision 1, "Estimation of Fracture Toughness of Cast Stainless Steels During Thermal Aging in LWR Systems," Argonne National Laboratory, May 1994.

The purpose of this letter is to provide the status of the Industry (PWR and BWR) activities associated with developing and proposing a generic screening criteria to address thermal and irradiation embrittlement of RPV internals fabricated of cast austenitic stainless steel (CASS).

Reference 1 was provided to the NRC in response to a Request for Additional Information (RAI) regarding BWRVIP-234. The RAI response contained supplemental information that provided the technical bases for an Industry screening criteria for CASS internals.

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A meeting was later held on July 15, 2014 at NRC offices in Washington, DC to discuss the Industry and NRC positions (References 2, 3). Based on that meeting, the Industry committed to investigate additional information where there was disagreement with the NRC regarding the screening criteria and provide said information to the NRC at a later date. That information was informally submitted for NRC's consideration (Reference 4) and is contained in Attachments A through D of this letter. A conference call was then held on November 20, 2014 with the NRC to discuss this information.

Following this conference call the NRC indicated that they were not willing to deviate from their position documented in Reference 3.

Despite the NRC's current stance on the matter, the following comments regarding a generic TE and IE criteria for evaluation of reactor internals are important in forming the basis for the industry position:

- The industry recognizes that the NRC is intending to revise its original IE position in the Grimes letter from $1x10^{17}$ n/cm^2 (0.00014 dpa) to a position in the region of 0.5 to 1.5 dpa. Industry agrees that this position is more appropriate and has proposed a conservative value of 1 dpa.
- It is not appropriate (for the staff) to penalize all non-Mo containing CASS (such as CF3 and CF8) because of the lower properties associated with the Mo-containing CF8M materials that are included in the ANL/NRC database, i.e., impose a lower bound.
- There is no substantive data that demonstrates a synergistic effect for CASS materials that are typical of reactor internals (such as CF3 and CF8). As such the industry has proposed criteria that do not combine TE and IE. Each mechanism is considered distinct and separate.
- The introduction of a new criteria set for the category of materials with ferrite content between 15% to 20% having a lower proposed screening value for IE of 0.45 dpa is unnecessary and technically unfounded. The introduction of this category of ferrite content is significantly burdensome to licensees since it will require more complex and potentially more error-prone assessments of CASS material components by virtue of having more categories. Industry maintains that the categories of materials and associated ferrite levels contained in the Grimes letter are appropriate.
- The criteria proposed by the industry (20% Ferrite and 1 dpa) have been shown to project significant margin on toughness reduction and therefore safety when compared to measured embrittlement behavior for CF3 and CF8 materials.

Regardless, this letter serves to formally submit this additional information to the NRC for review and consideration in developing a regulatory position for the screening criteria associated with TE and IE for CASS internals and to inform revisions to NUREG-4513, Rev. 1 (Reference 5). The PWR and BWR Industry position for TE and IE screening criteria is shown in Attachment D.

Irrespective of the staff's decision and future promulgation of a regulatory position on TE and IE for CASS internals, the BWRVIP formally requests the NRC to evaluate and resolve the RAI responses associated with BWRVIP-234 and issue a Safety Evaluation.

If you have any questions on this subject please call Ron DiSabatino (Exelon, BWRVIP Assessment Committee Technical Chairman) at 717.456.3685.

Sincerely,

A. O. McGehee Tim Hanley

Andrew McGehee, EPRI, BWRVIP Program Manager
Tim Hanley, Exelon Corp., BWRVIP Chairman

Industry Response to July 15, 2014 Meeting with NRC on CASS

On July 15, 2014, representatives from the BWRVIP/MRP Working Group on Cast Austenitic Stainless Steels (CASS) met with the NRC staff to discuss the thermal and irradiation embrittlement screening criteria for cast austenitic stainless steel. While the working group and NRC staff were in general agreement on the thermal embrittlement (TE) screening criteria, there was a marked difference of opinion on the irradiation embrittlement (IE) screening criteria, particularly for materials with delta ferrite contents of 15-20% (the NRC proposed 0.45 dpa, while the industry proposed 1 dpa).

Agreement was reached on the TE screening criteria in part because the data on low-molybdenum and high-molybdenum material are considered separately, resulting in separate TE screening criteria for these materials. This distinction is made because high-molybdenum materials show a distinctly greater loss of fracture toughness from TE and IE effects than low-molybdenum materials. This is reviewed and discussed further in Attachment A

The separate consideration of low- and high-molybdenum materials test data was not carried over into the IE domain. The data set used to determine the NRC's position on IE was obtained from NUREG-7027, which considered irradiated high- and low-molybdenum materials together, along with data on irradiated welds. Because these materials were considered together, the resulting lower bound curve is judged to be overly conservative relative to the low-molybdenum material. A reexamination of this data (see Attachment B), shows that by considering the low-molybdenum materials test data independently of the other materials it can be concluded that there is a substantial safety margin in the industry's proposed 1 dpa screening criteria.

These screening criteria are being implemented to ensure that CASS components in reactor vessel internals maintain adequate fracture toughness during the period of extended operation. The screening level to determine whether this requirement was met was a J value of 255 KJ/m^2 at a crack extension of 2.5 mm. This value was originally determined for pressure boundary components (i.e., large diameter piping, etc.) and was expected to be highly conservative for application to reactor vessel internals. Additional calculations (see Attachment C) demonstrate the level of this conservatism and show that reactor vessel internal components can safely operate with fracture toughness values much lower than the 255 KJ/m^2 value specified in the Grimes letter.

In summary, the actions taken by the CASS industry working group and summarized in Attachments A, B and C support the proposed screening criteria contained in Attachment D. These criteria provide a significant amount of margin for screening of TE and IE. It is concluded that that the use of the proposed screening criteria will allow for continued safe and reliable operation of the LWR fleet.

Attachment A

Discussion on Low Molybdenum vs High Molybdenum CASS Grades

Introduction

A meeting was held on July 15, 2014 at the NRC Office in Washington, DC between the staff of the U.S. Nuclear Regulatory Commission (NRC) and the BWRVIP/MRP Working Group on Cast Austenitic Stainless Steels (CASS). The topic of discussion focused on the thermal aging and neutron irradiation embrittlement screening criteria (separately) proposed by the industry and the NRC staff. The proposals included criteria for low-molybdenum CASS grades, such as CF-3 and CF-8, and high-molybdenum CASS grades, such as CF-8M. There was agreement between industry and the NRC staff regarding the differences in such measures of embrittlement as elastic-plastic crack growth resistance (J-R curve) for the low-Mo materials versus the high-Mo materials, at least where thermal aging embrittlement effects are dominant. In fact, screening criteria proposed by the staff are identical to the industry-proposed screening criteria for the case of thermal aging embrittlement.

However, the areas of agreement between the industry and the staff did not carry over to combined environments where the effects of neutron irradiation embrittlement begin to approach the same level as those from thermal aging embrittlement. In order to address these differences in criteria, the available data for CF-3, CF-8, and CF-8M materials in the literature are reviewed and assessed, with a recommendation to the NRC staff for a change to their proposed criteria to more closely agree with the criteria proposed by the industry.

Review and Summary of Thermal Aging Embrittlement Data

The significant differences in thermal aging embrittlement behavior of the low-molybdenum grades of cast austenitic stainless steel, such as CF-3 and CF-8, versus the thermal aging embrittlement behavior of the high-molybdenum grades, such as CF-8M, have been known for at least two decades, with extensive data and associated interpretations of said data documented in NUREG/CR-4513, Revision 1 [1]. The lower-bound thermal aging embrittlement estimates shown in Figures 3 (statically-cast steels) and 4 (centrifugally-cast steels) from Reference 1 with varying amounts of delta ferrite provide an excellent illustration of those significant differences, in this case with the measure of significance being the crack-growth resistance J-R curve. In particular, the lower-bound formulas cited in Section 3.1.1 of Reference 1 (and plotted in Figures 3 and 4) can be used to compare the estimated crack growth resistance values at 2.5 mm of crack extension for the CF-3, CF-8, and CF-8M steels with >15% delta ferrite. Note that Figure 3 provides lower-bound thermal aging estimates for static-cast steels, while Figure 4 provides lower-bound thermal aging estimates for centrifugally-cast steels.

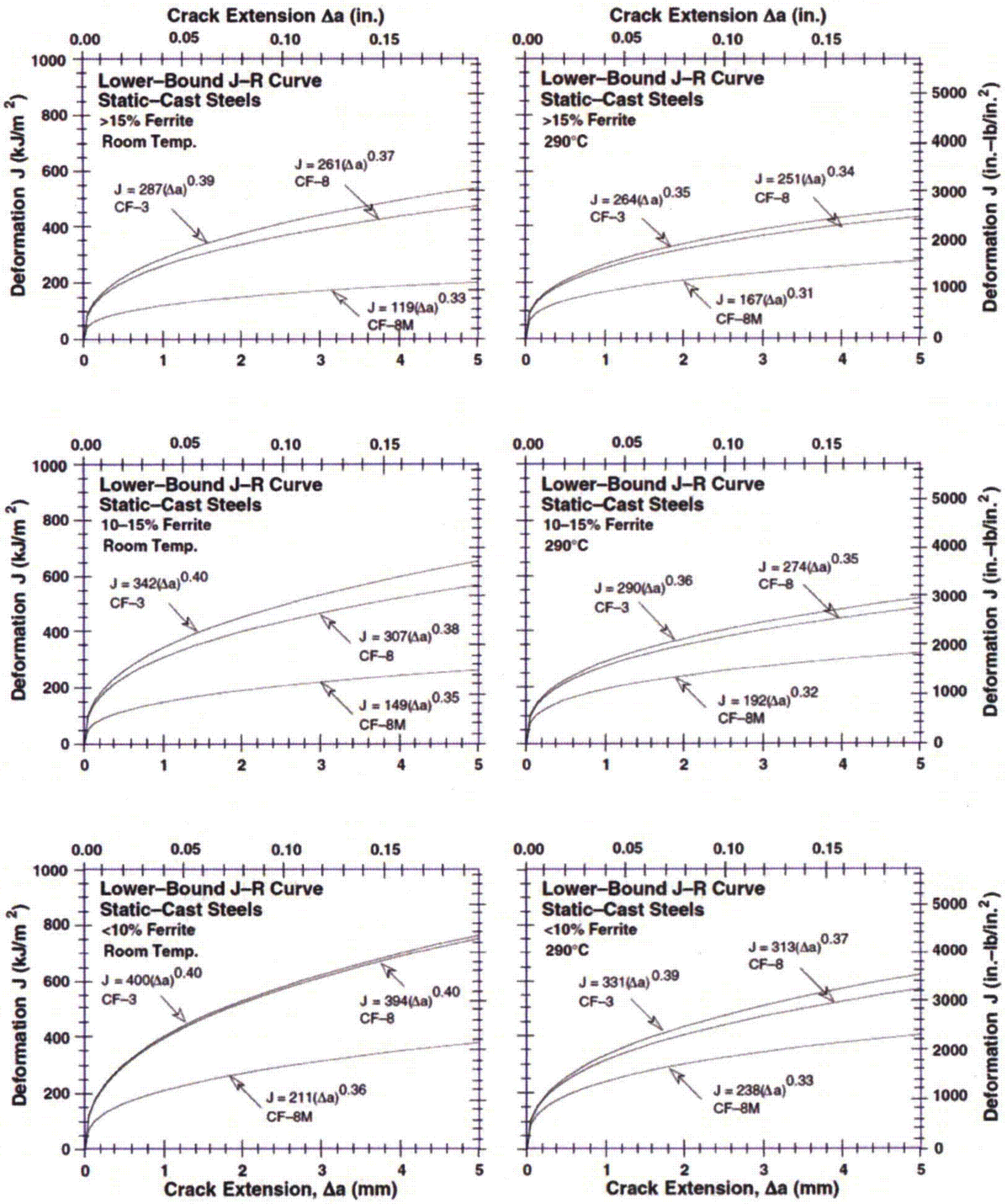

Figure 3. *Predicted lower-bound J-R curves at RT and 290°C for static-cast SSs with ferrite contents >15, 10–15, or <10%*

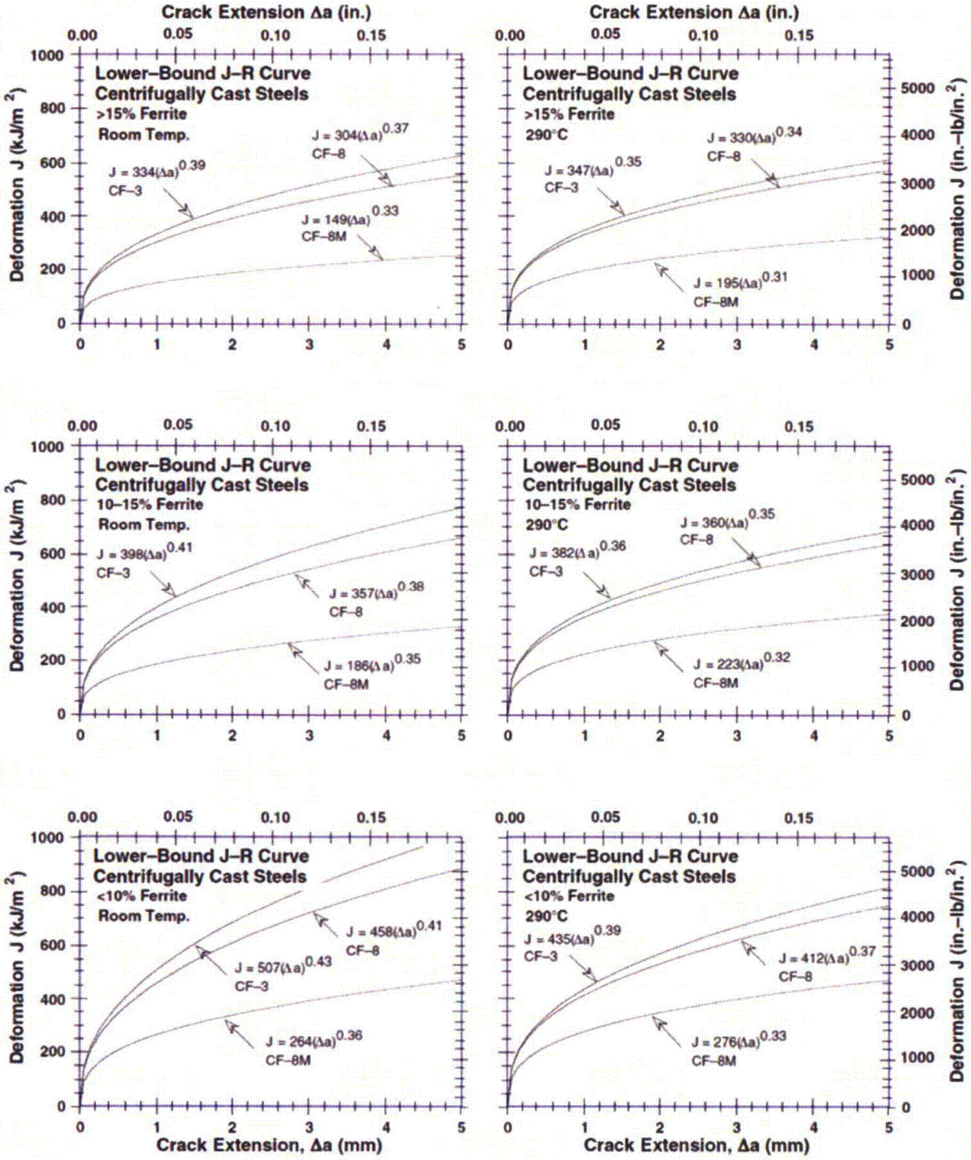

Figure 4. Predicted lower-bound J-R curves at RT and 290°C for centrifugally cast SSs with ferrite contents >15, 10–15, or <10%

For CF-3, the lower bound crack growth resistance, for statically- and centrifugally-cast materials, varies between 364 and 478 kJ/m^2, and for CF-8, between 343 and 451 kJ/m^2. On the other hand, the CF-8M values vary between 161 and 259 kJ/m^2. When the data are examined very closely, there is no significant difference between the static-cast lower-bound estimates for CF-3 and CF-8 in Figure 3 and the centrifugally-cast lower-bound estimates for CF-3 and CF-8 in Figure 4. The data also show that these insignificant differences are roughly identical to the differences between CF-3 and CF-8 estimates within the static-cast and centrifugally-cast populations. Therefore, based on this examination of lower-bound estimates, the CF-8M data exhibit substantially lower fracture toughnesses and are therefore unsuitable as a lower-bound estimate for the low-molybdenum grades. Lower bound estimates must be conservative, but they must also remain representative of the data. Table 1, shown below, succinctly summarizes the data comparisons extracted from Figures 3 and 4 from Reference 1.

Table 1. Lower Bound Fracture Toughness Estimates

CASS Steels	J-values at 2.5 cm of Crack Growth (kJ/m^2)	Comments
CF-3 Steels	364 to 478	Lower bound above the threshold value of 255 kJ/m^2
CF-8 Steels	343 to 451	Lower bound above the threshold value of 255 kJ/m^2
CF-8M Steels	161 to 259	Lower bound might be less than threshold values of 255 kJ/m^2

Table 1 clearly shows that lower bound fracture toughness values of CF-3 and CF-8 steels are much higher than CF-8M steels, and that only the fracture toughness of CF-8M steels fall below the threshold value of 255 kJ/m^2. Therefore, the screening criteria for CF-8M (high molybdenum) steels should be considered separately from CF-3 and CF-8 (low molybdenum) steels.

Thus far, the data evaluation has been based on lower-bound fracture toughness estimates derived from Charpy impact correlations. However, these lower-bound thermal aging embrittlement estimates can be confirmed by examining actual crack extension resistance curve measurements for various heats of CF-3, CF-8, and CF-8M with delta ferrite content in the range of 20%. For example, Figure 14 from Reference 1 shows J-R curve measurements, along with thermal aging saturation estimates for two heats of CF-3 material (Heat 69 and Heat I) and one heat of CF-8 material (Heat 68), while Figure 15 from Reference 1 shows similar results for three heats of CF-8M material (Heats 74, 75, and 758).

In this case, it should be noted that the actual fracture toughness data are based on thermal aging saturation conditions and are therefore somewhat higher than the lower-bound fracture toughness estimates. Also note that the thermal aging saturation fracture toughness data are based entirely on static-cast data for materials with delta ferrite in the range of 15% to 25%.

The crack extension resistance value at 2.5 mm of crack extension for the thermal aging saturation conditions for CF-3 and CF-8 materials ranges between 681 and 820 kJ/m^2 at room temperature, with values between 516 and 584 kJ/m^2 at operating temperature, while the values for CF-8M material are less than half of the low-molybdenum material values.

Therefore, the findings from the examination of the data in Figures 14 and 15, and the derived J values at 2.5 mm of crack extension, are completely consistent with the lower-bound thermal aging embrittlement estimates cited previously for both static-cast and centrifugally-cast material. In other words, the development of screening criteria for the low-molybdenum grades should be treated separately from the development of screening criteria for the high-molybdenum grades.

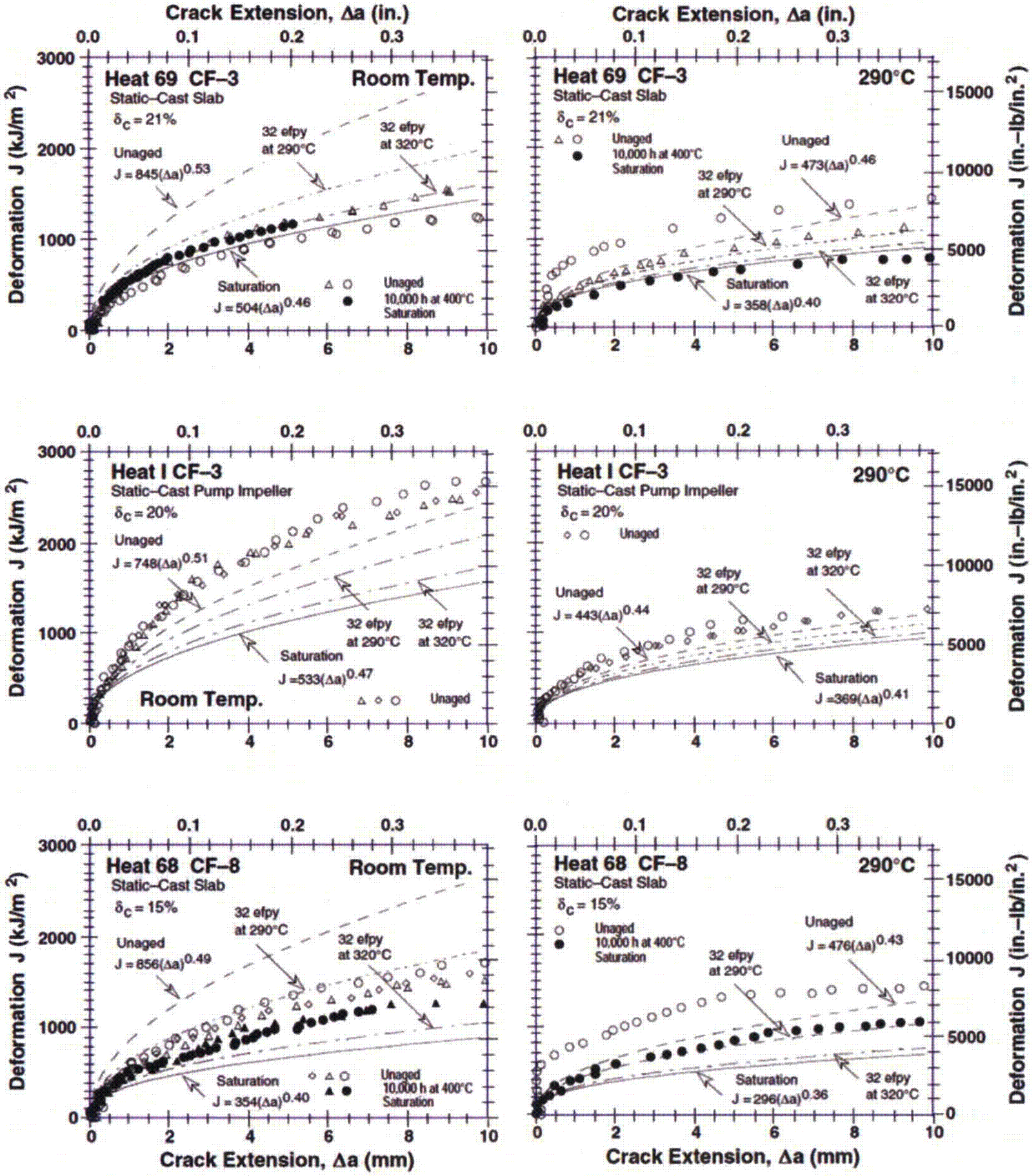

Figure 14. Saturation fracture toughness J-R curves at RT and 290°C, estimated from the chemical composition of static-cast CF-3 and CF-8 steels, and determined experimentally

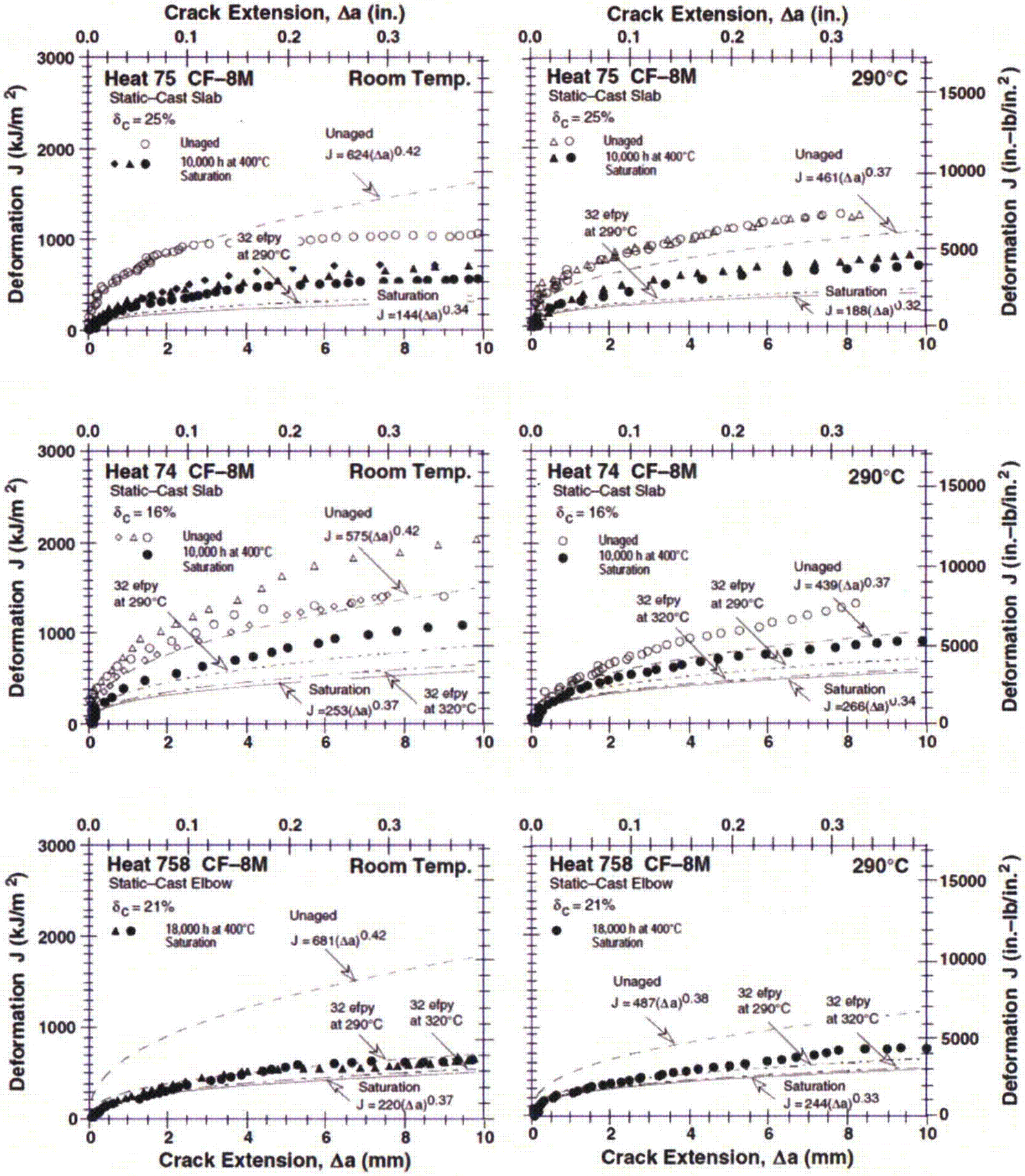

Figure 15. Saturation fracture toughness J–R curves at RT and 290°C, estimated from the chemical composition of static-cast CF-8M steels, and determined experimentally

Review and Summary of Combined TE and IE Data

The available data for purely thermally-embrittled CASS materials is quite extensive. However, that is not the case for a combination of thermal aging and neutron irradiation embrittlement. In spite of the limited data, the evaluation of available crack growth resistance data for CF-3, CF-8, and CF-8M material is not altered by including information on material subjected to both thermal aging and neutron irradiation embrittlement, as shown in Figures 23, 41, 49, and 58 from ANL-12/56 [2]. The results for Specimen B-1 (static-cast CF-3 material taken from Heat 69, with approximately 24% delta ferrite, thermally aged for 10,000 hours at 400°C, and then subjected to a neutron irradiation dose of 0.08 dpa) are shown in Figure 23 – taken from Reference 2. The extrapolated J value at 2.5 mm of crack extension is 789 kJ/m^2, very similar to the saturated, thermally-aged result, as shown in Figure 14 for Heat 69 from Reference 1.

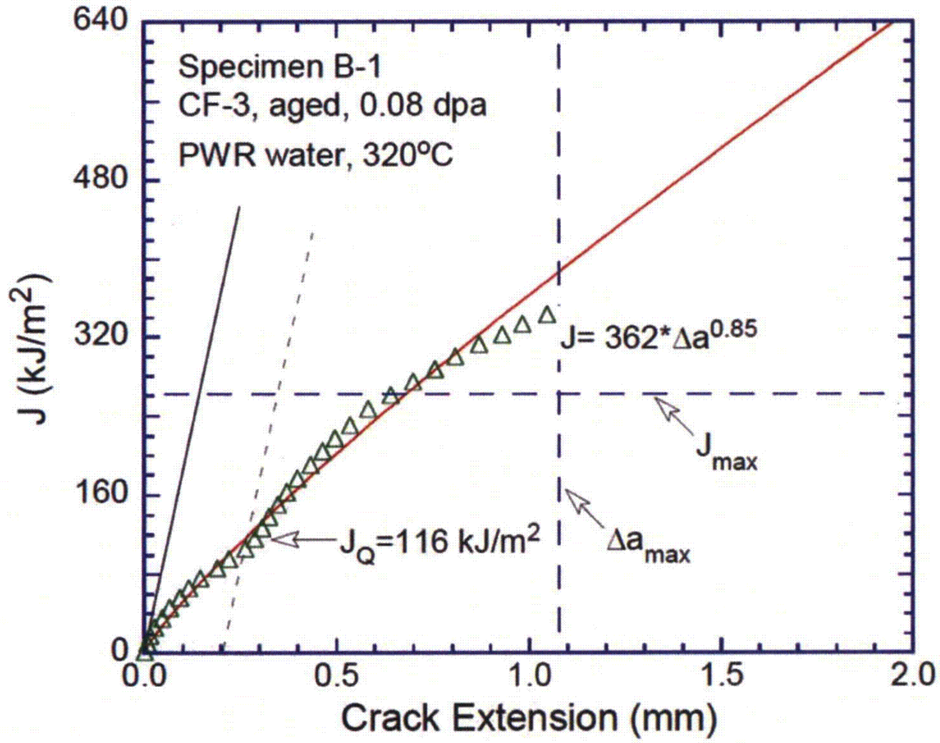

Figure 23. The J-R curve for specimen B-1.

Similarly, the results for Specimen F-1 (static-cast CF-8 material taken from Heat 68, with approximately 23% delta ferrite, thermally aged for 10,000 hours at 400°C and then subjected to a neutron irradiation dose of 0.08 dpa) are shown in Figure 41 – also taken from Reference 2. The extrapolated J value at 2.5 mm of crack extension is 657 kJ/m^2, very similar to the saturated, thermally-aged result, as shown in Figure 14 from Reference 1 for Heat 68.

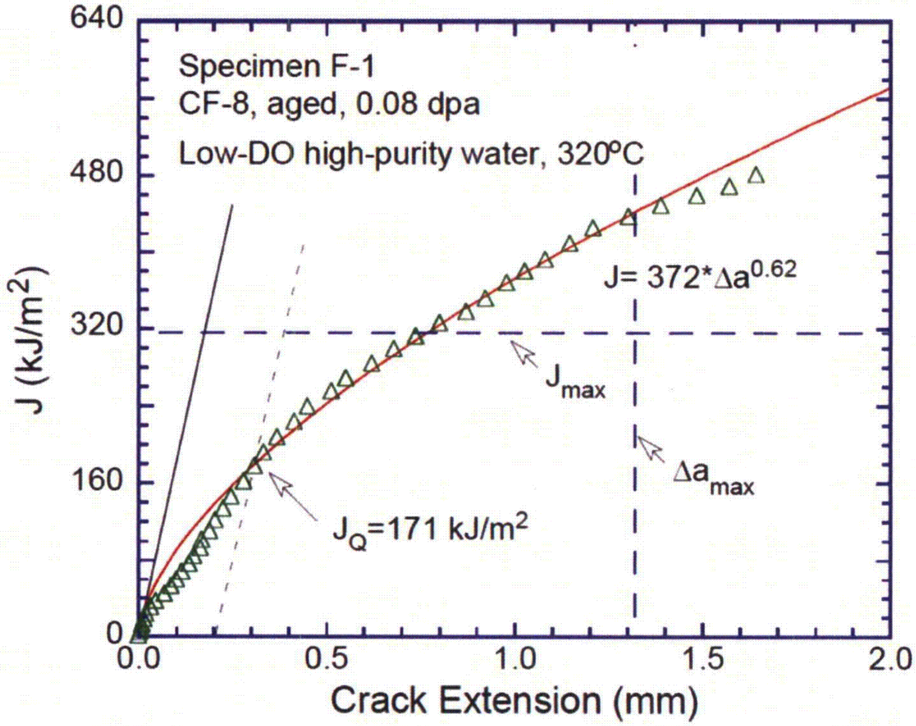

Figure 41. The J-R curve of specimen F-1.

Finally, the results for Specimens I-1 (CF-8M material taken from Heat 75, with approximately 28% delta ferrite, unaged but subjected to a neutron irradiation dose of 0.08 dpa) and J-1 (CF-8M material taken from Heat 75, with approximately 28% delta ferrite, thermally aged for 10,000 hours at 400°C, and then subjected to a neutron irradiation dose of 0.08 dpa) are shown in Figures 49 and 58 – also taken from Reference 2. In this case the extrapolated J value at 2.5 mm of crack extension for Specimen J-1 is 466 kJ/m^2, which can be compared to the results shown in Figure 15 from Reference 1 for Heat 75 that appear to be of the order of 300 to 400 kJ/m^2 at room temperature and operating temperature.

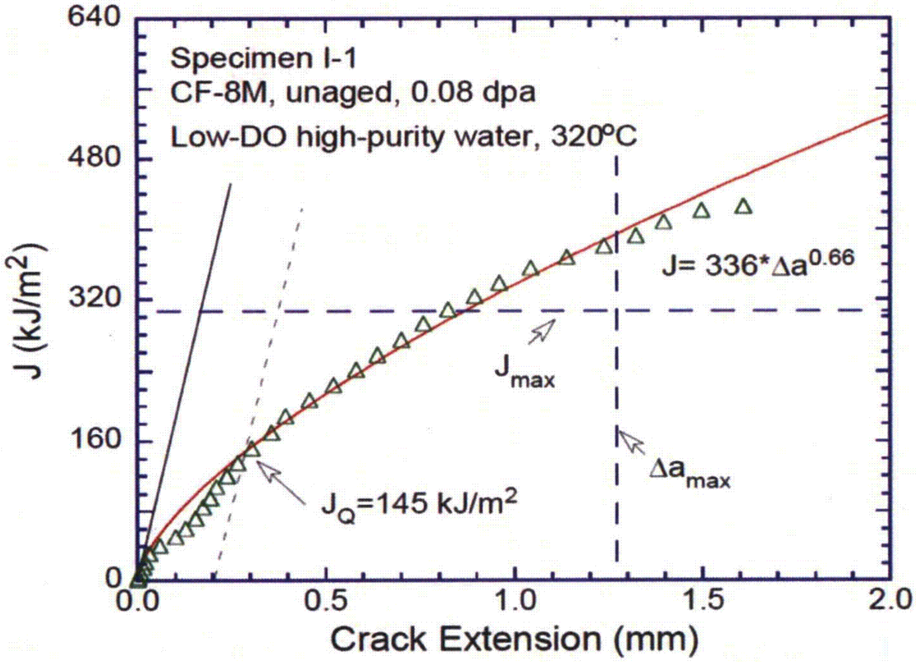

Figure 49. The JR curve of specimen I-1.

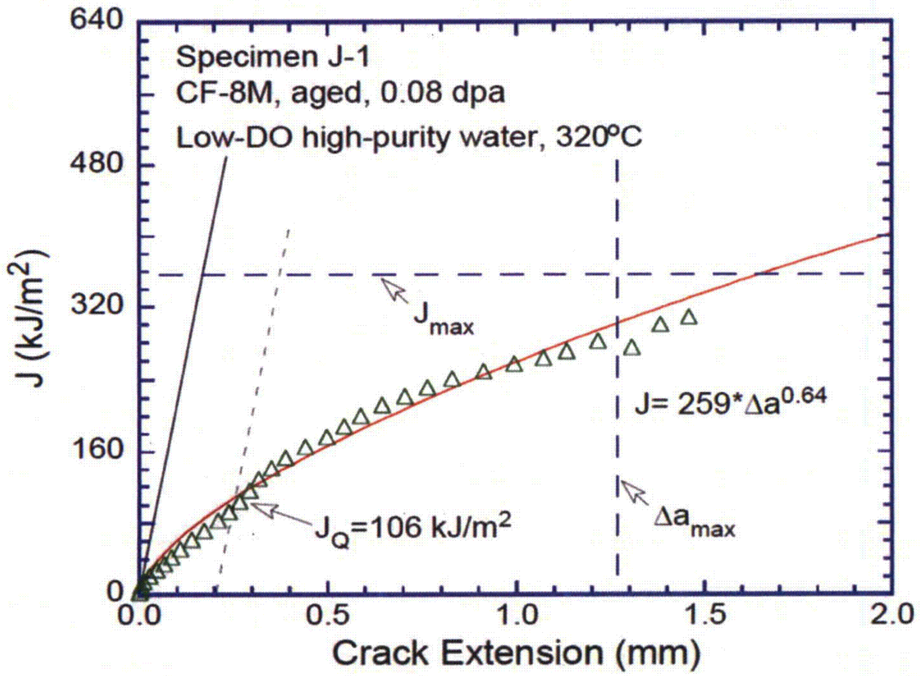

Figure 58. The JR curve of specimen J-1.

Conclusions and Recommendation

This review and summary of available data on CF-3, CF-8, and CF-8M CASS materials subjected to both individual and combined effects of thermal aging and neutron irradiation embrittlement demonstrated that:

- Thermal aging embrittlement effects on high-Mo grades are significantly more pronounced than the effects on the low-Mo grades, by roughly a factor of two or more based upon lower-bound crack growth resistance estimates. For CF-3, the lower-bound crack growth resistance values at 2.5 mm of crack extension for > 15% delta ferrite vary between 364 and 478 kJ/m^2, and for CF-8, between 343 and 451 kJ/m^2. On the other hand, the CF-8M values vary between 161 and 259 kJ/m^2 which are significantly lower compared to CF-3/8. These results are consistent with the results obtained by examining actual crack growth resistance value measurements at 2.5 mm of crack extension for the thermal aging to saturation for CF-3 and CF-8 materials (low-Mo) that range between 681 and 820 kJ/m^2 at room temperature, with values between 516 and 584 kJ/m^2 at operating temperature, while the values for CF-8M material (high-Mo) are less than half of the low-molybdenum material values.
- There is no significant difference between the static-cast lower-bound estimates and the centrifugally-cast lower-bound estimate for CF-3 and CF-8 materials, and those relatively small differences are roughly identical to differences between CF-3 and CF-8 lower-bound estimates. Using lower-bound crack growth resistance values at 2.5 mm of crack extension as the comparative measure, the CF-3 static-cast values of 364 and 410 kJ/m^2 compare very well to the 477 and 478 kJ/m^2 values for centrifugally-cast material, while the CF-8 static-cast values of 343 and 366 kJ/m^2 compare favorably with the 427 and 451 kJ/m^2 values for centrifugally-cast material. The differences between static-cast and centrifugally-cast values, and between CF-3 and CF-8 values are both inconsequential in comparison to the differences between low-Mo and high-Mo materials. Therefore these two grades may be considered as a combined category for screening purposes.
- The added effect of neutron irradiation embrittlement does not change the conclusions drawn with respect to low-Mo versus high-Mo fracture toughness. Finally, since the conclusions are drawn primarily from static-cast fracture toughness data, a recommendation to the NRC staff to maintain the screening threshold for low-Mo static-cast grades at 20% is supported by the data.

Therefore, this review shows that the CF-8M data provide an extremely conservative and thus unrepresentative lower bound to the data for the low-molybdenum grades. As such, the CF-8M lower bound is separable and distinct from the low-molybdenum grade lower bounds, which therefore require their own screening category and fracture toughness estimates. Thus, the delta ferrite levels stated in the BWRVIP-234 RAI response (from the Grimes letter) is further supported by this evaluation.

Finally, this review and the associated quantitative comparisons utilize the data sets as delineated in extensive documentation in NUREG/CR-4513, Revision 1 [1] and other relevant publically available references.

References

[1]. O. K. Chopra, "Estimation of Fracture Toughness of Cast Stainless Steels During Thermal Aging in LWR Systems," NUREG/CR-4513 (ANL-93/22), Revision 1, Argonne National Laboratory, Argonne, Illinois (August 1994).

[2]. Y. Chen, B. Alexandreanu, and K. Natesan, "Crack Growth Rate and Fracture Toughness Tests on Irradiated Cast Stainless Steels," Report No. ANL-12/56, Argonne National Laboartory, Argonne, Illinois (November 2012).

Attachment B

Conclusions Regarding Screening Criteria for Irradiation Embrittlement of CASS Materials

The screening criteria for TE and IE in CASS components proposed and discussed with the NRC [1] appears to be based on materials testing data that includes a high-molybdenum material, grade CF-8M, presented in Figure 64 in NUREG 7027 [2], with the following conclusions on page 79:

1. CF-8M materials represent a 'worst case' for thermal embrittlement
2. Thermal aging does not seem to lower the toughness below that expected for irradiation alone at the dose levels examined.

In regards to the use of this data, it is important to note that:

- CF-8M materials are not present in LWR core internal components.
- Moreover, the embrittlement identified in NUREG-7027 is conservative because many of the heats examined had delta ferrite contents greater than 20% and as high as 42% [3]. It is also important to emphasize that in LWR reactor internals, delta ferrite content does not typically exceed 20% as compared to the materials assessed in the NUREG database [2, 3].
- Loss of fracture toughness due to thermal embrittlement is driven by the amount of delta ferrite in a given material, thus the use of high delta ferrite material data is also conservative.
- ANL results comparing loss of fracture toughness measurements on unaged, thermally aged only, irradiation aged only and sequentially thermally aged and irradiation aged CF-3 and CF-8 materials show significant loss of toughness on ***all*** forms of aging. Measured toughnesses of thermally aged, irradiation aged and sequentially thermal plus irradiation aged materials are similar. Given the variances that are inherent in estimating J values as material characteristics, the differences in loss of toughness cited in Reference 4 cannot be taken to unequivocally demonstrate that irradiation and thermal aging are significantly additive effects to the loss of toughness in CF-3 and CF-8 cast austenitic stainless steels.
- The data summarized in Figure 64 of NUREG-7027 includes many high ferrite content and Mo-containing chemical compositions. The correlations developed in analyses based on this database are therefore expected to be very conservative with regard to the irradiation and thermal response of low ferrite content and low Mo containing chemical compositions.

The NRC is concerned that interaction between thermal and irradiation embrittlement mechanisms may lower the fracture toughness of CASS material below levels expected from the effect of either mechanism alone. Based on the potential for a synergistic effect and taking into account the NUREG-7027 data, the NRC has concluded that a very low level of irradiation would reduce the fracture toughness of a CASS component below the 255 KJ/m^2 criteria. This led to the NRC proposing a neutron irradiation screening criteria of 0.45 dpa for low molybdenum static CASS components with 15-20% delta ferrite. By reexamination of the data in NUREG-7027 a considerable amount of conservatism can be removed from the analysis while still providing reasonable assurance that CASS components in the LWR environment will retain adequate fracture toughness through the period of extended operations.

The irradiated materials data from NUREG-7027 were digitized from the plots of NUREG-7027 and reanalyzed to produce a trend curve for irradiated CF-3 and CF-8 materials only as shown in Figure 1 below. Note that the exposures of these materials not only represent irradiation effects but also some degree of thermal embrittlement. These data for CF-3 and CF-8 materials are most relevant to the behavior of CASS in LWR internals, as these are the materials that are principally known to be present in LWR reactor internals. Thus the correlation and proposed screening criteria are appropriately developed for these materials.

As an outcome of this analysis a plot of fracture toughness against neutron exposure was created, and a 'best fit' line was developed and the resulting curve was calculated to have a strong correlation with the data (R^2=0.94). The best fit line was then modified using conservative engineering judgment and standard curve offsetting techniques to bound all of the irradiated CF-3 and CF-8 material measured toughness values. (i.e., the pre-exponential constant multiplier was reduced by approximately 25% and the exponential factor was increased by 35% in order to bound every data point above the red-line exponential curve fit.) A constant of 30 kJ/m^2 was also included as a saturated fracture toughness value.

This saturated fracture toughness value is proposed by Chopra in NUREG-7027, and the overall form of the equation is consistent with irradiation hardening models [6]. This results in a curve fit where all data points are above the curve, with resulting curve fit of:

$$J_{2.5mm} = 30 + 520 \frac{KJ}{m^2} \times e^{-0.25 \times dpa}$$

This bounding line is shown as a red line in Figure 1.

By using the red (lower bound) line as a gauge for how CF-3 and CF-8 materials will age in the LWR environment, it can be shown that these materials will not encroach upon the 255 KJ/m^2 fracture toughness limit until the fluence level experienced by these components approaches 3.3 dpa. The industry proposed use of 1 dpa for neutron exposure screening criteria, provides more than a 2 dpa margin on neutron exposure between a CASS component at 1 dpa and the 255

KJ/m^2 fracture toughness limit. At 1 dpa, the fracture toughness predicted by the bounding curve in Figure 1 is 435 KJ/m^2, which results in a fracture toughness margin of 180 KJ/m^2.

Therefore, the industry's proposed criterion of 1 dpa has substantial margin in both the fluence and fracture toughness domains. This analysis and argument supports the use of the irradiation screening criteria of 1 dpa proposed by the industry for low molybdenum CASS components with ferrite content less than 20 percent.

Additionally, a study designed to investigate the potential interaction between thermal and irradiation embrittlement mechanisms concluded that irradiation can reduce the extent of thermal aging effects [5], suggesting an antergistic effect between the two mechanisms rather than a synergistic one.

This information indicates that the NRC's position is highly conservative, and that the industry's position on the screening criteria of CASS components, while also conservative, is justified.

References:

1. U.S. NRC, "NRC Staff Compiled Comments on Industry CASS Screening Position," July 18, 2014 (NRC ADAMS Accession Number ML14198A282.

2. NUREG/CR-7027, "Degradation of LWR Core Internal Materials due to Neutron Irradiation," December, 2010 (NRC ADAMS Accession Number ML102790482.

3. NUREG/CR-4513, "Estimation of Fracture Toughness of Cast Stainless Steels During Thermal Aging in LWR Systems," U.S. Nuclear Regulatory Commission, August 1994 (NRC ADAMS Accession No. ML052360554).

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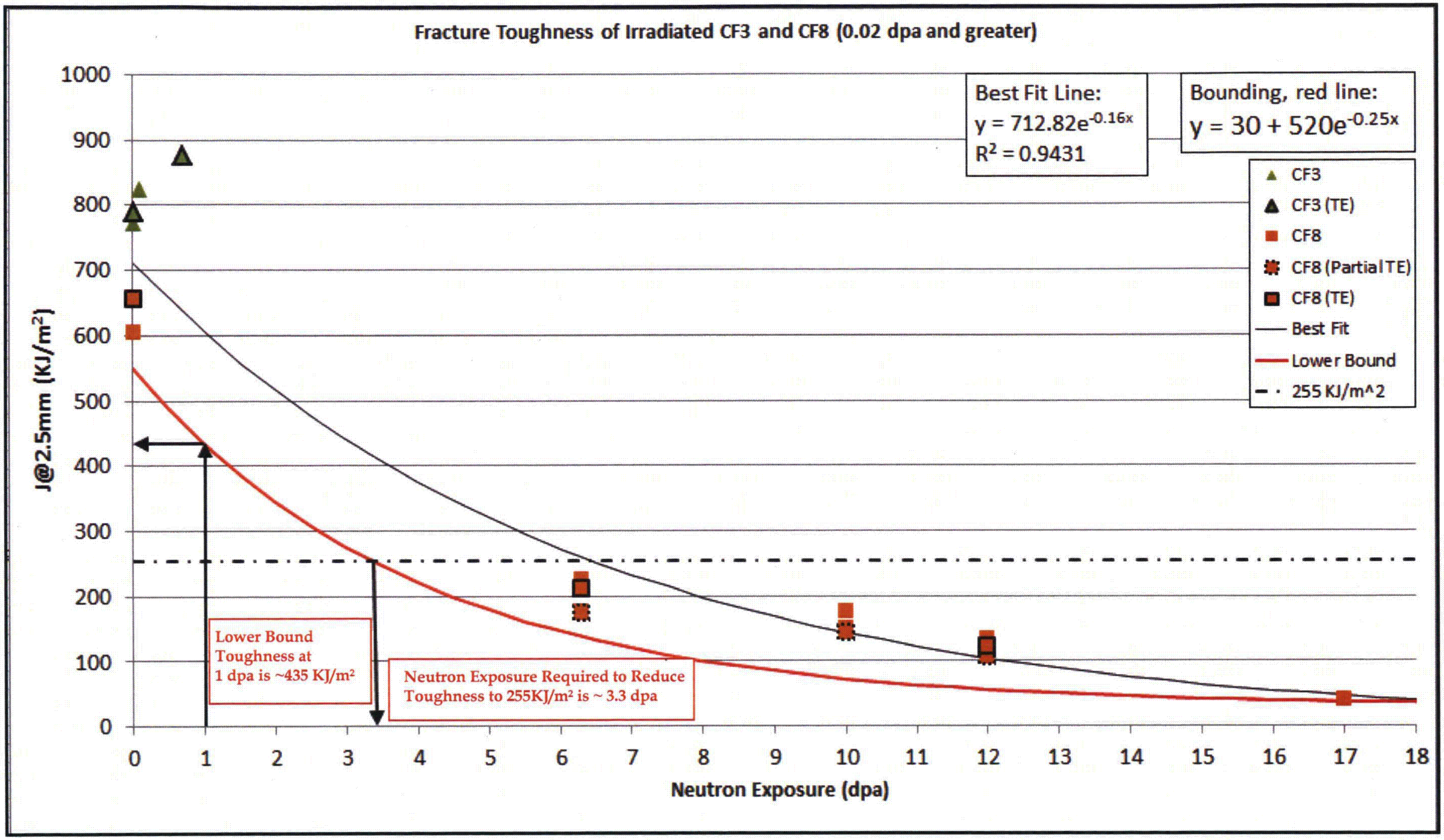
5. K Fuji, K. Fukuya, "Effects of Radiation on Spinodal Decomposition of Ferrite in Duplex Stainless Steel," Journal of Nuclear Materials, May 2012. Presented at the NuMat 2012 Conference, pages 613 to 616, October 22-25, 2012, Osaka, Japan.

6. Was, Gary S., "Fundamentals of Radiation Materials Science: Metals and Alloys," Springer-Verlag, 2007.

7. Kim, C., R. Lott, S. Byrne, M. Burke, and G. Gerzen, "Embrittlement of Cast Austenitic Stainless Steel Reactor Internals Components," Proc. 6th Intl. Symp. On Contribution of Materials Investigations to Improve the Safety and Performance of LWRs, Fontevraud 6, French Nuclear Energy Society, SFEN, Fontevraud Roayal Abbey, France, September 18-22, 2006.

Figure 1 – Irradiated CF-3 and CF-8 Fracture Toughness Data from Literature (Refs. 2, 4 and 7)



Attachment C

Reactor Internals CASS Flaw Tolerance

In the draft Interim Staff Guidance (ISG) on Aging Management of CASS Reactor Vessel Internal Components, issued in June 2014, the NRC technical position observed that "The fracture toughness screening value of 255 kJ/m^2 specified in the Grimes Letter is based on a generic flaw tolerance evaluation for piping, and may be overly conservative for RVI CASS components that are subject to mainly compressive stresses during operation, and are part of a population of redundant components where failure of individual components can be tolerated." The technical position went on to add that "therefore, the staff applies the 255 kJ/m^2 value for screening purposes with the knowledge that there likely is additional conservatism present in this screening for non-pressure boundary RVI components." In an effort to provide further evidence with respect to the NRC staff technical position, some industry efforts since the July 15, 2014 meeting with the NRC staff have been directed toward this issue. The results are summarized in the following paragraphs.

The industry selected three different geometries that can be related to typical BWR and PWR CASS reactor internals in order to estimate flaw tolerance capability: (1) a large-diameter cylinder with a through-wall vertical flaw located in a longitudinal seam weld, subjected to combined membrane and bending stress; (2) an edge-cracked beam-column subjected to combined membrane and bending stress; and (3) a six-inch-diameter, Schedule 40 pipe with a through-wall longitudinal flaw subjected to internal pressure. The internal pressure for the third geometry was selected such that the circumferential tensile stress in the pipe was identical to the membrane tensile stress level chosen for the first two geometries. In all three case studies, the initial flaw size (length for the first and third geometries, and depth for the second geometry) was selected to be consistent with reactor vessel internals fabrication workmanship standards. No flaw growth criteria were applied to the initial flaw sizes, although the initial flaw sizes were increased to some extent in order to determine the rate at which the crack driving force increased as a function of the increase in flaw size.

For the first geometry (large-diameter cylinder with through-wall vertical flaw), the diameter was selected to be 452 inches with a wall thickness of either one or two inches, the membrane tensile stress was selected to be 5 ksi, and the bending stress was selected to be 7.5 ksi. The total initial flaw length was selected to be 0.226 inches (about ¼-inch in length), but was increased in increments up to 4.294 inches. The applied stress intensity factors were found using linear-elastic fracture mechanics (LEFM), and were then converted to J-crack driving forces. For the largest initial flaw lengths examined, the typical LEFM stress intensity is of the order of 25 ksi$\sqrt{in}$, which converts to an elastic-plastic crack driving force of about 4 kJ/m^2. This implies a very large margin relative to the screening value of 255 kJ/m^2.

For the second geometry (edge-cracked beam column), the solid column diameter was selected to be three inches, and the membrane and bending stresses were selected to be identical to those selected for the first geometry. The smallest initial flaw depth was selected as 0.1 inches, and was incremented by 0.1 inch up to a maximum depth of 1.7 inches. The applied stress intensity factors were found using linear-elastic fracture mechanics (LEFM), and were then converted to

J-crack driving forces. For the largest initial flaw depth examined (1.7 inches), the LEFM stress intensity was 42 ksi$\sqrt{in}$, which converts to an elastic-plastic crack driving force of about 10 kJ/m^2. Again, this calculation implies a very large margin relative to the screening value of 255 kJ/m^2.

For the third geometry (six-inch diameter Schedule 40 pipe with a through-wall longitudinal flaw subjected to internal pressure), the internal pressure was selected such that the circumferential stress was approximately 5 ksi, matching the membrane tensile stress used for the first and second geometries. Because of the thin pipe wall, this case was found to be the most critical of the three geometries. The initial flaw length was selected to be 0.1 inches, and was then incremented in 0.1-inch increments up to a maximum flaw length of 2.0 inches. For this case, the applied stress intensity factors were found using linear-elastic fracture mechanics (LEFM), and were then converted to J-crack driving forces. In addition, this case was also analyzed using elastic-plastic fracture mechanics, in order to compare derived crack-driving forces with directly calculated elastic-plastic crack-driving forces. For an initial flaw length of 2.0 inches, the LEFM stress intensity factor was about 54 ksi$\sqrt{in}$, which converts to a crack driving force of about 96 in-lb/in^2 or about 16 kJ/m^2. The directly-calculated elastic-plastic crack driving force is almost exactly the same, but very slightly lower. When the initial flaw length was doubled – to about 4.0 inches, the applied LEFM stress intensity was found to be 120 ksi$\sqrt{in}$, which converts to a crack driving force of about 476 in-lb/in^2 or about 83 kJ/m^2. Even for this very severe example, the calculations show a sizable margin relative to the screening value of 255 kJ/m^2.

From this exercise, CASS reactor internals components subjected to nominal stress levels, even in the presence of initial flaws that are well beyond fabrication workmanship acceptance criteria, are extremely flaw tolerant, with margins against flaw instability of the order of a factor of five to 10 relative to the fracture toughness screening criterion of 255 kJ/m^2 specified in the Grimes letter. When this flaw tolerance is coupled with the additional margin inherent in the separation of CF-3/CF-8 screening data from CF-8M screening data, the conservatism of the industry technical position is further confirmed.

Attachment D

Table 1. Revised % Ferrite Ranges (Industry Position)

Molybdenum (wt. %)	Casting Method	% Ferrite	TE Screening Susceptibility Result	IE Screening Susceptibility Result
High 2.0-3.0% (CF-3M & CF-8M)	static	< 10	No	≥ 1 dpa
		≥ 10 - ≤ 14	No	≥ 0.45 dpa
		> 14	Yes	N/A
	centrifugal	≤ 20	No	≥ 1 dpa
		> 20	Yes	N/A
Low 0.5% max (CF-3 & CF-8)	static	≤ 20	No	≥ 1 dpa
		> 20	Yes	N/A
	centrifugal	All	No	≥ 1 dpa