OFFICE OF NUCLEAR REACTOR REGULATIONSTAFF ASSESSMENT OF THE PRESSURIZED WATER REACTOR OWNER’S GROUP REPORT PWROG-15032-NP, REVISION 0, “PA-MSC-1288 STATISTICAL ASSESSMENT OF PWR RV INTERNALS CASS MATERIALS”

1.0 INTRODUCTION

By letter dated January 13, 2016, the Pressurized Water Reactor Owner’s Group (PWROG) submitted to the Nuclear Regulatory Commission (NRC) for information only topical report PWROG-15032-NP, Revision 0, “PA-MSC-1288 Statistical Assessment of PWR RV Internals CASS Materials.”(Ref.1, the TR) The PWROG submitted the report in response to an email request from the NRC staff dated November 16, 2015 (Ref. 2).

The TR was developed with the intent to provide a more efficient and effective path for utilities to address Applicant/Licensee Action Item 7 (A/LAI 7) per MRP-227-A, “Materials Reliability Program: Pressurized Water Reactor Internals Inspection and Evaluation Guidelines,” (Ref. 3). in plant-specific RVI aging management plans. A/LAI 7 requires applicants or licensees to develop plant-specific analyses to demonstrate that cast austenitic stainless steel (CASS) reactor vessel internals (RVI) components requiring aging management will maintain their functionality during the period of extended operation (PEO), considering the potential loss of fracture toughness due to thermal embrittlement (TE) and irradiation embrittlement (IE).

Assessment of the potential significance of thermal embrittlement (TE) of a CASS component requires knowledge of the ferrite content of the CASS material. Ferrite content can be measured or calculated from the chemical composition of the material. The measured or calculated ferrite content is then compared to NRC-approved screening criteria to determine if TE is potentially significant. For CASS materials in RVI components, ferrite was not typically measured when the material was manufactured, thus the certified material test report (CMTR) for the material usually does not contain the ferrite content. Therefore, calculated ferrite is typically used to assess the potential significance of TE. However, CMTRs are not available for some CASS materials used in RVI of reactors in the United States. The TR provides a basis for determining a statistical upper-bound ferrite content and also a statistical lower-bound fracture toughness value for CASS materials without CMTRs. The statistical method is based on analysis of a large sample of CMTRs for domestic CASS RVI components.

The analysis documented in the TR addresses only TE, so does not provide a complete response to A/LAI 7, which also requires the consideration of the effect of IE on component functionality. Licensees may also need to provide assurance of continued safe operation by demonstrating the components of concern are part of redundant assemblies, are located in low neutron fluence regions that will not cause IE, or have low operating stresses or low consequences of failure.

2.0 TECHNICAL ANALYSIS

2.1 General Information

2.1.1 Summary of TR

Sections 1.0 and 2.0 of the TR contain the executive summary and introduction. Section 3 of the TR contains background, including a discussion of CASS chemistry and metallurgy in Section 3.1. The TR notes that Type CF8 CASS, which is the cast equivalent of Type 304 stainless steel, typically contains 5-15 percent delta ferrite compared to rolled or forged stainless steel which typically contains less than 4 percent delta ferrite. TR Section 3.1 also notes that molybdenum (Mo) is not added intentionally to Grade CF8 and Grade CF3 materials, but is present in small amounts. The TR indicates that some older specifications for Grade CF8 and CF3 did not set a limit on Mo, so it was sometimes not recorded on the CMTR. Other newer specifications set a maximum Mo content of 0.5 percent. When Mo content is not available on the CMTR, the TR notes that it is conservative to assume a Mo content of 0.5 percent. TR Section 3.1 notes that the as-cast condition of a CASS component is similar to that of an austenitic stainless steel weld since both contain delta ferrite, thus thermal aging research on austenitic stainless steel welds can provide insight to how CASS might thermally age. TR Section 3.1 also discusses the differences in failure mode of CASS versus stainless steel welds, and notes that, because of these differences, weld data would present very conservative properties if used to represent CASS behavior.

2.1.2 Staff Evaluation

Sections 1 through 3 of the TR generally contain background information. With respect to the assumption of 0.5 percent Mo content for materials that have no documented Mo data in their CMTRs, the staff notes that Mo content is available for 13 heats listed in Table E-3 of the report. The Mo data follow a bimodal distribution with the eight heats manufactured by Precision Founders (PF) having a mean of 0.065 percent Mo while the five heats from various other manufacturers have a mean of 0.30 percent. Using the mean and standard deviation of all 13 heats of 0.156 percent and 0.140 percent, the staff determined a 95/95 (95 percent probability with 95 percent confidence) upper tolerance limit on Mo of 0.52 percent. While this is slightly greater than 0.5 percent, the sample size is very small, and a larger sample size would most likely result in a reduction of the upper bound. Therefore, the staff finds the assumption of a maximum of 0.5 percent is reasonable. However, the staff also notes that the Mo content seems to be manufacturer dependent, and the 13 heats represent a very small sample of the population. The staff also notes that NUREG/CR-4513, Rev. 1, "Estimation of Fracture Toughness of Cast Stainless Steels During Thermal Aging in LWR Systems," (Ref. 4) contains chemical compositions for 29 heats of CF8 material, including Mo content. Two of the 29 heats have Mo content exceeding 0.5 percent. Given the information available, the staff considers the assumption of 0.5 percent Mo for materials that do not have Mo data documented in the CMTR is a reasonable approach to develop a conservative estimate of the ferrite content. Regarding the potential use of weld data, the TR does not make any comparisons between CASS and weld data so any consideration of welds is outside the scope of the TR and the staff makes no finding relative to whether weld properties can be used to conservatively represent CASS behavior.

2.2 Statistical Approach

2.2.1 Summary of TR

TR Section 4 describes the statistical approach used to determine a conservative estimate of ferrite content and toughness for CASS components lacking CMTRs. TR Section 4.1 describes the manufacturing records that were included in the data set. The data represent six of six operating B&W units, five of twelve operating Combustion Engineering (CE) units, and 26 of 47 operating Westinghouse units. A total of fourteen different manufacturers are represented with 1410 unique heats of material analyzed. The TR indicates that the ladle and product analyses for the same heat were treated as two separate data points, but in general the ladle and product data analyses yielded very similar 95/95-confidence-level saturated fracture toughness values. TR Section 4.1 lists the CASS components included in the data set. Both statically-cast and centrifugally-cast materials are included.

TR Section 4.2 describes the method of calculation of the ferrite content. The calculation of ferrite content from chemical composition uses the methodology developed by Hull (Ref. 5) and endorsed by the NRC (Ref. 6).

TR Section 4.3 addresses the conservatism in ferrite content calculations. The TR indicates that an assumption of 0.50 weight percent Mo was used when ferrite was not reported on the CMTR, which the TR states is conservative. The TR also indicates that a further conservatism is involved in the ferrite calculations that do not take into account heat treatment of the castings. The TR indicates that, since Hull's factors do not consider the effect of heat treatment that decreases ferrite content in casting, the use of that method to predict ferrite content in heat treated components is also conservative.

TR Section 4.4 indicates that the methods of NUREG/CR-4513, Revision 1, as updated by NUREG/CR-7185, "Effect of Thermal Aging and Neutron Irradiation on Crack Growth Rate and Fracture Toughness of Cast Stainless Steels and Austenitic Stainless Steel Welds", (Ref. 7) were used to determine the materials' tearing resistance in the presence of a 2.5 mm (0.1 inch) crack ($J_{2.5}$). TR Section 4.4 refers to Appendix D of the TR for details on the equations used to estimate fracture toughness.

TR Section 4.5 discusses the conservatism of the fracture toughness calculations. The TR argues that the toughness calculations are conservative because they represent the predicted saturated toughness as defined in NUREG/CR-7185. Given the analysis in Appendix D.1, the saturated fracture toughness will be conservative compared to 60 years of operation, particularly for components operating at T_{cold} (cold leg temperature), which may not result in the saturated condition.

TR Section 4.6 describes the statistical approach that was used to determine the upper-bound ferrite and lower-bound fracture toughness. The section indicates that the ferrite distribution for a given manufacturer was found to approximate a normal or lognormal distribution. The TR also indicates that two statistical tests were used to determine whether a given data set should be modeled using a normal or lognormal distribution. The first of these was the Andersen-Darling (A-D) parameter, which compares the cumulative distribution function for observed data with that for the fitted normal curve over the range of the data. A smaller value of the A-D indicates a better fit to the data set. The second statistical test was the p-value, with an acceptance criterion that p be greater than 0.05 (95 percent confidence). The TR also indicates engineering judgement was the third tool used in determining the appropriate distribution. TR section 4.6

states that, for normally and lognormally distributed data, one sided tolerance limits were calculated according to Section 9.12 of NUREG-1475, “Applying Statistics” (Ref. 8). The TR states that a 95/95 tolerance limit was used which equates to 95 percent confidence that at least 95 percent of the population is bounded by the tolerance limit. This method calculates the upper and lower tolerance limits using the following equations:
Upper Tolerance Limit = Y+ks

Lower Tolerance Limit = Y- ks,

where Y is the sample mean, s is the sample standard deviation, and k is a tolerance limit factor (dependent on the number n of data points in the sample) available in Table T-11b of Reference 8. The TR notes that an assumption critical to this type of analysis is that the sample (the CMTR chemistries) is representative of the entire population (all the CASS RV internals). The TR further indicates that, since the significant fraction of the domestic operating PWRs contributed data to the study and this fraction covers a wide variety of plant designs and vintages, the data presented in this report are representative of domestic operating PWRs. TR Section 4.7 addresses the conservatism in the statistical approach and states that using the 95/95 criteria for this analysis may be too conservative because many of the CASS RVI components being considered are part of redundant structures such as the lower core support columns, for which a single failure would not be limiting.

2.2.2 Staff Evaluation

The staff has reviewed the statistical analysis described in Section 4 and finds that the TR used a large and diverse database, including a wide range of components, manufacturers, and vintage of manufacture. Given the large and diverse sample size, the approach of modeling the distribution of ferrite for the various manufacturers using either a normal or lognormal distribution is a reasonable method to address the uncertainty inherent in Hull’s method for estimating the ferrite content.

Based on Section 4.1 of the TR, it appears that many specific components in multiple plants can be traced to specific material heats in the data set. In Draft RAI 1 the staff asked the PWROG if it intends to use the 95/95 upper limit on ferrite value for any component regardless of whether the component-specific composition is known, or only when the component-specific composition is unavailable (i.e., CMTR is missing). Draft RAI 1 further requests that if the intent is to allow the statistical approach even when the CMTR is available, the staff requests the PWROG to provide a technical justification.

During the May 5, 2016 public meeting, the PWROG clarified that the information in the data set was retrieved during searches performed in response to plant-specific RAIs. Therefore, additional effort would be required to retrieve additional plant-specific records. Thus, the data set evaluated in the TR will not be applicable to specific plants that have not yet searched for their records. Therefore the intent of the PWROG is to use the 95/95 upper limit on ferrite based on the data set to screen out TE for CASS components without searching for plant-specific CMTRs going forward. CMTRs could potentially be located for such plants, but to have to search for the CMTR would partially defeat the purpose of the TR.

The staff has reviewed the PWROG response and notes that the data set reflects better than half of all plants in the domestic fleet and less than 1 percent of the static-cast heats of CF8 exceeded 20 percent calculated ferrite content. Some heats were used in multiple plants. In the future, plants searching their records would expect to find some duplication of heats already in the data set. Therefore, the staff considers the 95/95 upper limit on ferrite based on the data set found in the TR provides reasonable assurance of the estimated ferrite content that could be calculated from Hull's factors if the heat-specific CMTR were available. Furthermore, the staff considers that there is little to be gained from further review of plant-specific records for CMTRs. The staff's concern expressed in Draft RAI 1 is resolved and the RAI does not need to be submitted for a formal response.

TR Section 4.3, on p. 4-6 states that a further conservatism is that, in practice, CASS components would have been heat treated, using a least a partial solution treatment. In Draft RAI 2, the staff asked the PWROG if it has documentation that heat treatment was performed on CASS components, or to remove this statement from the TR if such documentation is not available.

During the discussion at the May 5, 2016 meeting, the representatives from the PWROG confirmed that all CASS RVI components were solution treated and this is called out in material specifications and standards such as American Society for Testing and Materials (ASTM) A351.

The staff has reviewed ASTM A351 and found specific requirements for heat treatment of all castings that would constitute a complete solution annealing process. Given the clear requirement for complete solution annealing, the staff's concern expressed in draft RAI 2 is resolved and the RAI does not need to be submitted for a formal response.

Section 4.6 of the TR uses a normal or lognormal distribution to represent the distribution of ferrite and toughness values for each manufacturer. The PWROG used two quantitative statistical tests to assess how well the chosen statistical distribution represents the sample population, the p-test and the A-D parameter. In Draft RAI 3, the staff requested PWROG provide examples of the calculation of the p-values for some of the manufacturer's distributions – one for a p-value meeting the acceptance criteria and one example for a distribution where the p-value does not meet the acceptance criterion. Provide a reference for the use of p-values in this manner.

With respect to Draft RAI 3, the representatives from the PWROG stated during the meeting that the p-values were determined based on the Minitab software. The PWROG also stated that the p-values were only one of the three tools used to assess the fit of the data.

Given the discussion at the May 5, 2016 meeting, the staff has reexamined the distributions included in Section 5 (Results) and Appendix A (Detailed Results by Manufacturer). While two of the thirteen sub-populations for predicted ferrite content examined in the TR may not pass all normality tests, the fits that were used generally provide a conservative representation of the actual distribution. For example, in Figure 5-19 from the TR, the second datum point from the right of the graph has an x value (natural log of the calculated ferrite content) of 2.25, and a y value of about 96 percent, whereas the lognormal distribution represented by the straight line indicates the y value should be 99 percent. This indicates that more of the predicted ferrite contents are distributed towards the upper tail of the distribution. Since the actual distribution contains more estimated values towards the upper tail than would be predicted by the lognormal distribution, assumption of a lognormal distribution can provide a nonconservative prediction with respect to determining a statistical upper-bound tolerance limit for ferrite. However, even in this example, the chosen distribution is only slightly nonconservative and provides a reasonable representation of the actual data.

For another example, Waukesha static cast CF8, the TR notes that the calculated p value

(<0.005) associated with applying the lognormal distribution does not pass the acceptance criterion; however, it provides a reasonable and conservative fit to the data. Figure 5-30 of the TR shows the graph of the normality test for ferrite content of the Waukesha static-cast Type CF8 material. The staff notes that the situation in Figure 5-30 of the TR is the opposite of that in Figure 5-19 because the actual data tend to lie above the normal distribution toward the upper tail of the distribution. For example, the fourth data point from the right has an x value (percent delta ferrite) of about 17.5 percent and a y value of about 99 percent, meaning 99 percent of the actual data points are to the left of it, whereas the normal distribution line predicts the y value for 17.5 percent should only be about 95 percent. However, at the lower tail of the distribution, the deviation above the line of the data indicates more data towards the lower tail than would be predicted if the distribution were perfectly normal. Therefore, use of normal distribution to represent this data is conservative at the upper tail. Since high ferrite, not low ferrite is the concern, this is acceptable. Therefore, use of a normal distribution is conservative for Waukesha with respect to predicting a statistical upper tolerance limit on ferrite.

The staff notes that for determining the lower-bound fracture toughness of each material heat, the TR uses the equations from NUREG/CR-7185 that account for the material's specific chemical composition, in addition to its ferrite content. The equations in NUREG/CR-7185 for CF8 materials are very similar to those in NUREG/CR-4513, Rev. 1, the use of which has been previously endorsed by the NRC in Ref. 6; for CF3M, the fracture toughness predictions from NUREG/CR-7185 are more conservative than those in NUREG/CR-4513, Rev. 1. Variations in chemical composition can produce significant variations in the predicted fracture toughness, as seen in Figure 5-6 of the TR. For each manufacturer, a 95/95 confidence limit on the lowerbound fracture toughness was then determined based on the mean and standard deviation of the individual lower-bound fracture toughness value for each heat.

The A-D test was also used in the TR to assess how well the actual distributions fit the chosen distribution (normal or lognormal). According to the NIST e-Handbook of Statistical Methods (Ref. 9), the A-D test is used to test if a sample of data came from a population with a specific distribution. Reference 9 also indicates that the A-D test is a modification of the Kolmogorov-Smirnov (K-S) test and gives more weight to the tails of the distribution than does the K-S test. Reference 9 further indicates that the A-D test makes use of the specific distribution in calculating critical values, and that this has the advantage of allowing a more sensitive test and the disadvantage that critical values must be calculated for each distribution. Based on the above, the staff finds the A-D test to be an appropriate statistical test to assess whether the population data fits a normal or lognormal distribution well, and is appropriate for this application since the tails of the distribution are of the most importance. The upper tail of each distribution is of more importance with respect to ferrite content since the ferrite screening limit is an upper limit. The lower tail is of more importance to toughness since low toughness represents a safety issue.

For fracture toughness, most of the populations that failed the normality tests show nonconservative deviations at the upper tail of the distribution, indicating that there are a larger number of high fracture toughness values than would be predicted by a normal distribution. Since low toughness values rather than high values are a concern, the failure of these distributions to pass the normality tests is not a concern.

As an independent check on the validity of using a normal or lognormal distribution to represent the distribution of ferrite and toughness values, the staff performed the K-S test on the distribution of ferrite and fracture toughness for static-cast CF8 material for one manufacturer (Wollaston). NUREG-1475, Revision 1, "Applying Statistics" (Ref. 8), indicates that the K-S test is used to decide if a sample comes from a population with a specified cumulative distribution function. Reference 8 also indicates that the K-S test is always appropriate for small samples, unlike the chi-square test. For ferrite, the K-S test indicated that the hypothesis of either a normal distribution or lognormal distribution could not be rejected; however, the results indicated a better fit to the lognormal distribution, which is what was used in the TR. For fracture toughness, the K-S test indicated the hypothesis of normality could not be rejected.

In summary, the staff notes that the p-values do not have to meet the >0.05 criteria because the chosen normal or lognormal distributions, though they may not pass all normality tests, do provide a conservative representation of the actual distribution. Based on the discussion at the May 5, 2016 public meeting and the staff's independent check on validity, the staff found the choice or a normal or lognormal distribution to represent the ferrite and fracture toughness data to be reasonable because the data either passed the goodness-of-fit tests applied by PWROG, or the chosen distribution was generally observed to be conservative, or at worst only slightly nonconservative, with respect to how it represents the actual data (i.e., the distribution predicts more high values for ferrite than the actual data, and given a higher ferrite content, the model from NUREG/CR-7185 predicts more conservative, lower-bound values for toughness than the actual data). In addition, the staff found that the PWROG applied appropriate statistical tests and tools to assess the appropriateness of the chosen distributions. The staff's concern expressed in Draft RAI 3 is resolved and the RAI does not need to be submitted for a formal response.

2.3 Results & Conclusions

2.3.1 Summary of TR

TR Section 5 provides the results of the statistical analyses. The results consist of the ferrite contents calculated using the CMTRs via Hull's factors, in terms of percent ferrite, and the estimated lower-bound fracture toughness values that reflect saturation conditions (assumed to be represented by aging at 400°C for 10,000 hours), given in terms of $J_{2.5}$ at a temperature of 554°F (290°C). Results are presented for the overall population, and also, for each category (manufacturer and casting method) individually. Generally, a histogram of the distribution of ferrite content was provided, along with a graph showing the statistical tests (either normality or lognormality).

TR Table 5-1 provides the statistics for the overall population of static-cast CF8 from all manufacturers. The mean ferrite for all 914 heats of material is 8.8 percent with a standard deviation of 4.1. The overall population was modeled using a lognormal distribution. The mean of the natural logarithm of ferrite is 2.074 and the standard deviation of the natural logarithm of ferrite is 0.4571. The resulting 95/95 upper limit on ferrite value is 17.5 percent.

TR Section 5.2 discusses the analysis of results for subsets of the population, based on manufacturers, plants, components and vintage of production. The strongest correlation was found between ferrite content and manufacturer.

TR Section 5.3 provides the summary of results by manufacturer. Table 5-4 of the TR provides a summary of the ferrite content statistics by manufacturer including the number of heats, mean ferrite and standard deviation, minimum and maximum ferrite, distribution used (normal or lognormal), and the 95/95 upper limit on ferrite. For the various manufacturers, the 95/95 upper limit on ferrite ranges from 8.3 to 24.7 for Type CF8 materials. Statistics are also provided for one manufacturer that produced Type CF3M material, which is used in some B&W plant components.

TR Table 5-5 provides similar statistics for $J_{2.5}$, providing the 95/95 lower limits, ranging from 364 to 527 kJ/m^2 for static-cast type CF8, and from 488 to 711 kJ/m^2 for centrifugally-cast CF8 material. For the CF3M material, the lower-bound toughness is 141 kJ/m^2.

The remainder of TR Section 5 provides the detailed statistics for each individual manufacturer.

TR Section 6 contains the conclusions. The TR concludes that the ferrite content of CASS RV internals for the domestic PWR fleet has been shown to depend on material specification, casting method and manufacturer. The TR also concludes that the calculated ferrite contents are well approximated by a normal or lognormal distribution, especially when separated by manufacturer. The TR further concludes that the CMTR analysis results provide a basis for prediction of an upper-bound ferrite content in instances where only limited manufacturing records may be available. The TR further concluded that the calculated saturation fracture toughness after TE can be conservatively modeled by a normal or lognormal distribution and so a lower-bound fracture toughness can be predicted in a similar manner.

For static-cast Grade CF8 components, the TR concludes that the ferrite content rarely exceeds the 20 percent screening criterion, based on the 95/95 upper limit of the overall population being less than the screening criterion. The TR also concluded that segregating static-cast CF8 data by component, plant or vintage did not reveal any trends as significant as the dependence of ferrite content on the component.

With respect to fracture toughness, the TR concludes that all the centrifugally-cast and staticcast Grade CF8 materials have saturated fracture toughness well above the established screening criterion of 255 kJ/m^2 based on the 95/95 confidence level values as presented in Table 5-5. As in the case of ferrite prediction, the predicted value of saturated $J_{2.5}$ shows a strong dependence on manufacturer; manufacturers that produce lower ferrite materials produce components with high estimated saturated fracture toughness.

With respect to the ferrite content and $J_{2.5}$ of the Type CF3M material, the TR concluded that the ferrite content often exceeds the established screening criteria, and the fracture toughness was often below the established screening criterion of 255 kJ/m^2. The TR notes that the potential for low toughness of the components fabricated from this material is already accounted for in the aging management strategy and inspection scope of MRP-227-A.

2.3.2 Staff Evaluation

The TR indicates that a lognormal distribution was used to model the overall population for the calculated ferrite content due to the shape of the distribution, which is skewed toward the lower end with a distinctly extended tail at the upper end. The TR explains this by the fact that the overall distribution is composed of several overlapping, approximately normal or lognormal distributions with different means and standard deviations, which are essentially produced by the distributions from the individual manufacturers. The peak at 6 percent ferrite is the result of contributions from a single low-ferrite manufacturer (Kearsarge) that contributed more than 50 percent of the static-cast CF8 heats examined. The 95/95 upper-bound ferrite content for the overall population is 17.5 percent ferrite. The staff notes that for many of the manufacturers, the 95/95 upper-bound ferrite for the manufacturer is greater than 17.5. However, only two manufacturers of static-cast CF8 (PF and Wollaston) have 95/95 upper-bound ferrite contents for static-cast CF8 material greater than 20 percent. Based on the available CMTRs, these manufacturers are known to only produce specific component types for specific NSSS vendors. The staff notes that the manufacturers with the two lowest 95/95 confidence level fracture toughness ($J_{2.5}$) values are CSF, which has an upper-bound ferrite value of 19.3 percent, and

PF, which has an upper-bound ferrite value of 24.7 percent. Both of these manufacturers have a lower-bound $J_{2.5}$ of 364 kJ/m^2. However, Wollaston also has a relatively high upper-bound ferrite value for static-cast CF8 at 24.5 percent, but also has a relatively higher lower-bound $J_{2.5}$ at 448 kJ/m^2. This is the case because the equations used to estimate the lower-bound take into account the chemical composition of each heat in addition to the ferrite content. The staff notes that the TR calculates the lower-bound $J_{2.5}$ of each heat of material based on the known chemical composition of the heat, using the NUREG/CR-7185 equations. This method can result in considerable variation in the predicted lower-bound for heats of material that have the same predicted ferrite content, but different reported chemical compositions. For example, seven heats of static-cast Type CF8 material have the same calculated ferrite content of 14.9 percent predicted by Hull's factors, and the estimated lower-bound $J_{2.5}$ values range from 400 kJ/m^2 to 536 kJ/m^2.

2.4 Implementation

2.4.1 Summary of TR

Section 7 of the TR discusses three options for using the results of the statistical study to address TE of CASS components. These are: (1) Use of a ferrite upper limit based on the overall population; (2) Use of a ferrite upper limit based on a specific manufacturer; (3) Use of ferrite upper-limit for a specific component type, based on the upper limit of the manufacturers that supplied the component.

2.4.2 Staff Evaluation

Given the conservative nature of the approach taken in the TR, as described above in Section 2.3.2, the staff finds that any of the three options for characterizing the ferrite content of RVIs manufactured from CASS materials are acceptable to address TE of CASS RVI components.

3.0 DISCUSSION

The subject TR provides a basis for statistically determining 95/95 upper-bound ferrite levels for CASS materials for which the chemical compositions are unknown. Statistical upper-bound ferrite levels are defined for each manufacturer and the overall population. The 95/95 upperbound ferrite level is intended to be used to estimate the ferrite content for CASS RVI components for which documentation of the chemical composition is not available. The estimated ferrite content can then be compared to established screening criteria for thermal embrittlement, such as the NRC-approved criteria in LR Issue No. 98-0030.

Using the TR methodology and results, virtually all static-cast Grade CF8 CASS material can be shown to have a high probability of ferrite content below 20 percent, which is the ferrite screening criterion for static-cast low Mo material. The maximum calculated ferrite is less than 25 percent and those heats with a calculated ferrite above 20 percent would have adequate estimated toughness to pass the screening criteria in Reference 6. For centrifugally-cast Grade CF8 material, the TR showed that one of the two manufacturers have a 95/95 upper-bound ferrite greater than 20 percent. However, Reference 6 does not consider thermal aging to be significant for any centrifugally-cast low Mo material, regardless of ferrite content. For staticcast Grade CF3M material, only one manufacturer was included in the TR. The TR found that the 95/95 upper-bound ferrite is 27 percent, significantly above the 14 percent value used as a basis for the ferrite-based susceptibility screening in Reference 6 for static-cast, high-Mo materials.

The staff has reviewed all of the data and notes that Kearsarge accounts for over 50 percent of the CASS heats in the data set. Since the 95/95 upper-bound ferrite is relatively low for Kearsarge, this tends to skew the overall population. Therefore, the staff was initially concerned that it was nonconservative to use the overall population 95/95 upper-bound ferrite for components when the manufacturer is unknown. In Draft RAI 5, the staff requested the PWROG to:

a. Justify using the overall population 95/95 upper-bound ferrite value when the manufacturer is unknown, considering the bias due to the Kearsarge data;

b. Provide a 95/95 upper-bound ferrite value for the overall population excluding Kearsarge.

c. Describe how the conclusions about the fracture toughness would change if the Kearsarge data were excluded.

During the discussion at the May 5, 2016 meeting, the PWROG indicated that it had not determined a 95/95 upper-bound ferrite value for all the data excluding Kearsarge. The PWROG representatives indicated they believe it is not appropriate to exclude the Kearsarge data because it makes up a large percentage of the data and excluding it would unfairly skew the 95/95 upper bound ferrite value to a higher value.

The staff has considered the PWROG's evaluation and independently reviewed the data excluding Kearsarge. Of the 404 heats of static-cast CF8 supplied by manufacturers other than Kearsarge, only two heats from one manufacturer were actually above 20 percent; the estimated heat-specific $J_{2.5}$ values for the two were 476 and 481 kJ/m^2, well above the level where loss of fracture toughness is considered significant. Given the limited number of heats that have had a calculated ferrite content above 20 percent, and the relatively high estimated toughness of the actual heats in question, the staff's concern expressed in draft RAI 5 is resolved and the RAI does not need to be submitted for a formal response.

3.1 Conservatism of Ferrite Content

As stated earlier in this assessment, the ferrite content estimated using Hull's factors may be up to 6 percent higher or 6 percent lower than measured ferrite content. Appendix E of the TR tabulates the chemical composition, estimated mean value of ferrite and estimated lower-bound $J_{2.5}$ values for each material heat in the data set. For static-cast Grade CF8, there are a few heats that have predicted ferrite content above 20 percent. The highest estimated ferrite content for a static-cast Grade CF8 heat is 23.8 percent for Wollaston heat #2155; therefore, this heat could actually be as high as 30 percent. However, even up to 40 percent ferrite, the alternate methodology in NUREG/CR-7185 for unknown chemistry, but known ferrite would still predict a $J_{2.5}$ = 329 kJ/m^2, significantly above 255 kJ/m^2.

3.2 Conservatism of Fracture Toughness Predictions

In the TR methodology, fracture toughness for each heat in the data set was estimated using the NUREG/CR-7185 equations for material of known chemical composition. As previously noted, fracture toughness can vary significantly for CASS materials with identical estimated ferrite content but different chemical compositions. For example, with a calculated ferrite of 14.9 percent, there are seven heats listed in Table E-3 and the estimated lower-bound $J_{2.5}$ varies from 400 to 536 kJ/m^2.

NUREG/CR-7185 provides an alternative method to estimate the J-R curve for material of known ferrite content but unknown composition; the alternative tends to yield lower $J_{2.5}$ values compared to the NUREG/CR-7185 equations for material of known chemical composition. For example, for static cast Grade CF8 with 10 to 15 percent ferrite, the alternative methodology yields a lower-bound fracture toughness of 378 kJ/m^2. By comparison, the TR indicates that the $J_{2.5}$ values for static-cast Grade CF8 with 14.9 percent ferrite range from 400 kJ/m^2 to 536 kJ/m^2.

Table 1 below provides the 95/95 upper-bound ferrite from the TR, the 95/95 lower-bound $J_{2.5}$ from the TR (known composition), and the 95/95 lower-bound J-R curve from NUREG/CR-7185 for materials with known ferrite, but unknown chemistry. The NUREG/CR-7185 methodology for known ferrite/grade/casting method, but unknown chemistry does not contain estimates of the lower-bound J-R curve for static-cast CF3M material; to be conservative, values for CF8M were used for CF3M in Table 1. Appendix D of the TR indicates the equations from NUREG/CR-7185 for Grade CF8M material were used since the compositions are similar and CF8M should have greater aging response than CF3M. Therefore, for the calculated saturation value in Table 1, the staff used the parameters for unknown composition, but known ferrite/grade/casting method (ferrite content from Hull's methodology using the known composition) for the range of 25-40 percent ferrite, and nickel content ≥ 10 percent, for CF8M (nickel content ≥ 10 percent has a lower toughness than nickel content < 10 percent).

The results in Table 1 show that the use of the equations for material of known ferrite and unknown composition results in more conservative lower-bound $J_{2.5}$ values. However, all manufacturers of static-cast CF8, including the two manufacturers that had 95/95 upperbound ferrite level predicted by the TR to be above the screening limit of 20 percent (PF and Wollaston), would still be predicted to have $J_{2.5}$ values in excess of 255 kJ/m^2 by a considerable margin.

In Draft RAI 4, the staff requested that PWROG justify using the equations based on known chemical composition to estimate the fracture toughness values used to determine the 95/95 lower-bound toughness. Given the discussion at the May 5, 2016 meeting and the staff's evaluation summarized in Table 1, the staff has determined that the TR's discussion of toughness is strictly related to the screening of RVI components for susceptibility to TE alone; the TR was not intended to be applied to other issues like a flaw assessment. Given the limits of the stated purpose for the TR, the staff's concern expressed in draft RAI 4 is resolved and the RAI does not need to be submitted for a formal response.

To summarize, if an estimate of the lower-bound toughness was needed for a specific component where the CMTR was available, it would be more conservative to use the lowerbound J-R curve based on the equations in NUREG/CR-7185 for known ferrite/grade/casting method, but unknown chemical composition. If the CMTR is available, the ferrite content should be taken equal to the mean value from Hull's methodology with the CMTR used as input. If the CMTR is not available, but the manufacturer is known, the 95/95 upper-bound ferrite level in Table 5-4 of the TR for the specific manufacturer should be used. If the CMTR is not available and the manufacturer is not known, the 95/95 upper-bound ferrite level in the TR for the overall population may be used.

Table 1. Comparison of 95/95 Lower-bound $J_{2.5}$ – NUREG/CR-7185 (Composition &

Ferrite Known) vs. (Composition Unknown, Ferrite/Grade/Casting Method Known)

Manufacturer	Grade	Casting Method	95/95 Upper-bound Ferrite, %	Known chemistry & ferrite, $J_{2.5}$, kJ/m^2	Unknown chemistry, known ferrite $J_{2.5}$, kJ/m^2
AMP	CF8	Static	11.9	505	378
CSF	CF8	Static	19.3	364	364
ESCO	CF8	Static	18.4	397	364
Kearsarge	CF8	Static	9.7	527	439
PF	CF8	Static	24.7	364	364
QACC	CF8	Static	18.7	378	364
Valcast	CF8	Static	13.4	496	378
Waukesha	CF8	Static	18.7	398	364
Wollaston	CF8	Static	24.5	448	364
Kearsarge	CF8	Centrifugal	8.3	711	578
WC(Ladle)	CF8	Centrifugal	22.7	487	450
(Product)			20.8	488	450
Wollaston	CF3M	Static	27.0	141	78

4.0 CONCLUSIONS

The staff concludes that the three options to predict an upper-bound ferrite level, as described in Section 7 of the TR and summarized in Section 2.4.1 of this assessment, provide acceptable methods for estimating the ferrite content of RVI components manufactured from static-cast or centrifugal-cast Grade CF8 and static-cast Grade CF3M CASS for which documentation of the heat-specific chemical composition is not available. The resulting value for ferrite may be used as part of plant-specific responses to Action Item 7 from MRP-227-A (i.e., to screen RVI components manufactured from CASS for loss of fracture toughness due to TE alone). For estimating the lower-bound $J_{2.5}$ of materials subject to TE alone where the heat-specific chemical composition is not available, this assessment does not approve the method used in the TR, which used the equations for known ferrite and composition. An alternate method from NUREG/CR-7185 that uses known ferrite/grade/casting method, but unknown composition may be used where the ferrite content is taken equal to the 95/95 upper limit ferrite level from the TR. For CASS components subject to neutron fluences greater than 1×10^{17} n/cm^2, additional adjustments for the effects of irradiation must be applied to the methodology used to estimate toughness.

6.0 REFERENCES

1. PWROG-15032-NP, Revision 0, “PA-MSC-1288 Statistical Assessment of PWR RV Internals CASS Materials” (ADAMS Accession No. ML16068A245 & 16068A246).
2. NRC email from Joe Holonich to Jim Molkenthin, “Report Request”, dated November 16, 2015.
3. EPRI Report 1022863, Materials Reliability Program: Pressurized Water Reactor Internals Inspection and Evaluation Guidelines (MRP-227-A), Final Report, December 2011 (ADAMS Accession No. ML120170453) – Transmitted to NRC by MRP letter MRP2011-036 dated January 9, 2012.
4. NUREG/CR-4513, Revision 1, "Estimation of Fracture Toughness of Cast Stainless Steels During Thermal Aging in LWR Systems," May 31, 2016 (ADAMS Accession No. ML16145A082).
5. Hull, F.C., “Delta Ferrite and Martensite Formation in Stainless Steels,” Welding Journal, May 1973, pages 193-203.
6. License Renewal Issue No. 98-0030, "Thermal Aging Embrittlement of Cast Austenitic Stainless Steel Components," May 19, 2000 (ADAMS Accession No. ML003717179).
7. NUREG/CR-7185, "Effect of Thermal Aging and Neutron Irradiation on Crack Growth Rate and Fracture Toughness of Cast Stainless Steels and Austenitic Stainless Steel Welds", July 31, 2015 (ADAMS Accession No. ML16145A082).
8. NUREG-1475, Revision 1, "Applying Statistics", March 31, 2011 (ADAMS Accession No. ML11102A076)
9. NIST/SEMATECH e-Handbook of Statistical Methods, http://www.itl.nist.gov/div898handbook/, March 18, 2016.

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