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BWRVIP-234NP: BWR Vessel and Internals Project

Thermal Aging and Neutron Embrittlement Evaluation of Cast Austenitic Stainless Steels for BWR Internals

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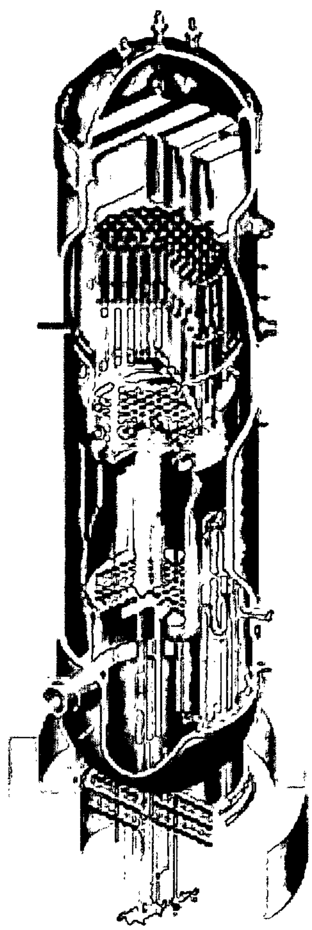

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Thermal Aging and Neutron Embrittlement Evaluation of Cast Austenitic Stainless Steels for BWR Internals

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REPORT SUMMARY

The purpose of this report is to evaluate the potential synergistic effects of thermal aging and neutron embrittlement of BWR internal components fabricated of cast austenitic stainless steels (CASS) and to determine if augmented inspections are necessary to detect degradation.

Background

NUREG-1801 Rev. 1, Section XI.M13, states that an ASME Code Section XI VT-3 examination is required to be performed of reactor internal components. In addition, the report specifies that for the license renewal period, these inspections shall be augmented by an aging management program to address the synergistic effects of thermal aging and neutron embrittlement in cast austenitic stainless steels. This aging management program consists of (a) identifying susceptible components; and (b) either performing additional inspections of these components, or performing a component-specific evaluation to confirm that the stresses in the components are sufficiently low such that augmented inspections are not warranted.

Objective

To evaluate the potential synergistic effects of thermal aging and neutron embrittlement of CASS components in BWR internals and recommend augmented inspections if needed.

Approach

The project team identified the BWR internal components fabricated of CASS, reviewed the material test reports for chemical compositions, and determined the relevant end of license fluence values for each component. They reviewed current literature on fracture toughness/embrittlement in cast austenitic stainless steel, including the roles of ferrite level, temperature effects, and irradiation on property degradation. Evaluation of the various CASS components was performed to determine if thermal aging and/or irradiation embrittlement could occur. A screening process was developed that included assessment of ferrite level, fluence, toughness, stress level and results of existing BWRVIP inspections. Given that many components will reach fluence levels where irradiation may have a potential effect on fracture toughness, the stress levels in each component and the predicted fracture toughness properties are included in the assessment. The results were compared against NRC approved criteria to determine whether component-specific evaluation or augmented inspections are needed. In addition to the NRC criteria, the current BWRVIP inspections were also evaluated to determine whether they satisfy the intent of NUREG-1801, Rev. 1.

Results

The evaluation shows that all the BWR CASS components have ferrite levels below the level for which aging embrittlement is a concern. Furthermore, for the Control Rod Guide Tube Base and

Core Spray Sparger Nozzle Elbows, the end of life fluence is less than the threshold value for toughness loss. The end-of-life fluence levels for the orificed fuel support, the jet pump assembly castings and the LPCI couplings exceed the threshold, but the toughness data for irradiated austenitic stainless steel show that that these components will have sufficient fracture toughness at end of the license renewal period so that augmented inspection is not required. It is concluded that augmented inspections are not required for the BWR CASS internals.

EPRI Perspective

Embrittlement of CASS has been studied extensively, identifying many of the key parameters that can affect the fracture toughness with long term exposure to the high temperature light water reactor environment. Long-term plant life and license renewal require an understanding of thermal aging and neutron embrittlement susceptibility for BWR materials. Such information—also needed in aging management of plant components—reduces the risk of component failure by increasing awareness of material behavior over time and possible material failure mechanisms.

Keywords

Boiling Water Reactor (BWR)
Cast Austenitic Stainless Steel (CASS)
Stress Corrosion Cracking (SCC)
Thermal Aging Embrittlement
Neutron Embrittlement

EXECUTIVE SUMMARY

NUREG-1801 Rev. 1, Section XI.M13, (hereafter referred to as the GALL report) states that a Section XI VT-3 examination is required to be performed of reactor internal components. In addition, the GALL report specifies that for the license renewal period, these inspections shall be augmented by an aging management program to address the synergistic effects of thermal aging and neutron embrittlement in cast austenitic stainless steels (CASS). This aging management program consists of (a) identifying susceptible components; and (b) either performing additional inspections of these components, or performing a component-specific evaluation to confirm that the stresses (tensile loading) in the components are sufficiently low such that augmented inspections are not warranted. The purpose of this report is to evaluate the material composition, fluence, stresses and the field experience of CASS components in BWR applications and recommend augmented inspections if needed.

The report presents a review of the current literature on fracture toughness/embrittlement in cast austenitic stainless steel, including the roles of ferrite level, temperature effects, and irradiation on property degradation. The review considers the clear distinction between PWR and BWR operating conditions as well as the casting composition (ferrite content) of CASS components. In this context, the report then reviews the different CASS components used in all types of operating BWRs. These include the Orificed Fuel Support, Control Rod Guide Tube Base, Core Spray Sparger Nozzle Elbows, Jet Pump Assembly, Jet Pump Restrainer Bracket and Low Pressure Core Injection (LPCI) Coupling. The specifications used in their procurement and their compositions based on certified material test reports (CMTRs) of cast components are summarized based on internal GEH records. This CMTR information is used to determine ferrite content calculated using Hull's equivalent factors and substantiate the use of non-Mo containing alloys. Expected levels of fluence, including operation through the license renewal period (based on GEH assessments) have also been determined from specific plant evaluations.

The report then presents an evaluation of the different CASS components to determine if thermal aging and/or irradiation embrittlement could occur. A screening process was developed that included assessment of ferrite level, fluence, toughness, stress level and results of existing BWRVIP inspections. Given that many components will reach fluence levels where irradiation may have a potential effect on fracture toughness, the stress levels in each component and the predicted fracture toughness properties are included in the assessment to develop the recommended inspection guidance. The results are compared against NRC approved criteria to determine whether component-specific evaluation or augmented inspections are needed. In addition to the NRC criteria, the current BWRVIP inspections were also evaluated to determine whether they satisfy the intent of NUREG-1801, Rev. 1.

The evaluation shows that all the BWR CASS components have ferrite levels below the level for which aging embrittlement is a concern. Furthermore, for the Control Rod Guide Tube Base and Core Spray Sparger Nozzle Elbows, the end of life fluence is less than the threshold value for toughness loss. The end of life fluence levels for the orificed fuel support, the jet pump assembly castings and the LPCI couplings exceed the threshold, but the toughness data for irradiated austenitic stainless steel show that that these components will have sufficient fracture toughness at end of the license renewal period so that augmented inspection is not required. In summary, based on this assessment, it is concluded that augmented inspections are not required for the BWR CASS internals.

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1 INTRODUCTION

1.1 Background

NUREG-1801 Rev. 1, Section XI.M13, (hereafter referred to as the GALL report) states that a Section XI VT-3 examination is required to be performed of reactor internal components. In addition, the GALL report specifies that for the license renewal period, these inspections shall be augmented by an aging management program to address the synergistic effects of thermal aging and neutron embrittlement in cast austenitic stainless steels (CASS). This aging management program consists of (a) identifying susceptible components; and (b) either performing additional inspections of these components, or performing a component-specific evaluation to confirm that the stresses (tensile loading) in the components are sufficiently low such that augmented inspections are not warranted.

The potential for aging embrittlement (and its detrimental effect on fracture toughness) is dependent on several material/environmental factors: ferrite level, operating temperature, chemical composition, casting methods, and fluence level. For example, molybdenum is known to have a synergistic effect on the formation of embrittling phases, such that the molybdenum-bearing grades are known to have a greater susceptibility to thermal aging. In order to evaluate the potential for embrittlement, all of these factors must be considered.

A second key contributor to evaluating the effects of embrittlement is the stress state of the individual components. There may be some components, for example, that do not experience high loads during service, and, as such, embrittlement would not be a significant concern for component performance.

1.2 Objectives and Scope

The purpose of this report is to evaluate the material composition, fluence, stresses and the field experience of CASS components in BWR applications and recommend augmented inspections if needed.

Ten (10) BWR internal components have been identified as fabricated of CASS, and within the scope of this evaluation (the BWRVIP document that contains the component description is included for reference):

- Orificed Fuel Support (OFS) (BWRVIP-47-A)
- Control Rod Guide Tube Base (BWRVIP-47-A)

- Core Spray Sparger Nozzle Elbows (BWRVIP-18, Rev.1)
- Jet Pump Transition Piece (BWRVIP-41, Rev. 1)
- Jet Pump Restrainer Bracket (BWRVIP-41, Rev. 1)
- Jet Pump Inlet Mixer Assembly (BWRVIP-41, Rev. 1)
- Jet Pump Elbow (BWRVIP-41, Rev. 1)
- Jet Pump Nozzle (BWRVIP-41, Rev. 1)
- Jet Pump Diffuser Collar/Guides (BWRVIP-41, Rev. 1)
- LPCI Coupling (BWRVIP-42-A)

This evaluation is composed of the following steps:

1. Literature review of CASS embrittlement
2. Material composition effects
3. Material data review from actual CASS components
4. Fluence effects
5. Development of generic screening criteria
6. Stress evaluation of typical component

Using the results of this evaluation, augmented inspection recommendations (if necessary) for CASS components have been developed.

1.3 Implementation Requirements

This report is provided for information only. Therefore, the implementation requirements of Nuclear Energy Institute (NEI) 03-08, Guideline for the Management of Materials Issues, are not applicable.

2 LITERATURE REVIEW

Embrittlement of cast austenitic stainless steels (CASS) has been studied extensively, identifying many of the key parameters that can affect the fracture toughness of CASS material with long term exposure to the high temperature light water reactor environment. This section reviews both thermal aging and neutron embrittlement and summarizes these key factors, which will be used in subsequent sections to evaluate the potential susceptibility of BWR CASS components to loss of fracture toughness.

2.1 Thermal Aging Embrittlement Phenomena

Thermal aging embrittlement (also termed as thermal embrittlement) of CASS components occurs as a result of long time aging at light water reactor operating temperatures [1]. Thermal embrittlement increases the hardness and tensile strength, and decreases ductility, impact strength, and fracture toughness. Austenitic welds and castings have a duplex microstructure consisting of austenite and δ-ferrite phases. Although the ferrite content is beneficial in preventing hot cracking and stress corrosion cracking, it is also the source of thermal embrittlement for austenitic welds and castings.

Studies investigating the cause of the thermal embrittlement of CASS have demonstrated that it can occur during the reactor design lifetime or life extension due to the precipitation of a Cr-rich α' phase as a result of spinodal decomposition, nucleation and growth of the γ' phase; precipitation of a G phase (a nickel and titanium rich silicide), formation of $M_{23}C_6$ carbides in the δ-ferrite, and/or additional precipitation and/or growth of existing carbides at the ferrite/austenite phase boundaries.

The effect of thermal embrittlement of austenitic stainless steel welds and castings is manifested in cleavage fracture in the ferrite phase or separation of the ferrite/austenite phase boundary. Materials with high ferrite content and/or large phase boundary carbides are more prone to thermal embrittlement. The effect of thermal aging is to decrease the lower and upper shelf Charpy energy of CASS. Significant reduction in fracture toughness is likely when the ferrite volume fraction exceeds 10% [2].

Even though there is potential for fracture toughness reduction, it is appropriate to consider a screening fracture toughness level to further differentiate materials subject to embrittlement, such that augmented inspections are not necessary. A screening crack growth resistance (J-R) value of 255 kJ/m^2 (1,450 in-lb/in^2) at a crack depth of 2.5 mm (0.1 in) is discussed in [4] and states these values can be used to differentiate between CASS materials that are non-susceptible and those that are subject to thermal aging embrittlement.

2.1.1 Temperature Effects

Chopra [3] discusses an Arrhenius model to determine the effect of aging temperature on the time to reach a given degree of embrittlement. A best estimate of the laboratory data at high temperatures suggests the following the equation:

$$t = 10^P \exp\left[\frac{Q}{R}\left\{\frac{1}{T} - \frac{1}{673}\right\}\right]$$

where Q is the activation energy, R the gas constant, T the absolute temperature, and P an aging parameter that represents the degree of aging reached after 10^P hours at 400°C (752°F). The activation energy for the process of embrittlement is a function of the chemical composition of the cast material. The relationship shows that the time to reach a given level of embrittlement is lower at higher temperatures, i.e. aging embrittlement is more significant at higher temperatures.

Sample data from Reference [4] (Figure 2-1) show clearly the effect of aging temperature on the fracture toughness of CF-8M material. While the saturation energy (i.e. Charpy energy at long times) does not depend on the aging temperature, the time to reach a given degree of embrittlement is much lower at higher aging temperatures. In other words, the higher the aging temperature, the greater is the deterioration with time. Based on this, one can conclude that CASS aging embrittlement effects in a BWR are significantly lower than components in a PWR.

2.1.2 Chemical Composition

Of the CASS materials commonly used in light water reactor applications (CF-3, CF-8, CF-3M and CF-8M), CF-8M is the most susceptible to aging embrittlement. The results indicate that thermal aging decreases the impact energy and shifts the ductile-to-brittle transition curves to higher temperatures. However, different heats exhibit different degrees of embrittlement. In general, the low-carbon CF-3 grades of cast materials are the most resistant, and the molybdenum-containing CF-8M grades are least resistant to embrittlement. For all grades of cast materials, the extent of embrittlement increases with an increase in ferrite content.

The quantity and distribution of the ferrite within the structure is an important aspect of thermal embrittlement of CASS materials. When the ferrite phase is continuous, e.g., large ferrite content, or the ferrite/austenite phase boundary provides an easy path for cracking, the material is much more susceptible to brittle failure than when the material contains lower ferrite levels. However, even with the decrease in toughness, the fracture margin is still significant due mainly to the high toughness of the austenite matrix.

Various studies have shown that higher ferrite contents (also called delta (δ) ferrite) correlate with increased susceptibility to embrittlement, and ferrite-forming elements such as Cr, Mo, Si, Cb and V increase the susceptibility to thermal embrittlement.

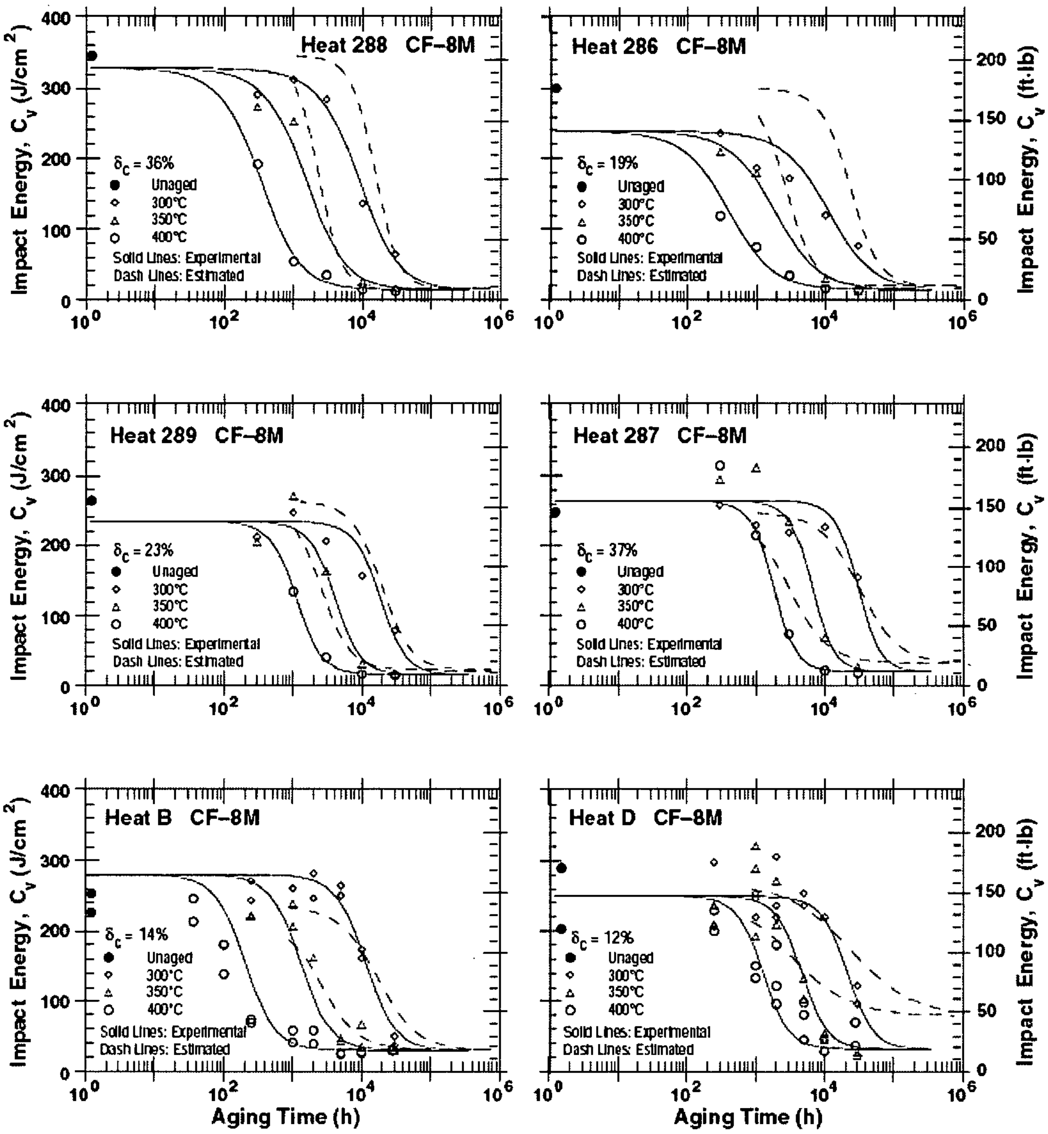

Figure 2-1
Effect of aging temperature on the fracture toughness of sample CF-8M heats

Because of the presence of ferrite, CASS materials show the typical brittle to ductile transition behavior that is often seen in ferritic steels. This is especially true in high ferrite CASS materials. Thermal aging causes the ductile-to-brittle transition temperature to increase and both room temperature and operating temperature toughness decrease with increasing embrittlement of the ferrite phase. Figures 2-2 and 2-3 from Reference [3] show charpy energy as a function of test temperature for different aging conditions for CF-3, CF-8, and CF-8M, respectively. A review of test data for different heats of material in Reference [3] leads to the following observations.

- For centrifugally-cast CF-8 material, 18% δ ferrite is acceptable even with the higher carbon (only 0.036 wt.% for this heat).

- Even at 28% δ ferrite, centrifugally cast low-molybdenum CASS (CF-8) has adequate toughness.
- Statically-cast, low-molybdenum material (CF-8) with relatively high δ ferrite content (> 20%) could be screened out from further evaluation.
- The fracture toughness of statically-cast CF-3 and CF-8 material is adequate and show very little aging effects for ferrite levels up to 15% for operating times close to the license renewal term.

The above study supports the traditional screening guideline for low temperature embrittlement of CASS, which is 20% ferrite for low molybdenum (CF-3 and CF-8) materials used in the BWR.

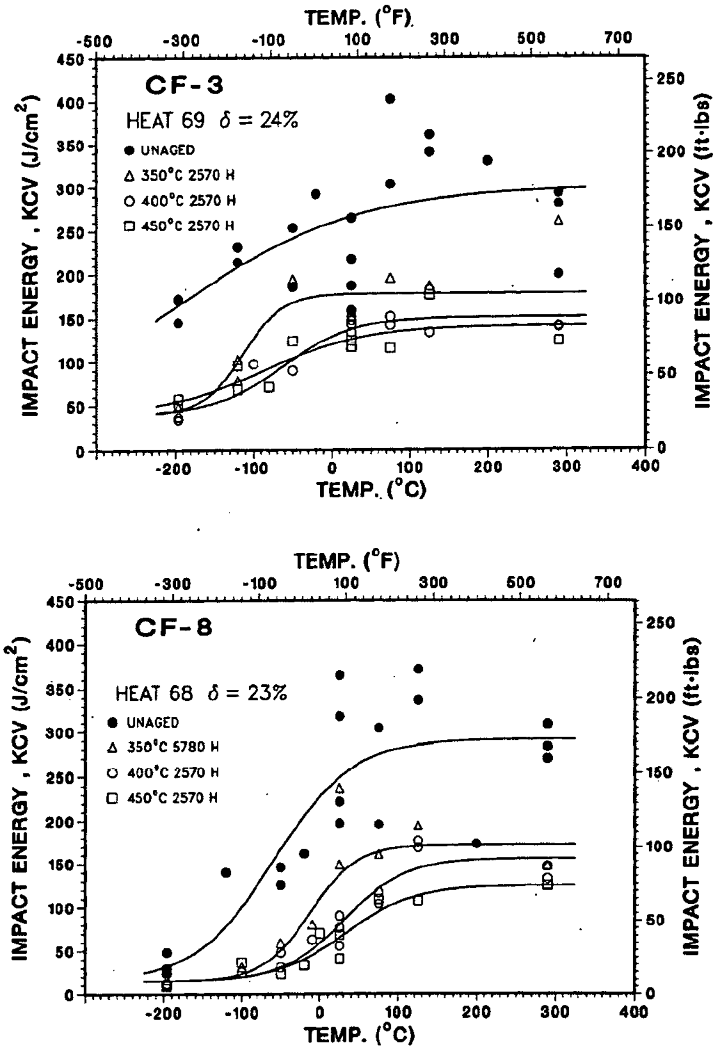

Figure 2-2
Charpy energy vs. test temperature for CF-3 and CF-8 under different aging conditions

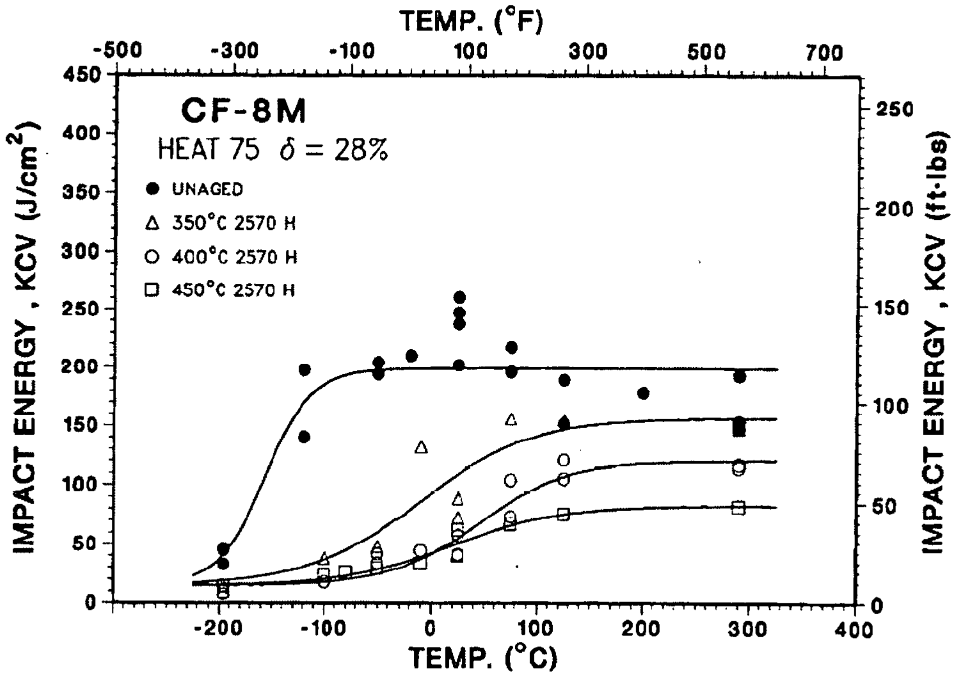

Figure 2-3
Charpy energy vs. test temperature for CF-8M under different aging conditions

The extent of the low temperature embrittlement is generally quantified by measuring the room temperature Charpy energy absorbed after aging at temperatures representative or slightly higher than those expected in service. Figure 2-4 from Reference [1] shows the effect of δ ferrite on material J-R curves for CF-8M. Table 2-1 shows the same data in terms of J_{IC} and J-R curve fits ($J = C\ \Delta a^n$). It is seen that there is a significant reduction in J-R properties at higher ferrite numbers. Figure 2-5 from Reference [4] shows the upper shelf Charpy energy as a function of ferrite number.

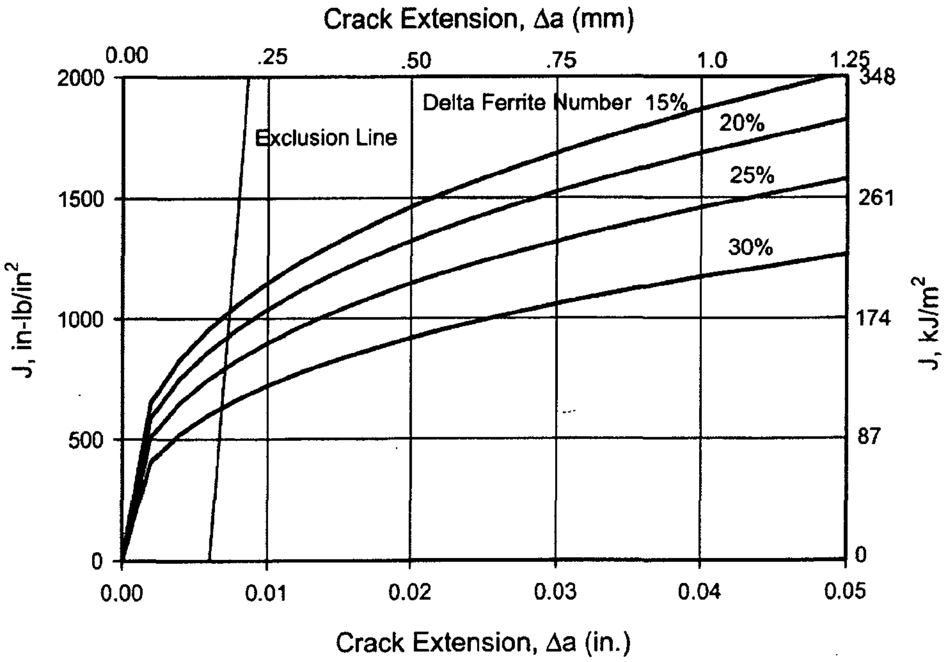

Figure 2-4
J-R curves for CF-8M CASS materials with various δ ferrite numbers

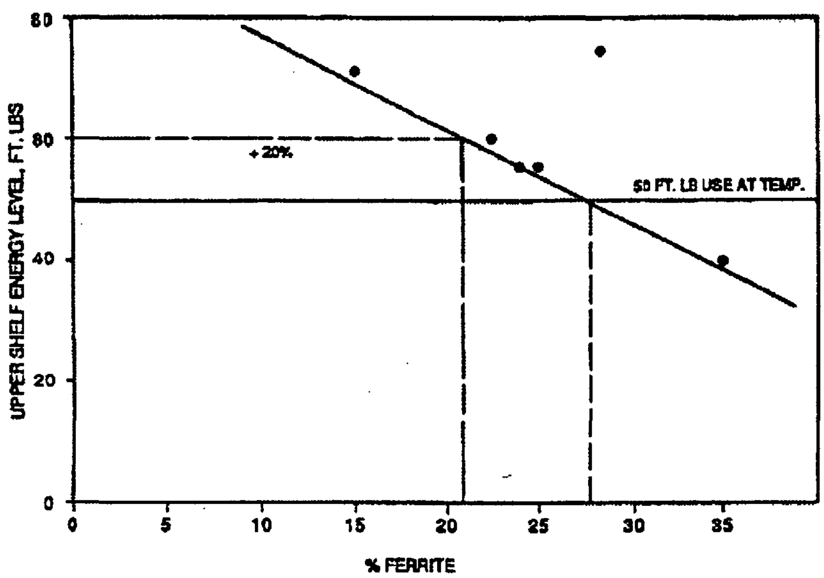

Figure 2-5
Upper shelf energy as a function of δ ferrite number

Table 2-1
J_{Ic} and J-R curve parameters ($J=C\Delta a^n$) as a function of δ ferrite number

DFN	J_{IC}		C		n
	in-lb/in²	kJ/m²	in-lb/in²	kJ/m²	
15	1000	175	5750	325	0.35
20	915	160	5200	294	0.35
25	800	140	4500	254	0.35
30	650	114	3610	204	0.35

For light water reactor applications, traditional guidelines have been that the low temperature embrittlement becomes a concern only when the volume fraction of the ferrite exceeds approximately 15 to 20%. The basis for this argument is that ferrite tends to form in pools in the austenite matrix and when ferrite levels are less than approximately 15%, there is significantly less likelihood that the embrittled ferrite phase can form a continuous path of embrittled material that can extend through the thickness of the cast component.

2.2 Neutron Fluence

As indicated in the GALL report, concurrent thermal embrittlement and exposure to neutron irradiation may result in a synergistic effect wherein the service-degraded fracture toughness can be less than that predicted for either of these processes independently. In the proposed resolution regarding the issue of thermal embrittlement of cast SS components [5], the NRC staff recommends that, to account for the synergistic loss of fracture toughness, "a program should be implemented consisting of either a supplemental examination of the affected components as part of the applicant's 10-year inservice inspection program during the license renewal term, or a component-specific evaluation to determine the susceptibility to loss of fracture toughness." The component-specific evaluation is based on the neutron fluence. The current guidance suggests that if the fluence is greater than 1×10^{17} n/cm^2 (E>1 MeV) (or ~0.15 mdpa) for a component, a supplemental examination is required. Alternatively, a mechanical loading assessment may be conducted to determine if the supplemental inspection program may be eliminated for the component. Considering that even for ferritic steels, the NRC position (as stated in Appendix G of 10CFR50) does not require fracture toughness assessment for fluences less than 1×10^{17} n/cm^2 (E>1 MeV), the threshold for the synergistic effects in CASS is overly conservative.

The EPRI assessment [6] by Nickell suggests that synergistic effects between thermal aging embrittlement and neutron irradiation embrittlement are not measurable for accumulated neutron irradiation at a fluence level of 1×10^{21} n/cm^2 (E>1 MeV) and below. Therefore, unless CASS internal components are subjected to higher neutron fluence levels, the potential synergistic effect of thermal aging embrittlement and neutron irradiation embrittlement need not be evaluated. Considering that radiation effects on mechanical properties of wrought stainless steel are significant at a fluence level of 1×10^{21} n/cm^2 (E>1 MeV), the suggested threshold for synergistic effects might be too high.

Similarly, MRP-175 [7] has identified a fluence level of 1 x 10^{21} n/cm^2 (E>1 MeV) as a screening criteria for the neutron embrittlement of wrought austenitic stainless steels, with a lower value of 6.7 x 10^{20} n/cm^2 for CASS components. These values, however, are based upon an acceptable fracture toughness value for PWR applications, and therefore may not representative of the synergistic effects for BWR applications.

Based on this discussion, it appears that neither the NRC threshold in [5], the EPRI threshold in Reference [6], or the MRP recommendation [7] are realistic or reasonable for BWR application. Clearly, the threshold for synergistic effects lies somewhere between the limiting numbers. In the absence of test data that validate the synergy threshold, a reasonable value of 3 x 10^{20} n/cm^2 is used as the upper bound fluence for application of limit load as defined in [8] which is approved by NRC. Currently, for shroud welds [9] (which are duplex materials similar to CASS) no fracture evaluation is needed for fluences less than 3 x 10^{20} n/cm^2 (E>1MeV). Since these welds are also subject to long term aging at reactor temperature and there are negligible fluence effects on mechanical properties below this value, it is reasonable to postulate that there will be no synergistic aging effects below 3 x 10^{20} n/cm^2 (E>1MeV). Chopra and Shack [10] state "Based on these very limited data and the general mechanism of embrittlement for cast SSs, the minimum fracture toughness of cast SSs can be taken as (a) the minimum predicted toughness for thermal aging for fluences less than 2 x 10^{20} n/cm^2 (E>1MeV) (or ~0.3 dpa) and (b) the lesser of the minimum predicted toughness for thermal aging or the lower bound curves for irradiated SS. The threshold fluence, taken as 0.3 dpa, is a slightly conservative value in light of the limited data and corresponding uncertainty." The suggested threshold of 3 x 10^{20} n/cm^2 (E>1MeV) is close enough to the 2 x 10^{20} n/cm^2 (E>1MeV) suggested by Chopra and Shack. The choice of the 3 x 10^{20} n/cm^2 threshold value is based on consistency with other BWRVIP documents. As discussed later in this report (Table 3-3) there are no CASS components where the 60-year fluence is within the range of 2-3 x 10^{20} n/cm^2 (E>1MeV). Thus, the evaluation remains unchanged regardless of whether the threshold is 2 x 10^{20} n/cm^2 suggested by Chopra and Shack [10] or the 3 x 10^{20} n/cm^2 value suggested in this report.

For fluences that exceed the 3 x 10^{20} n/cm^2 (E>1MeV) threshold, it is reasonable to use the CASS data in Reference [10] for highly irradiated welds. Since many of the irradiated weld test specimens were taken out of operating reactor components, the aging effect is indirectly included. Flaw evaluations based on Reference [11] would provide reasonable estimates of fracture margins and allowable flaw sizes.

3 MATERIALS AND ENVIRONMENT

There are two main forms of embrittlement for cast austenitic stainless steels (CASS): thermal and neutron. Thermal embrittlement is controlled by two key parameters: (1) material composition and (2) time exposed to elevated temperature. The role of material composition on thermal embrittlement is also affected by the secondary parameter of casting method. Neutron embrittlement of CASS is controlled by the chemical composition and fluence that the material will see during its lifetime. To evaluate the chemical composition, the material specifications and certified material test reports (CMTRs) for the cast components were reviewed. Given that the material requirements were similar across the components, and the materials were supplied to several plants, the CMTRs are representative of the complete scope of CASS internals components in all BWRs. In addition, the fluence at the locations for the CASS components was obtained.

3.1 Material Parameters

For the purpose of evaluating the effects of thermal embrittlement, material composition and casting method are the key parameters. Operating temperature also plays a role, but since all BWR CASS components are at a similar temperature, it is not used for the purposes of screening components that could be potentially susceptible to thermal embrittlement. For the cast components in the BWR, a review was conducted of the original material requirements (product specifications), as well as a representative sampling of CMTRs of the components identified as being potentially susceptible. The cast components for individual plants are identified in Table 3-1. As can be seen by this table, the material specified for the cast components was Grade CF8 in almost all cases.

3.2 Product Specifications

To further characterize the material specified for the individual components, a review of Jet Pump component drawings for three plants (BWR/3, 4 and 5) was conducted. All of the drawings specified GE specification B50YP43, which in turn specifies ASME SA-351 or ASTM A-351 grade CF-8 material. Early revisions of this GE specification contained a chemical requirement to control ferrite using a minimum chromium/nickel ratio of 1.9. By the early 1970s, ferrite was specified as a minimum 8% as calculated using the Schaeffler diagram [12]. No maximum ferrite was specified for these materials. It should also be noted that review of the revisions of this specification confirms that molybdenum-containing castings were never specified for these components.

Table 3-1
Material requirements

Component	Material	Applicable Plant (s)
Orificed Fuel Support	CF-8	All
Control Rod Guide Tube Base	CF-3, CF-8	All
Core Spray Sparger Nozzle Elbows	CF-8	All
Jet Pump Transition Piece	CF-8	All*
Jet Pump Restrainer Bracket	Type 304	BWR/3, Vermont Yankee
	CF-8	BWR/4 (except VY), BWR/5, BWR/6
Jet Pump Inlet Mixer Assembly	CF-8	All
Jet Pump Diffuser Collar/Guides	CF-8	All
Jet Pump Inlet Nozzle	CF-8	All
Jet Pump Inlet Elbow	CF-8	All
LPCI Coupling	CF-3, CF-8	BWR/4 (Hope Creek, Limerick) BWR/5 BWR/6

*As noted in BWRVIP-41, Rev. 1, some of the assemblies may be welded Type 304 material, but are assumed to be castings for this evaluation.

3.3 Casting Method

Casting method (centrifugal vs. static) has been identified as a screen for the effects of thermal aging. Centrifugally cast components are allowed a higher percent ferrite before thermal aging is of concern for the high Mo components, and centrifugally cast components that have low Mo content (such as CF-8) are not at risk for thermal aging following exposures of less than 320°C (608°F) for 525,000 hours [4]. Review of CMTRs for the CASS components supplied by GE could not confirm that any of the components were centrifugally cast. It should be noted, however, that this does not affect the final evaluation results, as casting method was not used as a screening criteria.

3.4 Ferrite Content

Since the specification limits do not adequately describe the ferrite content of the CASS materials present in the BWR, a review of CMTRs was performed. Approximately 80 heats of material chemistry were tabulated, as shown in Appendix A. All of the CMTR material was confirmed to be CF-8, consistent with the original product specifications.

Typically, the δ ferrite value for these materials was not reported. Therefore, in order to evaluate the ferrite levels, the δ ferrite, δ_c, was calculated in accordance with Hull's equivalent factors, and if nitrogen was not available, it was assumed to be 0.04% [13]:

$$Cr_{eq} = Cr + 1.21\,(Mo) + 0.48\,(Si) - 4.99$$

$$Ni_{eq} = Ni + 0.11\,(Mn) - 0.0086\,(Mn)^2 + 18.4\,(N) + 24.5\,(C) + 2.77$$

$$\delta_c = 100.3(Cr_{eq}/Ni_{eq})^2 - 170.72(Creq/Nieq) + 74.22$$

The ferrite calculations are summarized in Table 3-2, and the complete list of calculated ferrite values for the individual heats is tabulated in Appendix A. As can be seen, the ferrite levels are below the 20% threshold normally associated with thermal aging concerns [5]. In addition, a statistical evaluation of the data showed that there is a 99.8% confidence that the ferrite level will be below the 20% ferrite limit.

Table 3-2
Summary of CMTR data

Parameter	Value
Average % Ferrite	10.12
Standard deviation	3.37
Ferrite Range	3.21 to 18.8
Percent Ferrite Calculated from Average Chemistry	9.65
Percent of Castings Below 20% Limit for Ferrite	99.8

3.5 Fluence Effects

In order to evaluate the synergistic effects of neutron fluence, fluence values for CASS BWR components were obtained. Calculations have been performed for a BWR/6, 218 inch plant at extended power uprate (EPU) conditions in accordance with RG 1.190 methods [4]. Calculations for a BWR/4, 251 inch plant and BWR/5 251 inch plant for EPU conditions were also reviewed, and the BWR/6, 218 inch plant fluence values were bounding. For each of the ten CASS components of concern, the estimated peak fluence for each location is listed in Table 3-3; these values are for 60 years of operation. All of the cast components, except for the control rod guide tube base and core spray sparger elbows, are exposed to a neutron fluence greater than the 3×10^{20} n/cm^2 (E>1 MeV) discussed in Section 2.5.

Table 3-3
Fluence values for CASS components

[[

Component	Fluence (n/cm^2)
Orificed Fuel Support	
Control Rod Guide Tube Base	
Core Spray Sparger Nozzle Elbows	
Jet Pump Transition Piece	
Jet Pump Restrainer Bracket	
Jet Pump Inlet Mixer Assembly	
Jet Pump Diffuser Collar/Guides	
Jet Pump Inlet Nozzle	
Jet Pump Inlet Elbow	
LPCI Coupling	

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4
COMPONENT SCREENING

This section describes several ways to screen out BWR CASS components from augmented inspection requirements. The screening options are based on NRC positions as stated in [5] and [15]. The screening criteria are based on several considerations: ferrite content, fluence, available fracture toughness, applied stress and current inspection practice. These are briefly discussed in the following paragraphs.

4.1 Screening Based on Ferrite Content

As part of the evaluation of passive, long-lived reactor structures for license renewal, the NRC staff has proposed screening criteria to determine the susceptibility of cast SS components to thermal aging embrittlement [3]. The thermal embrittlement criteria are outlined in Table 4-1. Essentially it states that for low Molybdenum statically cast CASS (<0.5 wt.% Mo) the threshold ferrite (below which thermal embrittlement is unlikely) is 20%. This means that CF-3, CF-3A and CF-8 with percent ferrite less than 20% are unlikely to experience significant loss of toughness due to thermal embrittlement. For statically cast CASS with Mo>2% wt.% (CF-3M and CF-8M) the ferrite threshold is 14%. For components found or assumed to be potentially susceptible, an aging management program is required for the license renewal period.

Table 4-1
Screening criteria based on ferrite number

CASS Thermal Aging Susceptibility Screening Criteria			
Mo Content (Wt.%)	**Casting Method**	**Ferrite Level or Content**	**Susceptibility Determination**
High (2.0 to 3.0)	Static	≤ 14%	Not susceptible
		> 14%	Potentially Susceptible
	Centrifugal	≤ 20%	Not susceptible
		> 20%	Potentially Susceptible
Low (0.5 max.)	Static	≤ 20%	Not susceptible
		> 20%	Potentially Susceptible
	Centrifugal	ALL	Not susceptible

Cast stainless steel components have not experienced IGSCC in BWRs. Even in Type 308 stainless steel welds (which are duplex materials similar to CASS), crack initiation has been extremely rare except in a few cases where the ferrite content was less than 5%. CASS components in BWRs require a minimum ferrite level of 8%. Hughes, Clarke and Delwiche [16] performed an extensive study of the IGSCC resistance of CASS components in high temperature BWR environment. The tests involved CF-3, CF-3A, CF-8, CF-3M and CF-8M specimens in the as welded and furnace sensitized condition. Other tests considered the effects of nitriding (to simulate CRD CASS components) and stellite weld application (to simulate the inlet mixer belly band and the restrainer bracket). Several types of tests with aggressive loading were performed: i) constant extension rate tests (CERT), ii) pipe tests, iii) variable load tests and iv) constant load tests. Figure 4-1 from Reference [16] shows the influence of carbon content and percent ferrite on IGSCC susceptibility in CASS. The results of their tests are summarized here:

- Regardless of the percent ferrite there was no IGSCC in welded CASS with <0.05 wt.% carbon. This means that CF-3, CF-3M and CF-3A components are resistant to IGSCC regardless of the ferrite content.
- No SCC was observed beyond 12% ferrite, regardless of the carbon content. The curve representing the combination of carbon content and percent ferrite for IGSCC is somewhat lower for furnace sensitization compared to welded CASS, i.e. for a given percent ferrite, the maximum carbon content (above which IGSCC can occur) is lower for furnace sensitized CASS than for welded CASS.

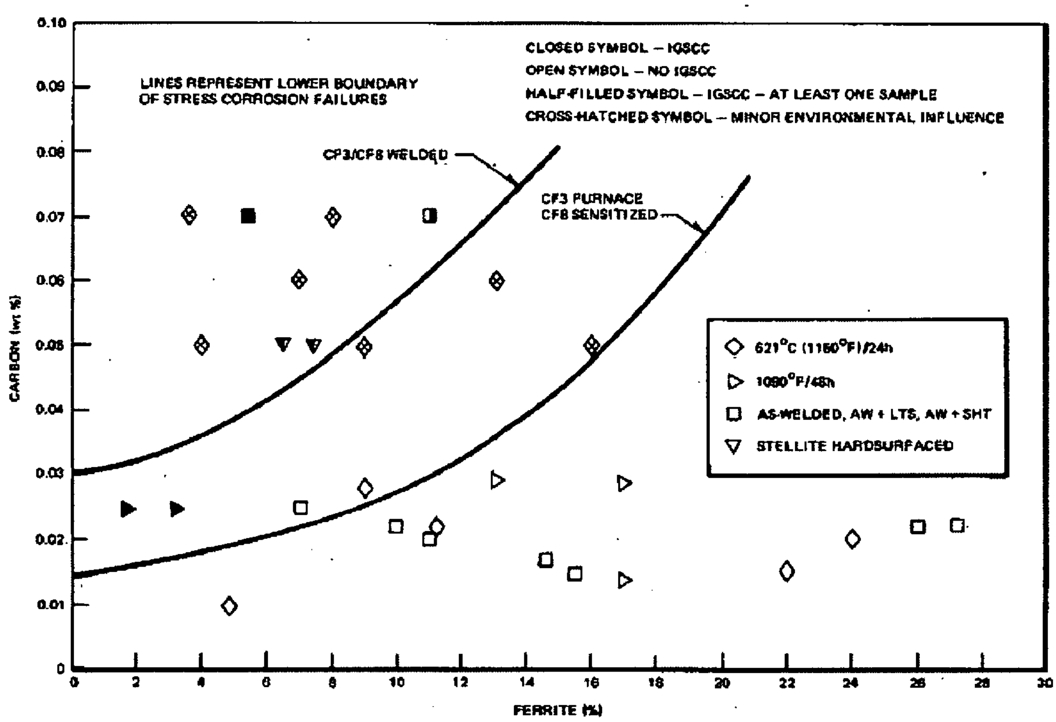

Figure 4-1
Role of carbon and ferrite content on IGSCC potential in CASS components [16]

Based on this assessment, the likelihood of crack initiation in CASS components is low. In particular, the case can be made that environmentally assisted cracking of low carbon CASS (CF-3, CF-3A and CF-3M) is extremely unlikely.

Fatigue due to system cycling is not a significant issue since all the CASS components in question are reactor internals and not subjected to either pressure or thermal cycling of any significance. The only source of fatigue usage is from potential vibrations in CASS jet pump components. The jet pump (JP) assembly (including the inlet mixer and restrainer bracket) is routinely inspected as part of the BWRVIP-41, Rev. 1 [17] inspections. No cracking has been found in CASS components in the JP assembly. Thus, while fatigue cracking cannot be ruled out, field experience in the past 30 years suggests that crack initiation due to fatigue in any of the CASS components is unlikely and the existing inspections per BWRVIP-41, Rev. 1 are sufficient.

Since the threshold for crack initiation by IGSCC is <12% ferrite based on the study in Reference [16] and the threshold for thermal aging embrittlement is 14% or higher, one can argue that concurrent crack initiation and loss of toughness due to thermal aging is unlikely and additional evaluation is not needed. However, many CASS reactor internals components are subject to neutron irradiation and therefore, the ferrite levels by themselves are not adequate to exempt CASS components from augmented inspections. Therefore, additional screening criteria must be considered as discussed in the following sections.

4.2 Screening Based on Fluence

As stated previously, the threshold for the synergistic effect of fluence is defined to be $1x10^{17}$ n/cm^2 (E>1MeV) in the GALL report [5, 15]. Below this value, additional evaluation to consider irradiation effects is not needed (over and above that for thermal aging). However, the fluence estimates for BWR CASS internals shows that almost all the components exceed the threshold for fluence regardless of which threshold value (1×10^{17} n/cm^2 in Reference [5], 2×10^{20} n/cm^2 in Reference [10] or 3×10^{20} n/cm^2 value recommended in this report) is selected. The only component that can be screened out is the control rod guide tube base and the core spray sparger elbows, as shown in Table 3-3. All other components must be considered for more detailed evaluation.

4.3 Screening Based on Toughness

The GALL report [15] also provides an alternative screening criterion employing fracture toughness. It is based on the recommendation that a fracture toughness value of 255 kJ/m^2 (1,450 in-lb/in.^{2}) at a crack depth of 2.5 mm (0.1 in.) can be used to differentiate between CASS materials that are non-susceptible and those that are subject to thermal aging embrittlement [4]. As stated earlier, the CF-3 and CF-8 materials used in the BWR CASS internals are not susceptible to thermal aging, but still must be evaluated for the combination of thermal aging and neutron embrittlement.

There is very little data on the fracture toughness of irradiated CASS, let alone data on CASS material that is both aged at temperature and subjected to irradiation. One way of estimating toughness is to use irradiated toughness data on stainless steel weldments [8][1]. Much of this data is derived from specimens taken from operating plants, so the data considers the synergistic effect of thermal aging and irradiation. Two methods are used to estimate the J values at a crack depth of 2.5 mm. This will be used to screen the different BWR CASS components against the NRC approved criterion of 255 kJ/m^2 (1,450 in-lb/in.^{2}) at a crack depth of 2.5 mm.

The bounding fluence (see Table 3-3) is [[ ]] for all other CASS components. Therefore, the fracture toughness assessment will be based on a fluence of [[ ]] TS

Table 4-2 and Figure 4-2 from Reference [8] show test data for irradiated stainless steel subjected to different fluence levels. The J-R curves were fit using the equation $J = C (\Delta a)^n$ and the table provides values for C and n for the different tests. It can be seen that the limited weld data exceeds 225 kJ/m^2 in the 4.0-4.8 x 10^{20} n/cm^2 fluence range. Only two curves are available for the appropriate fluence level. These points, irradiated to 6.3 x 10^{20} n/cm^2 and 6.4 x 10^{20} n/cm^2, respectively, are listed in Table 4-3. Both are for wrought material with the irradiation temperature being 536°F (280°C), which is close to the irradiation temperature for BWR CASS components). The test temperatures were 390°F (199°C) and 480°F (249°C) respectively. Table 4-3 shows the calculated J values at a crack depth of 2.5 mm. The second data point (638 kJ/m^2) in Table 4-3 for 6.4 x 10^{20} n/cm^2 fluence is more appropriate since the test temperature was at 480°F, which is closer to the operating temperature of most BWR internals. However, the data in Table 4-3 is valid for base (wrought) material. Toughness data for weldments under similar conditions is expected to be lower. One way of accounting for this is to use the Z-factors in Appendix C of Section XI [18] to reduce the toughness so that the equivalent toughness for weldments can be estimated. The basis for the Z-factors is described in Reference [19]. The methodology involved the determination of multipliers to be applied on the stress so that the fracture mechanics (J-T stability) results are represented by limit load evaluation using the stresses multiplied by the Z-factors. Essentially the Z-factors represent a way of accounting for the lower toughness of weld metal when applied to wrought material data. Z-factors are presented for both SMAW and SAW welds (flux welds). Z-factors need not be applied for non-flux (e.g. GTAW) welds since they have toughness values comparable to wrought materials. The Z-factor for SAW welds are higher and are given as a function of pipe diameter by the following expressions [19]:

$$Z_{SAW} = 1.30[1+0.010(OD-4)]$$

where OD is in inches and Z is the factor for SAW.

[1] The data in Reference [8] is mostly from wrought stainless steel with a limited amount of data points from welds.

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Table 4-2
J at Δa=2.5 mm calculated values at 6.3×10^{20} n/cm^2 fluence (taken from Table 4-2)

Spec ID	Material	Type	Irradiation Temperature °F (°C)	Test Temperature °F (°C)	Fluence (n/cm^2)	C (kJ/m^2)	n	J at 2.5 mm (kJ/m^2)
2, CT	Type 304	Base	536 (280)	390 (199)	6.3×10^{20}	516	0.4	744
2, CT	Type 304	Base	536 (280)	480 (249)	6.4×10^{20}	426	0.44	638

The diameter of most of the CASS components is less than 12 inches, so a conservative estimate for Z is 1.3[1+0.01(12-4)] = 1.404. This is the multiplier on stress. Since J is dimensionally proportional to K^2 or σ^2, a conservative penalty on J is to divide the wrought toughness by Z^2. Based on this, the estimated weld toughness is $638/1.404^2 = 324$ kJ/m^2. This is in excess of the required value of 255 kJ/m^2 (1,450 in-lb/in.^{2}). Based on this, it can be concluded that all the CASS components can be considered not susceptible to thermal or fluence embrittlement and no augmented inspections are warranted.

An alternate way to estimate the toughness is to use the recommended lower bound properties in Reference [8]. A power law fit was used to construct a line that bounds the available data for C as a function of fluence. The power law fit for n was defined as a function of fluence so that when it is used in combination with the bounding relationship for C, the resulting predicted J-R curves match or are conservative compared to the experimental J-R curves. The data and corresponding power law fits for C and n as a function of fluence are shown in Figures 4-3 and 4-4, respectively.

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For the fluence value of [[ ]] TS the value of n is 0.48 and the value of C is 190 kJ/m^2. Since this is the lower bound for base, heat affected zone (HAZ) and weld material, no additional correction is needed for the weldment toughness. Substituting these values, the lower bound J at 2.5 mm crack extension is 295 kJ/m^2. As in the previous case, this is in excess of the required value of 255 kJ/m^2 (1,450 in-lb/in.^{2}). Based on this, it can be concluded that all the CASS components can be considered not susceptible to thermal or fluence embrittlement and no augmented inspections are warranted.

4.4 Screening Based on Stress

NUREG-1801 allows as an alternative, the use of component-specific evaluation, including a mechanical loading assessment to determine the maximum tensile loading on the component during ASME Code Level A, B, C, and D conditions. If the loading is compressive or less than 5 ksi (34.5 MPa) and thus low enough to preclude fracture, then supplemental inspection of the component is not required. NUREG-1801 does not specify whether the limit on applied stress is intended for the membrane stress, membrane + bending or peak stress. Considering that the final application is for a fracture assessment, it is reasonable to assume that the 5 ksi (34.5 MPa) stress limit applies to membrane stress or membrane + bending stress. The specification of the same stress limit (5 ksi or 34.5 MPa) regardless of the conditions (Levels A, B, C or D) is somewhat inconsistent with the generally accepted ASME Code philosophy where the allowable values are higher for low probability events. In general, stress analysis of reactor internals is based on conservative assumptions and most components might not meet the conservative 5 ksi (34.5

MPa) limit, especially when the stresses during low probability events such as seismic and accident conditions are compared with the stress limit. Nevertheless, Section 5 will discuss the stress analysis of BWR CASS internals.

4.5 Screening Based on Current BWRVIP Inspections

The requirement to address the enbrittlement issue is based on the interpretation that augmented inspections are required unless the screening criteria described above are met. However, BWR internals are already being inspected under the different BWR Vessel and Internals Project (BWRVIP) Inspection and Evaluation Requirements. BWRVIP-41, Rev. 1 [17] specifies inspection requirements for the jet pump assembly. Similarly, BWRVIP-18, Rev. 1 [20] requires inspections of the core spray sparger nozzle elbows, BWRVIP-42-A [21] specifies inspections for the LPCI coupling and BWRVIP-47-A [22] specifies inspections for the control rod guide tube base and fuel support alignment pin.

5
STRESS EVALUATION

This section summarizes the results of the stress analysis for some of the different CASS internals.

5.1 Orificed Fuel Support

The orificed fuel support (OFS) is part of the lower plenum components covered by BWRVIP-47-A [19]. Figure 5-1 shows the schematic of the orificed fuel support. The stress analysis of the OFS is described in Reference [23]. The main steady state loading on the component is due to internal pressure differences. The ΔP values and the associated stresses are shown in Table 5-1.

In addition to the pressure stresses, the stresses for seismic loading were determined by testing due to the complex geometry of the OFS. The testing methodology included the use of simulated horizontal and vertical loads to represent the seismic loading expected for the OFS. Under normal operating conditions, the OFS does not see significant loads (only differential pressure, and the weight of the fuel). Under OBE and SSE conditions, the vertical component of the seismic load is transferred from the fuel through the OFS to the Control Rod Guide Tube (CRGT). The horizontal seismic component is transferred through the OFS, the CRGT, and then to the core plate. For the OFS, the stress intensity for the upset seismic event (OBE) was [[ ]] . The stress intensity for the faulted seismic event (SSE) was [[ ]] . There is no information on the actual tensile stress (rather than the stress intensity) but the stress intensity values were high enough that the NRC limit of [[ ]] is most likely exceeded. TS

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Figure 5-1]] **TS**
Schematic of the orificed fuel support assembly

5.2 Control Rod Guide Tube Base

The control rod guide tube base is excluded from augmented inspection because of the low fluence (<1 x 10^{17} n/cm^2) and the fact that it is made of CF-3 or CF-8 with ferrite number less than 12. Based on this, evaluation or augmented inspection for thermal aging or neutron embrittlement is not needed. Therefore, evaluation based on stress is not necessary. The control rod guide tube base is part of the lower plenum components covered by BWRVIP-47-A [22].

5.3 Core Spray Sparger Nozzle Elbows

The core spray sparger nozzle elbows are not subjected to any stresses except during core spray injection. The core spray ΔP during injection can range from [[ ]]. Based on the stresses reported in a several flaw evaluation handbooks, the Pm+Pb value for the core spray sparger pipe is estimated to be less than 5 ksi (34.5 MPa). The stress in the elbow is expected to be less than that in the pipe (because of the much lower diameter). Based on this stress assessment, it is clear that the stress is below the 5 ksi (34.5 MPa) threshold and evaluation or augmented inspection for thermal aging or neutron embrittlement is not needed. Inspections of the core spray piping and sparger are covered by BWRVIP-18, Rev. 1 [20]. TS

5.4 Jet Pump Assembly

Inspections of the jet pump assembly components are covered by BWRVIP-41, Rev. 1 [17]. The CASS components in the jet pump assembly include the transition piece, the inlet mixer assembly and the diffuser collar. Using the designations in BWRVIP-41, Rev. 1, the weld locations of interest are locations RS-3, the weld between the transition piece and riser pipe, IN-1 through IN-5 in the inlet elbow/nozzle, locations MX-1 through MX-7 in the inlet mixer and locations DF-1 through DF-3 in the diffuser. Figure 5-2 shows the different jet pump assembly weld designations, with the CASS weld locations in bold type. Since the jet pump assembly was not analyzed in detail in the original design, the stresses in the jet pump assembly were taken from a typical flaw evaluation handbook for a BWR/4 and a BWR/6 plant [24]. Although not all CASS component evaluations are included, Table 5-2 shows that the stresses at the different locations exceed the 5 ksi (34.5 MPa) limit.

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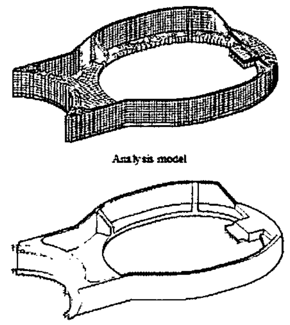
Figure 5-2
Jet pump assembly weld designations

5.5 Jet Pump Restrainer Bracket

The restrainer bracket merely serves to provide point support to the inlet mixer and does not experience any significant stress due to pressure or thermal loading. The only source of stress in the restrainer bracket is due to vibratory loading on the restrainer bracket pad. For nominal set screw gaps [[ ]] the loading on the restrainer bracket pad due to vibratory loading is estimated to be [[ ]]. Since there was no available stress analysis of the restrainer bracket, a finite element analysis was performed to determine the stresses in the bracket. Figure 5-3 shows the finite element model and the boundary conditions in the model. Figure 5-4 shows the stress analysis results. It is seen that the stresses are generally low everywhere except for the corner location of the restrainer bracket pad. The linearized stress, Pm+Pb is [[ ]] and exceeds the 5 ksi (34.5 MPa) stress threshold. TS



[[Supported at riser welds
load applied as pressure load]] TS

Figure 5-3
Restrainer bracket finite element model

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5.6 LPCI Coupling

Inspections of the LPCI coupling components are covered by BWRVIP-42-A [21]. There are two types of LPCI couplings: the straight through coupling used in BWR/4-5 plants (Figure 5-5) and the offset style coupling (Figure 5-6) used in BWR/6 plants.

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Figure 5-6]] TS
BWR/6 design LPCI coupling

BWRVIP-42-A describes the details and the inspection/evaluation requirements for the two coupling designs. In the BWR/4-5 design, the sleeve is made of CASS material whereas in the BWR/6 design, both the sleeve and the collar are made of CASS material. The LPCI coupling has a calculated end-of-license renewal period of [[ ]] which is similar to other CASS components in the BWR internals. Stress analysis information for the BWR/6 design [25] is summarized below. The analysis focused on the region of the weld between the LPCI ring (attached to the shroud) and the pipe extension (attached to the elbow). The highest stresses are in the region of the ring to elbow extension attachment, in the elbow and strut weld area. Only the high stress locations were reported, and therefore, there is limited information on the stresses in the CASS components (sleeves or collars). TS

Stress Evaluation

The main sources of loading on the sleeves and collars are the pressure differences ΔP as shown in Table 5-3:

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Assuming a diameter of 10 in. (254 mm) and a wall thickness of 0.3 in. (7.6 mm) the maximum pressure stress corresponding to the faulted condition is [[ ]], which is well below the 5 ksi (34.5 MPa) limit. Thermal and seismic stresses are not expected to be significant in the sleeve and collar because of the slip joint. Nevertheless the limiting primary stresses from Reference [25] are shown in Table 5-4. TS

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The limiting stresses in the above table were obtained in the strut, at the point where the strut attaches to the shroud. The loading on the sleeve and collar is relatively low; however, with no specific stresses on the sleeve and collar, the conservative approach is to assume that the LPCI coupling stresses exceed the 5 ksi (34.5 MPa) limit. Although the BWR/4-5 design was not specifically evaluated, the stresses are also assumed to exceed the 5 ksi (34.5 MPa) limit.

6 ASSESSMENT OF CASS COMPONENTS

This section describes the assessment of the need for additional analysis or augmented inspection based on the NRC criteria outlined in [5] and [15]. In addition, the BWRVIP inspection requirements outlined in BWRVIP-41, Rev. 1 [17], BWRVIP-18, Rev. 1 [20], BWRVIP-42-A [21] and BWRVIP-47-A [22] will be considered in the recommendations on augmented inspections. As described in Section 3, all the BWR CASS internals are made of CF-3 and CF-8 the average ferrite number is around 10. Therefore, thermal embrittlement alone is not an issue. The synergistic effects of neutron and thermal embrittlement are the primary focus.

6.1 Assessment of Orificed Fuel Supports

The stress due to pressure differences are within the 5 ksi (34.5 MPa) limit, but the seismic stresses exceed the limit. Therefore the stress criterion cannot be used to screen out the orificed fuel support (OFS). The fluence exceeds the 3×10^{20} n/cm^2 threshold. However, the OFS does meet the fracture toughness threshold value of 255 kJ/m^2 (1,450 in-lb/in.^{2}) at a crack depth of 2.5 mm. Thus, additional evaluation or augmented inspection is not needed. Although the OFS is included in the scope of BWRVIP-47-A, no inspections are required. In light of the fact that the OFS meets the toughness criterion and the fact that the steady state stresses are low, augmented inspections are not warranted.

6.2 Assessment of Control Rod Guide Tube Base

The control rod guide tube base is excluded from augmented inspection because of the low fluence (<1E17 n/cm^2) and the fact that it is made of CF-3 or CF-8 with ferrite number less than 12. Based on this, evaluation or augmented inspection for thermal aging or neutron embrittlement is not needed. Therefore, augmented inspections are not warranted.

6.3 Assessment of Core Spray Sparger Nozzle Elbows

The core spray sparger nozzle elbows meet both the 5 ksi (34.5 MPa) stress limit and the fluence limit. Per BWRVIP-18, Rev.1, the nozzle welds (S3 see Figure 6-1) are inspected with VT-1. If no cracking is detected, the inspection is complete. If cracking is detected, an EVT-1 of the cracked location is performed to better determine crack length for flaw evaluation. Reinspection includes a rotating sample. Since VT-1 or EVT-1 of the weld is already required, it is likely that the elbow itself would be visible as part of the inspection. In light of the fact that the stress threshold is met and the fact that inspections of the elbow welds are already being performed, no augmented inspections are warranted.

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6.4 Assessment of the Jet Pump Assembly

Although the CASS components in the jet pump assembly (the transition piece including the elbow, the inlet mixer and the diffuser collars) do not meet the 5 ksi (34.5 MPa) stress limit, the CASS jet pump assembly components do meet the fracture toughness threshold value of 255 kJ/m^2 (1,450 in-lb/in.^{2}) at a crack depth of 2.5 mm. Therefore, augmented inspections are not warranted.

BWRVIP-41, Rev. 1 already specifies some inspections of CASS welds. For example, the inlet elbow locations (IN-1 through IN-5), the mixer locations (MX-1 through MX-7) and diffuser collar locations (DC-1 through DC-4 and DF-1) are all covered by BWRVIP-41, Rev. 1. Figures 6-2 through 6-4 show the different inspection locations for CASS components. Most of the CASS weld inspections (where specified) are confined to the stainless steel welds that attach to the CASS material. For example, for the inlet elbows, the baseline inspection includes EVT-1 of 100% of HAZs on the mixer side of the weld. Similar inspections are required for the mixer weld locations. It should be noted, however, that the most likely source of degradation (however unlikely) for the CASS jet pump components would be IGSCC. Since the inspections cover the wrought side of the welds (which are considered more susceptible to IGSCC), the inspections would detect potential flaws before they become significant. Thus, the current inspections will provide information on the integrity of the CASS components and no augmented inspections are warranted.

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Figure 6-1
Inlet elbow inspection locations

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Figure 6-2]] TS
BWRVIP-41, Rev. 1 inlet mixer inspection locations

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Figure 6-3]] TS
Diffuser collar inspection locations (DC-1 through DF-4 and DF-1)

6.5 Assessment of the Jet Pump Restrainer Bracket

The jet pump restrainer bracket does not meet the 5 ksi (34.5 MPa) stress limit, but does meet the 255 kJ/m^2 (1,450 in-lb/$in.^2$) toughness requirement. Per BWRVIP-41, Rev. 1 inspection requirements, the restrainer bracket pad is frequently inspected for detection of wedge wear and/or rod wear from above and below the restrainer bracket. Thus, any cracking in the restrainer bracket would be detected. Consequently, no augmented inspections are warranted.

6.6 Assessment of the LPCI Coupling

The LPCI assembly CASS components (sleeve and collar) may have lower stresses, but based on the limited information in the stress report (which shows that the limiting locations exceed the 5 ksi (34.5 MPa) limit and does not provide stress information on the sleeve or the collar), it is assumed that the CASS components exceed the 5 ksi (34.5 MPa) limit. However, given that the CASS portions of the LPCI coupling are above the jet pumps and outside of the shroud, the fluence at this location is less then 5 x 10^{20} n/cm^2 (E>1 MeV). Since the fluence is less than the values of 6 x 10^{20} n/cm^2 (E>1 MeV) used to determine compliance with the 255 kJ/m^2 (1,450 in-lb/in.^{2}) toughness requirement, the CASS portions of the LPCI couplings are demonstrated to have adequate toughness. Based on this, the need for additional evaluation or augmented inspection is not necessary.

6.7 Summary of Assessment

Table 6-1 summarizes the assessment of the BWR CASS internals. As substantiated by the review of CASS CMTRs, the BWR materials have average ferrite levels of 10% with very high confidence that the levels are below 20%. The inspection recommendations given are based on the following criteria: (1) fluence <3 x 10^{20} n/cm^2 (E>1 MeV); (2) adequate toughness (>255 kJ/m^2) and (3) applied stresses (<5 ksi). If a component meets any one of the three criteria, then no augmented inspections are required. As shown in Table 6-1, the CASS materials have been demonstrated to meet at least one of the criteria, and no augmented inspections are recommended for CASS components. All CASS components either experience fluence levels of no concern, or the CASS material at the maximum fluence has adequate toughness. Several of the CASS components also experience stresses for which brittle fracture would not be an issue under any condition.

Table 6-1
Assessment of BWR CASS internals

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Component	Material	Ferrite Content <20% ?	Fluence (n/cm^2)	Toughness Requirement of 255 kJ/m^2 (1,450 $in\text{-}lb/in.^2$) met?	*Stress <5 ksi (34.5 MPa)?	Evaluations Results
Orificed Fuel Support	CF-8	Yes		Yes	No	No augmented inspections are warranted.
Control Rod Guide Tube Base	CF-3 or CF-8	Yes		Yes	Yes	No augmented inspections are warranted.
Core Spray Sparger Nozzle Elbows	CF-8	Yes		Yes	Yes	No augmented inspections are warranted.
Jet Pump Assembly	CF-8	Yes		Yes	No	No augmented inspections are warranted.
Jet Pump Restrainer Bracket	CF-8	Yes		Yes	No	No augmented inspections are warranted.
LPCI Assembly	CF-3 or CF-8	Yes		Yes	No	No augmented inspections are warranted.

* Augmented inspection is not required if either the toughness criteria or the stress limit requirements are met.

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CONCLUSIONS

NUREG-1801 Rev. 1, Section XI.M13 states that a Section XI VT-3 examination is required to be performed of reactor internal components. In addition, the GALL report specifies that for the license renewal period these inspections shall be augmented by an aging management program to address the synergistic effects of thermal aging and neutron embrittlement in cast austenitic stainless steels (CASS). This aging management program consists of (a) identifying susceptible components; and (b) either performing additional inspections of these components, or performing a component-specific evaluation to confirm that the stresses (tensile loading) in the components are sufficiently low such that augmented inspections are not warranted.

This report provides an evaluation of cast austenitic stainless steel components in BWR internals, and determines where additional evaluation or augmented inspections of CASS components are needed. The evaluation covers the orificed fuel support, the control rod guide tube base, the core spray sparger nozzle elbow, the CASS components in the jet pump assembly (inlet elbow, inlet mixer, diffuser collar and restrainer bracket) and the LPCI coupling.

The evaluation includes assessment of ferrite, fluence estimates, stress analysis and fracture toughness estimation. The results are compared with the NRC approved criteria – ferrite number, stress limit (5 ksi or 34.5 MPa) and toughness (255 kJ/m^2 or 1,450 $in\text{-}lb/in.^2$) – to determine whether component-specific evaluation or augmented inspections are needed. In addition to the NRC criteria, the current BWRVIP inspections were also evaluated to determine whether they already meet the intent of the NUREG-1801 requirement. Three components were identified as having fluence levels $>3 \times 10^{20}$ n/cm^2 sufficient to warrant further evaluation: (1) orificed fuel support, (2) the CASS components in the jet pump assembly (inlet elbow, inlet mixer and diffuser collar and the restrainer bracket and (3) the LPCI coupling. Based on stress and fracture toughness considerations, no augmented inspections of the CASS components are warranted.

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APPENDIX A: MATERIAL DATA

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