UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

May 19, 2000

Mr. Douglas J. Walters
Nuclear Energy Institute
1776 I Street, NW., Suite 400
Washington, DC 20006-3708

SUBJECT: LICENSE RENEWAL ISSUE NO. 98-0030, "THERMAL AGING EMBRITTLEMENT OF CAST AUSTENITIC STAINLESS STEEL COMPONENTS"

Dear Mr. Walters:

Enclosed is the NRC staff's evaluation and proposed resolution for the subject issue. The staff plans to incorporate the recommended resolution as part of the next revision to the draft Standard Review Plan for License Renewal. Accordingly, if there are any industry comments on the evaluation basis or the proposed resolution, we request that you document those comments within 30 days following your receipt of this letter, to ensure a timely resolution of this issue. We also would be willing to meet with industry representatives to discuss any comments you may have. If you have any questions regarding this matter, please contact Sam Lee at (301) 415-3109.

Sincerely,

CIGrimes

Christopher I. Grimes, Chief
License Renewal and Standardization Branch
Division of Regulatory Improvement Programs
Office of Nuclear Reactor Regulation

Project No. 690

Enclosure: As stated

cc w/encl: See next page

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STAFF EVALUATION OF LICENSE RENEWAL ISSUE NO. 98-0030,

"THERMAL AGING EMBRITTLEMENT OF

CAST AUSTENITIC STAINLESS STEEL COMPONENTS"

1.0 BACKGROUND

Some of the primary pressure boundary and reactor vessel internal (RVI) components in U.S. light-water reactors are constructed from a cast austenitic stainless steel (CASS) material per American Society of Mechanical Engineers (ASME) Section III Specification SA-351. Examples of structures constructed from this type of material include pump casings, valve bodies, primary system piping, and RVI components of various configurations. NRC-sponsored research at Argonne National Laboratory (ANL) has shown that aging of CASS at reactor operating temperatures of 280-350°C (536-662°F) can lead to changes in the mechanical properties of these materials, depending on the characteristics of the material and the environment to which the component is exposed. The effects of thermal aging on materials include increases in the tensile strength, hardness, and Charpy impact energy transition temperature, as well as decreases in ductility, fracture toughness, and impact strength (Refs. 1-6).

CASS components have a duplex microstructure consisting of austenite and ferrite phases. The ferrite phase improves the tensile strength, castability, weldability, and stress-corrosion cracking resistance of the material. Exposing these steels to elevated temperatures promotes the formation of additional phases within the ferrite, causing the increased tensile strength, decreased ductility, and reduced fracture toughness associated with thermal aging. This thermal embrittlement mechanism can be severe enough to make the material susceptible to low energy fracture if the ferrite forms a continuous phase surrounding the grain boundaries in the microstructure. This low energy fracture is characterized by cleavage of the ferrite and low energy grain boundary separation of the austenite. The degree of embrittlement strongly depends upon the amount and distribution of the ferrite phase within the microstructure.

Research at ANL has shown that the most important factors in determining the extent of thermal aging in CASS are the chemical composition of the steel, the casting method used to construct the component, the amount of ferrite in the microstructure, and the service history (time and temperature) of the component. The chemical element most influential to the thermal aging process in U.S. steels is molybdenum (Mo), which is added to the steel to promote the formation of ferrite in the microstructure. CASS with high levels of Mo shows a higher susceptibility to thermal aging than steels with low Mo levels. The casting process greatly influences the cast microstructure and is also an important factor in determining the extent of thermal embrittlement. CASS components in the nuclear industry are typically manufactured by centrifugal or static casting. Static castings tend to show more susceptibility

to thermal aging than centrifugal castings. Since it is the ferrite phase that undergoes the microstructural changes leading to thermal embrittlement, elevated ferrite content in the steel results in greater susceptibility to thermal aging. ANL studies have shown that room temperature impact energy decreases with aging time and eventually reaches the lowest level attainable for a given composition, or the saturation level for that composition. The service temperature of a component will affect the rate at which the material reaches this saturation limit. However, prior to saturation, increased service temperatures will increase the level of embrittlement in a material for a given exposure time.

2.0 EVALUATION

The staff has reviewed several industry submittals addressing thermal aging of CASS materials, including Electric Power Research Institute (EPRI) Technical Report 106092 (Ref. 7), the license renewal application from Baltimore Gas and Electric for the Calvert Cliffs plants (Ref. 8), and several topical reports from reactor owners groups (Refs. 9 to 11). Each of these submittals addresses thermal aging embrittlement of CASS in a different manner; the submittal by EPRI will be used as the benchmark for evaluation of the "industry position".

This evaluation addresses the industry position outlined in EPRI Technical Report 106092, "Evaluation of Thermal Aging Embrittlement for Cast Austenitic Stainless Steel Components in LWR Reactor Coolant Systems." The stated objectives of that report are to: (1) propose screening criteria to determine if a specific component should be inspected due to its potential susceptibility to thermal aging, (2) provide data supporting the proposed screening criteria, and (3) propose an aging management program for those components potentially affected by thermal aging. The report references data produced from the research performed at ANL (Ref. 1).

Screening Criteria

The screening criteria proposed in EPRI TR-106092 are applicable to all Class 1 reactor coolant system and primary pressure boundary components constructed from SA-351 Grade CF3, CF3A, CF8, CF8A, CF3M, CF3MA, or CF8M. The factors used in the screening criteria are the same as those described in the background section: Mo content, casting procedure, and ferrite content. In the review of this proposed screening criteria, the staff considered saturated lower bound J integral vs. crack depth (J-R) curves. J-R curves measure a material's resistance to stable, ductile crack growth.

EPRI's proposed screening criteria essentially divide all CASS components into the six categories shown in Table 1. The high Mo steels are those that meet CF3M, CF3MA, or CF8M grade specifications while the low Mo steels are those that meet CF3, CF3A, CF8, or CF8A grade specifications. The ferrite levels may be either calculated or measured values.

The industry proposes that all components deemed as having a potentially significant reduction in fracture toughness due to thermal aging must be placed in an aging management program, as described later.

Table 1: Proposed Thermal Aging Screening Criteria in EPRI TR 106092

Mo Content (Wt. %)	Casting Method	Ferrite Content	Significance of Thermal Aging
High (2.0 - 3.0)	Static	All	Potentially Significant
	Centrifugal	> 20%	Potentially Significant
		≤ 20%	Non-significant
Low (0.50 max)	Static	> 20%	Potentially Significant
		≤ 20%	Non-significant
	Centrifugal	All	Non-significant

Supporting Data

ANL has developed procedures for conservatively predicting the J-R curve behavior of aged CASS based on material chemistry information and/or service history (Refs. 2 and 6). These correlations were developed from 80 different compositions of cast stainless steel which were aged up to 58,000 hours at 350°C (662°F). As part of this research program several heats of SA 351 material were aged and tested in order to compare measured saturated J-R curves with the ANL predicted values. These heats included both commercial and laboratory heats as well as static and centrifugal castings. In addition to these heats tested by ANL, the ANL analysis included fracture toughness data from other sources (Westinghouse, EDF, Framatome, and EPRI). In all cases the ANL predicted J-R curves were accurate or conservative compared to the measured values.

These measured and predicted J-R curves are used in the EPRI report to justify the proposed screening criteria described above. A deformation J value of 255 kJ/m^2 (1450 $in\text{-}lb/in^2$) at a crack depth of 2.5 mm (0.1 in) was used to differentiate between a non-significant and a potentially significant reduction in fracture toughness for fully aged materials. Flaw tolerance evaluations described in Appendices A and B of EPRI TR-106092 show that a material toughness of 255 kJ/m^2 (1450 $in\text{-}lb/in^2$) adequately protects against a loss of structural integrity in cast austenitic stainless steel components. The staff finds that Appendices A and B of EPRI TR-106092 provide an acceptable justification that 255 kJ/m^2 is an acceptable screening value to use in differentiating between non-significant and a potentially significant reduction in fracture toughness of aged CASS components.

ANL also developed saturated lower-bound J-R curves for use when the composition of the steel is unknown (Refs. 2 and 6). In these situations given the steel grade, the casting procedure, and a measured ferrite level, a saturated lower bound J-R curve can be evaluated. The staff compared the J(2.5) values taken from these saturated lower bound J-R curves as well as J(2.5) values from the actual fracture toughness tests conducted on the various heats of material with

the screening value of 255 kJ/m^2 for the various categories defined by the screening criteria as follows:

(1) <u>High Mo - Static Castings</u>

For high Mo static castings with ferrite levels >15 percent, the saturated lower bound J(2.5) is 221 kJ/m^2. At ferrite levels between 10 and 15 percent, the saturated lower bound J(2.5) becomes 257 kJ/m^2, and at ferrite <10 percent, J(2.5) increases to 322 kJ/m^2. Heat L examined by ANL was a CF8M static casting with 19 percent ferrite. The actual fracture toughness data for this heat showed a J(2.5) value of approximately 250 kJ/m^2. CF8M static castings are more susceptible to thermal aging so that even at low ferrite levels the saturated fracture toughness is relatively low.

Based upon the cited J(2.5) levels for ferrite levels between 10 and 15 percent, the staff finds that high Mo static cast components with ferrite levels below 14 percent are not susceptible to thermal aging. The proposed screening criteria in the EPRI report finding all high Mo static cast components potentially susceptible to thermal aging, regardless of ferrite content, is conservative.

(2) <u>High Mo - Centrifugal Castings</u>

In high Mo centrifugal castings, the saturated lower bound J(2.5) value is 259 kJ/m^2 for ferrite >15 percent and 298 kJ/m^2 for ferrite levels between 10 and 15 percent. Heat 205 is a CF8M centrifugal casting with 21 percent ferrite. The measured J(2.5) value of this particular heat is approximately 500 kJ/m^2 which is well above the lower bound and the screening value for J(2.5). Based on this data, the staff finds that only those high Mo centrifugal cast components with >20 percent ferrite show a significant reduction in fracture toughness. Therefore, the proposed screening criteria is acceptable.

(3) <u>Low Mo - Static Castings</u>

Low Mo static castings with ferrite levels >15 percent have a saturated lower bound J(2.5) of 342 kJ/m^2. Ferrite levels between 10 and 15 percent for this material have a saturated lower bound J(2.5) value of 377 kJ/m^2. Heat 69, a CF3 static casting containing 21 percent ferrite has a J(2.5) value of 516 kJ/m^2 which is also well above the screening value for J(2.5). Based on this data, the staff finds that the use of a 20-percent ferrite to differentiate non-significant and potentially significant reductions in fracture toughness is acceptable.

(4) <u>Low Mo - Centrifugal Castings</u>

In the case of low Mo centrifugal castings with ferrite levels >15 percent, saturated lower bound J(2.5) values are 450 kJ/m^2. Heat P1 is a CF8 centrifugal casting with 18 percent ferrite. This heat shows actual J(2.5) data to be approximately 700 kJ/m^2 which is well above the screening value for J(2.5). Even at these ferrite levels, low Mo centrifugal castings show adequate toughness. Therefore, the proposed screening criteria of non-significant for low Mo centrifugal cast components is acceptable.

Aging Management Program

The EPRI report proposes the following aging management program:

> All components deemed as having a potentially significant reduction in fracture toughness due to thermal aging should be inspected in accordance with the plants' inservice inspection program. Any of these detected flaws would then be evaluated according to ASME Section XI IWB-3640 "Evaluation Procedures and Acceptance Criteria for Austenitic Piping." If the sized flaws do **not** meet the IWB-3640 acceptance criteria, the component must then be repaired and/or replaced. If the component is deemed to have a non-significant reduction in fracture toughness or the sized flaws meet the IWB-3640 flaw acceptance criteria, the component can continue to operate within the current licensing basis.

Current inspection requirements in Table IWB-2500-1 of Section XI of the ASME Code for CASS components are the following:

- Piping (Category B-J): Volumetric and surface examination of pressure-retaining welds for NPS ≥ 4 in.; surface examination of pressure-retaining welds for NPS < 4 in.

- Valve Bodies (Categories B-M-1 and B-M-2): Visual VT-3 examination of internal surfaces and volumetric examination of pressure-retaining welds for NPS ≥ 4 in.; surface examination of pressure-retaining welds for NPS < 4 in.

- Pump Casings (Categories B-L-1 and B-L-2): Visual VT-3 of internal surfaces and volumetric of welds

- RV Internals (Category B-N-3): Visual VT-3 of surfaces

The inspection requirements for piping, valve bodies and pump casings are not a 100 percent inspection but rather an inspection of samples within each grouping.

The proposal in the EPRI report provides for inservice inspections in accordance with the plants' inservice inspection program. The staff does not think that this is adequate since components which may be susceptible to thermal aging, such as piping base metal and RV internals, are not currently covered to a sufficient degree by ASME Code requirements.

The NRC has previously approved ASME Section XI IWB-3640 for evaluating flaws in thermally aged cast stainless steel components for license renewal (Ref. 13). IWB-3640 procedures were developed from fracture toughness data of Types 316 and 304 welds. CF8M shows the greatest susceptibility to thermal aging of any of the other SA-351 grades considered in the screening criteria. A comparison of IWB-3640 weld data to the CF8M saturated lower bound curves shows that the toughness levels of these two materials are similar (Ref. 13). IWB-3641 (b) states that "[t]he evaluation procedures and acceptance criteria are applicable to...cast stainless steel (with ferrite level less than 20 percent)." However, the lower bound curve developed by ANL which was compared to the IWB-3640 submerged arc weld (SAW) data was for CF8M steels with 15-

25 percent ferrite. Based on the similarity of the fracture toughness data, the staff believes that IWB-3640 procedures would be applicable to thermally aged CASS with ferrite levels up to 25 percent.

The staff noted several limitations based on the ANL research regarding the development and use of their correlations:

- The ANL database used to develop these correlations had a maximum δ-ferrite content of 25 percent. Recent data (Ref. 1) has shown that applying these correlations to steels with ferrite levels in excess of 25 percent can result in a non-conservative overestimation of the actual fracture toughness of the material.

- Little data exists for centrifugal castings constructed from a high Mo grade of stainless steel.

- The ANL correlations were based on calculated ferrite levels using Hull's Equivalent Factors. Other procedures for calculating ferrite content may result in a non-conservative estimation of the fracture toughness of the steel.

- Niobium (Nb) increases CASS susceptibility to thermal aging. Since the ANL heats did not contain Nb, the correlations and screening criteria would not strictly apply to Nb-containing steels. This should not be an issue since the CASS components in U.S. light-water reactors do not contain Nb.

3.0 RESOLUTION

Based upon the review of the various industry submittals, the staff has developed the following position for management during the license renewal period of thermal aging in reactor components constructed of cast austenitic stainless steel (CASS).

Susceptibility Screening Method

Determination of the susceptibility of CASS components to thermal aging can use a screening method based upon the Mo content, casting method, and ferrite content. (Alternatively, components can be assumed as "potentially susceptible" without considering such screening.) The specific screening criteria acceptable to the staff are outlined in Table 2, and are applicable to all primary pressure boundary and reactor vessel internal (RVI) components constructed from SA-351 Grade CF3, CF3A, CF8, CF8A, CF3M, CF3MA, or CF8M, with service conditions above 250°C (482°F).

Table 2: CASS Thermal Aging Susceptibility Screening Criteria

Mo Content (Wt. %)	Casting Method	δ-Ferrite Level	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

Note that calculated δ-ferrite should use Hull's equivalent factors or a method producing an equivalent level of accuracy (±6% deviation between measured and calculated values).

The significance of finding a particular component not susceptible or potentially susceptible is described below for each component type. The examination requirements for each component type are provided in Table 3. In addition, acceptable flaw evaluation procedures are described.

Table 3: Examination Requirements for CASS Components

Component	Grouping	Not Susceptible	Potentially Susceptible
Piping (Base Metal)	NPS ≥ 4 in.	None	Inspection or evaluation
	NPS < 4 in.	None	Inspection or evaluation
Valve Bodies (Base Metal)	NPS ≥ 4 in.	ASME Section XI requirements	ASME Section XI requirements
	NPS < 4 in.	ASME Section XI requirements	ASME Section XI requirements
Pump Casings (Base Metal)	NPS ≥ 4 in.	ASME Section XI requirements	ASME Section XI requirements
	NPS < 4 in.	ASME Section XI requirements	ASME Section XI requirements
RV Internals (Base Metal)	Fluence $\geq 1 \times 10^{17}$	All: Supplemental examination or component-specific evaluation	
	Fluence $< 1 \times 10^{17}$	ASME Section XI requirements	Supplemental examination

Piping (Base Metal)

Since the base metal of piping does not receive periodic inspection in accordance with Section XI of the ASME Code, the susceptibility of piping constructed from CASS should be assessed for each heat of material. Alternatively, an assumption of "potentially susceptible" can be assumed for each heat or specific heats.

Should a particular heat be found "not susceptible," no additional inspections or evaluations are required to demonstrate that the material has adequate toughness.

Should a particular heat be found or assumed "potentially susceptible" and subject to plausible degradation (e.g., thermal fatigue), aging management can be accomplished through volumetric examination or plant/component-specific flaw tolerance evaluation. The volumetric examination should be performed on the base material of each heat, with the scope of the inspection covering the portions determined to be limiting from the standpoint of applied stress level, operating time and environmental considerations. Alternatively, a plant/component-specific flaw tolerance evaluation, using specific geometry and stress information, can be used to demonstrate that the thermally-embrittled material has adequate toughness.

Valve Bodies and Pump Casings

Valve bodies and pump casings are adequately covered by existing inspection requirements in Section XI of the ASME Code, including the alternative requirements of ASME Code Case N-481 for pump casings. Screening for susceptibility to thermal aging is not required and the current ASME Code inspection requirements are sufficient.

Regarding valve bodies with NPS less than 4 in., this position is supported by a bounding fracture analysis finding that valves within this range do not require additional inspection or evaluation to demonstrate that the material has adequate toughness, even for severe thermal embrittlement conditions. (See attachment.)

Reactor Vessel Internals

For RVI components fabricated from CASS and hence subject to thermal embrittlement, concurrent exposure to high neutron fluence levels can result in a synergistic effect wherein the service-degraded fracture toughness is reduced from the levels predicted independently for either of the mechanisms. Therefore, components determined to be subject to thermal embrittlement require an additional consideration of the neutron fluence of the component to determine the full range of degradation mechanisms applicable for the component.

To account for this 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 ISI program during the license renewal term, or a component-specific evaluation to determine the susceptibility to loss of fracture toughness. The scope of the supplemental inspection should cover portions of the susceptible components determined to be limiting from the standpoint of thermal aging susceptibility (e.g., Mo content, δ-ferrite content, casting process, and operating temperature), neutron fluence, and cracking susceptibility (applied stress level, operating time and environmental conditions).

The component-specific evaluation looks first at the neutron fluence of the component. If the neutron fluence is greater than 1×10^{17} n/cm^2 (E > 1 MeV), a mechanical loading assessment would be conducted for the component. This assessment will determine the maximum tensile loading on the component during ASME Code Level A, B, C and D conditions. If the loading is compressive or low enough to preclude fracture of the component, then the component would not require supplemental inspection. Failure to meet this criterion would require continued use of the supplemental inspection program.

If the neutron fluence is less than 1×10^{17} n/cm^2 (E > 1 MeV), an assessment would be made to determine if the affected component(s) are bounded by the screening criteria in Table 2. In order to demonstrate that the screening criteria are applicable to RVI components, a flaw tolerance evaluation specific to the reactor vessel internals would be required, similar to that provided in Ref. 7. If the material is determined to be "potentially susceptible," then a supplemental examination would be required on the portions of the susceptible components determined to be limiting from the standpoint of thermal aging susceptibility (e.g., Mo content, δ-ferrite content, casting process, and operating temperature), and cracking susceptibility (applied stress level, operating time and environmental conditions). If the material is determined to be "non-

susceptible," no inspections or evaluations are required to demonstrate that the material has adequate toughness.

Supplemental Examination

The supplemental examination technique should be specified by the applicant in the license renewal application. Particular consideration must address the reliability of the supplemental examination technique in detecting the features of interest (such as crack appearance and size) in assuring the integrity of the component.

One example of a supplemental examination could be an enhancement of the visual VT-1 examination described in IWA-2210 of Section XI of the ASME Code. A description of such an enhanced VT-1 examination could include the following characteristics: the ability to achieve a 1/2-mil (0.0005 in.) resolution, with the conditions (e.g., lighting and surface cleanliness) for the in-service examination bounded by those used to demonstrate the resolution of the inspection technique.

Volumetric Examination

Current volumetric examination methods are not adequate for reliable detection of cracks in CASS components. Should an acceptable method for volumetric examination of CASS components be developed, the performance of the equipment and techniques should be demonstrated through a program consistent with the ASME Code, Section XI, Appendix VIII.

Flaw Evaluation

Flaws detected in CASS components should be evaluated in accordance with the applicable procedures of IWB-3500 in Section XI of the ASME Code. If the δ-ferrite content does not exceed 25 percent, then flaw evaluation would be in accordance with the principles associated with IWB-3640 procedures for submerged arc welds (SAW), disregarding the Code restriction of 20 percent in IWB-3641(b)(1). If the CASS material is "potentially susceptible" and the δ-ferrite content exceeds 25 percent, then flaw evaluation would be on a case-by-case basis using fracture toughness data supplied by the licensee, such as that published by Jayet-Gendrot, et al (Ref. 14).

4.0 REFERENCES

1. O.K. Chopra, "Estimation of Fracture Toughness of Cast Stainless Steels During Thermal Aging in LWR Systems," NUREG/CR-4513, June 1991.

2. O.K. Chopra, "Estimation of Fracture Toughness of Cast Stainless Steels During Thermal Aging in LWR Systems," NUREG/CR-4513, Rev. 1, August 1994.

3. O.K. Chopra and A. Sather, "Initial Assessment of the Mechanisms and Significance of Low-Temperature Embrittlement of Cast Stainless Steels in LWR Systems," NUREG/CR-5385, August 1990.

4. D.J. Gavenda, W.F. Michaud, T.M. Galvin, W.F. Burke, and O.K. Chopra, "Effects of Thermal Aging on Fracture Toughness and Charpy-Impact Strength of Stainless Steel Pipe Welds," NUREG/CR-6428, May 1996.

5. O.K. Chopra and W.J. Shack, "Mechanical Properties of Thermally Aged Cast Stainless Steels from Shippingport Reactor Components," NUREG/CR-6275, April 1995.

6. O.K. Chopra and W.J. Shack, "Assessment of Thermal Embrittlement of Cast Stainless Steels," NUREG/CR-6177, May 1994.

7. EPRI TR-106092, "Evaluation of Thermal Aging Embrittlement for Cast Austenitic Stainless Steel Components in LWR Reactor Coolant Systems," September 1997.

8. License Renewal Application, Calvert Cliffs Nuclear Power Plants Units 1 and 2, April 10, 1998.

9. G. D. Robinson et al., "Demonstration of the Management of Aging Effects for the Reactor Coolant System Piping," BAW-2243A, Framatome Technologies, June 1996.

10. W. H. Mackay and F. M. Gregory, "Demonstration of the Management of Aging Effects for the Reactor Vessel Internals," BAW-2248, Framatome Technologies, July 1997.

11. F. Klanica and C. Gay, "License Renewal Evaluation: Aging Management for Class 1 Piping and Associated Pressure Boundary Components," WCAP-14575, Westinghouse Electric Corporation, August 1996.

12. D. R. Forsyth, et al., "License Renewal Evaluation: Aging Management for Reactor Internals," WCAP-14577, Westinghouse Electric Corporation, June 1997.

13. S. Lee, P.T. Kuo, K. Wichman, and O. Chopra, "Flaw Evaluation of Thermally Aged Cast Stainless Steel in Light-Water Reactor Applications," International Journal of Pressure Vessels and Piping, 72, pp 37-44, 1997.

14. S. Jayet-Gendrot, P. Ould, and T. Meylogan, "Fracture Toughness Assessment of In-Service Aged Primary Circuit Elbows Using Mini C(T) Specimens Taken from Outer Skin," Fatigue and Fracture Mechanics in Pressure Vessels and Piping, PVP-Vol 304, ASME, 1996, pp 163-69.

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

October 6, 1999

MEMORANDUM TO: William H. Bateman, Chief
Chemical and Materials Engineering Branch
Division of Engineering, NRR

FROM: Michael E. Mayfield, Chief
Materials Engineering Branch
Division of Engineering Technology, RES

SUBJECT: INTEGRITY OF <4-INCH NPS VALVE BODIES MADE FROM CAST STAINLESS STEEL

Based on recent discussions among the staff, an issue was identified relating to the potential for thermal aging to degrade the integrity of valve bodies made from cast duplex stainless steels, commonly referred to as simply cast stainless steels or CASS. The concern was specific to those valve bodies with a high delta-ferrite content. The issue focused on 4-inch NPS and smaller valves because periodic in-service inspections would identify cracking in larger valve bodies before they could propagate to a critical size. However, in-service inspection for the valves less than 4-inch NPS does not require internal visual or volumetric inspection of the valve bodies. Rather, the ASME Code (Section XI, 1995 Edition, Table IWB-2500-1) requires surface examination of essentially 100 percent of all welds for at least one valve within each group of valves that are of the same size, constructional design, and manufacturing method, and that perform similar functions in the system. Thus, the staff was considering the need for additional inspection or evaluation criteria for these small valves.

The Materials Engineering Branch staff undertook two activities to evaluate the need for additional guidance. First, we reviewed the Licensee Event Report database and the Nuclear Reliability Data System (NPRDS) database to identify instances of cracking of valve bodies. Secondly, we performed a conservative bounding integrity analysis to estimate the crack sizes that could be present in degraded valve bodies without challenging the integrity of the valve.

Based on the information discussed below, we found that (1) there have been no reported instances of valve body cracking in these smaller size valves made from cast stainless steel, and (2) aged CASS valve bodies, even with extremely low fracture toughness, can withstand very large through-wall cracks.

Regarding the review of the LER and NPRDS databases, Attachment 1 provides a summary of the event reports which identified valve body cracks. The search included the Sequence Coding and Search System (SCSS), the NPRDS, and foreign event files for thermal fatigue. The SCSS search covered the last 20 years, and the NPRDS search covered 1987 to 1996.

Attachment

Ten events were identified but none of them involved small diameter CASS valve bodies. Six of the events were for valves less than 4-inch NPS, but none of those events were for CASS materials. Two of the events were associated with CASS material but were for 8-inch and 24-inch valves. Thus, service experience does not suggest a significant degradation mechanism for CASS valve bodies. While service experience alone does not provide a basis to eliminate the staff's concern, it also does not suggest that these valves are particularly susceptible to service cracking, a necessary prerequisite to a loss of integrity of the component.

With regard to the bounding integrity analysis, Attachment 2 provides information concerning the details of the analysis. An elastic-plastic assessment was performed using the "R6" Failure Assessment Diagram (FAD) methodology. This method has been shown to provide conservative assessment of the fracture integrity of operating structures. While the fracture mechanics formulation is specifically for cracks in a flat plate rather than a valve body, the overall bounding nature of the analysis is believed to offset this factor.

The key inputs to the analysis are the stress in the valve body, the yield and tensile strength of the material, Young's modulus, and the fracture toughness of the aged material. The stress values were obtained from earlier work performed by INEEL for another project addressing erosion-corrosion of valve bodies. In that work, a finite element analysis was performed for a 16-inch globe valve in the normally closed position. Full system pressure (225 psig for this valve) was applied to one side of the valve, in addition to seismic stresses and end-moments from the piping system analysis. In one computer run, the most severely eroded areas were modeled with a minimum wall thickness of 0.10-in. versus the 0.5 - 0.8-in. wall thickness actually observed in the valve. The peak stress found in the most severely eroded areas under these conditions varied between 22.9 ksi and 41.4 ksi. Yield stress at the applicable temperature is 34.4 ksi. It is important to note that even though the model simulated more severe erosion than was actually observed, these higher stresses only occurred in very small areas of the valve body. Displacements were sufficiently small so that the operation of the valve was judged not to be compromised. Stresses under normal operating pressures in areas that had not been eroded were significantly lower. For these reasons, we chose to use a stress of 20 ksi in the current fracture analysis. While the INEEL stress analysis is not specific to small diameter valves, it is believed to represent a high-stress condition for valve bodies and was used as input to this bounding analysis.

The yield strength, tensile strength, and Young's modulus values were taken from the ASME Code SC II for 550 F operating temperature. These values are for unaged materials but were used in lieu of specific data on the aged values.

With regard to the fracture toughness value, the staff's concern was for situations where the CASS material had a high delta ferrite content, specifically greater than 25 percent. Our research program did not include materials with these very high values of delta ferrite so we did not have specific data from which we could provide a bounding estimate. Consequently, we contacted Dr. O. Chopra of Argonne National Laboratory, who had performed our research in this area. Based on his knowledge of the literature, Dr. Chopra suggested a value as low as 69 ksi•in^{½} could be considered a worst-case fracture toughness for these materials.

With these conservative input assumptions, the FAD analysis shows that the small diameter CASS valve bodies could withstand a through-wall defect approximately 1.35 inches long. While the specific value would be specific to the application, the analysis demonstrates that the CASS valve bodies are flaw-tolerant, even for severely aged materials.

Based on the fact that we did not identify any service failure history associated with these small diameter CASS valve bodies, and the fact that they can withstand very long through-wall cracks, even under high stresses, suggests that additional inspections during a license renewal period are not warranted. We therefore conclude that the present requirements for in-service inspection are adequate.

If you or your staff have questions concerning this analysis, please contact me at (301) 415-6690 or Mark Kirk at (301) 415-6015.

Attachments: As stated

ATTACHMENT 1

SUMMARY OF VALVE BODY CRACKING EVENTS

The following event reports were identified with valve body cracks in a search of operational experience database files and several technical reports. The data search included the Sequence Coding and Search System (SCSS), the Nuclear Reliability Data System (NPRDS), and the foreign event files for thermal fatigue. The SCSS search covered the time period of the past 20 years, and the NPRDS search covered the period from 1987 to 1996. The technical reports included (1) INEL-95/0648, "An Evaluation of the Effects of Valve Body Erosion on MOV Operability," (2) NUREG/CR-4302, "Aging and Service Wear of Check Valves Used in ESF Systems of Nuclear Power Plant," (3) NUREG/CR-4747, "An Aging Failure Survey of LW Reactor Safety Systems and Components," and (4) NUREG/CR-6246, "Effects of Aging and Service Wear on Main steam Isolation Valves and Valve Operators."

I. Peach Bottom, LER 277/96-004

A small leak in the HPCI cooling water line relief valve (1x1-1/2" Crosby, Model JMB-C-E). The failure mechanism was IGSCC. It was determined that the relief valve base material consisted of a nickel alloy which, due to a high carbon content (0.4%), is highly susceptible to IGSCC.

2. Indian Point 3, LER 286/95-024

Both valves of SWN-43-5 and -43-1 of the essential service water containment isolation were found to be leaking through valve body. It was confirmed that the valve body had a small hole and UT had shown possible valve body wall thinning. The cause was under-deposit, oxygen concentration cell corrosion and /or microbiologically induced corrosion due to long-term stagnant service water. The valves were made of carbon steel and 2" size.

3. South Texas 1, LER 498/88-22

Slight leakage occurred at a number of locations in the aluminum-bronze Essential Cooling Water (ECW) system. Further investigation revealed that some small bore (2 inch and smaller) fittings and valves in the ECW system have undergone extensive crevice corrosion, resulting in through wall seepage.

4. Salem 1, LER 272/90-026

Through wall main steam (MS) leak at body of a check valve. This 1" Type 316 stainless steel valve (2MS57) was for the MS& turbine bypass AFW pump drain header. The failure was attributed to wall thinning due to erosion/corrosion.

5. <u>Salem 2, LER 311/88-22</u>

Containment spray valves 21 & 22 revealed cracks in the valve castings. Visual examination revealed a 2.5" crack with a buildup of boric acid crystals. An analysis indicated the apparent cause was attributed to TGSCC. These valves were 8" stainless steel gate valve (SA-351, Grade CF8).

6. <u>Duane Arnold 1 (event date: 07/14/1989)</u>

The 'B' vent control valve (2" carbon steel) in the condensate demineralizer system was found leaking severely. The cause was flaw in casting of valve body and erosion.

7. <u>Loviisa 2 (German) (event date; 1994)</u>

A leakage was observed through the body of a control valve in a pressurizer auxiliary spray line. The valve body was forged titanium stabilized austenitic stainless steel and of 2" size. The cracking was considered to be caused by thermal stratification and mixing.

8. <u>Haddam Neck, LER 213/96-019-01</u>

A pinhole leak in the body of an 8" RHR isolation valve (RH-V-791A) to the "A" RHR heat exchanger. A small buildup of boric acid on the valve body was noted. The root cause was not determined. This was a stainless steel gate valve Model 2216-SP manufactured by Aloyco (Crane).

9. <u>Palisades, LER 255/94-006</u>

An accumulation of boric acid on the valve body of 24" austenitic stainless steel (SA-351, Grade CF8M) check valve (CK-ES-3166) was confirmed to be caused by a through wall defect in the valve body. The valve is located between the containment sump and the suction piping for one train of the engineered safeguard system pumps. The cause was preferential corrosion at the grain boundary in a weld-repaired region of the valve casting.

10. <u>Cooper, LER 298/93-014</u>

A small through-wall leak was observed from a 18" valve in the SW line to the R.R. heat exchanger. The leak was determined to be caused by localized erosion. The valve is a 18" carbon steel Anchor Darling glove valve. Erosion of a large globe valve was the subject of NRC Information Notice 89-01.

Contact: Chuck Hsu (415-6356)

ATTACHMENT 2

Bounding Fracture Analysis of Inspection Requirements for Valve Bodies and Pump Casings having NPS < 4-in.

BACKGROUND

This attachment details the results of a bounding analysis on the fracture resistance of small diameter cast austenitic stainless steel (CASS) valve bodies, NPS < 4-in, with high delta ferrite (>25 percent) after severe thermal embrittlement. This analysis was undertaken to help determine if licensees should be required to perform either (a) inspection, or (b) analysis to demonstrate the fracture integrity of these components during a license extension period.

METHODOLOGY

An elastic-plastic fracture assessment was performed according to the "R6" Failure Assessment Diagram methodology developed by the Central Electricity Generating Board in the United Kingdom [1,2]. Adherence to the protocols described in references [1,2] has repeatedly been demonstrated to provide conservative assessments of the fracture integrity of operating structures.

INPUTS

- Stress values were obtained from earlier work performed by INEEL for another project addressing erosion-corrosion of valve bodies [3]. In that work, a finite element analysis was performed for a 16-inch globe valve, in the normally closed position. Full system pressure (225 psig for this valve) was applied to one side of the valve, in addition to seismic stresses and end-moments from the piping system analysis. In one computer run, the most severely eroded areas were modeled with a minimum wall thickness of 0.10-in. versus the 0.5 - 0.8-in. wall thickness actually observed in the valve. The peak stress found in the most severely eroded areas under these conditions varied between 22.9 ksi and 41.4 ksi. Yield stress at the applicable temperature is 34.4 ksi. It is important to note that even though the model simulated more severe erosion than was actually observed, these higher stresses only occurred in very small areas of the valve body. Displacements were sufficiently small so that the operation of the valve was judged not to be compromised. Stresses under normal operating pressures in areas that had not been eroded were significantly lower. For these reasons, we chose to use a stress of 20 ksi in the current fracture analysis. While the INEEL stress analysis is not specific to small diameter valves, it is believed to represent a high-stress condition for valve bodies and was used as input to this bounding analysis.

- The following properties are taken from ASME Code SC II for use in this analysis. They are representative of CASS properties (SC 351-CF8) at 550°F without thermal embrittlement.
  - Yield strength 18 ksi
  - Ultimate strength: 67 ksi
  - Modulus: 25,550 ksi

- RES does not have specific fracture toughness test data for aged CASS materials with delta ferrite > 25 percent. However, Dr. O. Chopra (*Argonne National Laboratory*), who performed the NRC's research on the fracture toughness of CASS materials, described work performed by EDF on both severely aged CASS (up to 100,000 hours), and trepan samples removed from operating components. From this work he suggested that the lowest observed J_{IC} value for CASS was on the order of 171 in-lbs/in^2 (30 kJ/m^2). This fracture toughness corresponds to a casting having a ferrite content of between 35% and 45%. This J_{IC} was converted to an equivalent *K* value of 69 ksi*in$^{0.5}$ assuming plane strain conditions.

- A valve body thickness of ½-in was assumed. However, because of the assumptions of the collapse solution (see below), valve body thickness does not enter the analysis.

FLAW MODEL / IDEALIZATION

As this was a bounding analysis, it was of interest to demonstrate that the valve body having the lowest anticipated toughness could sustain a through-wall crack in the presence of the highest anticipated stress without fracturing. The R6 methodology requires that both a stress intensity factor (*K*) solution and a collapse solution be available for the flaw in question. The *K* solution for a through-wall crack in an infinite body is as follows:

$$K = \sigma_{applied}\sqrt{\pi a} \tag{1}$$

where *a* is half of the through-wall crack length. For the collapse solution, it was assumed that the crack would not be large enough to significantly diminish the load-bearing cross section of the valve.

RESULTS

To perform an Option 1 R6 analysis, two quantities are computed: K_r and L_r. K_r is the ratio of the applied stress intensity factor (from eq. (1)) to the material fracture toughness (69 ksi*in$^{0.5}$ in this case). L_r is the ratio of the applied stress (20 ksi) to the yield stress (18 ksi). A point at location (L_r, K_r) is then plotted on a general failure assessment diagram, as illustrated in Figure 1. On

this diagram, points located between the axes and the failure assessment curve (a lower-bound curve appropriate to all metallic materials) are deemed to be "safe," while those outside of the failure assessment curve are "unsafe." The curve is thus a failure locus. In this analysis we increased the length of the crack (a in eq. (1)) until the assessment point lay on the curve. By this method, we determined that the CASS valve could sustain a 1.35-in long through wall crack before failure occurred.

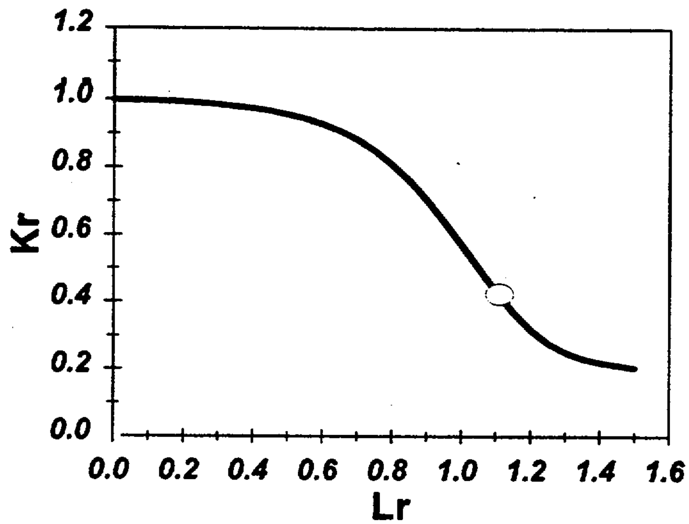

Figure 1: Failure Assessment Diagram.

CONCLUSIONS

Even after severe thermal embrittlement, a CASS valve loaded to the maximum anticipated stress can sustain a through wall crack well in excess of its wall thickness without fracturing. The worst case conditions assumed here suggest that requirements for licensees to either (a) inspect, or (b) provide analysis to demonstrate the fracture integrity of these components would represent an unnecessary duplication of effort.

REFERENCES

[1] Milne, I., et al., "Assessment of the Integrity of Structures Containing Defects," CEGB Report R/H/R6 (Revision 3), 1986.

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