October 30, 2001

Mr. James F. Mallay
Director, Regulatory Affairs
Framatome ANP, Richland, Inc.
2101 Horn Rapids Road
Richland, WA 99352

SUBJECT: SAFETY EVALUATION OF FRAMATOME TECHNOLOGIES TOPICAL REPORT BAW-10046, REVISION 4, "METHOD OF COMPLIANCE WITH FRACTURE TOUGHNESS AND OPERATIONAL REQUIREMENTS OF 10 CFR 50, APPENDIX G" (TAC NO. MA8237)

Dear Mr. Mallay:

By letter dated January 3, 2000, Babcock and Wilcox Owners Group (B&WOG) submitted Framatome Technologies Topical Report (TR) BAW-10046, Revision 4, "Method of Compliance with Fracture Toughness and Operational Requirements of 10 CFR 50, Appendix G," for review. By letter dated July 10, 2000, the staff requested additional information (RAI) in regard to the proposed methodology for calculating the P-T limits for B&WOG member nuclear plants.

The NRC staff has determined that the methods stated in Chapters 1–5 of TR BAW-10046, Revision 4, as amended by the contents of the B&WOG letter OG-1797 dated August 25, 2000, are acceptable for application to the generation of P-T limit curves for pressurized water reactor (PWR) applications. The staff has not included Chapter 6 within the scope of its review, and will address the B&WOG's recommended methodology for performing low-temperature overpressure protection (LTOP) analyses at a later time, if requested by the owners group. The staff has completed its review of the subject TR and finds it is acceptable for referencing in licensing applications to the extent specified and under the limitations delineated in the report and in the associated safety evaluation (SE). The SE defines the basis for acceptance of the report.

We do not intend to repeat our review of the matters described in the subject report, and found acceptable, when the report appears as a reference in license applications, except to ensure that the material presented applies to the specific plant involved. Our acceptance applies only to matters approved in the report.

In accordance with procedures established in NUREG-0390, the NRC requests that the B&WOG publish an accepted version of the submittal within 3 months of receipt of this letter. The accepted version shall incorporate (1) this letter and the enclosed SE between the title page associated responses, and (3) an "-A" (designating "accepted") following the report identification symbol.

Should our criteria or regulations change so that our conclusions as to the acceptability of the report are invalidated, B&WOG and/or the applicants referencing the TR will be expected to revise and resubmit their respective documentation, or submit justification for the continued applicability of the TR without revision of their respective documentation.

Sincerely,

/RA/
Stuart A. Richards, Director
Project Directorate IV
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Project No. 693

Enclosure: Safety Evaluation

cc w/encl: See next page

associated responses, and (3) an "-A" (designating "accepted") following the report identification symbol.

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SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT BAW-10046, REVISION 4

"METHODS OF COMPLIANCE WITH THE FRACTURE TOUGHNESS

AND OPERATIONAL REQUIREMENTS OF 10 CFR 50, APPENDIX G"

PROJECT NO. 693

1.0 INTRODUCTION

On January 3, 2000 (Reference 1), the Babcock and Wilcox Owners Group (B&WOG) submitted Topical Report BAW-10046, Revision 4, "Methods of Compliance with Fracture Toughness and Operational Requirements of 10 CFR 50, Appendix G," for NRC review. On July 10, 2000 (Reference 2), the NRC staff issued a request for additional information (RAI) in regard to the specified contents and methodology of the topical report. On August 25, 2000 (Reference 3), the B&WOG amended the contents of BAW-10046, Revision 4, with its response to the staff's inquiries in the RAI. Section 2.0 provides the staff's evaluation of Topical Report BAW-10046, Revision 4, as amended by the contents of the B&WOG's August 25, 2000, submittal.

The subsections below discuss the regulatory basis for the generation of the pressure-temperature (P-T) limit curves.

1.1 Code of Federal Regulations Requirements for Generating P-T Limits for Nuclear Power Generation Facilities

The NRC has established requirements in Section 50.60 and in Appendix G to Part 50 of Title 10, *Code of Federal Regulations* (10 CFR 50.60 and Appendix G to Part 50, respectively) (References 4 and 5), to protect the integrity of the reactor pressure vessel (RPV) and reactor coolant pressure boundary (RCPB) in nuclear power plants. Subparagraph (a) to 10 CFR 50.60 requires that commercial nuclear light-water reactor facilities must meet the fracture toughness requirements specified in Appendix G to Part 50. Subparagraph (b) to 10 CFR 50.60 allows licensees to use alternatives to these requirements if an exemption is granted by the Commission pursuant to the provisions and exemption acceptance criteria of 10 CFR 50.12 (Reference 6).

Section IV.A.2 of Appendix G to Part 50 establishes the guidelines for determining the P-T limits and minimum temperature requirements that are used to protect the RPV and RCPB during normal operating conditions (including heatups, cooldowns, and anticipated operational transients), and during leak rate or hydrostatic testing conditions. Section IV.A.2 of Appendix G to Part 50 states that the P-T limits and minimum permissible temperature for the RPV, as summarized in Table 1 of the appendix, must be met for all conditions. In this case, Section IV.A.2, when taken in context with Table 1 of the appendix, defines that the P-T limits and

minimum temperature requirements for the RPV will vary according to the following four RPV parameters:

- the operating condition (i.e., normal operating or pressure testing conditions as defined previously),
- vessel pressure as a function of the preservice hydrostatic test pressure for the facility,
- whether fuel is located within the confines of the reactor vessel, and
- whether or not the reactor core is critical.

Section IV.A.2 of Appendix G to Part 50 also requires the P-T limits for an operating plant to be at least as conservative as those that would be generated if the methods of Appendix G to Section XI of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (Appendix G to the Code) (Reference 7) were applied. This necessitates that the P-T limit curves be generated from the most conservative of the P-T data points from P-T limit calculations and the minimum temperature requirements. The staff currently endorses editions of Appendix G to the Code through the 1995 Edition of Section XI, inclusive of the Summer or Winter 1996 Addenda.

1.2 Methods of Appendix G to the Code for Generating P-T Limits

The methodology of Appendix G to the Code postulates the existence of a sharp surface flaw in the RPV that is normal to the direction of the maximum applied stress. For materials in the beltline and upper and lower head regions of the RPV, the maximum flaw size is postulated to have a depth that is equal to one-fourth of the thickness and a length equal to 1.5 times the thickness. For the case of evaluating RPV nozzles, the surface flaw is postulated to propagate parallel to the axis of the nozzle's corner radius. The basic parameter in Appendix G to the Code for calculating P-T limit curves is the stress intensity factor, K_I, which is a function of the stress state and flaw configuration. The methodology requires that licensees determine the dynamic crack arrest reference stress intensity (K_{Ia}) factors, which vary as a function of temperature, from the reactor coolant system (RCS) operating temperatures, and from the adjusted reference temperature (RT_{NDT}) for the limiting material in the RPV. Thus, the critical locations in the RPV beltline and head regions are the 1/4-thickness (1/4T) and 3/4-thickness (3/4T) locations, which correspond to the points of the crack tips if the flaws are initiated and grown from the inside and outside surfaces of the vessel, respectively. Regulatory Guide (RG) 1.99, Revision 2 (Reference 8), provides an acceptable method of calculating RT_{NDT} values for ferritic RPV materials; the methods of RG 1.99, Revision 2, include methods for adjusting the RT_{NDT} values of materials in the beltline region of the RPV, where the effects of neutron irradiation may induce an increased level of embrittlement in the materials.

The methodology of Appendix G to the Code requires that P-T curves must be calculated to satisfy the following equation:

$$K_{Ia} \geq SF * K_{Im} + K_{It} ,$$

where:

K_{Ia} = defined dynamic crack arrest reference stress intensity factor (as discussed previously)

K_{Im} = the stress intensity in the vessel arising from primary membrane stress

SF = an additional safety factor to be imposed on K_{Im},

K_{It} = the stress intensity arising from the thermal gradient across the RPV shell wall.

In this case, the methodology dictates that SF on K_{Im} be set at 2.0 during normal plant operations of the plant (including heatups, cooldowns, and transient operating conditions), and at 1.5 when leak rate or hydrostatic pressure tests are performed on the RCS. For areas of the RPV near nozzles, flanges, or other geometric discontinuities, the methodology states that the P-T calculation equation must be modified to account for stress intensities arising from primary bending stresses (including a safety factor of 2.0 imposed on these stresses), and for secondary membrane and bending stresses. In this case, the methodology of Appendix G to the Code states that the methodology in Appendix 5 to Welding Resource Council Bulletin WRC-175 (Reference 9) may be used to analyze the inside corner flaw of a nozzle joined to a cylindrical shell and to approximate the stress intensities arising from the internal pressure stress (membrane stress). The methodology of the 1995 Edition of Appendix G to the Code treats thermal stresses as secondary stresses, and allows them to be determined from either the appropriate equations in Paragraph G-2214.3 of the appendix or from the plant-specific thermal stress gradient determinations for plant heatups and cooldowns.

1.3 Exemptions to the Requirements of Appendix G to Part 50

As stated in Section 1.1 of this safety evaluation (SE), subparagraph (b) to 10 CFR 50.60 allows licensees to use alternatives to the requirements of Appendix G to Part 50 if an exemption is granted by the Commission pursuant to the provisions and exemption acceptance criteria of 10 CFR 50.12. The staff has previously granted permission, through the exemption request process, to apply the methods in a number of ASME code cases to the methodology for plant-specific P-T limit calculations.

1.3.1 Code Case N-588

The current methods of Appendix G to the Code mandate consideration of an axial flaw in full penetration RPV welds, and thus, for circumferential welds, dictate that the flaw be oriented transverse to the axis of the weld. ASME Code Case N-588 (Reference 10) allows applicants seeking an exemption to evaluate circumferential RPV shell and head welds by postulating a circumferential flaw in the weld in lieu of the axially-oriented flaw typically assumed by the methods of analysis in Appendix G to the Code. Postulation of an axial flaw in a circumferential weld is unrealistic because the length of the flaw would extend well beyond the girth of the circumferential weld and into the adjoining base metal material. Industry experience with the repair of weld indications found during preservice inspection, and data taken from destructive examination of actual vessel welds, confirms that any remaining flaws are small, laminar in nature, and do not transverse the weld bead orientation. Therefore, any potential defects

introduced during the fabrication process, and not detected during subsequent nondestructive examinations, would only be expected to be oriented in the direction of weld fabrication. For circumferential RPV welds, the methods of the Code Case therefore postulate the presence of a flaw that is oriented in a direction parallel to the axis of the weld (i.e., in a circumferential orientation).

An analysis provided to the ASME Code's Working Group on Operating Plant Criteria (WGOPC) (in which Code Case N-588 was developed) indicated that if an axial flaw is postulated on a circumferential weld, then based on the correction factors for membrane stress (M_m) given in the Code Case for the inside diameter circumferential (0.443) and axial (0.926) flaw orientations, it is equivalent to applying a safety factor of 4.18 on the pressure loading under normal operating conditions.(1) Appendix G to the Code only requires that a safety factor of 2 be placed on the contribution of the pressure load in the case of an axially-oriented flaw in an axial weld, shell plate, or forging. By postulating a circumferentially-oriented flaw on a circumferential weld and using the appropriate correction factor, the margin of 2 is maintained for the stress integrity calculation for the circumferential weld. Consequently, the staff determined that the postulation of an axially-oriented flaw on a circumferential RPV weld adds a level of conservatism in the P-T limits that goes beyond the margins of safety required by Appendix G of the Code, and thus by Appendix G to Part 50. For this reason, the methods of the Code Case reduce the applied stress intensities for primary membrane and bending stresses in circumferential flaws by a factor of approximately 2 ($\approx$0.926/0.443).(2) This is realistic since the postulated circumferential flaw in the vessel will propagate if a stress is applied in a direction normal to the axis of the flaw (i.e., by application of an axially oriented stress that results in Mode I crack propagation of the circumferential flaw). Such tensile stresses in the RPVs are typically about half the magnitudes of the corresponding membrane stresses.

Application of Code Case N-588 will only matter if the code case is applied for the case where a circumferential weld is the most limiting material in the beltline region of the RPV. Since application of the code case methods allow licensees to reduce the stress intensities attributed to the circumferential weld, the net effect of the code case would allow an applicant to use the next most limiting base metal or axial weld material in the RPV as the basis for evaluating the vessel and generating the P-T limit curves, if a circumferential weld is the most limiting material in the RPV.

1.3.2 Code Case N-640

Code Case N-640 (Reference 11) permits application of the lower bound static initiation fracture toughness value equation (K_{Ic} equation) as the basis for establishing the curves in lieu of using the lower bound crack arrest fracture toughness value equation (i.e., the K_{Ia} equation, which is

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(1) The margin of safety of 4.18 is arrived at by dividing 0.926 by 0.443 and then multiplying by the required safety factor of 2.

(2) The Code Case accomplishes this by reducing the M_m factors for circumferential welds that are used for calculations of the stress intensities attributed to primary membrane stresses (K_{Im}) and primary bending stresses (K_{Ib}). As stated previously, for RPVs with wall thicknesses in the range of 4.0-12.0 inches, the M_m factor for circumferential welds is 0.443.

based on conditions needed to arrest a dynamically propagating crack, and which is the method invoked by Appendix G to Section XI of the ASME Code). Use of the K_{Ic} equation in determining the lower bound fracture toughness in the development of the P-T operating limits curve is more technically correct than the use of the K_{Ia} equation since the rate of loading during a heatup or cooldown is slow and is more representative of a static condition than a dynamic condition. The K_{Ic} equation appropriately implements the use of the static initiation fracture toughness behavior to evaluate the controlled heatup and cooldown process of a reactor vessel. The staff has required use of the initial conservatism of the K_{Ia} equation since 1974 when the equation was codified. This initial conservatism was necessary due to the limited knowledge of RPV materials. Since 1974 additional knowledge has been gained about RPV materials. Therefore, the lower bound static fracture toughness K_{Ic} equation provides an acceptable method for calculating P-T limits. In addition, P-T curves based on the K_{Ic} equation will enhance overall plant safety by opening the P-T operating window with the greatest safety benefit in the region of low temperature operations.

Generating the RCS P-T limit curves developed in accordance with Appendix G to the Code, without the relief provided by ASME Code Case N-640, would unnecessarily require the RPV to be maintained at a temperature exceeding 212°F during the pressure test. Consequently, steam vapor hazards would continue to be one of the safety concerns for personnel conducting inspections in primary containment. Implementation of the proposed curves, as allowed by ASME Code Case N-640, provides an adequate margin of safety and would eliminate steam vapor hazards by allowing inspections in primary containment to be conducted at a lower coolant temperature. Thus, pursuant to 10 CFR 50.12(a)(2)(ii), the underlying purpose of the regulation will continue to be served.

1.3.3 Code Case N-514

ASME Code Case N-514 (Reference 12), recommends that the low-temperature overpressure protection (LTOP) systems be effective at RCS inlet temperatures less than 200°F or at RCS inlet temperatures corresponding to a RPV metal temperature less than RT_{NDT} value + 50°F, whichever is greater. The code case further recommends that the LTOP systems limit the maximum pressure for the RPV to 110 percent of the pressure determined to satisfy Paragraph G-2215 of Appendix G to the Code. This later recommendation is actually a relaxation of 10 percent in the limits used in the LTOP analysis. The methods of Code Case N-514 have been incorporated into Paragraph G-2215 of the 1995 edition of Appendix G to the Code. The staff notes, however, that exemptions to use the methods of Code Case N-640 (Refer to Section 1.3.2 of this SE) will not be granted when requested in combination with the 10 percent relaxation allowed by Code Case N-514 or the 1995 Edition of Appendix G to the Code.

2.0 EVALUATION

The methods proposed by the B&WOG in Topical Report BAW-10046, Revision 4, for generating P-T limit curves for B&W member facilities or other PWR-design facilities, as amended by the contents and methods stated in the B&WOG submittal of August 25, 2000, are consistent with the following regulatory requirements and regulatory positions stated in Section 1.0 of this SE:

- The P-T limit requirements and minimum temperature requirements specified in Section IV.A.2. of Appendix G to Part 50.
- The P-T limit generation methods stated in the 1995 Edition of Appendix G to the ASME Code, including methods for determining the stress intensities due to membrane, bending and thermal stresses (i.e., K_{Im} , K_{Ib} , and K_{It} , respectively) and methods for determining critical stress intensity factors (i.e., either K_{Ia} , or K_{Ic} if an exemption is granted to apply the methods stated in Code Case N-640).
- The methods stated in RG 1.99, Revision 2, for determining adjusted reference temperature values for RPV beltline materials (i.e, RT_{NDT} values).
- The methods stated in Code Cases N-588 and N-640 when exemption requests to use the methods in these Code Cases are submitted under the provisions of 10 CFR 50.60(b) and granted pursuant the exemption acceptance criteria of 10 CFR 50.12.
- Use of the methods stated in Code Case N-640 are not allowed in combination with the 10 percent relaxation on the Appendix G pressure limits that are included in Code Case N-514 and in the 1995 and more recent editions of Appendix G to the Code.

It should be noted that the B&WOG submittal of August 25, 2000, replaces the Raja-Newman methods for analyzing the stress intensities attributed to longitudinal semi-elliptical surface flaws (Section 5.5.1 of the topical report) and methods of Kumar for analyzing stress intensities attributed to circumferential semi-elliptical surface flaws (Section 5.5.2 of the topical report) with the corresponding stress intensity solutions of the 1995 edition of Appendix G to the Code, as modified by the methods of Code Case N-588 (as stated in the new Sections 5.5.1 and 5.5.2 listed in Attachment 1 of the B&WOG submittal of August 25, 2000). Since the staff has endorsed editions of Section XI to the ASME Code through the 1995 edition, inclusive of the Winter 1996 Addenda, and since the staff has granted a number of exemptions to allow the use of Code Case N-588 for the generation of plant-specific P-T limits, the staff concludes that this change is acceptable.

It should also be noted that Chapter 6 of the topical report provides a recommended methodology for performing LTOP analyses. However, the staff did not include Chapter 6 within the scope of its review in that: (1) the LTOP methods are not necessary for the calculation of the PT limits themselves, and (2) the section appears to be deficient with respect to providing certain details about how B&WOG's recommended practices for performing LTOP analyses.

3.0 CONCLUSIONS

The staff has determined that the methods stated in Chapters 1-5 of Topical Report 10046, Revision 4, as amended by the contents of the B&WOG letter OG-1797 dated August 25, 2000, are acceptable for application to the generation of P-T limit curves for PWR applications. The staff has not included Chapter 6 within the scope of its review, and will address the B&WOG's

recommended methodology for performing LTOP analyses at a later time, if requested by the owners group.

4.0 REFERENCES

1. B&W Owners Group Letter OG-1780, submitting Topical Report BAW-10046, Revision 4, "Methods of Compliance with Fracture Toughness and Operational Requirements of 10 CFR 50, Appendix G," to the U.S Nuclear Regulatory Commission Document Control Desk, dated January 3, 2000.

2. Letter from Mr. Stewart Bailey, Project Manager, U.S. Nuclear Regulatory Commission, to the B&W Owners Group, "Request for Additional Information (RAI) - B&W Owners Group Report BAW-10046, Revision 4, 'Methods of Compliance with Fracture Toughness and Operational Requirements of 10 CFR 50, Appendix G,' (TAC No. MA8237)," dated July 10, 2000.

3. B&W Owners Group Letter OG-1797, "Request for Additional Information (RAI) - B&W Owners Group Report BAW-10046, Revision 4, 'Methods of Compliance with Fracture Toughness and Operational Requirements of 10 CFR 50, Appendix G,' (TAC No. MA8237), July 10, 2000," dated August 25, 2000.

4. Section 50.60 to Part 50 of Title 10, *Code of Federal Regulations*, "Acceptance Criteria for Fracture Prevention Measures for Lightwater Nuclear Power Reactors for Normal Operation."

5. Appendix G to Part 50 of Title 10, *Code of Federal Regulations*, "Fracture Toughness Requirements."

6. Section 50.12 to Part 50 of Title 10, *Code of Federal Regulations*, "Specific Exemptions."

7. Appendix G to Section XI of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code, "Fracture Toughness Criteria for Protection Against Failure."

8. Regulatory Guide 1.99, Revision 2, "Radiation Embrittlement of Reactor Vessel Materials," approved May 1988.

9. Welding Resource Council Bulletin WRC-175, "PVRC Recommendations of Toughness Requirements for Ferritic Materials," dated August 1972.

10. ASME Code Case N-588, "Alternative to Reference Flaw Orientation of Appendix G for Circumferential Welds in Reactor Vessels, Section XI, Division 1," dated December 12, 1997.

11. ASME Code Case N-640, "Alternative Reference Fracture Toughness for Development of P-T Limit Curves, Section XI, Division 1," dated February 26, 1999.

12. ASME Code Case N-514, "Low Temperature Overpressure Protection," dated February 12, 1992.

Principle Contributor: J. Medoff

Date: October 30, 2001