FINAL SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

BOILING WATER REACTOR VESSEL AND INTERNALS PROJECT

"BWRVIP-173: BWR VESSEL AND INTERNALS PROJECT, EVALUATION OF CHEMISTRY DATA FOR BWR VESSEL NOZZLE FORGING MATERIALS"

ELECTRIC POWER RESEARCH INSTITUTE TECHNICAL REPORT 1014995

PROJECT NO. 704

1.0 INTRODUCTION

1.1 Background

By letter dated July 19, 2007 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML072010321), the Boiling Water Reactor (BWR) Vessel and Internals Project (BWRVIP) submitted for U.S. Nuclear Regulatory Commission (NRC) staff review and approval Electric Power Research Institute (EPRI) technical report 1014995, "BWRVIP-173: BWR Vessel and Internals Project, Evaluation of Chemistry Data for BWR Vessel Nozzle Forging Materials," dated May 2007 (ADAMS Accession No. ML072010324). The BWRVIP-173 report was submitted for the purpose of providing evaluations of BWR nozzle forging materials used in reactor vessels (RVs) to support the determination of an estimate of chemistry properties used in predicting RV material embrittlement due to neutron irradiation. The report specifically addresses the statistical analysis of SA508, Class 2 (SA508-2) forging chemistry data for determining reference temperature (RT_{NDT}) shift, if data are limited or unavailable for a particular heat of SA508-2 forging material.

1.2 Purpose

RV materials projected to receive end of license (EOL) neutron fluences greater than 1×10^{17} n/cm^2 (E > 1 MeV) are recognized as RV beltline materials and must be evaluated for embrittlement due to neutron irradiation. As neutron fluence increases, additional RV materials may expand the number of beltline materials. Embrittlement due to neutron irradiation may be predicted in accordance with Regulatory Guide (RG) 1.99, Revision 2, "Radiation Embrittlement of Reactor Vessel Materials." When the copper content and nickel content of a RV material is not available, RG 1.99, Revision 2, specifies upper-bound values. Since these values for RV nozzle materials are often scarce or incomplete, the BWRVIP-173 report was developed to analyze and document a realistic determination of RV nozzle forging material properties, as an alternative to the upper-bound values for copper content and nickel content in RG 1.99, Revision 2. The NRC staff reviewed the BWRVIP-173 report to determine whether it will provide an acceptable technical basis for determining best-estimate values for copper, nickel, manganese, and phosphorus content for SA508-2 forging materials.

ENCLOSURE 2

1.3 Organization of this Report

A brief summary of the contents of the subject report is given in Section 2 of this safety evaluation (SE), with the evaluation presented in Section 3. The conclusions are summarized in Section 4. The presentation of this safety evaluation is structured according to the organization of the BWRVIP-173 report.

2.0 SUMMARY OF BWRVIP-173 REPORT

The BWRVIP-173 report addresses the following topics:

- Section 2: Background – provides a discussion of design information and materials history for BWR RV forging materials. Sources of BWR RV forging material data are listed and the total number of data entries for copper, nickel, manganese, and phosphorus chemical contents are provided.

- Section 3: Evaluation of SA508-2 Forging Data – discusses the analyses performed on the data for RV nozzle forging material type SA508-2. Only data which could be independently verified, data from certified material test reports (CMTRs), or data from highly reliable sources was analyzed.

- Section 3.1: Determination of Best-Estimate Chemistry – provides a description of the BWRVIP approach developed in 1998 to resolve missing RV plate and weld chemistry information, and to establish best estimate chemistry values for the limiting plate and weld materials for each BWR. The results of this work were reported in the BWRVIP-86-A report, “BWR Vessel and Internals Project, BWR Integrated Surveillance Program Implementation Plan.”

- Section 3.2: Evaluation of Copper in SA508-2 Forgings – describes the evaluation of copper data, ranging from 0.01 weight percent, to 0.19 weight percent. The statistical methods used in evaluating the data are described in Appendix A. For heats of SA508-2 RV nozzle forgings with no measured values, a best-estimate value for copper content of [ ] weight percent is proposed.

- Section 3.3: Evaluation of Nickel in SA508-2 Forgings – discusses the analysis of nickel content from the data available for SA508-2 forgings. There were 341 measurements for nickel in the SA508-2 data survey, with a range of 0.50 to 1.0 weight percent nickel. For heats of SA508-2 RV nozzle forgings with no measured values, a best-estimate value for nickel content of [ ] weight percent is proposed.

- Section 3.4: Evaluation of Manganese in SA508-2 Forgings — discusses the analysis of manganese content from the data available for SA508-2 forgings. There were 344 measurements for manganese in the SA508-2 data survey. Five points in excess of the material specification limit of 1.0 weight percent manganese were determined to be non-representative of the data population. Based on 339 data points, for heats of SA508-2 RV nozzle forgings with no measured values, a best-estimate value for manganese content of [ ] weight percent is proposed.

- Section 3.5: Evaluation of Phosphorous in SA508-2 Forgings — discusses the analysis of phosphorous content from the data available for SA508-2 forgings. There were 344 measurements for phosphorous in the SA508-2 data survey. The material specification for SA508-2 forging materials identifies a maximum value of 0.025 weight percent for phosphorus. For heats of SA508-2 RV nozzle forgings with no measured values, a best-estimate value for phosphorous content of [ ] weight percent is proposed.

- Section 3.6: Determination of Initial Reference Temperature – provides a parameter for evaluating the RV fracture toughness. Approaches for the determination of initial RT_{NDT} in forging materials are described in Appendix B. These approaches include the standard method of determining initial RT_{NDT}, testing Charpy V-notch specimens with transverse orientations. The alternative contained in NRC Branch Technical Position (BTP) MTEB 5-2, Revision 1, "Fracture Toughness Requirements" is described, and a second alternative approach developed by General Electric Company (GE) is also described. Examples illustrating each alternative approach are included.

3.0 NRC STAFF EVALUATION

The BWRVIP-173 report proposes best-estimate values of copper, nickel, manganese, and phosphorous content for use when no measured values are available for a particular heat of SA508-2 RV nozzle forging materials, in addition to describing alternative methods for determining initial RT_{NDT}.

3.1 Background

Section 2 of the BWRVIP-173 report addresses the need for identifying the best-estimate values of copper, nickel, manganese, and phosphorous content for RV SA508-2 nozzle forging materials, when no measured values are available. SA508-2 forging material is a low nickel-chromium-molybdenum steel that was used extensively in RV flanges, nozzles, and rings. Although there are specified limits on the composition range of nickel, manganese, and sulfur, there was no control on the copper content in these forgings. Since most foundries did not measure the copper content, there is limited data for the copper content in SA508-2 RV nozzle forging materials.

During the review of license renewal submittals, RV beltline materials are evaluated for the effects of neutron embrittlement. As neutron fluence increases, additional materials in the RV may be considered beltline materials. The effects of neutron embrittlement are predicted in accordance with RG 1.99, Revision 2. When data is not available, RG 1.99, Revision 2 specifies upper-bound values for the copper content (0.35 weight percent) and nickel (1.0 weight percent). Data for the chemical composition of the RV nozzle forging materials are generally scarce or incomplete. Use of the upper-bound values identified in RG 1.99, Revision 2 may result in the RV nozzle forgings becoming the limiting RV material with regards to neutron embrittlement. The BWRVIP-173 report contains a statistical evaluation of available SA508-2 forging data for determining best-estimate values for the copper, nickel, manganese, and phosphorous chemical compositions, and a method for determining initial RT_{NDT} for RV nozzle forgings with limited or no measured data.

A data collection effort was conducted to identify SA508-2 material properties in RV forgings. The number of data groups indicates the number of independent sources with valid chemistry measurements. The total number of measurements and sources for each element were as follows:

Element	Number of Data Measurements	Number of Data Groups
Copper	107	65
Nickel	341	164
Manganese	339	164
Phosphorous	344	166

Appendix C of the BWRVIP-173 report contains a compilation of data for the SA508-2 forgings.

3.2 Evaluation of SA508-2 Forging Data

Section 3 of the BWRVIP-173 report discusses the data that was collected from a limited set of measurements from similar RV materials. Data were restricted to SA508-2 data that could be independently verified, data from CMTRs, or data that came from highly reliable sources.

Determination of Best-Estimate Chemistry

Previously, the BWRVIP had developed an approach to resolve missing RV plate and weld chemical composition information by establishing best-estimate chemistry values for the limiting RV plate and weld materials for each BWR. The evaluation and results were reported in the BWRVIP-86 report. NRC staff approved the BWRVIP-86 report in the safety evaluation dated February 1, 2002 (ADAMS Accession No. ML0203806910).

Evaluation of Copper in SA508-2 Forgings

The SA508-2 data collection resulted in 344 valid data records, of which 107 had valid copper measurements. When the data included multiple measurements of the same heat or volume of material, they were not considered to be independent. Specimens with multiple copper measurements were averaged, resulting in 65 independent copper values for SA508-2 nozzle forging materials.

Appendix A ("Overview of Statistics") of the BWRVIP-173 report, provided a description of the statistical information used in analyzing the SA508-2 data. The initial analysis was performed using all 107 data points. The copper content ranged from 0.01 weight percent to 0.19 weight percent. A histogram of the data, contained in Figure 3-1 of the report, shows a bimodal distribution. Examination of the data sources did not provide an obvious cause for the bimodal distribution. As described in Appendix A, a correlation between the confidence limit and mean plus standard deviation (σ) values was developed. A confidence limit of [ ] percent, equivalent to a mean plus 2σ value was selected to represent the best estimate properties of SA508-2 RV nozzle forging materials. Whereas the mean plus 1σ confidence level bounds [ ] percent of the unknown values, and the mean plus 3σ confidence limit bounds essentially [ ] percent of the data, staff agreed that the mean plus 2σ value, with a [ ] percent confidence limit, provides an acceptable and conservative limit for the best estimate properties. The value for copper content in SA508-2 materials was determined to be [ ] weight percent with a [ ] percent confidence limit. The probability distribution for measured copper in SA508-2 forgings is illustrated in Figure 3-2 of the report. Repeating the analysis with the 65 independent copper values also resulted in a best-estimate value of [ ] weight percent with a [ ] percent confidence limit. NRC staff concluded that although a cause of the bimodal distribution could not be identified, that the best-estimate value of [ ] weight percent for copper is an acceptable value for SA508-2 forging materials lacking measured copper values. The staff notes that the difference between [ ] weight percent copper (the value determined in the report as the mean plus 2σ) and [ ] weight percent copper (the bounding copper content from the available data) would have a negligible practical impact upon the RV integrity evaluations that this data will support.

Evaluation of Nickel in SA508-2 Forgings

Specifications for the manufacture of SA508-2 forging materials included a nickel content ranging from 0.5 weight percent to 1.0 weight percent. When measured nickel values are not available for a specific forging material, RG 1.99, Revision 2 identifies a default value of 1.0 weight percent.

The data survey contained 341 measurements for nickel content in SA508-2 forging materials. A histogram of the data, as shown in Figure 3-5 of the report, can be fitted with a normal or Gaussian curve. This curve fit results in a mean nickel value of [ ] weight percent. The σ of the curve fit is [ ] weight percent. Therefore, the mean plus 2σ upper confidence level of [ ] percent, is [ ] weight percent nickel for SA508-2 forging materials, and the staff has concluded that this value may be assumed for SA508-2 forging materials that lack measured nickel values.

Evaluation of Manganese in SA508-2 Forgings

Specifications for SA508-2 forging materials include a manganese content ranging from 0.50 weight percent to 1.0 weight percent. Although the embrittlement model contained in RG 1.99, Revision 2, does not include manganese, future embrittlement models may include this term.

The SA508-2 data survey contained 344 measurements for manganese. Five points exceeded the material specification limit of 1.0 weight percent manganese. Since these data points were determined not to be representative of the data population, they were excluded and the analysis was based upon the remaining 339 data points. The staff concluded that the five excluded points, out of a total number of 344 data points in a normal distribution, would have had a negligible impact upon the RV integrity evaluations that this data will support, if they had been included. A histogram of the data is shown in Figure 3-7. It can be fitted with a normal or Gaussian curve. The mean value of this curve is [ ] weight percent, and the σ is [ ] weight percent. The resulting mean plus 2σ value is [ ] weight percent for manganese in SA508-2 forgings. Therefore, for SA508-2 forging materials lacking measured manganese values, the staff has concluded that a value of [ ] weight percent may be used.

Evaluation of Phosphorus in SA508-2 Forgings

The allowable limit of phosphorus in the manufacture of SA508-2 forging materials is 0.025 weight percent phosphorous. Table 3-9 contains a distribution of phosphorous values in the SA508-2 data survey. Based on the 344 measurements for phosphorous content in the SA508-2 data survey, the mean phosphorous value from the Gaussian curve fit is [ ] weight percent. Since the σ is [ ] weight percent phosphorous, the mean plus 2σ total is

[ ] weight percent phosphorous. If measured values for phosphorous content in a SA508-2 forging material are not available, the staff has concluded that the estimated value of [ ] weight percent may be used.

Determination of the Initial Reference Temperature

Appendices G and H of Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50 contain requirements for assure RV integrity against brittle fracture. For pressure-temperature (P-T) limits, Appendix G to 10 CFR Part 50 details determination of the adjusted reference temperature (ART) of materials susceptible to radiation, where the ART is the sum of the initial RT_{NDT} plus the shift in RT_{NDT} resulting from accumulated neutron fluence and a margin term to account for uncertainties. In addition, Appendix G to 10 CFR Part 50 contains upper-shelf energy (USE) requirements.

Appendix B of the submittal describes methods of determining initial RT_{NDT} in vessel forgings. First, the standard method for determining RT_{NDT} involves drop weight nil-ductility transition temperature (NDTT) tests and Charpy V-notch tests. As determined by drop weight tests, the NDTT is the RT_{NDT} if, at 60 degrees Fahrenheit (°F) above the NDTT, at least 50 foot-pounds (ft-lbs) of energy and 35 millimeters of lateral expansion are obtained from Charpy V notch tests on specimens oriented transverse to the direction of maximum working. One alternative approach is described BTP MTEB 5-2, Revision 1. For forgings, this approach is as follows:

- If dropweight NDTT tests were not performed, the NDTT may be estimated as the lowest of the following temperatures: 60˚F; the temperature of the Charpy V-notch upper-shelf; or the temperature at which 100 ft-lbs was obtained on Charpy V-notch tests if the USE results were above 100 ft-lbs.

- If tests on transversely-oriented Charpy V-notch specimens were not performed, the temperature at which 50 ft-lbs and 35 millimeters lateral expansion would have resulted from testing transverse Charpy specimens may be estimated by either reducing test results from longitudinally-oriented specimens to 65 percent of their measured values or increasing the temperatures at which 50 ft-lbs and 35 millimeters lateral expansion were obtained from longitudinally-oriented specimens by 20˚F.

As described above, the results for BTP MTEB 5-2, Revision 1 provide an equivalent value for Charpy V-notch testing results of transversely-oriented specimens. Lastly, BTP MTEB 5-2, Revision 1 states that if limited Charpy V-notch tests were performed at a single temperature to confirm that results of at least 30 ft-lbs was obtained, that temperature may be used as an estimate of the RT_{NDT} if at results of at least 45 ft-lbs were obtained for longitudinally-oriented specimens. If the minimum test result was less than 45 ft-lbs, the RT_{NDT} may be estimated as the test temperature plus 20˚F.

An alternative approach for determining an initial RT_{NDT} value was developed by GE. An RT_{NDT} value equal to the longitudinal Charpy V-notch 35 ft-lb transition temperature is derived. The lowest longitudinal Charpy V-notch data point is used to obtain at least 50 ft-lbs transition temperature by adding 2˚F per ft-lb, or where possible by plotting a curve of ft-lbs versus temperature. If transverse Charpy V-notch data are not available, an adjustment must be made to convert to the transverse 50 ft-lbs transition temperature from the longitudinal value. BTP MTEB 5-2, Revision 1 indicates a 20˚F shift. The GE approach suggests a 30˚F shift. The NRC staff has accepted both longitudinal to transverse shift methodologies. The RT_{NDT} is the higher of the RT_{NDT} temperatures from either the longitudinal Charpy V-notch 35 ft-lb transition temperature or the transverse Charpy V-notch 50 ft-lbs transition temperature determined by the methodology previously described minus 60˚F.

4.0 CONCLUSION

The NRC staff has reviewed the BWRVIP-173 report and found that the report is acceptable for providing an estimate of the properties to be used in current embrittlement prediction methods, if there is limited or no data available for SA508-2 RV nozzle forging materials. When measured values of copper, nickel, manganese, or phosphorous content are available, then the measured values are to be used. When multiple measurements are available, an average of measured values for the same heat of forging material should be used.

The BWRVIP-173 report provided statistical analyses of copper, nickel, manganese, and phosphorous measurements from a data collection effort which collected and validated credible data for BWR SA508-2 materials. Staff reviewed the statistical analyses and for SA508-2 forging materials which do not have measured values, the following best-estimate values may be assumed:

- [ ] weight percent copper
- [ ] weight percent nickel
- [ ] weight percent manganese
- [ ] weight percent phosphorous.

RG 1.99, Revision 2, provides a basis for predicting RV embrittlement due to neutron irradiation, and identifies bounding copper and nickel values for determining the change in RT_{NDT} when data are not available. The NRC staff review has concluded that when measurements of copper and nickel content for SA508-2 forging materials are not available, the best-estimate values identified in BWRVIP-173 may be used as an alternative to the default values contained in RG 1.99, Revision 2. When initial RT_{NDT} values for SA508-2 forging materials are not available, the two approaches for determining the initial RT_{NDT} as described in Appendix B may be followed.

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RESOLUTION OF COMMENTS ON DRAFT SAFETY EVALUATION FOR

BOILING WATER REACTOR VESSEL AND INTERNALS PROJECT

"BWRVIP-173: BWR VESSEL AND INTERNALS PROJECT, EVALUATION OF CHEMISTRY

DATA FOR BWR VESSEL NOZZLE FORGING MATERIALS"

ELECTRIC POWER RESEARCH INSTITUTE TECHNICAL REPORT 1014995

PROJECT NO. 704

This Attachment provides the U.S. Nuclear Regulatory Commission (NRC) staff's review and disposition of the comments made by the Boiling Water Reactor Vessel and Internals Project (BWRVIP) on the draft safety evaluation (SE) for "BWRVIP-173: BWR Vessel and Internals Project, Evaluation of Chemistry Data for BWR Vessel Nozzle Forging Materials." The BWRVIP provided its comments in a letter dated July 7, 2010, "Re-transmittal of Comments and Proprietary Information Identification Regarding NRC Draft Safety Evaluation of BWRVIP-173."

Editorial changes suggested by the BWRVIP are noted in bold.

1. BWRVIP Comment (draft SE Page 4, Line 41):

The following change is suggested: Replace symbol "δ" used for standard deviation with common industry practice symbol of "**σ**" for standard deviation.

NRC Resolution for Comment 1 on the draft SE:

The NRC staff agrees with this comment; all uses of the symbol "δ" were replaced by the symbol "σ."

2. BWRVIP Comment (draft SE Page 2, Lines 33):

Electric Power Research Institute proprietary information was identified in numerous locations throughout the draft SE.

NRC Resolution for Comment 2 on the draft SE:

The NRC staff agrees that the identified information is proprietary; the proprietary information has been redacted as indicated by brackets.