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

February 21, 2001

Mr. Mark Reddemann
Site Vice President
Kewaunee and Point Beach Nuclear Power Plants
Nuclear Management Company, LLC
6610 Nuclear Road
Two Rivers, WI 54241

SUBJECT: KEWAUNEE NUCLEAR POWER PLANT - REQUEST FOR EXEMPTION FROM THE REQUIREMENTS OF 10 CFR PART 50, APPENDICES G AND H, AND 10 CFR 50.61 (TAC NO. MA8585)

Dear Mr. Reddemann:

The Nuclear Regulatory Commission (NRC) has reviewed your submittals dated June 7, 1999, February 4, September 26, and December 18, 2000, regarding your requested exemptions from 10 CFR Part 50, Appendices G and H, and 10 CFR 50.61 for the Kewaunee Nuclear Power Plant (KNPP).

The NRC staff has determined that your proposed methodology needs to be modified using the methodology contained in the enclosure. In addition, the NRC staff has determined that the following must be obtained regarding the next KNPP surveillance capsule: (a) a valid measurement of the fracture toughness-based T_0 parameter for the KNPP reactor pressure vessel (RPV) surveillance weld, (b) an estimate of the Charpy V-notch 30 ft-lb transition temperature shift for the surveillance weld, and (c) an estimate of the upper shelf energy drop for the surveillance weld. Also, the NRC staff has determined that when additional fracture toughness data relevant to the evaluation of the KNPP RPV circumferential weld is acquired as part of the KNPP surveillance program, that data should be incorporated into the evaluation of the KNPP RPV using the methodology in the enclosure.

A written response is requested within 15 days of the date of this letter notifying the Commission whether you (1) agree to use the methodology contained in the enclosure, (2) agree to make the changes stated above, and (3) wish the NRC to continue to process your exemption request or whether you wish to withdraw the exemption request.

Please contact me at (301) 415-1446 if you have any questions or if future circumstances should require a change in the response date.

Sincerely,

John G. Lamb, Project Manager, Section 1
Project Directorate III
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Docket No. 50-305

Enclosure: NRC Staff Method Evaluation

cc w/encl: See next page

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Site Vice President
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The NRC staff has determined that your proposed methodology needs to be modified using the methodology contained in the enclosure. In addition, the NRC staff has determined in the enclosed method evaluation that the following information should be obtained regarding the next KNPP surveillance capsule: (a) a valid measurement of the fracture toughness-based T_0 parameter for the KNPP reactor pressure vessel (RPV) surveillance weld, (b) an estimate of the Charpy V-notch 30 ft-lb transition temperature shift for the surveillance weld, and (c) an estimate of the upper shelf energy drop for the surveillance weld. Also, the NRC staff has determined that when additional fracture toughness data relevant to the evaluation of the KNPP RPV circumferential weld is acquired as part of the KNPP surveillance program, that data should be incorporated into the evaluation of the KNPP RPV using the methodology in the enclosure.

A written response is requested within 15 days of the date of this letter notifying the Commission whether you (1) agree to use the methodology contained in the enclosure, (2) agree to obtain the information stated above regarding the next KNPP surveillance capsule, and (3) wish the NRC to continue to process your exemption request or whether you wish to withdraw the exemption request.

Please contact me at (301) 415-1446 if you have any questions or if future circumstances should require a change in the response date.

Sincerely,
/RA/
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NRC STAFF METHOD EVALUATION

1.0 NRC STAFF EVALUATION

The NRC staff has completed its review of the licensee submittal. The NRC staff has examined this submittal by considering questions regarding: (1) regulatory implementation of a Master Curve-based methodology for RPV integrity assessment, (2) RPV surveillance program modifications necessary to support a Master Curve-based methodology, (3) the technical adequacy of the methodology proposed by the licensee for using the available data to assess the KNPP RPV and, (4) the justification for proposed plant-specific licensing actions given the approval of an acceptable Master Curve-based methodology. In some cases, the NRC staff's position regarding a subject area has been developed to specifically address aspects which are likely to be unique to the review of this submittal. In other cases, more general conclusions, which would be equally relevant to the current licensee submittal and to future Master Curve-based submittals from other licensees, have been provided.

Regarding regulatory implementation of a Master Curve-based methodology for RPV integrity assessment, the licensee determined that three exemptions were necessary to implement a Master Curve-based methodology for RPV integrity assessment. Although, the details of the NRC staff's assessment regarding these issues of regulatory implementation will be somewhat different from those submitted by the licensee, fundamentally the NRC staff concurs with the licensee conclusion that exemptions to 10 CFR 50.61, and Appendices G and H to 10 CFR Part 50 are required for this application. The NRC staff has concluded that the need for such exemptions is not specific to the licensee submittal and could be equally applicable (depending on scope of application) to Master Curve submittals from other licensees. The NRC staff's detailed conclusions regarding this exemptions related to the submittal are provided in Sections 1.1 through 1.2.2 below.

Concerning RPV surveillance program modifications necessary to support a Master Curve-based methodology, the NRC staff has reviewed the additional information submitted by the licensee in their September 26, 2000, letter. The NRC staff has concluded that an adequate RPV surveillance program can be defined which incorporates the acquisition of fracture toughness. The NRC staff's detailed conclusions regarding the KNPP surveillance program are provided in Section 1.2.3 below.

On the subject of the technical adequacy of the methodology proposed by the licensee for using their available data to assess the KNPP RPV, the NRC staff has identified a number of technical aspects in the methodology proposed by the licensee with which the NRC staff disagrees. However, sufficient information was provided for the NRC staff to develop an independent, acceptable methodology for utilizing the available licensee data to evaluate the integrity of the KNPP RPV. The NRC staff's methodology is discussed in detail in section 1.3 below and serves as the basis for the NRC staff's approval of a Master Curve-based methodology for KNPP. Finally, the results of using the NRC staff's methodology to evaluate both RPV P-T limits and the compliance of the KNPP RPV with the requirements of 10 CFR 50.61 through EOL are discussed in Section 1.4. It should be noted, however, that the NRC staff did not evaluate the condition of the KNPP RPV at EOLE fluence for the purpose of justifying the integrity of the RPV to that fluence value. Rather, the NRC staff evaluated the $ART_{T0\text{-}EOLE\text{-}ID}$ value of the KNPP RPV using the methodology acceptable to the NRC staff only for comparison to the value determined from the licensee's methodology. This comparison was necessary to determine whether the licensee's proposed methodology was at least as conservative as that accepted by the NRC staff.

ENCLOSURE

1.1 Exemption to 10 CFR 50.61

10 CFR Part 50.61 establishes the regulatory structure to ensure that appropriate evaluations are performed to demonstrate that pressurized water reactor RPVs maintain sufficient fracture toughness throughout their operating lifetime to withstand potential PTS transients. The basis of 10 CFR Part 50.61 is that a material parameter, RT_{PTS}, is established for each RPV beltline material and this value is compared to screening limits given in 10 CFR Part 50.61 (270 °F for axial welds, plates, and forgings; 300 °F for circumferential welds). These screening limits were established based on probabilistic fracture mechanics evaluations performed in the early 1980s.[24]

Specific methodologies for the determination of plant-specific RT_{PTS} values were established to ensure that consistency would be maintained between the basis for their calculation and the screening criteria in 10 CFR Part 50.61. 10 CFR Part 50.61(c) notes, "RT_{PTS} must be evaluated using the same procedures used to calculate RT_{NDT} [the nil-ductility transition reference temperature], as indicated in paragraph (c)(1) of this section, and as provided in paragraphs (c)(2) and (c)(3) of this section." These sections go on to define the procedures to be based on the use of Charpy V-notch and drop weight test data. Hence, the NRC staff has concluded that the licensee proposal to replace the use of the existing Charpy V-notch and drop weight-based methodology by a Master Curve fracture toughness-based methodology for demonstrating compliance with 10 CFR Part 50.61 requires an exemption.

Further, the NRC staff has concluded that the "general approach" (i.e., the definition of a new indexing parameter, ART_{T0}, which when determined from irradiated and unirradiated fracture toughness data under appropriate conditions, replaces RT_{PTS}) taken by the licensee to develop this new fracture toughness-based methodology is consistent with the existing framework of 10 CFR Part 50.61. Since both the existing and proposed indexing methodologies are linked to an acceptable database of ASTM E 399 valid K_{IC} data, the NRC staff concluded that the fundamental technical basis exists for comparing the existing screening criteria of 10 CFR Part 50.61 to the ART_{T0} values developed through the "general" licensee Master Curve-based approach. Provided all necessary technical considerations are addressed (see Section 1.3 below), indexing parameter values determined through Master Curve evaluation of fracture toughness data provide an acceptable technical alternative. Hence, the licensee's requested exemption may be approved in accordance with 10 CFR Part 50.12(ii).

1.2 Exemptions to Appendices G and H to 10 CFR Part 50, and the RPV Surveillance Program

1.2.1 Exemption to Appendix H to 10 CFR Part 50

10 CFR Part 50.60 invokes the requirements of Appendix H to 10 CFR Part 50 regarding the establishment of a RPV surveillance program to monitor changes in the fracture toughness of RPV materials due to exposure to neutron irradiation and the thermal environment. Further, 10 CFR Part 50.60(b) requires that licensees who propose to invoke alternatives to the described requirements in Appendix H to 10 CFR Part 50 obtain NRC approval via an exemption per the requirements of 10 CFR Part 50.12. Appendix H to 10 CFR Part 50 then establishes that testing and reporting of surveillance data be done in accordance with the 1982 Edition of ASTM Standard E 185 (ASTM E 185-82), and ASTM E 185-82 requires, in part, that Charpy V-notch testing be performed to assess the change in fracture toughness of the RPV surveillance materials. This emphasis on the use of Charpy testing is, therefore, consistent with the technical bases of the current evaluational methodologies, as discussed in Sections 1.1

above, for demonstrating compliance with the requirements of 10 CFR Part 50.61 and Appendix G to 10 CFR Part 50.

The NRC staff has concluded that, since the technical basis to be employed by the licensee for demonstrating compliance with the requirements of 10 CFR 50.61 and Appendix G to 10 CFR Part 50, will be modified given the NRC staff's approval of the licensee submittal, corresponding changes in the definition of the KNPP RPV surveillance program are also required. As such, the NRC staff agrees with the licensee's conclusion that an exemption to the requirements of Appendix H to 10 CFR Part 50 is required as part of the licensee's overall submittal. Further, based on the NRC staff's review of RPV surveillance program modifications submitted by the licensee and discussed in detail in Section 1.2.3 below, the NRC staff has concluded that an adequate surveillance program can be defined to support the licensee's Master Curve-based methodology. Hence, in accordance with the provisions of 10 CFR Part 50.12(ii), the NRC staff has concluded that the alternative surveillance program submitted by the licensee provides an acceptable technical alternative to the requirements of Appendix H to 10 CFR Part 50.

1.2.2 Exemption to Appendix G to 10 CFR Part 50

10 CFR Part 50.60 invokes the requirements of Appendix G to 10 CFR Part 50 for the establishment of P-T limit curves to adequately protect RPVs during heatup, cooldown, and hydrostatic/leak testing. 10 CFR Part 50.60(b) requires that licensees who propose alternatives to the described requirements in Appendix G to 10 CFR Part 50 obtain NRC approval via an exemption per the requirements of 10 CFR Part 50.12. The methodology given in Appendix G to 10 CFR Part 50, like that discussed in Section 1.1.1 above regarding PTS evaluations, is clearly based on the use of Charpy V-notch and drop weight data. This is evident since Appendix G to 10 CFR Part 50 invokes, through reference to 10 CFR Part 50.55(a), the requirements and methodology given in Appendix G to ASME Code Section XI for P-T limit curve development. 10 CFR 50.55(a) approves the use of versions of ASME Code Section XI through the 1996 Addenda to the 1995 Edition. All editions of Appendix G to ASME Code Section XI through the 1996 Addenda to the 1995 Edition incorporate Charpy and drop weight-based methodologies for defining a reference temperature (RT_{NDT}) used to develop facility P-T limits. Hence, the NRC staff has concluded that the licensee proposal to replace the use of the existing Charpy and drop weight-based methodology by a Master Curve fracture toughness-based methodology for demonstrating compliance with Appendix G to 10 CFR Part 50, requires an exemption per the condition established in 10 CFR Part 50.60(b).

Further, consistent with what was noted in Section 1.1 above regarding PTS evaluations, the NRC staff has concluded that the "general approach" taken by the licensee to develop this new Master Curve fracture toughness-based methodology is consistent with the existing framework of Appendix G to 10 CFR Part 50 and Appendix G to ASME Code Section XI. Provided all necessary technical considerations are addressed (see Section 1.3 below), indexing parameter values determined through Master Curve evaluation of fracture toughness data provide an acceptable technical alternative. Hence, the licensee's requested exemption to the requirements of Appendix G to 10 CFR Part 50 may be approved in accordance with 10 CFR Part 50.12(ii).

1.2.3 KNPP RPV Surveillance Program

As addressed in the licensee's submittal, the proposed changes to the KNPP surveillance program can be discussed in two parts. The first part considers the incorporation of data from the fracture toughness (K_{JC}) testing of archival material and reconstituted specimens fabricated from the materials in KNPP surveillance capsule S and Maine Yankee surveillance capsule A-35. The second part considers the surveillance program modifications to be incorporated into the testing of future KNPP surveillance capsules.

1.2.3.1 Testing of Archive Material and Previously Tested RPV Surveillance Capsules

The details of the licensee's program for acquiring fracture toughness data for materials samples manufactured from archival material and previously tested surveillance capsules are addressed in WCAP-14279, Revision 1. The NRC staff's conclusions below were based on the review of information in this topical report.

First, the NRC staff confirmed that the material samples cited by the licensee adequately represented the KNPP RPV circumferential weld such that they can be considered in the KNPP RPV integrity evaluations. The NRC staff concluded that the fracture toughness data from these surveillance welds could be used for this purpose since both the KNPP and Maine Yankee surveillance welds were reported to have been fabricated with the same weld wire heat (1P3571) as the KNPP RPV circumferential weld and were subjected to similar post-weld heat treatment conditions. In addition, for the irradiated materials from KNPP surveillance capsule S and Maine Yankee surveillance capsule A-35, the NRC staff confirmed that the irradiation conditions (irradiation temperature, neutron flux) to which these materials were exposed adequately represented the irradiation conditions for the KNPP RPV, within the allowable limits of ASTM E185. The irradiation temperature conditions for the KNPP RPV and surveillance capsule were reported to be nearly identical to those for the Maine Yankee surveillance capsule (± 1 °F), and this information was confirmed through an independent NRC database.[25]

Next, the NRC staff examined questions about specimen fabrication (i.e., reconstitution) and testing practices. Regarding the reconstituted PCVN specimens, the NRC staff confirmed that acceptable guidelines (ASTM Standard E 1253) were used to ensure that valid results should have been acquired in the licensee's testing activities. The NRC staff also noted that an acceptable practice, ASTM E 1921-97, had been used to define the testing procedure used for obtaining fracture toughness data.

Therefore, based on the conclusions above regarding material similarity, irradiation conditions, and specimen reconstitution and testing practices, the NRC staff concluded that the data cited in Reference 5 was acceptable for the evaluation of the integrity of the KNPP RPV. With the approvals granted in this safety evaluation, the licensee may therefore be permitted to incorporate this data into the KNPP licensing basis.

1.2.3.2 Future RPV Surveillance Program Testing

As submitted by the licensee in a letter dated September 26, 2000, the NRC staff has reviewed the surveillance program planned by the licensee given the approval of this Master Curve-based submittal. The NRC staff's review was predicated on determining the minimum acceptable KNPP surveillance program to adequately monitor radiation damage to the KNPP RPV through the end of its current operating license.

Based on the data submitted in Reference 5, the NRC staff has concluded that two data points, one from KNPP surveillance capsule S and one from Maine Yankee surveillance capsule A-35, have been acquired to evaluate the fracture toughness properties of the KNPP RPV circumferential weld. Although the Maine Yankee and KNPP surveillance welds exhibit markedly different material properties, particularly with the regard to chemical composition and thus radiation sensitivity, given appropriate adjustments (as incorporated in the NRC staff's methodology in Section 1.3) for these differences, the two data points can be used as an acceptable combined data set for evaluating the KNPP RPV circumferential weld. Further, these two data points represent fluence values consistent with the projected EOL fluence of the KNPP RPV circumferential weld and with nearly two times the projected EOL fluence. As such, they represent a range in fluence values which adds additional robustness to the conclusions drawn from the data.

The NRC staff has, therefore, concluded that the KNPP proposal to remove and test one additional surveillance capsule at a fluence level corresponding to the projected fluence for the KNPP RPV circumferential weld at 60 years of operation is acceptable to monitor radiation damage to the KNPP RPV through the end of its current, forty year, operating license. This will provide the licensee with an additional data point at a fluence approximating 1.5 times the EOL fluence for the RPV circumferential weld and thus represent another data point at an intermediate fluence with respect to the two data points which have already been acquired. In addition, the removal and testing of the next KNPP surveillance capsule at such a fluence level also completes the current KNPP surveillance program requirements (considering the withdrawal schedule requirements of ASTM E 185-82, which is cited in the KNPP updated safety analysis report (USAR) as the basis for the KNPP withdrawal schedule).[26]

The NRC staff's conclusion, however, is predicated on the licensee achieving the following with the testing of the surveillance specimens from the next KNPP surveillance capsule: (a) obtain a valid measurement of the T_0 parameter for the KNPP RPV surveillance weld; (b) obtain a reliable estimate of the Charpy 30 ft-lb transition temperature shift for the KNPP RPV surveillance weld; and, (c) obtain a reliable or conservative estimate of the upper shelf energy drop for the KNPP RPV surveillance weld. The licensee may obtain a valid measurement of the T_0 parameter for the RPV surveillance weld using: (1) original PCVN weld specimens, (2) reconstituted PCVN weld specimens fabricated from HAZ specimens, or (3) reconstituted PCVN weld specimens fabricated from the end tabs of original, broken weld specimens. If reconstituted specimens from the end tabs of previously broken specimens are used, appropriate limits on the amount of plastic deformation that can be present in the end tabs shall be considered. Further, reconstituted PCVN specimens must be fabricated following the guidance in ASTM E 1253. The licensee must obtain a reliable estimate of the Charpy 30 ft-lb transition temperature shift for their surveillance weld inasmuch as this information will provide a rare data point for the comparison of radiation-induced shifts in the Charpy 30 ft-lb value and the value of T_0. Finally, the licensee must obtain a reliable or conservative estimate of the upper shelf energy drop for the surveillance weld to address issues regarding low energy ductile tearing which cannot be adequately evaluated by data taken in the ductile-to-brittle failure transition region.

Note, these performance goals are not intended to specify that a full Charpy V-notch impact curve is required for the surveillance weld material, only that the licensee must provide a written explanation in their next surveillance capsule report as to how these performance goals were achieved. Furthermore, regarding reporting requirements, the NRC requires that all information specified in paragraphs 11.1 through 11.2.3 of ASTM E 1921-97 be reported for the surveillance weld fracture toughness testing performed on samples from the next KNPP surveillance capsule. The NRC staff also requests that the next KNPP surveillance capsule report provide all information specified in paragraphs 11.1 through 11.2.3 of ASTM E 1921-97 for the fracture toughness specimens from KNPP surveillance capsule S, Maine Yankee surveillance capsule A-35, and any unirradiated specimens which were tested as part of the basis for the current licensee submittal. The NRC staff requests this information so that a comparisons can be made at that time between the results from the next surveillance capsule and the previously-cited results.

In summary, the NRC staff agrees that the licensee may use ASTM E 185-98 to define the requirements for evaluating transition temperature properties from the testing of weld specimens (either original or reconstituted) from the next KNPP RPV surveillance capsule. This capsule will be removed and tested at a fluence level approximately equal to the projected fluence for the KNPP RPV circumferential weld after sixty years of operation. Other testing requirements (e.g., tensile testing) remain as stipulated in ASTM E 185-82. The NRC staff also agrees that fracture toughness testing data shall be the basis of their surveillance program for the RPV weld and that the licensee does not need to acquire a complete Charpy impact curve, as required by ASTM E 185-98, for this material. In addition, for the HAZ specimens, no Charpy V-notch testing is required. Finally, the testing requirements for other materials, the KNPP surveillance plate and correlation monitor material, remain as defined in ASTM E 185-82.

1.3 NRC Staff's Methodology for Application of a Master Curve-Based Methodology

The development of an acceptable Master Curve-based methodology for the evaluation of a RPV material was the central component of the licensee submittal. The other aspects of this submittal which have been discussed previously: exemptions to the regulatory structure to implement such a methodology; revisions to the KNPP surveillance program to incorporate the acquisition of fracture toughness data; etc., were contingent on the development of an acceptable methodology. Therefore, the majority of the NRC staff's review effort was focused on evaluating the methodology submitted by the licensee, raising and resolving technical concerns regarding the proposed methodology, and, eventually, developing a methodology acceptable to the NRC staff for the use of the KNPP fracture toughness data.

In order to complete this review, the NRC staff considered a wide range of information regarding the Master Curve technology and RPV material properties. This not only included the information submitted by the licensee, but also: (1) technical information associated with consensus Codes and Standards organizations (ASTM, ASME) activities on the Master Curve technology; (2) information developed through the NRC's Office of Nuclear Regulatory Research as part of established programs to evaluate the use of this technology; (3) information submitted by the industry to address previous NRC initiatives on RPV integrity issues; and (4) documentation of the NRC's basis for the current regulatory structure and methodologies for ensuring that RPV integrity is maintained.[17, 27, 21, 22, 24] The methodology addressed in this section, developed by and acceptable to the NRC staff, was a product of the NRC staff's review of all this information.

However, even with this effort, the NRC staff acknowledges that the state of knowledge regarding some specific technical topics associated with this application may be improved upon in the future. The NRC staff's methodology incorporates appropriate consideration of margins to be applied to account for RPV material property uncertainty, fluence uncertainty, and potential biases due to the use of PCVN testing, for example, which are subjects on which the existing state of knowledge could be improved upon. Hence, while the methodology discussed in this SE is acceptable, the NRC staff acknowledges that it reflects a technical approach which is still under development. Additional "conservatisms" in this methodology may be identified in the future and potentially such conservatisms may be reduced/removed provided that a sufficient technical justification can be made for their reduction/removal.

A detailed, mathematical description of the complete NRC staff methodology is provided in Appendix A to this SE. The methodology in Appendix A is the methodology which is acceptable to the NRC staff and the basis for the NRC staff's approval of the licensee's submittal. With the issuance of this SE, the methodology of Appendix A must be incorporated into the KNPP licensing basis for the NRC staff's approval of the licensee's submittal to be valid.

1.3.1 Basic Methodology for the Determination of RT_{T0}

As discussed in Section 3.3.1, the methodology submitted by the licensee uses fracture toughness data to establish an indexing parameter, $RT_{T0,}$ to position the K_{Ic} (static, plane strain, lower bound) fracture toughness curve from the ASME Code. The NRC staff concurs that this is a generally acceptable approach for utilizing fracture toughness data within the current regulatory structure. This would be as opposed to a methodology which could be proposed to directly utilize not only the T_0 parameter, but also the general Master Curve "shape" through the fracture toughness transition region; a proposal which would require significant additional evaluation to understand the relation of such an approach to the current regulatory structure.

The NRC staff also concurs with the licensee position that "direct measurement" of fracture toughness properties in the irradiated condition is, in theory, an acceptable basis upon which to utilize the Master Curve technology to evaluate the material properties of RPVs. However, as noted during the NRC staff's review of the KNPP submittal, the concept of "direct measurement" of RPV material properties must be clearly understood if it is to applied in an acceptable manner. The NRC staff's position is that "direct measurement," in its strictest sense, results from obtaining and testing material samples from the RPV material itself. Fracture toughness data derived from other sources (in the KNPP submittal, data obtained from the testing of irradiated samples of surveillance welds made with the same weld wire heat as the RPV weld) does not represent "direct measurement" of RPV material properties in the irradiated condition. Testing of surveillance weld materials which are linked to the RPV weld in question by the same weld wire heat number is considered by the NRC staff to be an application of "surrogate" material testing. Necessary "adjustments" and margins to account for the use of "surrogate" materials are further discussed in Sections 1.3.2 and 1.3.3.

As substantiated in the licensee submittal, a mechanism for adjusting data must be established to relate the data derived from their "direct measurement" of the KNPP and Maine Yankee surveillance weld fracture toughness properties in the irradiated condition to the KNPP RPV circumferential weld. The NRC staff concurs with the licensee's conclusion that an implicit reliance on evaluating the "shift" in T_0 between the unirradiated and irradiated conditions for the KNPP and Maine Yankee surveillance welds must to used to make these adjustments. Therefore, while both the licensee and the NRC staff methodologies may be considered to be "more direct" paths to establishing the KNPP RPV circumferential weld material properties at EOL and EOLE conditions when compared to the current Charpy V-notch and drop weight-based "initial plus shift" approach, neither can be accepted as a definitive "direct measurement" approach to establishing the material properties of the RPV weld. This issue of "adjustments," and associated effects on uncertainties and margins, will be discussed in Section 1.3.3. Regarding the licensee's proposal to utilize the methods of ASTM E 1921-97 to define the procedures for obtaining and evaluating the fracture toughness data via the Master Curve technology, the NRC staff concurs that this use of this Standard is acceptable. Use of ASTM E 1921-97 will provide acceptable values of T_0 from the testing of KNPP and Maine Yankee surveillance weld samples in both the irradiated and unirradiated conditions and the NRC staff concurs with the values obtained by the licensee and given in column 4 of Table 4. However, at this time, the NRC staff does not endorse the use of the multi-temperature maximum likelihood methodology for combining data for different size specimens to obtain "overall T_0" values as shown in column 5 of Table 4. The NRC staff may reconsider its position on the multi-temperature method for this purpose once action within the governing ASTM Standards organization has been completed and a revision to E 1921 published. The NRC staff's evaluation will therefore be restricted to the evaluation of data derived from the testing of PCVN specimens.

Finally, the NRC staff concurs with the KNPP use of ASME Code Case N-629 to define an acceptable expression for calculating the RT_{T0} parameter. As noted in Section 3.3.1, ASME Code Case N-629 states that RT_{T0} shall be calculated as given in Eqn. 1, $RT_{T0} = T_0 + 35$ °F. This definition of RT_{T0} is accepted by the NRC staff based on the supporting evaluations provided in the technical basis document for ASME Code Case N-629. These evaluations demonstrated that defining RT_{T0} in this manner would result in a parameter which, when comparing to the data base of ASTM E 399 valid K_{Ic} fracture toughness data cited in the technical basis document, would position the lower bound ASME Code K_{Ic} fracture toughness curve with nearly the same degree of "implicit" conservatism as RT_{NDT}.[17] Furthermore, this NRC staff position is consistent with NRC representatives' votes which favored passage of ASME Code Case N-629 during the ASME Code consensus process. The NRC staff's evaluations regarding the issue of "implicit" margins within the definition of the RT_{T0} parameter are discussed in Section 1.3.3.

1.3.2 <u>Assessment of Systematic Difference Between Surveillance Data and RPV Conditions</u>

As noted previously, given the licensee proposal to rely on "direct measurement" of the fracture toughness of irradiated surveillance weld samples from the KNPP and Maine Yankee surveillance programs, a necessary development in the licensee and NRC staff methodologies was a way to adjust the test results to the EOL and EOLE conditions of the KNPP RPV circumferential weld. As part of the NRC staff's methodology, general provisions were developed in these "adjustments" to account for differences in fluence, best-estimate chemical composition, and irradiation temperature (although in the KNPP case, no meaningful irradiation temperature differences existed). In effect, implementing these adjustments defines the entire structure (outside of separable activities to determine appropriate margins and a PCVN bias term) of the NRC staff's methodology as given in Appendix A to this SE. Finally, it should be noted that all of the aforementioned adjustments are consistent with similar adjustments required in the current Charpy V-Notch and drop weight-based methodology by the provisions of 10 CFR 50.61 and the guidance in RG 1.99, Rev. 2.

The methodology developed by the NRC staff for implementing these adjustments was consistent with that proposed by the licensee in that it depends on "shift in T_0" for the KNPP and Maine Yankee surveillance welds between the unirradiated and irradiated conditions and the embrittlement model in RG 1.99, Rev. 2 to characterize the shifts. A fundamental difference, however, was that while the licensee methodology evaluated EOL RPV conditions from data derived from KNPP surveillance capsule S material and EOLE RPV conditions from data derived from Maine Yankee surveillance capsule A-35, the NRC staff's methodology was developed to ensure that both data points could be integrated into the evaluation of any specified RPV condition. The NRC staff's position was that the integration of data in this manner: (1) provided a more robust and defensible evaluation of any specified RPV condition, (2) was consistent with current guidelines related to data sufficiency established in RG 1.99, Rev. 2 and 10 CFR 50.61, for the use of plant-specific Charpy results, and (3) provided a framework for the integration of additional future data points into the evaluation of the KNPP RPV circumferential weld.

The general procedure established by the NRC staff is discussed below, with a more condensed, mathematical documentation of the methodology provided in Appendix A. The goal is to obtain estimates of T_0 for the KNPP RPV circumferential weld at a specified condition. For example, if considering EOLE conditions at the clad-to-base metal interface, two independent estimates of this value can be established from the KNPP surveillance capsule S and Maine Yankee surveillance capsule A-35 data points, called $T_{0\text{-EOLE-ID-K-S}}$ and $T_{0\text{-EOLE-ID-MY-A35}}$, respectively.

To demonstrate, $T_{0\text{-EOLE-ID-K-S}}$ would be determined as:

[Eqn.7] $$T_{0\text{-EOLE-ID-K-S}} = T_{0\text{-K-S}} - (\Delta T_{0\text{-K-S}} - \Delta T_{0\text{-EOLE-ID-K-S}})$$

In this case, $T_{0\text{-K-S}}$ is the T_0 value determined from the testing of PCVN specimens from KNPP surveillance capsule S, $\Delta T_{0\text{-K-S}}$ is the shift in the value of T_0 between unirradiated specimens from the KNPP surveillance weld and the samples from KNPP surveillance capsule S, and $\Delta T_{0\text{-EOLE-ID-K-S}}$ is the estimated shift in T_0 for the KNPP RPV circumferential weld based on the observed shift in the KNPP surveillance weld. While it appears complicated, the expression above could be rewritten to show that it is merely the value of T_0 established for the KNPP RPV surveillance weld in the unirradiated condition plus the estimated shift in T_0 for the KNPP RPV circumferential weld based on the observed shift in the KNPP surveillance weld. The expression above is used, however, to parallel the licensee's intent of not "explicitly" using the T_0 values from unirradiated specimen testing in the calculation.

The value of $\Delta T_{0\text{-EOLE-ID-K-S}}$ is then calculated as:

[Eqn. 8] $$\Delta T_{0\text{-EOLE-ID-K-S}} = [\Delta T_{0\text{-K-S}} - (t_{IRR\text{-}RPV} - t_{IRR\text{-}K\text{-}S})] * (FF_{EOLE\text{-}ID} / FF_{K\text{-}S}) * (CF_{RPV} / CF_{K\text{-}S})$$

and it is this relationship which quantitatively adjusts the observed shift in T_0 from the testing of KNPP surveillance capsule S to the EOLE fluence, irradiation temperature, and best-estimate chemistry of the KNPP RPV circumferential weld. Although in this specific case no irradiation temperature difference exists between the surveillance capsule and the RPV, the $(t_{IRR\text{-}RPV} - t_{IRR\text{-}K\text{-}S})$ term enables a one degree shift per degree difference in irradiation temperature adjustment if such a difference existed. The $(FF_{EOLE\text{-}ID} / FF_{K\text{-}S})$ term adjusts for fluence difference between the peak, clad-to-base metal interface fluence for RPV circumferential weld and the fluence for KNPP surveillance capsule S. As noted before, this relies on the use of the "fluence factor" (FF) calculation from RG 1.99, Rev. 2 and thus, assumes that although the magnitudes may be different, the "shape" or "dependence" of the shift in T_0 with increasing fluence can be expressed by the same functional form as the shift in Charpy V-notch 30 ft-lb energy level. Likewise, the $(CF_{RPV} / CF_{K\text{-}S})$ term which adjusts for chemical compositional (i.e., radiation sensitivity) differences between the surveillance weld and the KNPP RPV circumferential weld is based upon the tabulated "chemistry factor" values from RG 1.99, Rev. 2. Using the information in Table 5, CF_{RPV} is determined from the best-estimate chemistry for the KNPP RPV circumferential weld and $CF_{K\text{-}S}$ is determined by the specific chemistry of the KNPP surveillance weld. Table 6 provides the fluences and FF values for all materials and conditions relevant to the evaluation of the KNPP RPV circumferential weld.

In summary, the NRC staff's approach to implementing adjustments to data acquired from the testing of surveillance welds to account for RPV conditions is fundamentally similar to that proposed by the licensee, yet somewhat more general. The NRC staff has concurred, based on observations made from an available data base of T_0 shift values (including both plate and weld materials), with the licensee's position that the use of the RG 1.99, Rev. 2 fluence function adequately describes the "dependence" of the shift in T_0 with increasing fluence in the absence of an embrittlement model specifically based on T_0 shift data.[28, 29] Further, characterization of material "irradiation sensitivity" based on CFs from RG 1.99 Rev. 2 for the purpose of scaling T_0 values from RPV surveillance weld testing to KNPP RPV circumferential properties was also found to be acceptable.

Additional discussion regarding use of the methodology described above to integrate multiple data points into the evaluation of the KNPP RPV circumferential weld at a specified condition will be presented in Section 1.3.5.

1.3.3 Assessment of Uncertainties and Margins

As noted, the ability to adequately determine the explicit margins to be applied when using a Master Curve-based methodology is a critical element for ensuring that RPV integrity will be maintained when the methodology is used. This topic also represents the major area of disagreement between the methodology accepted by the NRC staff and the one proposed by the licensee. The NRC staff has concluded that the margins which were suggested to exist in the licensee methodology are, in some cases, unfounded. In total, the NRC staff has concluded that the margins proposed by the licensee are inadequate to ensure that RPV integrity will be maintained when all sources of uncertainty identified in 10 CFR 50.61 are considered. Below, the NRC staff has provided its assessment of margins proposed by the licensee and the basis for the margins endorsed by the NRC staff.

1.3.3.1 Assessment of Implicit Margin in the Definition of RT_{T0}

Two sources of margin were cited to exist within the licensee methodology. The first was an "implicit" margin of 18 °F from the licensee's conclusion that the definition of RT_{T0} as (T_0 + 35 °F) was "more conservative" than RT_{NDT}-based approaches for positioning the ASME Code K_{IC} curve. The NRC staff rejects the licensee contention that only the data from plate HSST-02 (i.e., the lowest data in the original K_{IC} database) should be considered when determining what adder should be applied to T_0 to make RT_{T0} an acceptable replacement for RT_{NDT}. The ASME Code K_{IC} curve could only have been established as a "lower bound" curve given the existence of an extensive K_{IC} data base from many different RPV grade materials. That is, although the shape of the ASME Code K_{IC} curve may have been defined by the HSST-02 data, one can only have confidence in the lower bound nature of the ASME Code K_{IC} curve given the existence of the entire database.

Hence, the NRC staff concluded that to determine the appropriate adder to T_0, one must look at how RT_{T0} and RT_{NDT} position the ASME Code K_{IC} curve for each material from the original K_{IC} data base.[18] To integrate this information for the purpose of establishing an appropriate adder to T_0, the NRC staff reexamined a previously-published statistical analysis on this subject.[30] Reference 29 presented an analysis which first calculated the mean sum of squares distance between the data in the original K_{IC} data base and K_{IC} curve as indexed by RT_{NDT} for each material. Next, the analysis varied the adder to T_0 until the mean sum of squares distance between the data in the original K_{IC} data set and K_{IC} curve as indexed by RT_{T0} for each material produced the same value for mean sum of squares distance as with RT_{NDT}. By this method, it was concluded that an adder of 33 °F achieved this equality. The NRC staff considered this to be an acceptable analysis for comparing the "conservatism" inherent to each indexing parameter since it: (1) utilized all data from the original K_{IC} data base and (2) provided a "stable" interpretation which would likely be only minimally affected by the addition of new data to the K_{IC} data base. Analyses like that proposed by the licensee, based on only the small K_{IC} data set from the testing of plate HSST-02, could be subject to considerable instability if another RPV material were tested and found to be more limiting than plate HSST-02 and/or if more data from the testing of plate HSST-02 significantly changed the analysis. In addition, the NRC staff could not conclude, from the documentation in the ASME Code technical basis document, that the ASME Code group responsible for ASME Code Case N-629 considered there to be additional implicit margin on the order of 18 °F when the code case was approved.

To summarize, on the subject of additional, implicit margin in the definition of RT_{T0} relative to the use of RT_{NDT} in the current regulatory structure, the NRC staff concluded that, at most 2 °F of implicit margin existed (the difference between the ASME Code Case N-629 adder of 35 °F and the 33 °F adder acceptable to the NRC staff). The NRC staff disagrees with the licensee's contention that 18 °F of implicit margin exists and the NRC staff credits the 2 °F amount of additional, implicit margin in the methodology given in Appendix A.

1.3.3.2 Assessment of Explicit Margins to Account for Material and Fluence Uncertainties

As noted in the NRC staff's July 16, 1999, letter to the licensee, 10 CFR 50.61 requires that "explicit" margin shall be added, "to account for uncertainties in the values of $RT_{NDT(U)}$, copper and nickel contents, fluence, and the calculational procedures." The NRC staff concluded that the original the licensee proposal to only utilize the statistical uncertainty in the determination of T_0 from the testing of material from KNPP surveillance capsule S and Maine Yankee surveillance capsule A-35 was inadequate to address all of the sources of uncertainty noted above. The NRC staff agreed that the probabilistic assessments provided by the licensee along with their letter of February 4, 2000, were an appropriate mechanism for evaluating the effects of some sources of uncertainty. However, the NRC staff concluded that the analyses submitted by the licensee did not effectively address uncertainty in initial material fracture toughness and did not fully investigate the margin required to address uncertainties in the irradiation embrittlement behavior of the KNPP RPV circumferential weld. Hence, the NRC staff undertook to perform its own analysis of the "explicit" margin to be added to account for the all sources of uncertainty noted above, and the method and results of the NRC staff's analysis are discussed below.

First, the NRC staff examined those sources of uncertainty which would directly contribute to the uncertainty in the irradiation embrittlement behavior of the KNPP RPV circumferential weld. This included uncertainty in copper content, nickel content, and fluence. The NRC staff chose to establish mean values and uncertainties for two case studies, as shown in Table 7. Case 1 uses mean copper and nickel contents, and uncertainties (1σ level) in each, for weld wire heat 1P3571 based on information submitted by the Combustion Engineering Owners Group in response to NRC GL 92-01, Revision 1.[21, 22] Case 2 uses the same mean values and the same uncertainty in nickel content, but invokes a different uncertainty in copper content based on an assessment of the variability in copper from data for all CE copper-coated weld wire heats. The NRC staff concluded, based on the aforementioned data, that although mean copper contents may vary significantly from one CE copper-coated weld wire heat to another, consistency in the uncertainty in the mean is expected between such heats. Thus, the pooling of data from many such heats was acceptable for estimating the copper uncertainty, but not the mean copper value, for weld wire heat 1P3571. The best-estimate fluence was taken to be 4.7 x 10^{19} n/cm^2 (E > 1.0 MeV) at 51 EFPY from the licensee's February 4, 2000, submittal based on assuming an 85 percent capacity factor and an uncertainty of ±20 percent. Again, the mean values for each of these inputs would have some effect on the Monte Carlo analysis to assess overall uncertainty in irradiation embrittlement behavior, however, for this particular evaluation, they were of secondary importance since the mean values fell in regions where the behavior of the available embrittlement models are relatively "stable." All distributions in the analysis were assumed to be normal.

The result of the NRC staff's analysis showed that, depending on the level of truncation assumed for each input distribution (2σ, 3σ, none), slightly varying answers could be obtained. When the NRC staff analyzed Case 1, the calculated values for overall uncertainty at the 1σ level were between 29 °F and 33 °F. Using the reduced copper uncertainty in Case 2, the calculated values for overall uncertainty at the 1σ level were between 25 °F and 29 °F. The NRC staff noted that while any of the various values could be selected based on engineering judgment, it would be difficult to develop a definite case for the selection of one over another based solely on the information from this analysis. Therefore, as discussed below, additional considerations were incorporated to define a precise value to be used in the NRC staff's Master Curve-based methodology from the range of equally-acceptable values resulting from the Monte Carlo analysis. However, it should be made clear that this Monte Carlo-based approach, which correctly assesses the necessary margin based on the uncertainties associated with the KNPP RPV circumferential weld material (as opposed to "margin" evaluations derived solely from the analysis of available test data), is the only fundamentally acceptable basis available at this time for defining the necessary margin to address these uncertainties.

The NRC staff also noted that the value given in RG 1.99, Rev. 2, which is linked to addressing these same uncertainties, σ_Δ, has an accepted value of 28 °F, although the basis for this value of σ_Δ is not directly the product of a Monte Carlo-based evaluation.[23] Also, the methodologies of RG 1.99, Rev. 2 have already been utilized by both the licensee and the NRC staff as the basis for adjusting T_0 data from the KNPP and Maine Yankee surveillance welds to the chemistry and fluence of the KNPP RPV circumferential weld, hence, establishing a precedent for the consideration of information from RG 1.99, Rev. 2 in this analysis. In the absence of compelling evidence from the Monte Carlo-based analysis to alter the established value used to address copper, nickel, and fluence uncertainties, the NRC staff concluded that a value of 28 °F is acceptable for this purpose within the context of the NRC staff's Master Curve-based methodology as well. Given the parallels that will be developed with the margins methodology in RG 1.99, Rev. 2, this 28 °F value will be identified as $\sigma_{\Delta T0}$ in the remainder of this discussion.

The remaining issue to be addressed is the incorporation of margin to account for uncertainty in the initial fracture toughness properties of the KNPP RPV circumferential weld. Although, as discussed in Sections 1.3.1 and 1.3.2, the licensee proposed to utilize "direct measurement" of fracture toughness properties in the irradiated condition as the basis for their Master Curve-based methodology, actual test data was only derived from surveillance weld samples, not the RPV circumferential weld itself. The initial material properties of these "surrogate" surveillance weld samples cannot be demonstrated to be precisely the same as those of the RPV weld since no actual results exist from the testing of the RPV weld for comparison. In the case of the licensee submittal, this necessitates the incorporation of margins into the methodology to relate the data from these "surrogate" materials to the KNPP RPV circumferential weld. Information which relates the "surrogate" surveillance welds to the KNPP RPV circumferential weld (same welding flux, similar post-weld heat treatments, etc.) helps to establish the expected degree of initial property similarity of these "surrogates" to the RPV weld and the amount of margin required.

The NRC staff examined the existing data base of fracture toughness test results relevant to Master Curve evaluation for weld wire heats used by CE for fabricating RPVs. The NRC staff considered the fact that previous analyses to develop a generic unirradiated nil-ductility reference temperature concluded that welds manufactured from Linde weld fluxes 1092, 0124, and 0091 were sufficiently similar in their initial properties (and microstructures) to be grouped together. Hence, the initial NRC staff assumption was that at least observations of weld-to-weld variability of initial fracture toughness properties, if not the absolute fracture toughness values themselves, from welds made with these same weld fluxes would also constitute an analyzable population. The NRC staff identified CE weld wire heats (87986, 87984, 33A277, 1P3571, and tandem weld 20291/12008) for which a significant amount of fracture toughness data existed. All data from each weld wire heat was pooled and random sampling performed to generate a distribution of T_0 values for each weld wire heat. The distributions were assumed to be normal and a 1σ value of each distribution of T_0 values calculated. The results of this analysis are shown in Table 8. The NRC staff concluded that a bounding value of 14 °F could be established for uncertainty in the initial properties (henceforth referred to as σ_{IT0}) based on this analysis for the given CE weld wire heats and, further, that such value would also address uncertainties in the "calculational procedures" as required by 10 CFR 50.61. The NRC staff, however, recognizes that while this analysis is adequate to support the KNPP evaluation this topic area is one in which additional analyses and/or additional data may refine the value in the future.

This value of σ_{IT0} was then included in a square-root-sum-of-squares (SRSS) summation with $\sigma_{\Delta T0}$ to provide the complete "explicit" margin to be applied in the NRC staff's analysis.

In summary, the "explicit" margin, M, was calculated as:

[Eqn. 9] $$M = 2 * \sqrt{(\sigma_{IT0}^2 + \sigma_{\Delta T0}^2)} = 2 * \sqrt{(14^2 + 28^2)} = 62.5\ °F$$

This methodology for combining these two margin terms is consistent with the technical basis established in RG 1.99, Rev. 2 and 10 CFR 50.61. The multiplier of 2 is enforced to provide sufficient margin such that the final analysis is, given the assumptions above, interpreted to be bounding at the 2σ level on the expected material properties of the KNPP RPV circumferential weld. This level of conservatism is consistent with the current regulatory structure incorporated into 10 CFR 50.61.

1.3.4 Assessment of Bias in the Use of PCVN Specimens in Master Curve Testing

With respect to the Master Curve methodology, issues regarding the use of small specimen testing, adequate constraint, and the potential for non-conservative bias in test results arose as far back as the passage of ASTM Standard E 1921-97. To summarize the issue, if the size and geometry of the specimens tested are insufficient to maintain an adequate level of constraint at the crack tip, excessive yielding (plasticity) may result. This excessive yielding may be manifest as an apparent increase in load carrying capacity (due to the work absorbed in plastically deforming the material) and thus, an overestimation of the fracture toughness of the material. To mitigate the potential for such effects, a constraint limit for the purpose of data censoring was established in ASTM E 1921-97 for Master Curve-related testing.

In Figure 3, "T_0 PC-CVN" is the T_0 value determined for a particular material based upon the testing of PCVN specimen sets per ASTM E1921-97 (including the censoring limit) and "T_0 Ref." is the T_0 value calculated for the same material from larger specimens. Thus, the ordinate axis in Figure 3 represents the difference in calculated values of T_0 with negative values indicative of a potentially non-conservative bias in the T_0 value determined from the PCVN data set. This T_0 differential was then plotted relative to the constraint parameter, M_0, which is the non-dimensional deformation level associated with K_0, the 1T equivalent K_{JC} value associated with the 62.3 percent cumulative failure probability from the data derived from the

PCVN testing of the material. A large M_0 value means that the PCVN data set for the material exhibited a lower load carrying capacity, a correspondingly higher degree of constraint, and less potential for "bias" when compared to large specimen test results. Each data point shown represents a different material and the points shown are limited to those materials for whom a "T_0 Ref." value could be determined from sets of 1T-CT or larger test specimens. The NRC staff chose to impose this restriction to ensure that a clear constraint differential could exist between PCVN data set and the "reference" data set used to determine "T_0 Ref." Table 9 provides the value of the M_0 constraint parameter calculated for each irradiated and unirradiated data set relevant to the KNPP evaluation.

From Figure 3, the NRC staff concluded that although a statistically significant bias of 8.5 °F was evident in the data, no defined trend with M_0 was able to be resolved. The NRC staff also observed other data points for which "T_0 Ref." values could be calculated from specimens as small as 0.5T-CTs. With the inclusion of this additional data, a trend of increasing PCVN bias with decreasing M_0 may have been resolvable, but the complication of including data wherein the size (and thus the expected constraint) of the specimens used to define "T_0 Ref." was nearly the same size as the PCVN specimens would have made any such conclusions highly speculative. It can, however, be noted that with regard to addressing bias related to the licensee application, either interpretation would have yielded the same net effect in the NRC staff's overall methodology.

The NRC staff acknowledges that the lack of a definable trend in Figure 3 calls into question whether the observed bias from PCVN test results can be simply addressed as a matter of specimen constraint. Other theories have been postulated, including consideration of specimen geometry and T-stress, to explain the observed differences in PCVN and CT specimen results. The NRC staff recognizes that additional research in this area may help to better define this issue and modify the conclusions of this SE. However, the NRC staff concludes, at this time, that the assumption of a 8.5 °F bias in PCVN-based T_0 values relative to values obtained with larger size CT specimens, to be applied to each unirradiated and irradiated PCVN data set in the licensee submittal, is adequate to address this potential source of non-conservatism in the NRC staff's methodology as developed in Appendix A to this SE.

The methodology developed by the NRC staff, however, includes sufficient flexibility to incorporate specific bias values for each of the four PCVN data sets relevant to this evaluation of the KNPP RPV circumferential weld should additional information demonstrate that different bias values are appropriate. To provide this flexibility, each of these four data sets must be addressed separately since the effect of bias on the evaluation of the shift in T_0 must be assessed given the NRC staff's methodology discussed in Section 1.3.2 above. As such, the effect of "accounting for bias in PCVN data" in the NRC staff's methodology cannot be easily discussed as a stand alone item, but must instead be presented as it is integrated into achieving results from the overall NRC staff methodology. This integration of bias into the NRC staff's methodology is addressed in Appendix A and discussed further in Section 1.3.5 below.

1.3.5 <u>Overall NRC Staff Methodology for KNPP Master Curve-Based Evaluation</u>

This section brings together aspects of the NRC staff's methodology discussed in Section 1.3.2, the assessment of margins discussed in Section 1.3.3, and evaluation of PCVN testing bias covered in Section 1.3.4. Again, the general procedure established by the NRC staff is discussed below through an example, with a more condensed, mathematical documentation of the methodology provided in Appendix A.

Section 1.3.2 described the NRC staff's methodology for determining the two estimates of the T_0 value for the KNPP RPV circumferential weld (at a given through-wall location and given number of EFPY of operation) based on the data from the testing of material from KNPP surveillance capsule S and Maine Yankee surveillance capsule A-35. For the KNPP RPV circumferential weld material properties at the clad-to-base metal interface at EOLE conditions, these estimates were called $T_{0\text{-EOLE-ID-K-S}}$ and $T_{0\text{-EOLE-ID-MY-A35}}$, respectively. Correspondingly, two estimates of a T_0-based PTS reference temperature to replace RT_{PTS} can be determined from these estimates of T_0 and can be called $ART_{T0\text{-EOLE-ID-K-S}}$ and $ART_{T0\text{-EOLE-ID-MY-A35}}$, respectively. These estimates for a T_0-based reference temperature are determined from the use of ASME Code Case N-629, plus the consideration of margin and PCVN testing bias and are determined as:

[Eqn. 10] $$ART_{T0\text{-EOLE-ID-K-S}} = T_{0\text{-EOLE-ID-K-S}} + 33\ °F + 62.5\ °F + B_{PCVN\text{-K-S-U}}$$

[Eqn. 11] $$ART_{T0\text{-EOLE-ID-MY-A35}} = T_{0\text{-EOLE-ID-MY-A35}} + 33\ °F + 62.5\ °F + B_{PCVN\text{-MY-A35-U}}$$

where the 33 °F value comes from the 35 °F adder given in ASME Code Case N-629 minus the 2 °F of implicit margin discussed in Section 1.3.2, 62.5 °F is the margin term from Section 1.3.3, and B values are adjustments added to account for PCVN testing bias. It should be noted that the 33 °F and 62.5 °F values are invariant and would apply to any KNPP RPV integrity evaluation (i.e., determining appropriate PTS or P-T limit reference temperatures at EOL or EOLE conditions), whereas the bias term (as discussed below) and the T_0 estimates (as discussed in Section 1.3.2) from the two surveillance capsules may change based on the adjustments required to evaluate a specific RPV condition and through-wall location.

Working through how the bias in the T_0 values determined for each of the four relevant data sets from the KNPP submittal (the unirradiated and irradiated PCVNs from the KNPP surveillance weld and the unirradiated and irradiated PCVNs from the Maine Yankee surveillance weld) affects the overall methodology:

[Eqn. 12] $$B_{PCVN\text{-K-S-U}} = B_{PCVN\text{-K-U}} + [(FF_{X\text{-}Y} / FF_{K\text{-}S}) * (CF_{RPV} / CF_{K\text{-}S}) * (B_{PCVN\text{-K-S}} - B_{PCVN\text{-K-U}})]$$

[Eqn. 13] $$B_{PCVN\text{-MY-A35-U}} = B_{PCVN\text{-MY-U}} + [(FF_{X\text{-}Y} / FF_{MY\text{-}A35}) * (CF_{RPV} / CF_{MY\text{-}A35}) * (B_{PCVN\text{-MY-A35}} - B_{PCVN\text{-MY-U}})]$$

where $B_{PCVN\text{-K-U}}$ is the bias associated with the unirradiated PCVN data from the KNPP surveillance weld, $B_{PCVN\text{-MY-U}}$ is the bias associated with the unirradiated PCVN data from the Maine Yankee surveillance weld, $B_{PCVN\text{-K-S}}$ is the bias associated with the irradiated PCVN specimens from KNPP surveillance capsule S, and $B_{PCVN\text{-MY-A35}}$ is the bias associated with the irradiated PCVN specimens from MY surveillance capsule A-35. Again, these representations provide the general form for determining $B_{PCVN\text{-K-S-U}}$ and $B_{PCVN\text{-MY-A35-U}}$ if different bias values are established for each of the four PCVN data sets relevant to this evaluation. The FF and CF ratios are as discussed in Section 1.3.2 and must be incorporated since the bias in each data set affects how the shifts in T_0 for the KNPP surveillance weld and the Maine Yankee surveillance weld are applied to the evaluation of PTS for the KNPP RPV circumferential beltline weld at EOLE. For the present evaluation, the use of a constant 8.5 °F bias value for each of the PCVN data sets in this evaluation results in $B_{PCVN\text{-K-S-U}}$ and $B_{PCVN\text{-MY-A35-U}}$ both being calculated to be 8.5 °F as well.

Considering Eqns. 10 and 11, the two estimates of a T_0-based PTS reference temperature to replace RT_{PTS} for EOLE conditions ($ART_{T0\text{-EOLE-ID}}$ to be consistent with the terminology), from the NRC staff's methodology can be determined to be

$ART_{T0\text{-}EOLE\text{-}ID\text{-}K\text{-}S}$ = 298.5 °F and $ART_{T0\text{-}EOLE\text{-}ID\text{-}MY\text{-}A35}$ = 277.5 °F. The best-estimate value for $ART_{T0\text{-}EOLE\text{-}ID}$ is then the average of these two, or 288 °F. As additional surveillance capsules are tested, additional estimates of $ART_{T0\text{-}EOLE\text{-}ID}$ will be obtained and will be averaged with the above values to give an updated best-estimate for $ART_{T0\text{-}EOLE\text{-}ID.}$

Similar calculations have been completed by the NRC staff to evaluate the PTS reference temperature at EOL for the KNPP RPV circumferential weld and the proposed KNPP P-T limit amendment. The results of all these calculations are discussed further in Section 1.4 below. Table 10 also provides a comparison of similar values which can be extracted from, if they do not readily fall out of, the NRC and the licensee methodologies. The information in Table 10 provides a means of comparing the implicit or explicit components which contribute to the ART values determined by the NRC and the licensee for the RPV circumferential weld at the clad-to-base metal interface for EOL and EOLE conditions.

1.4 NRC Staff Results for PTS and P-T Limits Assessments

In addition to the example discussed in Section 1.3.5 which calculated $ART_{T0\text{-}EOLE\text{-}ID}$ utilizing the methodology acceptable to the NRC staff, the NRC staff has also determined values of $ART_{T0\text{-}EOL\text{-}ID,}$ $ART_{T0\text{-}EOL\text{-}1/4T}$, and $ART_{T0\text{-}EOL\text{-}3/4T}$ which are important to the evaluation of PTS and P-T limits for the KNPP RPV at the end of its current operating license. These values were determined using the same methodology as discussed in Section 1.3.2, Section 1.3.5, and Appendix A, with only the appropriate modifications to reflect the fluence level of interest. The NRC staff concurred with the licensee's use of the attenuation function from RG 1.99, Rev. 2 for the purpose of determining fluences at the 1/4T and 3/4T locations based on the direct calculation of the clad-to-base metal (E > 1.0 MeV) fluence at EOL conditions.

All relevant information from the licensee submittals for the determination of $ART_{T0\text{-}EOL\text{-}ID}$, $ART_{T0\text{-}EOL\text{-}1/4T}$, and $ART_{T0\text{-}EOL\text{-}3/4T}$ has been given in Tables 4 through 8. Again, for each of these parameters, two estimates of their value would be established, one based on the fracture toughness data from the testing of PCVN specimens from KNPP surveillance capsule S and the other based on fracture toughness data from the testing of PCVN specimens from Maine Yankee surveillance capsule A-35. The two estimates for each parameter were then averaged to provide the best-estimate value for each. The NRC staff's best-estimate values for $ART_{T0\text{-}EOLE\text{-}ID}$, $ART_{T0\text{-}EOL\text{-}ID}$, $ART_{T0\text{-}EOL\text{-}1/4T}$, and $ART_{T0\text{-}EOL\text{-}3/4T}$ are summarized in Table 11.

Based on these results, the NRC staff reached the following conclusions. First, the value of $ART_{T0\text{-}EOL\text{-}ID}$, which replaces the calculated value of RT_{PTS} at EOL conditions, was 271 °F. This value was below the screening criteria given in 10 CFR 50.61 and the methodology developed by the NRC staff makes the determination of $ART_{T0\text{-}EOL\text{-}ID}$ consistent with the bases for the screening criteria. Therefore, this evaluation supported continued operation of the KNPP RPV through EOL. In addition, the values of $ART_{T0\text{-}EOL\text{-}1/4T}$ and $ART_{T0\text{-}EOL\text{-}3/4T}$ were 247 °F and 196 °F, respectively. These values did not support the revised cooldown P-T limit curve (shown in Figure 2) submitted by the licensee, which was based on the licensee's determination of $ART_{T0\text{-}EOL\text{-}1/4T}$, and $ART_{T0\text{-}EOL\text{-}3/4T}$ as 210 °F and 157 °F, respectively. The values calculated for $ART_{T0\text{-}EOL\text{-}1/4T}$ and $ART_{T0\text{-}EOL\text{-}3/4T}$ by the NRC staff indicate that at the higher pressure and temperature portion of the cooldown curves the KNPP RPV circumferential weld will continue to be the limiting material. Hence, the composite nature of the current KNPP P-T limit curves (shown in Figure 1) must be maintained. It should be noted, however, that all of the aforementioned values must be recalculated when additional surveillance data or other information is acquired with could affect the conclusions of this SE.

However, the NRC staff did note that in the NRC staff SE which granted approval for the current KNPP P-T limits, a restriction on their validity to 28 EFPY of operation was imposed because the NRC staff calculated the cooldown curves in Figure 1 to be 5 to 7 °F non-conservative at 33 EFPY.[31] This was based on the NRC staff's conclusion that the EOL 1/4T and 3/4T reference temperatures for the KNPP RPV circumferential weld (under the Charpy V-notch and drop weight-based methodology) would be 256 °F and 210 °F, respectively. Reestablishing the EOL 1/4T and 3/4T reference temperatures as 247 °F and 196 °F, respectively, using the NRC staff's Master Curve-based approach, "corrects" for this 5 to 7 °F non-conservatism in the current KNPP cooldown P-T limit curves and would justify, if requested by the licensee, their use through 33 EFPY of operation. The NRC staff's prior conclusion, that the other current KNPP P-T limit curves (e.g., the heatup limit curves, which were based on the material properties of the most limiting KNPP beltline forging and the limiting RPV closure flange material) would be acceptable through 33 EFPY, remains valid.

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Attachment: Appendix A

Principal Contributor: Matthew Mitchell

Date: February 21, 2001

Table 1 - Fracture Toughness Data Obtained from the Testing of Unirradiated KNPP and Maine Yankee Surveillance Weld Material

Specimen	K_{JC} (ksi√in)	$K_{JC(1T)}$ (ksi√in)
KNPP PCVN specimens tested at -200 °F		
WPS201	108.0	89.4
WPS202	61.8	52.8
WPS205	67.4	57.2
WPS206	61.3	52.3
WPS207	66.1	56.1
WPS208	79.5	66.8
WPS209	79.1	66.5
WPS210	81.1	68.0
Reconstituted KNPP PCVN specimens tested at -200 °F		
RKW1	91.0	75.9
RKW3	77.4	65.1
RKW6	59.1	50.5
RKW7	73.7	62.2
RKW8	91.0	75.9
RKW10	102.4	84.9
RKW11	61.7	52.7
KNPP 0.5T-CT specimens tested at -187 °F		
WPS101	86.2	75.4
WPS102	63.7	56.5
WPS103	85.5	74.8
WPS104	71.8	63.3
WPS105	72.3	63.7
WPS106	48.6	43.8
WPS107	67.4	59.6
Maine Yankee PCVN specimens tested at -200 °F		
CO4-4	62.0	52.9
CO4-5	67.2	57.0
CO4-2	88.0	73.5
CO4-7	88.4	73.7
CO4-8	90.4	75.4
CO4-3	94.5	78.7
CO4-6	95.5	79.4

Table 2 - Fracture Toughness Data Obtained from the Testing of Irradiated KNPP Surveillance Weld Material from KNPP Surveillance Capsule S

Specimen	K_{JC} (ksi√in)	$K_{JC(1T)}$ (ksi√in)
Reconstituted KNPP PCVN specimens tested at 136 °F		
W24	97.9	81.3
W19	68.1	57.7
H17	131.7	108.1
H18	119.3	98.3
W23	124.4	102.3
H20	144.4*	114.8
H19	78.0	65.6
W17	100.6	83.5
H21	103.8	86.1
Reconstituted KNPP PCVN specimens tested at 59 °F		
W21	53.3	46.4
W20	59.2	51.0
W22	64.5	55.2
1X-WOL specimens tested at 136 °F		
W5	70.4	70.4
W6	55.9	55.9

* - Exceed the K_{JC} limit of ASTM E1921-97 and was censored accordingly.

Table 3 - Fracture Toughness Data Obtained from the Testing of Irradiated Maine Yankee Surveillance Weld Material from Maine Yankee Surveillance Capsule A-35

Specimen	K_{JC} (ksi√in)	$K_{JC(1T)}$ (ksi√in)
Reconstituted Maine Yankee PCVN specimens tested at 210 °F		
322	72.6	61.3
36a	54.7	47.1
313	95.3	79.3
37la	152.0*	124.2
33u	65.6	55.8
375	78.4	65.9
37lb	76.0	64.0
37ua	100.8	83.6
H21	103.8	86.1

* - Exceed the K_{JC} limit of ASTM E1921-97 and was censored accordingly.

Table 4 - T_0 Values Determined by the Licensee from Various Data Sets Given in Tables 1 through 3

Data Sets	$K_{JC(1T)median}$ (ksi√in)	Test Temp. (°F)	T_0 (°F) per ASTM E1921-97 (Single Temperature Methodology)	Combined T_0 Values Based on Multi-Temperature Methodology (°F)
KNPP Unirradiated 0.5T-CTs	62.6	-187	-129	-144
KNPP Unirradiated PCVNs	64.2	-200	-148	
KNPP Reconstituted Unirradiated PCVNs	66.6	-200	-154	
Maine Yankee Unirradiated PCVNs	68.3	-200	-158	-158
KNPP Surv. Capsule S Irradiated PCVNs	100.2	136	136	148*
Maine Yankee Surv. Capsule A-35 Irradiated PCVNs	77.2	210	223**	223**

* This value includes the data from the testing of 1X-WOL specimens at 136 °F.

** This corrected value was provided in the licensee letter dated September 26, 2000.[12] The original value cited by the licensee, and incorporated into the discussion in Section 3.0, was 232 °F.

Table 5 - Chemical Compositions and Chemistry Factors for the KNPP Surveillance Weld, the Maine Yankee Surveillance Weld, and the KNPP RPV Circumferential Weld

Material	Copper Content	Nickel Content	CF from RG 1.99 Rev. 2 Tables (°F)	CF based on Licensee Interpretation of Fracture Toughness Data (°F)
KNPP Surveillance Weld	0.219	0.724	187.2	222
Maine Yankee Surveillance Weld	0.351	0.771	237.2	271
KNPP RPV Circumferential Weld	0.287	0.756	214.0	248

Table 6 - Fluences and Fluence Factors for Specific Surveillance Capsule and RPV Circumferential Weld Locations and Conditions

Item	Operating Time	Through-Wall Location	Effective Fluence Accepted by NRC Staff (in n/cm^2, E > 1.0 MeV)	Fluence Factor
KNPP Surveillance Capsule S	Not Applicable	Not Applicable	3.36×10^{19} *	1.32
Maine Yankee Surveillance Capsule A-35	Not Applicable	Not Applicable	6.11×10^{19} *	1.44
KNPP RPV Circumferential Weld	End of Licence (33 EFPY)	Clad-to-Base Metal Interface	3.34×10^{19} **	1.32
KNPP RPV Circumferential Weld	End of Licence (33 EFPY)	1/4T Depth	2.26×10^{19} **	1.22
KNPP RPV Circumferential Weld	End of Licence (33 EFPY)	3/4T Depth	1.04×10^{19} **	1.01
KNPP RPV Circumferential Weld	End of Extended Licence (51 EFPY)	Clad-to-Base Metal Interface	4.7×10^{19} ***	1.39

* Value from WCAP-14279, Revision 1 (Reference 5).
** Value from WCAP-14278, Revision 1 (Reference 4).
*** Value from the licensee letter dated February 4, 2000 (Reference 10).

Table 7 - Input Parameters Chosen for Two NRC Staff Monte Carlo Case Studies to Assess Margin Value to be Applied to the KNPP Evaluation

Case	Mean Copper Content	Mean Nickel Content	1σ Level Uncertainty in Copper	1σ Level Uncertainty in Nickel	Fluence Distribution
1	0.287	0.756	0.072	0.042	$4.7 \times 10^{19} \pm 20$ percent
2	0.287	0.756	0.05	0.042	$4.7 \times 10^{19} \pm 20$ percent

Table 8 - Results of NRC Staff Monte Carlo-based Analysis of the Variability in Unirradiated T_0 for Combustion Engineering RPV Weld Wire Heats

Combustion Engineering Weld Wire Heat/Heats	Weld Flux	1σ Uncertainty in Unirradiated T_0 from Monte Carlo Simulation (in °F)
20291/12008 **	Linde 1092	14.0
1P3571*	Linde 1092	10.8
87986	Linde 0124	9.6
87984	Linde 0124	13.2
33A277	Linde 0091	13.3

* Weld wire heat found in the KNPP RPV Circumferential weld.
** Limiting weld wire heat on which the NRC staff's uncertainty in T_0 for the KNPP evaluation is based.

Table 9 - Constraint Parameter M_0 and Bias Value Associated with Relevant KNPP and Maine Yankee Surveillance Weld PCVN Data Sets

Data Set	Constraint Parameter M_0	Bias Value Assumed in NRC Staff Evaluation (in °F)
Unirradiated KNPP Surveillance Weld PCVNs	121	8.5
Unirradiated Maine Yankee Surveillance Weld PCVNs	111	8.5
KNPP Capsule S Irradiated Surveillance Weld PCVNs	61	8.5
Maine Yankee Capsule A-35 Irradiated Surveillance Weld PCVNs	81	8.5

Table 10 - Comparison of Implicit and Explicit Components Used to Determine ART Values for the KNPP RPV Circumferential Weld at the Clad-to-Base Metal Interface Via the NRC and the Licensee Methodologies

	At EOL Conditions		At EOLE Conditions[9]	
	NRC	Licensee	NRC	Licensee
T_0[1]	167 °F[2]	183 °F[3]	184 °F[2]	190 °F[4]
RT_{T0}	T_0 + 33 °F[5]	T_0 + 35 °F[6]	T_0 + 33 °F	T_0 + 35 °F
Explicit Margin	62.5 °F	16 °F	62.5 °F	24 °F
PCVN Bias	8.5 °F[7]	0 °F[8]	8.5 °F	0 °F
ART_{T0}	271 °F	234 °F	288 °F	249 °F

[1] "T_0" in this table refers to the estimated value of T_0 for the RPV weld at the specified condition after all chemistry and fluence adjustments were made to the data sets of interest.

[2] Although this value is not explicitly calculated in the NRC methodology, it represents the "average" T_0 which would be calculated from the KNPP and Maine Yankee PCVN data using the NRC methodology.

[3] Value based on all KNPP surveillance weld fracture toughness data alone.

[4] Value based on all Maine Yankee surveillance weld fracture toughness data alone.

[5] Based on ASME Code Case N-629 definition of RT_{T0} with 2 °F of implicit margin removed.

[6] The licensee claims that this relationship contains 18 °F of implicit margin relative to the current impact test-based approach.

[7] As with note [1], "average" bias adjustment applied to the KNPP and Maine Yankee surveillance data.

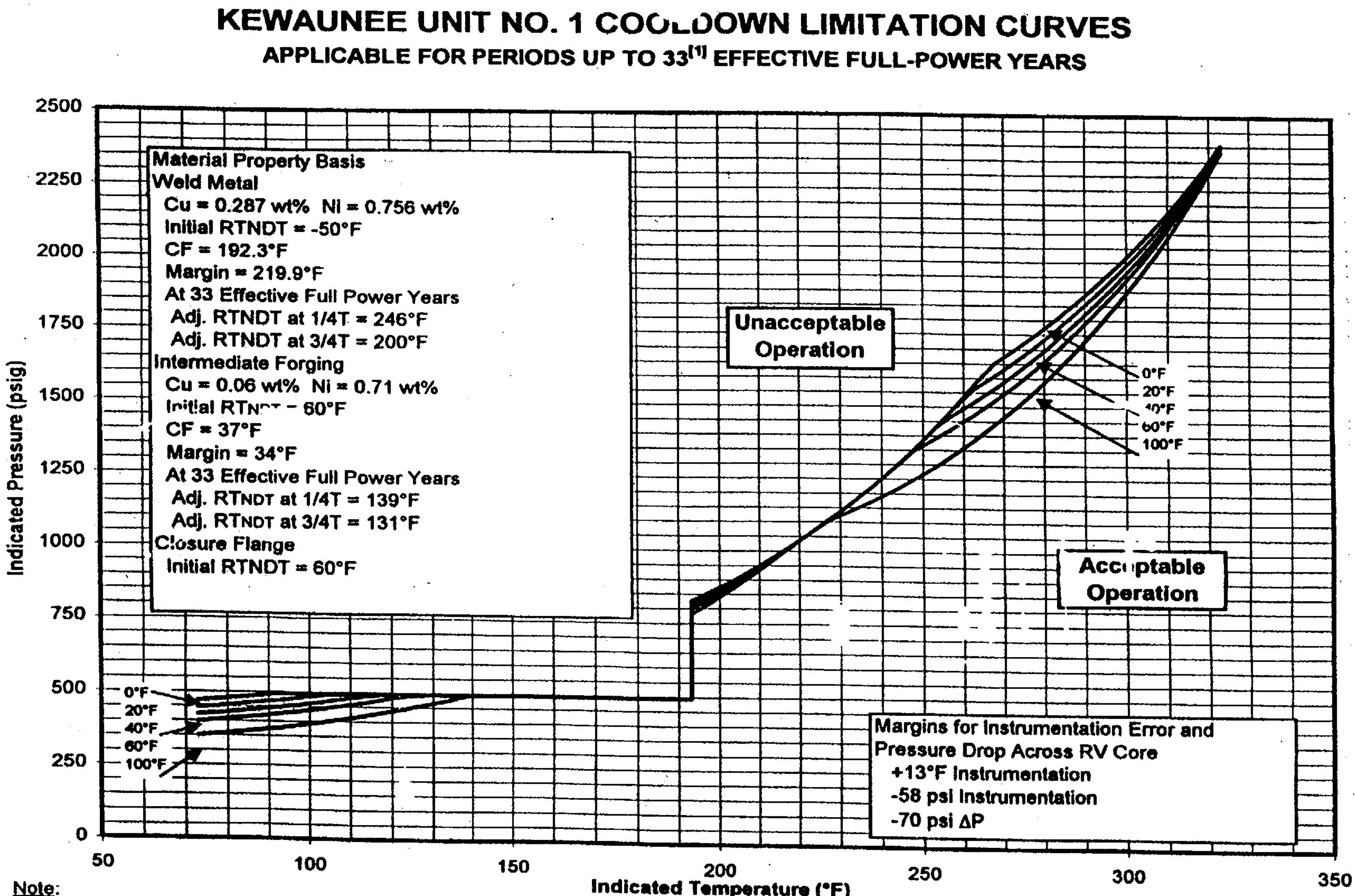
[8] The licensee claimed that no bias term was required for their methodology, but noted that a 4 °F bias term might be necessary for the NRC methodology which is based on only the available PCVN fracture toughness test data.

[9] The EOLE fluence chosen by the licensee was 5.1 x 10^{19} n/cm^2 based on assuming a conservative future capacity factor of 97 percent. The EOLE fluence chosen by the NRC was 4.7 x 10^{19} n/cm^2 based on a 85 percent future capacity factor.

Table 11 - NRC Staff Best-Estimate Values for KNPP RPV Circumferential Weld Integrity Evaluation Indexing Parameters

Parameter	Application	NRC Staff Value
$ART_{T0\text{-}EOL\text{-}1/4T}$	P-T Limit Determination	247 °F
$ART_{T0\text{-}EOL\text{-}3/4T}$	P-T Limit Determination	196 °F
$ART_{T0\text{-}EOL\text{-}ID}$	PTS Evaluation at EOL	271 °F
$ART_{T0\text{-}EOLE\text{-}ID}$	PTS Evaluation at EOLE	288 °F

Figure 1 - Current KNPP RPV Cooldown P-T Limit Curves Through 28 EFPY



Note:
[1] Although the curves were developed for 33 EFPY, they are limited to 28 EFPY (corresponding to the end of cycle 28) by WPSC Letter NRC-99-017.

Figure 2 - Proposed KNPP RPV Cooldown P-T Limit Curves Through 33 EFPY

KEWAUNEE UNIT NO. 1 COOLDOWN LIMITATION CURVES

APPLICABLE FOR PERIODS UP TO 33 EFFECTIVE FULL-POWER YEARS

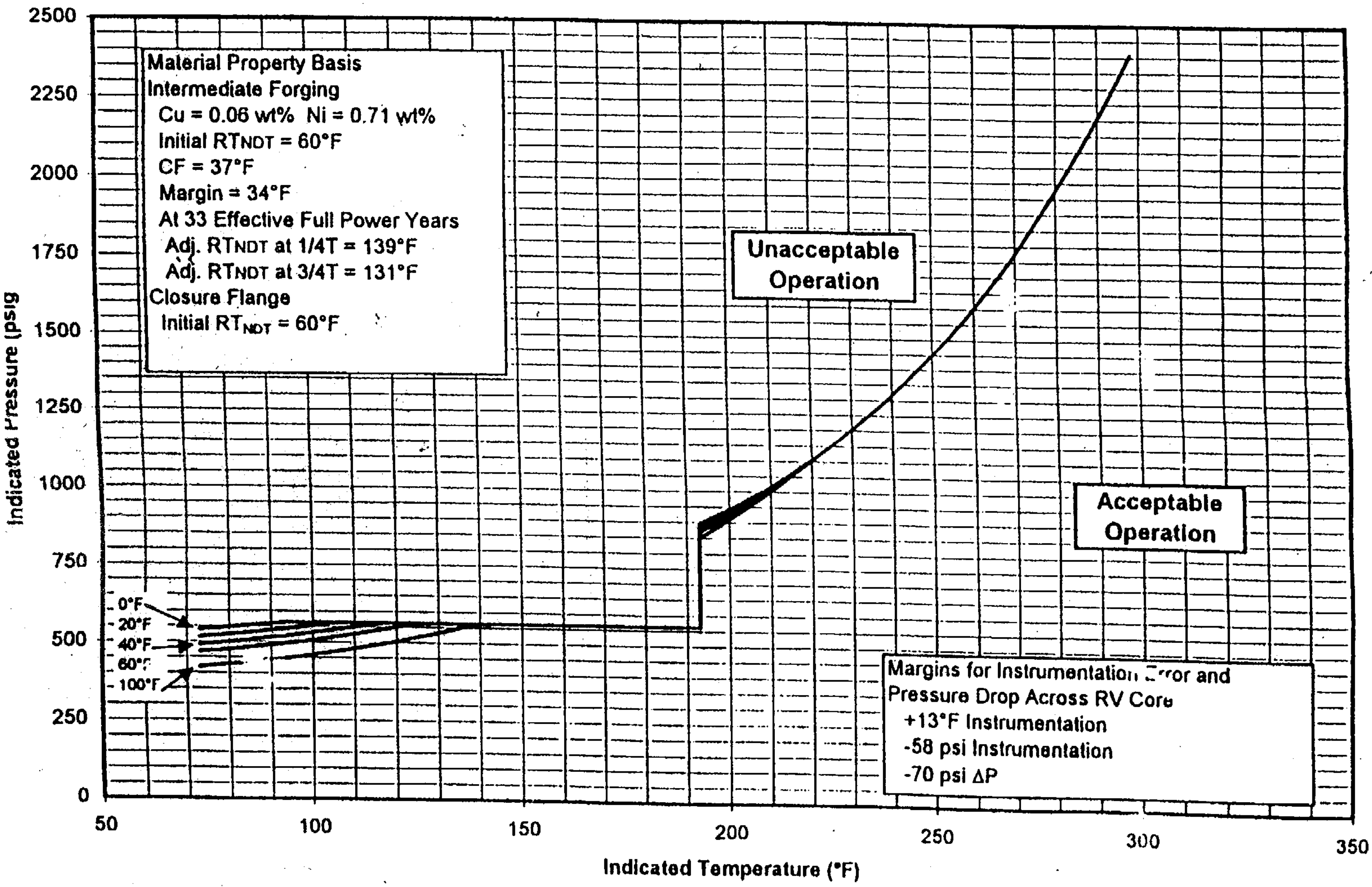
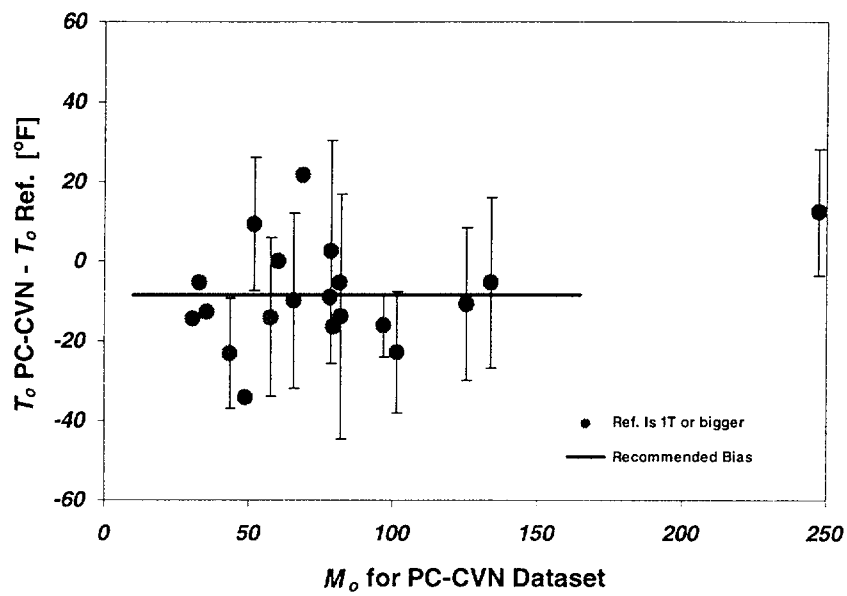


Figure 3 - Plot of Available Data Sets Containing Both PCVN and 1T-CT or Larger Data to Estimate the Bias in PCVN T_0 Results as a (Potential) Function of the Constraint Parameter, M_0 for the PCVN data set.



APPENDIX A

NRC Staff-Approved Methodology for the Application of PCVN Fracture Toughness Data for the Evaluation of the KNPP RPV Circumferential Weld

The methodology of this Appendix applies the fundamental data and calculational relationships given above for the purpose of KNPP RPV integrity evaluations. To do so, an index parameter relevant to the integrity evaluation being performed must be specified (for example, in a pressure-temperature limit evaluation, the material reference temperature at the 1/4T depth at EOL, $ART_{T0(EOL\ 1/4T)}$). Two estimates of the index parameter are then determined. The first estimate (from Calculation #1) is based on the data acquired from the testing of Maine Yankee Surveillance Capsule A-35 material. The second estimate (from Calculation #2) is based on the data acquired from the testing of KNPP Surveillance Capsule S material. These two estimates are then averaged to provide the best-estimate of the index parameter. In the methodology which follows, a generic "index parameter" is defined, $ART_{T0\text{-}X\text{-}Y}$, corresponding to a generic condition of interest at "operating time X" and KNPP RPV circumferential weld "through-wall location Y."

When additional, irradiated fracture toughness data is obtained as part of the KNPP surveillance program, an additional entry must be made under the "Fundamental Data" heading similar to those in items (1) and (2) below. This data will provide the basis from obtaining a third estimate of any relevant index parameter, and all three estimates will be averaged to provide the best-estimate of the index parameter.

Fundamental Data

(1) Maine Yankee Surveillance Capsule A-35, PCVN Surveillance Weld Samples

Unirradiated T_0 = -158 °F

Fluence = 6.11×10^{19} n/cm^2 (which corresponds to a $FF_{MY\text{-}A35}$ = 1.44 from RG 1.99, Rev. 2)

Irradiated $T_0 = T_{0\text{-}MY\text{-}A35}$ = 223 °F

$\Delta T_{0\text{-}MY\text{-}A35}$ = (223 °F - (-158 °F)) = 381 °F

$CF_{MY\text{-}A35}$ = 237.2 °F (0.351 % Cu, 0.771 % Ni, based on RG 1.99, Rev. 2 Tables)

$t_{irr\text{-}MY\text{-}A35}$ = The irradiation temperature of Maine Yankee Surveillance Capsule A-35 = 532 °F

$B_{PCVN\text{-}MY\text{-}U}$ = bias associated with unirradiated Maine Yankee surv. weld PCVN data = 8.5 °F

$B_{PCVN\text{-}MY\text{-}A35}$ = bias associated with irradiated Maine Yankee Surv. Capsule A-35 PCVN data = 8.5 °F

Fundamental Data (Continued)

(2) KNPP Surveillance Capsule S, PCVN Surveillance Weld Samples

Unirradiated T_0 = -151 °F (average of -154 and -148 from whole and reconstituted PCVNs)

Fluence = 3.36 x 10^{19} n/cm^2 (which corresponds to a $FF_{K\text{-}S}$ = 1.32)

Irradiated T_0 = $T_{0\text{-}K\text{-}S}$ = 136 °F

$\Delta T_{0\text{-}K\text{-}S}$ = (136 °F - (-151 °F)) = 287 °F

$CF_{K\text{-}S}$ = 187.2 °F (0.219 % Cu, 0.724 % Ni, based on RG 1.99, Rev. 2 Tables)

$t_{irr\text{-}K\text{-}S}$ = The irradiation temperature of KNPP Surveillance Capsule S = 532 °F

$B_{PCVN\text{-}K\text{-}U}$ = bias associated with unirradiated KNPP surveillance weld PCVN data = 8.5 °F

$B_{PCVN\text{-}K\text{-}S}$ = bias associated with irradiated KNPP Surveillance Capsule S PCVN data = 8.5 °F

(3) KNPP RPV Circumferential Weld

EOL Clad-to-Base Metal Interface Fluence = 3.34 x 10^{19} n/cm^2 (which corresponds to a FF = 1.32)

EOL 1/4T Depth Effective Fluence = 2.26 x 10^{19} n/cm^2 (which corresponds to a FF = 1.22)

EOL 3/4T Depth Effective Fluence = 1.04 x 10^{19} n/cm^2 (which corresponds to a FF = 1.01)

EOLE Clad-to-Base Metal Interface Fluence = 4.7 x 10^{19} n/cm^2 (which corresponds to a FF = 1.39)

CF_{RPV} = 214.0 °F (0.287 % Cu, 0.756 % Ni, based on RG 1.99, Rev. 2)

$t_{irr\text{-}RPV}$ = The irradiation temperature of the KNPP RPV = 532 °F

Fundamental Calculational Relationships

$RT_{T0} = T_0 + 33$ °F (with 2 °F implicit margin already removed to reduce the 35 °F adder of ASME Code Case N-629 to 33 °F)

$$\text{Margin} = M = 2\sqrt{(\sigma_{IT0}^2 + \sigma_{\Delta T0}^2)} = 2\sqrt{(14^2 + 28^2)} = 62.5\ °F$$

$$T_{0\text{-RPV-SURV CAPSULE}} = T_{0\text{-SURV CAPSULE}} - (\Delta T_{0\text{-SURV CAPSULE}} - \Delta T_{0\text{-RPV-SURV CAPSULE}})$$

$T_{0\text{-RPV-SURV CAPSULE}}$ = the T_0 estimate for the RPV material based on data from a particular surveillance capsule

$T_{0\text{-SURV CAPSULE}}$ = the T_0 value obtained from the testing of material from a particular surveillance capsule

$\Delta T_{0\text{-SURV CAPSULE}}$ = the shift in T_0 observed by comparing the results of testing performed on unirradiated material and material from a particular surveillance capsule

$\Delta T_{0\text{-RPV-SURV CAPSULE}}$ = the estimated shift in T_0 for the RPV material based on comparing the results of testing performed on unirradiated material and material from a particular surveillance capsule, and adjusting for fluence and chemistry differences

$$ART_{T0\text{-RPV-SURV CAPSULE}} = T_{0\text{-RPV-SURV CAPSULE}} + 33\ °F + M + B_{PCVN\text{-MY-A35-U}}$$

$ART_{T0\text{-RPV-SURV CAPSULE}}$ = the adjusted reference temperature for the RPV material based on data from a particular surveillance capsule

$B_{PCVN\text{-RPV-SURV CAPSULE}}$ = the PCVN bias term to be applied as part of the RPV evaluation based on the use of PCVN data from a particular surveillance capsule

$$\text{Best Estimate } ART_{T0\text{-RPV}} = \sum_{i=1}^{n} (ART_{T0\text{-RPV-SURV CAPSULE } i}) / n$$

Calculation #1: Determination of Index Parameter $ART_{T0\text{-}X\text{-}Y}$ Estimate based on PCVN Data from Maine Yankee Surveillance Capsule A-35

To obtain an estimate of $ART_{T0\text{-}X\text{-}Y}$, a method is established for normalizing the Maine Yankee Surveillance Capsule A-35 PCVN data to the RPV fluence and best-estimate chemistry information at operating time "X" (usually EOL or EOLE) and through-wall location "Y" (usually the clad-to-base metal interface, 1/4T depth, or 3/4T depth). This first estimate of the parameter will be called $ART_{T0\text{-}X\text{-}Y\text{-}MY\text{-}A35}$.

All known relationships which could be used to perform this normalization are in terms of shift (i.e., RG 1.99, Rev. 2). Therefore, appropriate adjustments to calculate how much different the RPV material's projected shift would be when compared the chemistry and fluence of the Maine Yankee Surveillance Capsule A-35 data are made and applied to the absolute T_0 value determined from the irradiated material testing.

Mathematically:

$$T_{0\text{-}X\text{-}Y\text{-}MY\text{-}A35} = T_{0\text{-}MY\text{-}A35} - (\Delta T_{0\text{-}MY\text{-}A35} - \Delta T_{0\text{-}X\text{-}Y\text{-}MY\text{-}A35})$$

where: $T_{0\text{-}X\text{-}Y\text{-}MY\text{-}A35}$ is the estimate of the KNPP RPV circumferential weld T_0 value at operating time X and through-wall location Y based on Maine Yankee Surveillance Capsule A-35 PCVN data

$T_{0\text{-}MY\text{-}A35} = 223$ °F $\quad\quad$ $\Delta T_{0\text{-}MY\text{-}A35} = 381$ °F

$\Delta T_{0\text{-}X\text{-}Y\text{-}MY\text{-}A35}$ is the projected shift in T_0 for the KNPP RPV circumferential weld at operating time X and through-wall location Y based on the shift in T_0 observed for the Maine Yankee Surveillance Capsule A-35 data and correcting for fluence and chemistry differences

$\Delta T_{0\text{-}X\text{-}Y\text{-}MY\text{-}A35}$ is given by:

$$\Delta T_{0\text{-}X\text{-}Y\text{-}MY\text{-}A35} = [\Delta T_{0\text{-}MY\text{-}A35} - (t_{irr\text{-}RPV} - t_{irr\text{-}MY\text{-}A35})] * [(FF_{X\text{-}Y} / FF_{MY\text{-}A35}) * (CF_{RPV} / CF_{MY\text{-}A35})]$$

where: $(FF_{X\text{-}Y} / FF_{MY\text{-}A35})$ corrects the Maine Yankee Surveillance Capsule A-35 data to the RPV circumferential weld fluence at operating time X and through-wall location Y.

$(CF_{RPV} / CF_{MY\text{-}A35})$ corrects the Maine Yankee surveillance weld chemistry to the RPV circumferential weld best-estimate chemistry.

$(t_{irr\text{-}RPV} - t_{irr\text{-}MY})$ would, if necessary, correct the irradiation temperature of Maine Yankee Surveillance Capsule A-35 to the irradiation temperature of the KNPP RPV. Since the irradiation temperatures are the same, this term is zero.

From the above, $T_{0\text{-}X\text{-}Y\text{-}MY\text{-}A35}$ has been determined. $ART_{T0\text{-}X\text{-}Y\text{-}MY\text{-}A35}$ is then given by:

$$ART_{T0\text{-}X\text{-}Y\text{-}MY\text{-}A35} = T_{0\text{-}X\text{-}Y\text{-}MY\text{-}A35} + 33\ °F + M + B_{PCVN\text{-}MY\text{-}A35\text{-}U} = T_{0\text{-}X\text{-}Y\text{-}MY\text{-}A35} + 95.5\ °F + B_{PCVN\text{-}MY\text{-}A35\text{-}U}$$

where $B_{PCVN\text{-}MY\text{-}A35\text{-}U}$ is the bias associated with using the PCVN fracture toughness data from Maine Yankee Surveillance Capsule A-35 and the unirradiated PCVN fracture toughness data from the Maine Yankee surveillance weld. $B_{PCVN\text{-}MY\text{-}A35\text{-}U}$ is given by:

$$B_{PCVN\text{-}MY\text{-}A35\text{-}U} = B_{PCVN\text{-}MY\text{-}U} + [(FF_{X\text{-}Y} / FF_{MY\text{-}A35}) * (CF_{RPV} / CF_{MY\text{-}A35}) * (B_{PCVN\text{-}MY\text{-}A35} - B_{PCVN\text{-}MY\text{-}U})]$$

Calculation #2: Determination of Index Parameter ART_{T0-X-Y} Estimate based on PCVN Data from KNPP Surveillance Capsule S

To obtain an estimate of ART_{T0-X-Y}, a method is established for normalizing the KNPP Surveillance Capsule S PCVN data to the RPV fluence and best-estimate chemistry information at operating time "X" (usually EOL or EOLE) and through-wall location "Y" (usually the clad-to-base metal interface, 1/4T depth, or 3/4T depth). This second estimate of the parameter will be called $ART_{T0-X-Y-K-S}$.

All known relationships which could be used to perform this normalization are in terms of shift (i.e., RG 1.99, Rev. 2). Therefore, appropriate adjustments to calculate how much different the RPV material's projected shift would be when compared the chemistry and fluence of the KNPP Surveillance Capsule S data are made and applied to the absolute T_0 value determined from the irradiated material testing.

Mathematically:

$$T_{0-X-Y-K-S} = T_{0-K-S} - (\Delta T_{0-K-S} - \Delta T_{0-X-Y-K-S})$$

where: $T_{0-X-Y-K-S}$ is the estimate of the KNPP RPV circumferential weld T_0 value at operating time X and through-wall location Y based on KNPP Surveillance Capsule S PCVN data.

$T_{0-K-S} = 136$ °F $\qquad$ $\Delta T_{0-K-S} = 287$ °F

$\Delta T_{0-X-Y-K-S}$ is the projected shift in T_0 for the KNPP RPV circumferential weld at operating time X and through-wall location Y based on the shift in T_0 observed for the KNPP Surveillance Capsule S data and correcting for fluence and chemistry differences.

$\Delta T_{0-X-Y-K-S}$ is given by:

$$\Delta T_{0-X-Y-K-S} = [\Delta T_{0-K-S} - (t_{irr-RPV} - t_{irr-K-S})] * [(FF_{X-Y} / FF_{K-S}) * (CF_{RPV} / CF_{K-S})]$$

where: (FF_{X-Y} / FF_{K-S}) corrects the KNPP Surveillance Capsule S data to the RPV circumferential weld fluence at operating time X and through-wall location Y.

(CF_{RPV} / CF_{K-S}) corrects the KNPP surveillance weld chemistry to the RPV circumferential weld best-estimate chemistry.

$(t_{irr-RPV} - t_{irr-K-S})$ would, if necessary, correct the irradiation temperature of KNPP Surveillance Capsule S to the irradiation temperature of the KNPP RPV. Since the irradiation temperatures are the same, this term is zero.

From the above, $T_{0-X-Y-K-S}$ has been determined. $ART_{T0-X-Y-K-S}$ is then given by:

$$ART_{T0-X-Y-K-S} = T_{0-X-Y-K-S} + 33\ °F + M + B_{PCVN-K-S-U} = T_{0-X-Y-K-S} + 95.5\ °F + B_{PCVN-K-S-U}$$

where $B_{PCVN-K-S-U}$ is the bias associated with using the PCVN fracture toughness data from Maine Yankee Surveillance Capsule A-35 and the unirradiated PCVN fracture toughness data from the Maine Yankee surveillance weld. $B_{PCVN-K-S-U}$ is given by:

$$B_{PCVN-K-S-U} = B_{PCVN-K-U} + [(FF_{X-Y} / FF_{K-S}) * (CF_{RPV} / CF_{K-S}) * (B_{PCVN-K-S} - B_{PCVN-K-U})]$$

Calculation #3: Determination of Best-Estimate Value for $ART_{T0\text{-}X\text{-}Y}$

Having determined two estimates of $ART_{T0\text{-}X\text{-}Y}$ from Calculations #1 and #2, these estimates can the be used to develop a final best-estimate value as follows:

$$ART_{T0\text{-}X\text{-}Y} = (ART_{T0\text{-}X\text{-}Y\text{-}MY\text{-}A35} + ART_{T0\text{-}X\text{-}Y\text{-}K\text{-}S}) \ / \ 2$$

$ART_{T0\text{-}X\text{-}Y}$ may then be used as the appropriate materials property parameter for PTS or P-T limits evaluations, as applicable.