ATTACHMENT 2

SUBMITTAL OF IRRADIATED REACTOR VESSEL SURVEILLANCE CAPSULE TEST RESULTS FOR CAPSULE T PER 10 CFR 50 APPENDIX H

WCAP-16609-NP, REVISION 0, "MASTER CURVE ASSESSMENT OF KNP RPV WELD METAL," OCTOBER 2006

KEWAUNEE POWER STATION

DOMINION ENERGY KEWAUNEE, INC.

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Master Curve Assessment of Kewaunee Power Station Reactor Pressure Vessel Weld Metal

Westinghouse

WCAP-16609-NP, Revision 0

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PREFACE

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RECORD OF REVISION

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FORWARD

The first application of the Master Curve approach for an irradiated reactor vessel weld metal was approved by the NRC for the Kewaunee Power Station (KPS) in 2001 (*Safety Evaluation by the Office of Nuclear Reactor Include the Use of a Master Curve-based Methodology for Reactor Pressure Vessel Integrity Assessment*, Docket No. 50-305, May 2001). Testing of the next surveillance capsule for KPS included the requirement to perform additional fracture toughness tests to help validate the previous Master Curve evaluation accepted by the NRC. Two reports have been prepared to describe the results and evaluation of the additional fracture toughness testing performed as part of the Capsule T evaluation.

Capsule Requirements

In accordance with the NRC Safety Evaluation (SE), removal and testing of one additional capsule at a fluence equivalent to End-of-License-Renewal (EOLR) for the vessel weld of concern would be acceptable for monitoring radiation damage. The currently evaluated fluence for EOLR is documented in WCAP-16641-NP, the Capsule T analysis report, where the value was determined to be 5.37×10^{19} n/cm^2 (E>1.0 MeV).

Additionally, the removal and testing of the capsule with fluence equivalent to 60 years will complete the current KPS surveillance program requirements. In accordance with the SE requirement, Capsule T was removed at a calculated fluence of 5.62×10^{19} n/cm^2 (E>1.0 MeV), which closely approximates the EOLR vessel fluence.

Master Curve Fracture Toughness T_0 Determination

The methodology detailed in Appendix A of the NRC SE is the methodology accepted by the NRC. The licensee agreed to use this methodology for future Master Curve fracture toughness testing and to incorporate the results into the KPS licensing basis. All margin terms are defined in Appendix A. Specific to the testing requirements, the NRC stated the following:

1. Use of ASTM E 1921-97 is acceptable,
2. The use of multi-temperature maximum likelihood methodology is currently not endorsed (since it was not included in the ASTM Standard).

It was acknowledged that the state of knowledge regarding specific technical topics associated with the Master Curve approach may be improved in the future. Additional conservatisms may be reduced or removed provided technical justification is made. The NRC recognized that it may reconsider it's position based on action within ASME Standards organizations and revisions to ASTM E 1921.

In establishing a valid measurement of T_0 for weld wire heat 1P3571, several sources for the test specimens were deemed acceptable:

1. Charpy V-notch (CVN) weld specimens,
2. Reconstituted specimens from the weld portion of untested CVN heat-affected-zone (HAZ) specimens, and/or
3. Reconstituted weld specimens from broken halves of the original, broken weld CVN specimens.

All specimens for fracture toughness testing were to be single-edge bend, SE(B), geometry as defined in ASTM E 1921; these specimens when fatigue precracked and conforming to CVN size are generally referred to as precracked Charpy V-notch (PCVN) specimens. All of the information in paragraphs 11.1 through 11.2.3 of ASTM E 1921-97 for Capsule T, Capsule S, the Maine Yankee Capsule A35, and any unirradiated specimens used for the current licensee submittal were required to be included in the final reports for Capsule T and the new Master Curve evaluation. Use of Code Case N-629 to define a suitable expression for calculating the RT_{T_0} parameter was considered acceptable.

The actual PCVN specimens utilized in determining the measurement of T_0 for Capsule T were fabricated from a combination of the original irradiated CVN weld specimens (eight total) along with the reconstitution of four unbroken CVN HAZ specimen portions to provide a total of twelve specimens. Details concerning the testing of the PCVN specimens are documented in WCAP-16609-NP (Master Curve Report) and WCAP-16641-NP (Capsule T Analysis). In accordance with NRC guidance, the methodology in Appendix A of the SE was used and presented in WCAP-16609-NP. In addition to this methodology, a new methodology has been developed under International Atomic Energy Agency (IAEA) sponsorship which has been applied and documented in WCAP-16609-NP.

The actual test results are presented in WCAP-16641-NP and the analysis is described in WCAP-16609-NP.

Charpy V-Notch Testing and Analysis

In accordance with the NRC SE, a full CVN curve was not required to be developed for the surveillance weld, heat 1P3571. However, information regarding material properties was still required to be estimated to include the transition temperatures at 30 ft-lb, 50 ft-lb, and 35 mils along with the drop in upper shelf energy (USE). Accordingly, the methodology used in determining these values was documented in WCAP-16641-NP. Reconstitution of specimens needed to determine material properties was to be performed in accordance with ASTM E 1253, as described in WCAP-16641-NP. For the forging and correlation monitor materials, full CVN curves were required and testing/analysis performed in accordance with ASTM E 185-82. CVN impact testing of the HAZ material was not required.

A full CVN curve was not developed for the surveillance weld; however, the transition temperature values representing 30 ft-lbs, 50 ft-lbs and 35 mils were determined using the methodology presented in WCAP-16641-NP. The drop in the surveillance weld USE was also documented as a part of this analysis. The test results for the forging and correlation monitor materials also were documented in WCAP-16641-NP. As indicated earlier, four of the HAZ CVN specimens were reconstituted and used as weld metal PCVN specimens to help determine the Master Curve T_0 value for the surveillance weld.

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EXECUTIVE SUMMARY

Master Curve fracture toughness data on irradiated weld metal heat 1P3571 from the Kewaunee Power Station (KPS) Irradiation Surveillance Program, Capsule T, have been evaluated to derive a direct measurement of irradiated RT_{To} for use in place of adjusted RT_{NDT} for the reactor pressure vessel limiting circumferential weld. The RT_{To} for a fluence corresponding to the end of license extension was determined by making direct measurement of irradiated fracture toughness using fatigue precracked Charpy surveillance specimens. Fracture toughness data generated on the same weld wire heat from a previous capsule (Capsule S) and from another nuclear plant surveillance program (Maine Yankee Capsule A-35) were also included in the new evaluation.

The adjusted reference temperature (ART = RT_{To} + Margin) was determined using several different methods, including the approach used by the NRC in a Safety Evaluation (SE) for the KPS weld in 2001. Following the NRC approach, the ART value at the inside wall of the reactor pressure vessel is just below the pressurized thermal shock screening criterion currently specified in the Code of Federal Regulations, 10CFR50.61 at an extended license life corresponding to a capacity factor of 0.956. This optimistic capacity factor sets the upper limit for how high the neutron fluence will reach at sixty years of operation. Lower values of ART will be achieved when less optimistic operation is realized. The Margin term assumed by the NRC Staff in their 2001 SE contains excess conservatism that has now been quantified by a more accurate uncertainty analysis and with three sets of irradiated fracture toughness results. Use of a more realistic Margin term could allow the KPS vessel to operate beyond the sixty year extended license life.

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1 INTRODUCTION

Operating nuclear power plants maintain surveillance programs to monitor the irradiation induced increase in the fracture toughness transition temperature for the reactor pressure vessel (RPV). Federal regulations (10 CFR Part 50 [1]) require use of the reference transition temperature (RT_{NDT}) for indexing the ASME Code reference fracture toughness curve (K_{IC} curve) [2] throughout the operating life of the RPV as delineated in Appendix G. Federal regulations (10 CFR Part 50, Appendix H [1]) also require Charpy V-notch impact testing to monitor irradiation induced increases in the ductile-to-brittle transition temperature, which is then used to define the irradiated RT_{NDT}.

The Charpy V-notch impact test provides a simple measure of the ductile-to-brittle transition of ferritic steels. Characterization of the ductile-to-brittle transition requires a series of tests over a range of temperatures. The Charpy impact test provides a quick determination of the ductile-to-brittle transition temperature with a minimal amount of material. It is often used in qualification testing to demonstrate sufficient resistance to brittle fractures at the design operating temperature. Qualification requirements such as RT_{NDT} assume a correlation between the Charpy V-notch transition temperature and the fracture toughness transition temperature. To assure appropriate margins of safety, these correlations are necessarily conservative. Recent advances in fracture testing technology have made it feasible to eliminate these conservative correlations by measuring the fracture toughness transition temperature directly using pre-cracked Charpy sized specimens.

Analysis of the Charpy V-notch data from the Kewaunee Power Station (KPS) surveillance program indicates that the estimated RT_{NDT} value for the circumferential weld (weld wire heat 1P3571) will approach the limits set to avoid brittle failure due to pressurized thermal shock (10 CFR Part 50.61 [1]) during the license renewal period . The relatively high RT_{NDT} value estimated for this weld also puts restrictions on the plant heat-up and cool-down curves under the requirements of 10 CFR Part 50, Appendix G [1]. Due to the potential adverse effect on plant operation during the license renewal period, the utility augmented the normal surveillance data from the fourth surveillance capsule (Capsule S [3]) with a supplemental fracture toughness testing program that carried forward into the later testing of Capsule T.

The Charpy and supplemental fracture toughness data from KPS Capsule S were reported in September 1998 (WCAP-14279 R1 [3]). The fracture toughness data were derived primarily from testing of single-edged notch bend specimens, SE(B), also commonly referred to as precracked Charpy V-notch (PCVN) specimens reconstituted from the original surveillance Charpy V-notch test specimens. These fracture toughness tests were used to determine the Master Curve fracture toughness transition temperature, T_0, as defined in ASTM E 1921 [4]. Additional PCVN specimens were reconstituted from weld specimens from the Maine Yankee power plant surveillance program (Capsule A-35). The Maine Yankee and KPS surveillance welds were fabricated from the same weld wire heat (1P3571) using equivalent welding procedures. Subsequent analysis has consistently shown that the Maine Yankee surveillance weld has higher Cu levels and more radiation sensitivity than the KPS surveillance weld.

Both RT_{NDT} and T_0 provide measures of the temperature at which the ductile-to-brittle transition in fracture toughness occurs. However they are not numerically identical because RT_{NDT} references a bounding toughness curve and T_0 references a median toughness curve. In addition the two parameters are referenced to the corresponding curves at slightly different toughness levels. ASME Code Cases N-629 [5] and N-631 [6] allow an alternative T_0-based reference temperature for indexing the ASME K_{IC} curve (RT_{T0}). The Code Cases define RT_{T0} as T_0 +35°F for both non-irradiated and irradiated ferritic steels.

A request for an exemption to the existing rules for evaluating reactor vessel integrity to allow use of the T_0 based methodology was originally filed by the operating utility, Wisconsin Public Service Corporation, in 1999 for evaluating the weld metal in the KPS RPV. After continued discussion and detailed review, the Nuclear Regulatory Commission (NRC), granted three specific exemptions to the utility operating KPS, Nuclear Management Company (NMC), in 2001 [7]. The three exemptions were:

1. An exemption to establish a new methodology to meet the requirements of Appendix G to 10 CFR Part 50;

2. An exemption to establish the use of a new methodology to meet the requirements of 10 CFR 50.61; and

3. An exemption to modify the basis for the KPS reactor pressure vessel (RPV) surveillance program (required by Appendix H to 10 CFR Part 50) to incorporate the acquisition of fracture toughness data.

The fracture toughness based methodology approved for the exemption was described in Appendix A of the Safety Evaluation (SE) report issued by the NRC [7]. The NRC methodology accepted the use of T_0 to estimate RT_{NDT}, but included margins over and above the levels originally suggested by the utility.

The exemption approval required the testing of one additional surveillance capsule at a fluence equivalent to sixty years exposure in the RPV circumferential weld. This report provides an analysis of the fracture toughness data obtained from the sixty year capsule, KPS Capsule T. Details of the testing program along with data from Charpy V-notch tests and tensile tests are provided in a separate report [8]. The projected fluence for sixty years for the KPS vessel is 5.37×10^{19} n/cm^2 and 3.44×10^{19} n/cm^2 for forty years using an optimistically-projected capacity factor of 0.956. Note that all neutron fluence values used in this report are for E > 1 MeV. Traditionally, some utilities have assumed a capacity factor of 0.8 which would correspond to a fluence of 4.99×10^{19} n/cm^2 for sixty years and 3.37×10^{19} n/cm^2 for forty years. The actual fluence at either 40 or 60 years will likely be bounded by the projected values assuming a capacity factor of 0.956.

2 BACKGROUND ON FRACTURE TOUGHNESS AND TRANSITION TEMPERATURES

The primary role of fracture mechanics testing of RPV steels is to provide estimates of the fracture toughness to be used in the analysis of reactor pressure vessel integrity. Ferritic steels undergo a characteristic transition from low toughness brittle failures to high toughness ductile failures with increasing temperature. Therefore, analysis of the fracture behavior of the steel requires characterization of the toughness over a range of temperatures encompassing the ductile-to-brittle transition. The development of the Master Curve testing procedure has provided a powerful new tool for performing this characterization.

ASTM E 616, Standard Terminology Relating to Fracture Testing [9], defines fracture toughness as "...a generic term for measures of resistance to extension of a crack." However, the standard also notes that "The term is sometimes restricted to results of fracture mechanics tests, which are directly applicable to fracture control." There are multiple measures of fracture toughness that come under both definitions. The broad definition would include tests such as the Sharp Notch Tension Test or the Charpy V-notch test (see ASTM E 23 [10]), which are useful for characterizing material response but do not provide data that can be used directly in a fracture mechanics analysis of the RPV. The narrower definition would be limited to the type of linear-elastic (K stress intensity) and elastic-plastic (J-integral) fracture mechanics tests defined in ASTM E 1820 [11]. All RPV integrity analysis is based on linear-elastic assumptions and the primary measure of fracture toughness is K_{IC}, the stress intensity required for initiation of crack growth. The objective of the fracture toughness testing program is to determine K_{IC} as a function of temperature.

The size requirements for linear-elastic testing are so restrictive that it is impractical to perform an adequate number of tests on unirradiated materials to fully characterize the fracture toughness transition curve. Furthermore, these large specimen size requirements are totally incompatible with the space limitations imposed on RPV surveillance programs. Therefore, RPV surveillance programs have adopted indirect means (i.e. correlations between Charpy V-notch specimens and toughness) to assess the fracture toughness in irradiated reactor pressure vessels. The development of elastic-plastic fracture mechanics techniques introduced a new fracture toughness measure, the J-integral, which can be measured in much smaller specimens. The J-integral has been used both as a measure of ductile fracture toughness and to estimate equivalent linear-elastic toughness values in the lower transition region. The Master Curve provides a framework for using the linear-elastic toughness estimates derived from the J-integral to characterize the fracture toughness in the ductile-to-brittle transition regime.

Ferritic steels used in RPV construction exhibit a characteristic transition from brittle behavior at low temperatures to ductile behavior at higher temperatures. Under normal operating conditions, a nuclear RPV should always be in the high toughness ductile region. The stresses in the RPV must be carefully controlled during heatup and cooldown to avoid brittle fracture. It is therefore important to characterize the temperature at which the ductile-to-brittle transition occurs in a pressure vessel steel. A complete characterization of the transition requires testing at multiple temperatures. The temperature range over which this transition occurs depends on two factors: the properties of the material and the loading conditions. There are numerous tests designed to characterize the ductile-to-brittle transition in ferritic steels. Each test presents a unique combination of specimen geometry and loading and therefore a ductile-to-brittle behavior that is specific to the test method. This test-specific behavior is generally described in terms of a characteristic transition temperature. While it is common to speak of the ductile-to-brittle transition temperature of a material, there is not a unique definition of this value. In practice, any definition of transition temperature must refer to the test procedure (e.g., Charpy V-notch 30 ft-lb transition, drop weight nil-ductility temperature, and Master Curve T_0). In each test, the transition temperature describes the ductile-to-brittle transition in the material.

For RPV steels, the most commonly used tests are the nil-ductility drop weight test and the Charpy impact test. The characteristic temperature in the drop weight test is defined as the nil-ductility point at the low temperature end of the transition (NDT). For nuclear RPV steels, the Charpy V-notch transition is usually characterized by the temperature at a specific absorbed energy level (30 ft-lb or 50 ft-lb). However, Charpy V-notch tests may also be characterized in terms of the fracture appearance transition temperature (FATT) or the temperature at a specific level deformation (e.g., 35 mils lateral expansion).

Although it has long been recognized that fracture toughness, as defined in ASTM E 1820, undergoes a ductile-to-brittle transition (which is what is really needed for accurate integrity assessment), a characteristic transition temperature for the fracture toughness has only recently been defined. The development of J-integral based techniques for measuring fracture toughness (J_C) in the transition region has allowed a much clearer definition of fracture toughness behavior in ferritic steels. Based on this experience, it has been observed that ferritic steels have a common temperature dependence of fracture toughness in the transition regime. It was this observation that led Wallin to the definition of a Master Curve [12] that allows the fracture toughness for any ferritic steel to be characterized solely in terms of a reference temperature, T_0, corresponding to a fracture toughness of 100 MPa-m$^{1/2}$ (91 ksi-in$^{1/2}$). ASTM E 1921, which was originally adopted in 1997, provides a standard test method for the determination of T_0. This reference temperature can be used to index the Master Curve or some bounding curve. This behavior is in sharp contrast to the Charpy V-notch behavior, where both the transition curve shape and characteristic temperature vary between materials and after irradiation.

The ductile-to-brittle transition behavior of a material may be characterized using any combination of the above mentioned tests. The availability of test specimens and the expense of performing the tests generally determine the particular test employed to characterize the material transition temperature. While there are multiple measures of the ductile-to-brittle transition, the underlying mechanisms of deformation and fracture are clearly inter-related. For this reason, the various measures of transition temperature tend to be correlated. These correlations allow a determination from one test technique to be used to estimate characteristic transition temperatures for the remaining tests. While it is difficult to demonstrate a correlation between NDT and the Charpy V-notch related transition temperature, recent test results have indicated a reasonable correlation between Charpy V-notch transition temperatures and T_0. This correlation is fundamental to all Charpy based procedures for estimating toughness values in current RPV integrity analysis.

3 CHANGES IN ASTM E 1921 TESTING AND EVALUATION METHODS

When the KPS Capsule S fracture toughness tests were generated, the first version of ASTM E 1921 was just being finalized. As mentioned earlier, the first published version was ASTM E 1921-97. Since the publication of the 1997 version, there have been several revisions that have involved some minor and more significant changes. The following discussion describes the more significant changes as related to the testing and evaluation performed earlier for Capsule S and more recently for Capsule T. For the 1P3571 weld tests, the net effect of the changes in the ASTM E 1921 test method from 1997 to 2005 was a decrease of 1-3°F in the measured T_0 values. Although the old 1997 test method produces values that are slightly conservative with respect to the current procedure, the changes were deemed to be insignificant. Therefore, the previously accepted ASTM E 1921-97 T_0 values have been maintained in this analysis. The Kewaunee Capsule T specimens were analyzed using ASTM E 1921-05, which is the test method in place at the time of the testing of Capsule T.

3.1 MULTI-TEMPERATURE T_0 VERSUS SINGLE TEMPERATURE T_0

One of the most significant changes was the move to make ASTM E 1921 based on the multi-temperature method rather than testing at a single test temperature. The 1997 version was strictly a single temperature method, but later versions allowed both approaches since the single temperature method is a mathematical simplification of the multi-temperature approach. Also, some test results from other test temperatures will not be lost by utilizing the multi-temperature method; often the optimum test temperature(s) can be difficult to define when testing a new or irradiated material. The original data used for the KPS surveillance weld Master Curve submittal were primarily based on the single temperature approach, although the multi-temperature approach was used in some calculations by combining different specimen types, SE(B) – PCVN and compact tension [C(T)] for the unirradiated condition and SE(B) – PCVN and modified 1T-WOL* from Capsule S. It is now acknowledged that a specimen bias does exist between SE(B) and C(T) geometries, and this combination of specimen types would not be done today without making adjustments to the K_{Jc} data to account for the differences. The analysis approach used by the NRC Staff in the KPS Master Curve SE [7] only used the single temperature data for the PCVN tests. The testing for Capsule T was performed at a single temperature to be consistent with the previous testing and the choice of a test temperature was relatively easy due to the extensive testing performed earlier. A temperature dependent value of the elastic modulus also has been used for the determination of K_{Jc} for the KPS 1P3571 weld metal.

3.2 ELASTIC MODULUS

The 1997 version of ASTM E 1921 used a plane stress elastic modulus (E), which was a technically questionable value to be used for low toughness material being tested in the early transition region. The 2002 change to ASTM E 1921 (which has been carried forward into the 2005 version) converted the elastic modulus to a plane strain value: $E / (1 - \nu^2)$ where ν is Poisson's Ratio. This plane strain modulus is applied both in converting the elastic stress intensity term into an equivalent $J_{elastic}$ value and in

* Modified 1T-WOL is a one-inch thick wedge-open loading (WOL) test specimen that has been modified to be tested in a manner similar to a C(T) specimen.

converting the combined $J_{elastic}$ and $J_{plastic}$ values into the equivalent K_{Jc} value. The combination of conversion of K to J and then J back to K effectively cancels out the elastic contribution. However, there is an increase in the $J_{plastic}$ contribution. The maximum potential increase in the calculated K_0 is approximately 5%. The increase in K_0 is more typically 2%. This change can lead to a decrease in the T_0 value by 1-2°F.

3.3 ELIMINATION OF SUBTRACTION OF 0.3068 TERM IN DETERMINING T_0

A subtraction term of 0.3068 from the number of valid test measurements was included in the 1997 version of ASTM E 1921. This conservative value was eliminated in the 2002 version (and continued in the 2005 version) and the effect results in a decrease in T_0 of less than 1°F.

3.4 FACTORS IN THE SE(B) EQUATION FOR J

Some minor changes have been made that involve the η factor used in calculating the load line displacement from clip gage mouth opening measurements. These changes have been minor and do not affect the results reported for the testing of the KPS 1P3571 weld metal.

3.5 BIAS EFFECT BETWEEN SE(B) AND C(T) SPECIMENS

The latest data relative to specimen bias between SE(B) and C(T) specimens suggests a bias value of about 18°F for non-irradiated specimens. ASTM E 1921 [4] now acknowledges this fact by stating that:

> "Median K_{Jc} values tend to vary with the specimen type at a given test temperature, presumably due to constraint differences among the allowable test specimens ... K_{Jc} variability among specimen types is analytically predicted to be a function of the material flow properties and decreases with increasing strain hardening capacity for a given yield strength material. This K_{Jc} dependency ultimately leads to discrepancies in calculated T_0 values as a function of specimen type for the same material. T_0 values obtained from C(T) specimens are expected to be higher than T_0 values obtained from SE(B) specimens. Best estimate comparisons of several materials indicate that the average difference between C(T) and SE(B)-derived T_0 values is approximately 10°C [18°F]. C(T) and SE(B) T_0 differences up to 15°C [27°F] have also been recorded. However, comparisons of individual, small datasets may not necessarily reveal this average trend. Datasets which contain both C(T) and SE(B) specimens may generate T_0 results which fall between the T_0 values calculated using solely C(T) or SE(B) specimens."

As stated above, the material flow properties and the strain hardening capacity can affect the degree of constraint and the value of bias that can exist between C(T) and SE(B) specimen types. Limited data have suggested that irradiated materials may show a smaller bias than non-irradiated materials [13]. The NRC Staff used a value of bias of 8.5°F in the SE for KPS, which is a reasonable value to use for the analyses to be presented in this report since there is no technical consensus on the proper value to be used.

Additionally, the degree of constraint for a part-through surface flaw in a reactor pressure vessel is quite different than that of a C(T) specimen. It has been inherently assumed that the proper normalization for applying the Master Curve is the C(T) specimen since it has a high level of constraint which results in conservatively high values of T_0. The SE(B) PCVN specimen is actually closer to the level of T-stress constraint of a flaw in an RPV. This aspect also supports using a reasonably small value for a bias correction.

3.6 LOADING RATE EFFECTS

Loading rate effects were originally assumed to be inconsequential in the range of static loading covered under ASTM E 1921-97. Later studies have shown that a loading rate dependence exists, even in the range specified by the ASTM Standard. The higher loading rates lead to higher values of T_0. Later changes in ASTM E 1921 have restricted the loading rate range at the higher end by about a factor of 10. This loading rate range reduction reduces significantly the potential differences in T_0 that can exist for quasi-static testing. The 2005 version of ASTM E 1921 requires testing at a specific range of stress intensity loading rates of 0.1 to 2 $MPa\text{-}m^{1/2}/s$. All of the testing for both Capsules S and T was in the ASTM E 1921-05 specified loading rate range.

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4 KPS CIRCUMFERENTIAL WELD METAL CHEMISTRY AND ΔT_{30} UPDATE

As described in WCAP 15074, Rev. 1 [14], the weld metal Cu and Ni chemistries for weld wire heat 1P3571 are unchanged. Additional chemical analyses were conducted at Argonne National Laboratory on the LaSalle-1 surveillance weld (weld wire heat 1P3571), but these results have been found to be of a confirmatory nature to testing performed by General Electric and have not been as rigorously documented as other measurements generated by the nuclear steam supply system vendors. Therefore, the ANL data have not been included in the determination of the best estimate chemistry of the overall 1P3571 weld metal. The best estimate chemistry of 0.287 wt% Cu and 0.756 wt% Ni will continue to be used for weld wire heat 1P3571.

Charpy V-notch ΔT_{30} estimates from Capsule T [8] are in agreement with expectations based on previous capsule testing. Therefore, there is no concern that the material and results from Capsule T could be anomalous relative to previous testing and results. The extensive testing that has been conducted on the 1P3571 weld metal, especially related to the KPS and Maine Yankee surveillance welds, has helped to quantify the specifics on the variability in Cu and Ni content for 1P3571 welds. This variability in Cu and Ni between the KPS and Maine Yankee welds also has been quantified showing differences in the Charpy V-notch and measured fracture toughness properties. This understanding for these two specific welds allows uncertainties to be accurately determined which should allow a reasonable margin to be applied, as discussed later in this report.

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5 MARGINS APPLIED IN PAST ANALYSES

The issue of the proper Margin to be applied for the Master Curve methodology as used for the KPS RPV circumferential weld was an area of discussion between the utility and the NRC Staff. The final Margin as applied by the NRC Staff in the SE [7] included several terms that were not proposed by the utility and its contractors. In fact, the final Margin applied to the more appropriate and accurate Master Curve fracture toughness results was greater than the Margin that would have been applied to Charpy V-notch data. This inconsistency was presumably due to the fact that this application was the first direct licensing use of the Master Curve approach. Since the time of the SE, more knowledge and experience have been gained in applying Master Curve data. For the direct use of irradiated Master Curve results, better quantification of the areas of uncertainty has been developed which should be applied in future assessments. These uncertainties and factors included in a proper Margin term are discussed in more detail in Section 8.

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6 FRACTURE TOUGHNESS MEASUREMENTS

The fracture toughness of the surveillance specimens is measured in terms of the J-integral. ASTM E 1820 provides a general procedure for conducting J-integral tests. The Master Curve used in ASTM E 1921 describes the temperature dependence of the cleavage initiation toughness. A cleavage event is readily identifiable as a rapid, unstable crack advance. Cleavage initiation implies that this fracture instability must occur prior to the onset of significant stable tearing crack extension. For a known starting crack length, the elastic and plastic contributions to the J-integral can be determined by measuring the specimen load and the amount of plastic work applied to the specimen. The testing procedure requires unloading compliance measurements to demonstrate that stable tearing has not initiated prior to the cleavage failure. If cleavage initiation occurs and the measurement meets the various validity requirements of the testing standard, the value of the J-integral at the point of instability is defined as J_C. The equivalent linear elastic plane-strain fracture toughness at cleavage instability is K_{Jc}. The Master Curve describes the temperature dependence of K_{Jc}.

The determination of the fracture toughness transition temperature, T_0, requires multiple measurements of K_{Jc}. In the original testing program, fracture toughness measurements were conducted on irradiated weld specimens from KPS Capsule S and Maine Yankee Capsule A-35. Unirradiated archival material from the KPS surveillance weld was also tested. Fracture toughness values for the unirradiated Maine Yankee were provided by the utility. Additional fracture toughness tests were conducted as part of the surveillance testing program for KPS Capsule T.

6.1 SUMMARY OF PREVIOUS FRACTURE TOUGHNESS TESTS

The fracture toughness tests on the unirradiated KPS surveillance welds are summarized in Appendix A, Table A-1. These toughness values were originally reported in WCAP-14279 R1 [3]. Two different specimen geometries were tested to determine the distribution of unirradiated K_{Jc} values. PCVN specimens were machined from the archival material and tested (Table A-1a). The broken halves of the Charpy specimens were then reconstituted to provide additional unirradiated PCVN specimens for testing (Table A-1b). All of the PCVN specimens were tested at -200°F. A series of six ½-T C(T) unirradiated specimens were also tested at -187°F (Table A-1c).

A total of twelve PCVN specimens were reconstituted from the broken halves of the weld and HAZ specimens from KPS Capsule S. Nine of the PCVN specimens were tested at 136°F (see Table A-2a) and three at 59°F (see Table A-2b). Note that the fluence for Capsule S has been revised in the new fluence evaluation performed for Capsule T [8]. The revised Capsule S fluence is 3.67×10^{19} n/cm^2.

Eight PCVN specimens were reconstituted from the broken ends of Charpy specimens from Maine Yankee Capsule A-35. All of these specimens were tested at 210°F (see Table A-3).

Refer to Appendix A for a summary of detailed test information for these previous tests conducted by Westinghouse. The test data provided by the utility for the Maine Yankee unirradiated weld metal are listed in Table A-4, but the details of the testing is not listed.

6.2 CAPSULE T FRACTURE TOUGHNESS TEST RESULTS

Fracture toughness testing of PCVN weld specimens was also conducted as part of the surveillance testing program for KPS Capsule T. These results are included in a separate report [8]. The initial testing was carried out using the eight weld Charpy specimens from Capsule T. The Charpy V-notches in the surveillance specimens were modified to produce sharp crack starters for the pre-cracks. The specimens were side-grooved after pre-cracking to provide uniform crack fronts for testing, which should lead to more valid test results and improved accuracy in determining T_0. Note that specimens from the previous capsules and for the unirradiated condition were not side-grooved; use of side-grooved specimens is now recommended in ASTM E 1921, but side-grooving is not a specific requirement.

The minimum number of specimens required to determine T_0 is set by ASTM E1921. However the standard also indicates that additional tests may be required to minimize the effect of material variability. All eight of the weld Charpy V-notch specimens were converted to PCVN specimens and tested at 136°F (see Table 6-1). The initial results verified previous observations of significant variability in data from weld 1P3571. For materials with significant variability, the testing of a minimum of twelve specimens is recommended by ASTM E1921 to minimize the effects of the scatter. In accordance with the recommendations of the standard, an additional four PCVN specimens were reconstituted using the weld portion of unbroken HAZ specimens. These additional weld specimens were also tested at 136°F as indicated in Table 6-1. The ASTM Standard requires that all measurements be included in the T_0 determination. The values for the measured K_{Jc} are listed as well as the 1T size adjusted values, $K_{Jc(1T)}$.

Table 6-1 Fracture Toughness Results from Capsule T

Specimen Code	Specimen Type	Test Temperature (°F)	K_{Jc} (ksi-in$^{1/2}$)	$K_{Jc(1T)}$ (ksi-in$^{1/2}$)
W25	PCVN	136	54.6	47.0
W26	PCVN	136	65.0	55.3
W27	PCVN	136	90.1	75.1
W28	PCVN	136	149.7	122.4
W29	PCVN	136	79.6	66.8
W30	PCVN	136	78.9	66.3
W31	PCVN	136	46.0	40.2
W32	PCVN	136	59.6	51.0
H25	Recon. PCVN	136	119.0	98.0
H29	Recon. PCVN	136	75.6	63.6
H30	Recon. PCVN	136	53.1	45.0
H31	Recon. PCVN	136	53.2	46.0

7 DETERMINATION OF T_0 FOR CAPSULE T FRACTURE TOUGHNESS RESULTS

The version of ASTM E 1921 that was in place when the original testing program was conducted in 1998 (ASTM E 1921-97) required multiple tests at a single temperature to determine T_0. However, multi-temperature methods for estimating were well-established at that time and WCAP-15075 [15] reported the results of several alternative methods for determining T_0 from the measured K_{Jc} values. As expected the multiple analysis methods gave reasonably consistent results. The NRC methodology employed only data collected at a single temperature on a single specimen geometry (PCVN) that met the existing ASTM E 1921 requirements to determine T_0. The established values for the four measured material conditions were:

Maine Yankee, unirradiated: -158°F

Maine Yankee, Capsule A-35: 223°F *

KPS, unirradiated: -151°F

KPS, Capsule S: 136°F †

Although the current version of ASTM E 1921 allows multi-temperature determination of T_0, past practice was used as a guide for the Capsule T testing program, and all of the PCVN specimens were tested at 136°F. At this temperature, eight tests should have been sufficient for determining T_0. However, as illustrated in Figure 7-1, one of the eight specimens tested was clearly outside the normal distribution of values. ASTM E 1921 provides the following guidance on data that falls outside the normally expected tolerance bound:

> "If the suspected datum is outside the tolerance bounds dictated by Eqs. (14) (for example, $K_{Jc} < K_{Jc}$ (0.02) or $K_{Jc} >$ K_{Jc} (0.98)) it may be possible to reduce the influence of the outlier datum on $K_{Jc(med)}$ by testing additional specimens."

The data set illustrated in Figure 7-1 demonstrates the level of variability in the data. The variability in chemistry and embrittlement response of welds from wire heat 1P3571 is well established. The ASTM E 1921 Procedure goes on to provide the following additional advice concerning data sets with apparent material variability:

> "Typically, a total of <u>12 replicate specimens</u> is sufficient. However, outliers shall not be discarded from the data utilized

* Note that a translation error for the value of T_0 was made and listed in Table 5-19 in WCAP-14279 R1 [3] for the Maine Yankee Capsule A-35 value for the reconstituted PCVN specimens; Table 5-19 in WCAP-14279 R1 lists a value of T_0 = 232°F, not T_0 = 223°F, which is the value that the NRC SE uses.

† Note that if the multi-temperature approach was used with all of the PCVN data (combining Tables A-2a and A-2b), the value of T_0 would be 142°F, which is very close to the single temperature value of 136°F.

to calculate $K_{Jc(med)}$. The emergence of additional outliers may indicate that the test material is not homogeneous."

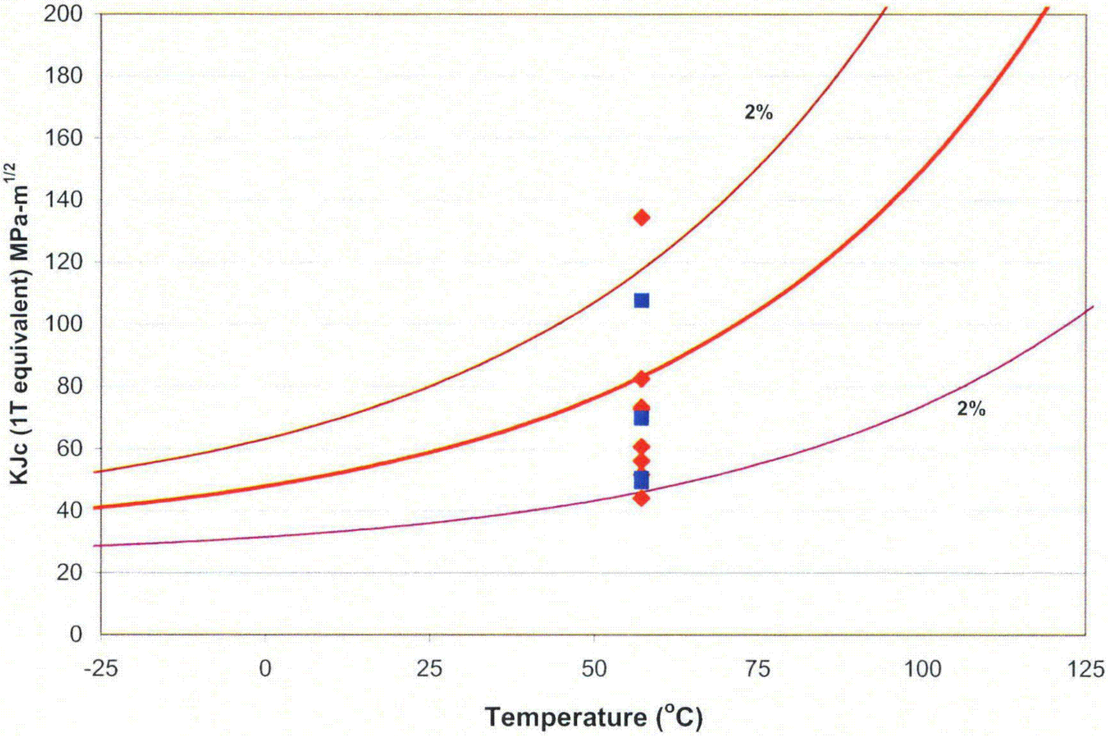
Consistent with this advice, an additional four PCVN specimens were constructed by reconstituting the weld ends of HAZ specimens from Capsule T. The results from these additional specimens are also illustrated in Figure 7-1. It appears that these additional toughness values have a distribution similar to the original eight measurements.

The variability in these fracture toughness results appears to be somewhat larger than normally expected in a Master curve distribution for a completely homogeneous material. Examination of the fracture surfaces reveals a non-homogeneous structure, apparently associated with the structure of the weld passes. This structure, which is on the size scale of the test specimen, may help explain some of the excess variability in the test results. Additionally, the Cu and Ni variability in the 1P3571 weld metal subjected to radiation exposure can lead to enhanced variability in irradiated fracture toughness properties, as has been observed in other weld metals in which the weld wire has been Cu coated. It should be noted that the 1P3571 weld has exhibited a large degree of irradiated variability in previous testing of the KPS and Maine Yankee surveillance welds, but this large variability has been consistent with the known Cu and Ni contents of the two welds.

The T_0 value for the Capsule T specimens was determined by analyzing all twelve specimens:

KPS, Capsule T: 161°F.

The Master Curve and confidence bounds associated with this value are illustrated in Figure 7-1.



◆ - Weld Charpy Specimens ■- Reconstituted HAZ Specimens

Figure 7-1 Calculation of Adjusted Reference Temperature

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8 EVALUATION FOR KPS VESSEL

The original request to use measurements of the Master Curve transition temperature, T_0, to index the irradiated fracture toughness curves for the KPS circumferential weld was submitted to the NRC by Wisconsin Public Service Corporation in June 1999. Existing analysis indicated that the limiting material in the KPS reactor pressure vessel was the circumferential weld, which was fabricated using weld wire heat 1P3751. This same weld wire was used to fabricate the surveillance welds in the KPS and Maine Yankee plants. The original request proposed using data generated using weld specimens from these two surveillance programs to determine the value of T_0 as a function of the irradiation dose. T_0 values were determined using specimens from KPS Capsule S (revised fluence = 3.67×10^{19} n/cm^2 based on the Capsule T evaluation) and Maine Yankee A-35 (fluence = 6.11×10^{19} n/cm^2). Strategies for applying this data to the assessment of the KPS reactor pressure vessel were outlined in WCAP-15075 [15]. In response to the original request, the NRC staff issued a Safety Evaluation (SE) proposing extensive modifications to the WCAP-15075 application strategy. The utility (Nuclear Management Company, LLC) agreed to use those modified procedures. In May 2001, the NRC granted exceptions to allow the use of Master Curve to assess the KPS pressure vessel as indicated in the SE [7].

8.1 NRC SE METHODOLOGY AND PROJECTIONS

The SE [7] developed by the NRC staff provided both an evaluation of the available data and a procedure for determining the ART value for the circumferential weld in the KPS vessel. The NRC directed that the same analysis technique be used for the remaining surveillance capsule, which was to be withdrawn at the end of license renewal (EOLR) peak fluence.

The appendix to the SE provided sample calculations to illustrate the approved methodology for determining the adjusted reference temperature (ART), which can then be used for input for pressure temperature curves and pressurized thermal shock (RT_{PTS}) evaluations. To assure consistency with the SE methodology, the fundamental data assumptions used in the SE have been used for the current analysis. The parameter definitions and data values used in these calculations are outlined next in Section 8.1.1. For information and clarity, the data for Maine Yankee Surveillance Capsule A-35 and KPS Capsule S are duplicated from the SE (except for the revised fluence for Capsule S). The data set for KPS Capsule T has been adjusted for the measured T_0 value and the measured capsule fluence. Projections of the circumferential weld properties also require estimates of the fluences in the RPV weld and the vessel weld chemistry. The values used in this analysis duplicate the methodology in the SE. Note that the peak EOLR fluence in the NRC analysis is projected to be 4.7×10^{19} n/cm^2. This fluence is lower than the estimate in the utility submittal because the NRC assumed a much lower capacity factor.

8.1.1 Fundamental Data for Assessing the NRC Method

Data for the NRC calculations are presented next. Note that the calculations require use of chemistry factor (CF) values from tables and the fluence function (FF) values as determined in Regulatory Guide 1.99, Revision 2 [16].

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

Unirradiated T_0 = -158°F

Fluence = 6.11 x 10^{19} n/cm^2 (which corresponds to a $FF_{MY\text{-}A35}$ = 1.44)

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

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

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

$Tirr_{MY\text{-}A35}$ = The irradiation temperature of MY Capsule A-35 = 532°F

$B_{PCVN\text{-}MY\text{-}U}$ = Bias associated with unirradiated MY PCVN data = 8.5°F

$B_{PCVN\text{-}MY\text{-}A35}$ = Bias associated with irradiated MY PCVN data = 8.5°F

(#2) KPS Surveillance Capsule S, PCVN Surveillance Weld Samples

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

Fluence = 3.67 x 10^{19} n/cm^2 (which corresponds to a $FF_{K\text{-}S}$ = 1.34)

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

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

$CF_{K\text{-}S}$ = 187.2°F (0.219 wt% Cu, 0.724 wt% Ni, based in Reg. Guide 1.99, Rev. 2)

$Tirr_{K\text{-}S}$ = Irradiation temperature of KPS Capsule S = 532°F

$B_{PCVN\text{-}K\text{-}U}$ = Bias associated with unirradiated KPS PCVN data = 8.5°F

$B_{PCVN\text{-}K\text{-}S}$ = Bias associated with irradiated KPS PCVN data = 8.5°F

(#2a) KPS Surveillance Capsule T, PCVN Surveillance Weld Samples

Unirradiated T_0 = -151°F (average of whole and reconstitued PCVNs)

Fluence = 5.62 x 10^{19} n/cm^2 (which corresponds to a $FF_{K\text{-}T}$ = 1.42)

Irradiated T_0 = $T_{0K\text{-}T}$ = 161°F

$\Delta T_{0K\text{-}T}$ = [161°F – (-151°F)] = 312°F

$CF_{K\text{-}T}$ = 187.2°F (0.219 wt% Cu, 0.724 wt% Ni, based in Reg. Guide 1.99, Rev. 2)

$Tirr_{K\text{-}T}$ = Irradiation temperature of KPS Capsule T = 532°F

$B_{PCVN\text{-}K\text{-}U}$ = Bias associated with unirradiated KPS PCVN data = 8.5°F

$B_{PCVN\text{-}K\text{-}T}$ = Bias associated with irradiated KPS PCVN data = 8.5°F

The SE supplied by the NRC provided a step by step process for using the measured T_0 values to estimate the ART value at any position in the KPS circumferential weld. The SE methodology is based on the measured shift in T_0, ΔT_{0meas}.

The SE methodology includes an adjustment to the measured shift to correct for differences between the surveillance capsule temperature and the vessel temperature. The time weighted average irradiation temperatures for all three capsules are essentially at 532°F and the time weighted average irradiation temperature for the KPS RPV circumferential weld is slightly greater than 532°F since the cycles of operation for KPS since April 2003 have led to an increase in the cold leg temperature of about 8°F due to a power uprate. In the calculations to be presented Sections 8.1.2 to 8.1.5, the correction is conservatively assumed to be 0°F since higher irradiation temperatures lead to less embrittlement than lower irradiation temperatures. Additionally, for the KPS vessel, service at the lower temperature for 26 cycles relates to when most of the radiation damage has occurred, and future damage at the higher irradiation temperature (as high as 537°F for EOLR fluences) should have little effect.

After correcting for temperature, the measured shift is normalized to the RPV conditions using the chemistry factors (CF) and fluence function values (FF) from NRC Reg. Guide 1.99, Rev. 2. The irradiated value of T_0 for the RPV can be determined from the estimate of the adjusted shift. The margin terms used to calculate the ART values in the NRC methodology are taken directly from Reg. Guide 1.99, Rev. 2. The primary purpose for the shift based methodology used by the NRC appears to be to provide an apparent link between the margin terms defined in the Reg. Guide and the T_0 estimation used here. The ART estimate for the vessel also includes a small bias term (8.5°F) designed to account for the observed differences between T_0 values determined in SE(B) specimens as compared to C(T) specimens; thus, the constraint level in the C(T) specimen has been set as the correct value for the NRC calculation method .

This procedure was originally applied to the Maine Yankee Capsule A-35 data (Calculation #1) and the KPS Capsule S data (Calculation #2). The best estimate ART value was determined by averaging the results of the two calculations (Calculation #3). The SE further required that future surveillance capsules be analyzed in a similar fashion and the best estimate be taken as the average of all three determinations. The KPS Capsule T data has been analyzed (Calculation 2a) and the best estimate value of ART adjusted accordingly to Calculation #3. Each of the three estimates of T_0 (Calculation #1, #2, and #2a) provides an independent means of estimating the ART value.

8.1.2 Calculation #1: Determination of Index Parameter ARTTo-X-Y Based on PCVN Data from MY Surveillance Capsule A-35

The following calculation for the Maine Yankee surveillance weld metal follows the NRC methodology as described in the SE.

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

for X-Y corresponding to EOLR at the Clad-to-Base Metal Interface, $FF_{X\text{-}Y} = 1.39$. The calculated ΔT_0 is then:

$$\Delta T_{0\text{-X-Y-MY-A35}} = [381 - (532 - 532)]*[(1.39 / 1.44)*(214 / 237.2)] = 331.8°F$$

The T_0 value estimated at position X-Y as estimated using the data from Maine Yankee Capsule A-35 is then:

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

For the clad-to-base metal interface at EOLR, the estimated T_0 value is then:

$$T_{0\text{-X-Y-MY-A35}} = 223 - (381 - 331.8) = -158 + 331.8 = 173.8°F$$

The corresponding ART value is then taken as:

$$ART_{X\text{-Y-MY-A35}} = T_{0\text{-X-Y-MY-A35}} + 33 + M + B_{PCVN\text{-MY-A35}},$$

where M = Margin = 62.5°F

For the clad-to-base metal interface the ART value estimated using the Maine Yankee surveillance data is therefore:

$$ART_{T0\text{-X-Y-MY-A35}} = 173.8 + 33 + 62.5 + 8.5 = 277.8°F.$$

8.1.3 Calculation #2: Determination of Index Parameter ARTTo-X-Y Based on PCVN Data from KPS Surveillance Capsule S

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

for X-Y corresponding to EOLR at the Clad-to-Base Metal Interface, $FF_{X\text{-}Y} = 1.39$. The calculated T_0 shift is then:

$$\Delta T_{0\text{-X-Y-K-S}} = [287 - (532 - 532)]*[(1.39 / 1.34)*(214 / 187.2)] = 340.3°F$$

The T_0 value estimated at position X-Y as estimated using the data from KPS Capsule S is then:

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

For the clad-to-base metal interface at EOLR, the estimated T_0 value is then:

$T_{0\text{-}X\text{-}Y\text{-}K\text{-}S} = 136 - (287 - 340.3) = 189.3°F$

The corresponding ART value is then taken as:

$ART_{X\text{-}Y\text{-}K\text{-}S} = T_{0\text{-}X\text{-}Y\text{-}K\text{-}S} + 33 + M + B_{PCVN\text{-}K\text{-}S}$,

where M = Margin = 62.5°F

For the clad-to-base metal interface the ART value estimated using the KPS Capsule S surveillance data is therefore:

$ART_{X\text{-}Y\text{-}K\text{-}S} = 189.3 + 33 + 62.5 + 8.5 = 293.3°F.$

8.1.4 Calculation #2a: Determination of Index Parameter ARTTo-X-Y Based on PCVN Data from KPS Surveillance Capsule T (New Data Analysis)

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

for X-Y corresponding to EOLR at the Clad-to-Base Metal Interface, $FF_{X\text{-}Y} = 1.39$. The calculated T_0 shift is then:

$\Delta T_{0\text{-}X\text{-}Y\text{-}K\text{-}T} = [312 - (532 - 532)]*[(1.39 / 1.42)*(214 / 187.2)] = 349.1°F$

The T_0 value estimated at position X-Y as estimated using the data from KPS Capsule T is then:

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

For the clad-to-base metal interface at EOLR, the estimated T_0 value is then:

$T_{0\text{-}X\text{-}Y\text{-}K\text{-}T} = 161 - (312 - 349.1) = 198.1°F$

The corresponding ART value is then taken as:

$ART_{X\text{-}Y\text{-}K\text{-}T} = T_{0\text{-}X\text{-}Y\text{-}K\text{-}T} + 33 + M + B_{PCVN\text{-}K\text{-}T}$,

where M = Margin = 62.5°F

For the clad-to-base metal interface the ART value estimated using the KPS Capsule T surveillance data is therefore:

$ART_{X\text{-}Y\text{-}K\text{-}T} = 198 + 33 + 62.5 + 8.5 = 302.1°F.$

8.1.5 Determination of Best Estimate Value for $ART_{T0\text{-}X\text{-}Y}$

At the time the initial SE was issued, only data from Maine Yankee Capsule A-35 and KPS Capsule S were available. The SE identified the best estimate of ART for the vessel as the average of these two determinations, which equated to a value of 288°F. Using the revised Capsule S fluence values the best estimate ART is:

$$ART_{To\text{-}X\text{-}Y} = (ART_{To\text{-}X\text{-}Y\text{-}MY\text{-}A35} + ART_{To\text{-}X\text{-}Y\text{-}K\text{-}S})/2 = 285.6°F.$$

The SE indicates that additional determinations should be similarly averaged. Therefore, the best estimate of the ART value at the peak EOLR fluence defined in the SE (for fluence = 4.7 x 10^{19} n/cm^2) is:

$$ART_{To\text{-}X\text{-}Y} = (ART_{To\text{-}X\text{-}Y\text{-}MY\text{-}A35} + ART_{To\text{-}X\text{-}Y\text{-}K\text{-}S} + ART_{X\text{-}Y\text{-}K\text{-}T})/3 = 291.1°F.$$

The three estimates and their projections are illustrated in Figure 8-1 for Calculations #1, #2 and #2a, as well as the average of the three values (dashed curve for Calculation #3). Note that the Kewaunee Capsule S (Calculation #2) and Kewaunee Capsule T (Calculation #2a) projections are nearly identical.

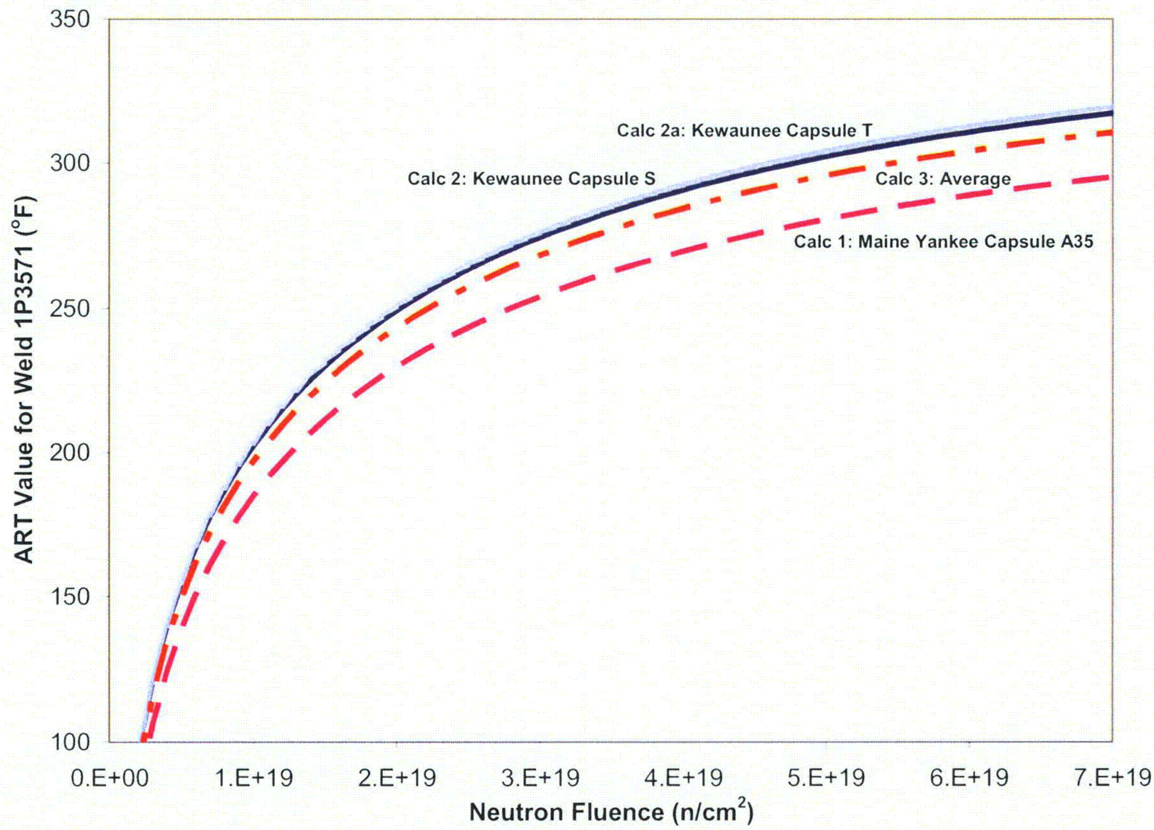

Figure 8-1 Projections for ART Based on the Different Measurements and the Average Using the NRC SE Methodology *(Note that the Curves for Calc 2 for KPS Capsule S and 2a for KPS Capsule T Essentially Lie on Top of Each Other)*

8.2 ALTERNATIVE METHODOLOGIES AND PROJECTIONS

Several alternative methods for analyzing the data were outlined in WCAP-15075 [15]. The WCAP provided a table that compared the various terms contributing to the various calculated ART values. A similar comparison is outlined here in Table 8-1, which illustrates the direct measurement approach (no shift required – fourth row in the table), the use of unirradiated RT_{To} and Charpy shift (the fifth row in the table), and the NRC SE method, which is a shift-based ΔRT_{To} approach (rows 1 through 3 in the table). Each of the terms represents a different step in the process of using the surveillance capsule data to estimate the ART for the vessel. The process can be broken down into the following steps:

1. Best estimate of the initial (unirradiated) fracture toughness reference temperature value (IRT).
2. Standard deviation of estimated initial fracture toughness reference temperature value (σ_i).
3. Estimate of irradiation induced shift in surveillance material fracture toughness reference temperature at fluence corresponding to vessel target vessel (ΔRT).
4. Standard deviation of estimated surveillance material reference temperature shift (σ_Δ).
5. Best estimate of irradiated fracture toughness reference temperature for surveillance weld at RPV target fluence (IRT + ΔRT).
6. Total margin for estimate of irradiated reference temperature (combined σ_i and σ_Δ).
7. Adjusted reference temperature (ART) for surveillance material at target vessel fluence.
8. Adjustment for difference between surveillance material composition and the "best estimate" vessel composition.
9. Adjusted reference temperature for the vessel material at the target fluence.

Although the proposed methodologies do not all follow this exact protocol, the calculations can be broken down in a similar manner. The SE methodology requested by the NRC combines the adjustments for vessel fluence and vessel composition in a single step. However, the effective value of the individual steps can be determined by applying the calculations in a sequential manner. In Table 8-1separate entries are shown for each step used in calculating the ART values.

In WCAP-15075, the preferred method for determining ART was direct measurement of the irradiated value (Method 6 in WCAP-15075 and the fourth row in Table 8-1). This method eliminates the need to estimate the first four steps in the process listed earlier. In this direct measurement method, the irradiated value can be determined at the surveillance capsule fluence without reference to the unirradiated value. The methodology requires that the surveillance capsule measurements correspond to (or bound) the fluence at which the ART is required. In this case, the best estimate of the irradiated reference temperature is based on ASME Code Case N-629, which defines RT_{To} as T_0 + 35°F. As T_0 is measured directly, there is no error associated with extrapolating this measurement and the margin is determined by the measurement error. Since the direct measurement must be adjusted to match the best estimate chemistry for the vessel, a heat adjustment term must be determined. ART values corresponding to the three surveillance capsule fluences are also shown in the Table 8-1. Note that the calculations for Maine Yankee Capsule A-35 and KPS Capsule S vary slightly from the WCAP-15075 values because the fundamental data has been adjusted to match the values in the SE. The heat adjustments are smaller in the WCAP-15075 analysis because the calculation is based on the Reg. Guide 1.99, Rev. 2 chemistry factors rather than the T_0 measured chemistry factors.

The WCAP-15075 analyses also used the T_0 shift as a basis for estimating an ART value. The unirradiated RT_{T_0} for the Kewaunee surveillance capsule was measured directly at a fluence that exceeds the expected life extension fluence. The standard deviation of the unirradiated value was estimated from the measurement uncertainty. The WCAP analyses fit the T_0 shifts from the two KPS capsules to get a single best estimate chemistry factor. Since the chemistry factor from two surveillance capsules was based on credible surveillance data, the standard deviation for the shift value was taken as 14°F. The adjustment to the vessel chemistry was based on the difference in the predicted Charpy shifts between the surveillance welds and the vessel.

The WCAP-15075 approaches for calculating ART using the direct Master Curve results produce lower values of ART than the NRC SE method. The difference is in the final Margin applied to the best estimate mean value of RT_{T_0} to obtain ART. A newer direct measurement calculation approach was recently developed under an International Atomic Energy Agency (IAEA) Coordinated Research Project (CRP) as discussed next. The IAEA methodology uses the direct measurement of RT_{T_0} and applies a detailed and realistic uncertainty analysis to determine an appropriate margin. The IAEA method should be the approach used in assessing the KPS limiting weld metal since it is more rigorous with regard to assessing uncertainties and, therefore, reflects the most accurate condition of the KPS limiting weld metal. If the NRC wishes to impose the NRC SE method, it should be noted that the SE method contains considerably more margin leading to a much more conservative evaluation of the KPS limiting weld.

Table 8-1 Alternative Methodologies for Estimating ART for the RPV 1P3571 Weld using Master Curve Fracture Toughness Data

Method	Best Estimate of Initial RT_{NDT} Value (IRT), °F	Standard Deviation for IRT (σ_i), °F	Kewaunee Surveillance Estimate of Shift (ΔRT), °F	Standard Deviation for ΔRT (σ_Δ), °F	Best Estimate of Irradiated Value, °F	Total Margin (M), °F	Adjusted Reference Temperature (ART), °F	Adjustment for Heat Uncertainty (ΔRT_{HT}), °F	Heat Adjusted Reference Temperature (ART_{HT}), °F
NRC SE Calc. #1 (MY Capsule A-35)	Unirradiated T_0 + 33°F + bias = -116.5	14	$\Delta RT = \Delta T_0$ determined from CF_{eff} = 381/1.44 = 264.6 For FF = 1.39 367.8	PTS Rule and Reg. Guide 1.99, Rev. 2 28	IRT +ΔRT 251.3	$2(\sigma_i^2+\sigma_\Delta^2)^{1/2}$ 62.5	IRT + ΔRT + M 313.8	Equivalent value for NRC SE method -36.0	For $\phi t = 4.7 \times 10^{19}$: **277.8**
NRC SE Calc. #2 (KPS Capsule S)	Unirradiated T_0 + 33°F + bias = -109.5	14	$\Delta RT = \Delta T_0$ determined from CF_{eff} = 287/1.34 = 214.2 For FF = 1.39 297.7	PTS Rule and Reg. Guide 1.99, Rev. 2 28	IRT +ΔRT 188.2	$2(\sigma_i^2+\sigma_\Delta^2)^{1/2}$ 62.5	IRT + ΔRT + M 250.7	Equivalent value for NRC SE method 42.6	For $\phi t = 4.7 \times 10^{19}$: **293.3**
NRC SE Calc. #2a (KPS Capsule T)	Unirradiated T_0 + 33°F + bias = -109.5	14	$\Delta RT = \Delta T_0$ determined from CF_{eff} = 312/142 = 219.7 For FF = 1.39 305.4	PTS Rule and Reg. Guide 1.99, Rev. 2 28	IRT +ΔRT 195.9	$2(\sigma_i^2+\sigma_\Delta^2)^{1/2}$ 62.5	IRT + ΔRT + M 258.4	Equivalent value for NRC SE method 43.7	For $\phi t = 4.7 \times 10^{19}$: **302.1**
WCAP 15075 (Direct Measurement for Each Capsule)	NA	NA	NA	ASTM E 1921 $\sigma_{T_0}=\beta/\sqrt{n}$ 12 12 10	T_0 + 35°F MY: 258 KPS-S: 171 KPS-T: 196	$2\sigma_{T_0}$ 24 24 20	Irr RT_{T_0} + M 282 195 216	CF Ratio Adj. -33 36 38	For ϕt = 6.11×10^{19}: **249** 3.67×10^{19}: **231** 5.60×10^{19}: **256**
WCAP 15075 (Shift Measurement Approach for KPS Capsules)	Unirradiated T_0 + 35°F -116	ASTM $\beta/\sqrt{n}$ 8.5	Data Fit, KPS Capsules T and S CF_{eff} = 217 302	Reg .Guide 1.99, Rev. 2 (Credible Data Assumed) 14	IRT +ΔRT 186	$2(\sigma_i^2+\sigma_\Delta^2)^{1/2}$ 33	IRT + ΔRT + M 219	CF Ratio Adj. 37	For $\phi t = 4.7 \times 10^{19}$: **256**
IAEA Methodology (Based on KPS Capsule T Results)	NA	NA	NA	ASTM E 1921 $\sigma_{T_0}=\beta/\sqrt{n}$ 9.8	$T_0 + T_{proj}$ + bias + 35°F 198.0	$2\,[\sigma_{T_0}^2 + \sigma_{Cu}^2 + \sigma_{Ni}^2 + \sigma_{Tirr}^2 + \sigma_{\phi t}^2 + \sigma_{Proj}^2]^{1/2}$ 42.1	Irr RT_{T_0} + M 240.1	CF Ratio for KPS weld metal to the RPV 37.3	For $\phi t = 4.7 \times 10^{19}$: **277.4**

Note that the fluence used for most of the evaluations in this table is that defined in the NRC SE for EOLR (4.7×10^{19} n/cm^2). This value is used to provide a common EOLR fluence for comparisons back to the NRC SE evaluation. Evaluations using current assessments of EOL and EOLR fluences are provided in Section 9. Also note that the results in columns 4 and 5 for the WCAP-15075 measurement methods are based on the direct and shift methods presented in WCAP-15075 [15].

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8.3 IAEA METHODOLOGY

The IAEA has recently published guidelines for the application of the Master Curve [17]. The IAEA guidelines suggest extending the direct measurement methodology described in WCAP 15075 by using the measured points as the base for extrapolating shifts to the target fluence. The largest portion of the radiation induced increase in fracture toughness reference temperature occurs in the early stages of irradiation. Beyond a fluence near 1×10^{19} n/cm^2, the rate of increase in the radiation induced shift is relatively low. The IAEA methodology suggests using an existing model of embrittlement to predict the difference between the shift in transition temperature at the surveillance capsule fluence and the target fluence. For the Kewaunee surveillance weld, the measured RT_{To} (T_0 + 35°F) value at the Capsule S fluence of 3.67×10^{19} n/cm^2 is 171°F. Using the Regulatory Guide 1.99, Rev. 2 fluence function, and a chemistry-based CF of 187.2 for the KPS surveillance weld metal [8] the difference between the shift at the Capsule S fluence and the shift at the NRC SE target EOLR fluence of 4.7×10^{19}n/cm^2 is 10°F.

Because the IAEA methodology does not require a determination of the unirradiated T_0, there is no uncertainty associated with the initial reference toughness. As long as the fluence extrapolation produces a relatively small change in the shift value, the uncertainty in the RT_{To} estimation is dominated by the measurement uncertainty in the irradiated T_0 value. This situation is analogous to the uncertainty analysis for the direct RT_{To} measurements. The vessel ART value is estimated by applying the direct measurement uncertainties and heat chemistry adjustments from the direct measurement technique to the IAEA based RT_{To} estimate. The IAEA methodology is compared to the WCAP 15075 and NRC SE methodologies in Table 8-1 using the Capsule T result since it conservatively predicts the highest values of ART using the NRC SE methodology.

The ART using the direct measurement approach involves a form for extrapolation from the measured irradiated RT (Irr RT), Capsule T in this case, to the fluence of interest:

$$ART = Irr\ RT + T_{proj} + Margin = Irr\ RT + CF * \Delta FF(\phi t) + Margin$$

where CF is taken as the chemistry-based value of 187.2°F for the KPS surveillance weld metal; this value for CF was chosen since it is more conservative than using the CF for the vessel. This extrapolation from Irr RT is small (T_{proj} is a decrease of 6.5°F from the Capsule T fluence) compared to starting at the unirradiated condition (IRT_{To}); $\Delta FF(\phi t)$ is the difference in $FF(\phi t)$ between the irradiated point and the fluence being extrapolated. An uncertainty in projected fluence is then a function of the uncertainty in CF or CF_{eff}.

The development of the Margin is based on the uncertainties in the important parameters affecting irradiation changes in fracture toughness. These parameters and their corresponding uncertainties are: copper content, nickel content, irradiation temperature (T_{irr}), and fluence (ϕt). Other uncertainties that in general should be considered are the accuracy of the measured irradiated T_o (σ_{To}) and the projection to other fluences (σ_{Proj}). The irradiation sensitive parameters can be determined from the ASTM E 900-02 model for embrittlement [18]. The way that an uncertainty in an independent variable propagates through the model to produce an uncertainty in the predicted value can be estimated through a simple error analysis. The effect of the uncertainty in the independent variable on the prediction uncertainty can be determined by taking the partial differential of the prediction equation. The model provides a function *f(x₁,x₂,x₃,...)*, where x_i represents the ith independent variable. The contribution of uncertainty in x_i to the uncertainty in the prediction, *dP*, is:

$$d_i P = \partial f / \partial x_i \; dx_i$$

If the uncertainties in the independent variables are independent, then the composite uncertainty can be determined by taking the square root of the sum of the squares of the individual contributions. The uncertainties in the predictions are not constant and can vary as a function of fluence. Values of dx_i must be established from measurements or other methods of assessing the uncertainty of the parameters. Estimates of uncertainties for the individual ASTM E 900-02 model parameters (Cu, Ni, ϕt, and T_{irr}) for the KPS RPV material and irradiation conditions have been used to calculated uncertainties in the prediction of RT_{irr}. These prediction uncertainties, the determination of RT_{To}, and projections from the measured fluence where RT_{To} have been determined to assess Margin:

$$\text{Margin} = Y\,[\sigma_{To}^2 + \sigma_{Cu}^2 + \sigma_{Ni}^2 + \sigma_{Tirr}^2 + \sigma_{\phi t}^2 + \sigma_{Proj}^2]^{1/2}$$

Y is a value typically from 1 to 3 depending upon the judgment of the analyst and/or the regulatory authority; in most cases the value of Y will be between 1 and 2 since these values are most commonly used in engineering evaluations. σ_{To} is the uncertainty calculated as $\beta/N^{1/2}$, where N is the number of valid test results used to determine the irradiated T_o, and β is the statistical quantity from ASTM E 1921 [4]; for an individual data set of 12 valid tests, σ_{To} is 9.8°F for the results from Capsule T. σ_{Proj} is partially included in the $\sigma_{\phi t}$ estimate and can be determined by the uncertainty in CF (or CF_{eff}) produced by the uncertainties in Cu, Ni, irradiation temperature, and fluence; σ_{Proj} is typically of the order of 1°F when on the plateau region of the shift-ϕt curve; i.e., at fluences indicative of EOLR. σ_{Cu}, σ_{Ni}, σ_{Tirr}, and $\sigma_{\phi t}$ are based on the statistics and best estimates of uncertainties in the measured Cu and Ni values and the irradiation temperature (T_{irr}) and fluence (ϕt) values. The cumulative value of uncertainty using this process leads to a Margin (using a value of 2 for Y) as listed in Table 8-1 for a fluence of 4.7×10^{19} n/cm^2. Table 8-2 lists the uncertainties used at a fluence of 4.7×10^{19} n/cm^2. The low value of prediction uncertainty due to Cu, even when a 25% uncertainty in the value of Cu can exist, is due to the saturation of Cu at values above 0.301 wt% as defined in ASTM E 900-02 [18].

For a good estimate of a 2σ Margin, the results using the uncertainty in prediction values in Table 8-2 give 2σ = 42.1°F. All of the σ values in Table 8-2, except for σ_{To}, are a function of fluence,* but the net effect on the overall σ is a net change of no more than 1°F over a large fluence range around the Capsule T value of 5.62×10^{19} n/cm^2; this essentially constant value of 2σ is illustrated in Figure 8-3. It could be argued that three measurements of Master Curve RT_{To} for the 1P3571 weld metal should be adequate to assure credibility and thus reduce the assumed value of Y equal to 2. One key argument is that the ±2σ lines in Figure 8-3 almost encompass the three measured data points, even before they are corrected for known chemistry differences.

* The effect of decreasing fluence decreases the σ associated with Cu, Ni, and irradiation temperature, whereas decreasing fluence increases the σ associated with fluence and fluence projection back from the Capsule T fluence used as the basis for this calculation.

In the SE methodology, the NRC staff included an additional contribution for the uncertainty in the initial transition temperature, σ_i. Although the direct measurement and IAEA methodologies do not rely on the measurement of the initial transition temperature, the NRC staff argued that this term accounts for an inherent material variability. The 7°F difference in the initial T_0 values measured for the MY surveillance weld (-158°F) and the KPS surveillance weld (-151°F) is less than the σ_{T_0} uncertainty in the measurement. This σ_{T_0} term is an indirect measure of material variability as indicated by the master curve. Note that the effects of irradiation are characterized by the other uncertainties in Cu, Ni, T_{irr} and ϕt. Therefore, the IAEA method does not typically include a separate σ_{Mat} term.

Table 8-2. Prediction Uncertainties using ASTM E 900-02 Model Parameters for EOLR and Results from Capsule T

Parameter	Approximate 1σ Uncertainty in Parameter	Approximate 1σ Uncertainty in Prediction at EOLR, $\phi t = 4.7 \times 10^{19}$ n/cm^2 (°F)
Cu	25% for Cu = .287 wt%	8.0
Ni	0.065 wt%	13.8
T_{irr}	5°F	6.5
ϕt	5%	7.1
T_0	Per ASTM E 1921	9.8
ϕt_{proj}	Projection back from Capsule T, $\phi t = 5.62 \times 10^{19}$ n/cm^2; 10% in CF	0.6

The plot of the IAEA method for irradiated RT_{irr} in Figure 8-3 shows that there is excess Margin included in the NRC SE approach. Therefore, all values calculated using the NRC SE methodology are overly conservative by 10 – 15°F. It is reemphasized here that the IAEA methodology is the most technically detailed approach for assessing the KPS limiting weld metal since it directly uses the measurements of RT_{T_0} and applies a thorough uncertainty analysis leading to a reasonable 2σ Margin.

8.4 RECOMMENDED METHODOLOGY AND PROJECTIONS BASED ON CURRENT STATE OF KNOWLEDGE

The determination of the RT_{To} for the Kewaunee surveillance weld requires an extrapolation from the values measured in Capsules S and T. The methodologies outlined in WCAP-15075, the SE written by the NRC Staff, and the IAEA guidelines all use slightly different extrapolation schemes. However, as illustrated in Figure 8-2, within the relevant range of fluences, these three extrapolation schemes are keyed to the data and give very similar results.

Although the proposed methodologies give consistent predictions for RT_{To}, there is a much wider variation in the corresponding ART values. Figure 8-3 illustrates the magnitude of the margin included in the NRC SE method of ART determination for the KPS RPV weld. The RT_{To} values plotted for the two Kewaunee surveillance capsules and the Maine Yankee capsule are direct measurements. The measured T_0 values have been adjusted to include an 8.5°F Charpy bias. The measured RT_{To} values have been fit to create a projection for the "best estimate" vessel weld chemistry. The difference between the "best estimate" projection and the ART curve is the margin implied by the NRC SE methodology. The IAEA methodology for Margin determination is more structured and adds up to estimates of ART that are less than the NRC SE method. The NRC SE recommended method conservatively uses all of the full Charpy uncertainties from Regulatory Guide 1.99, Rev. 2 assuming no credible data as applied to the measured RT_{To} values. Although the predictions were based on surveillance capsule results that are very consistent, no credit was given for credible data or the fact that the data from measured fracture toughness tests are more relevant to the integrity of the KPS vessel weld.

The plot of the IAEA method (IAEA + 2 s.d., meaning IAEA + 2σ, for the Capsule T results) for irradiated RT_{irr} in Figure 8-3 shows that there is excess Margin included in the NRC SE approach, (which is the average of three capsules). Therefore, values calculated using the NRC SE methodology are overly conservative by 10 – 15°F with the difference decreasing as the fluence is reduced to lower values. If a comparison is made just for the Capsule T method using the NRC SE methodology, the excess Margin using the NRC SE method can be as high as 25°F. It is reemphasized here that the IAEA methodology is the most technically detailed approach for assessing the KPS limiting weld metal since it directly uses the measurements of RT_{To} and applies a thorough uncertainty analysis leading to a reasonable 2σ Margin.

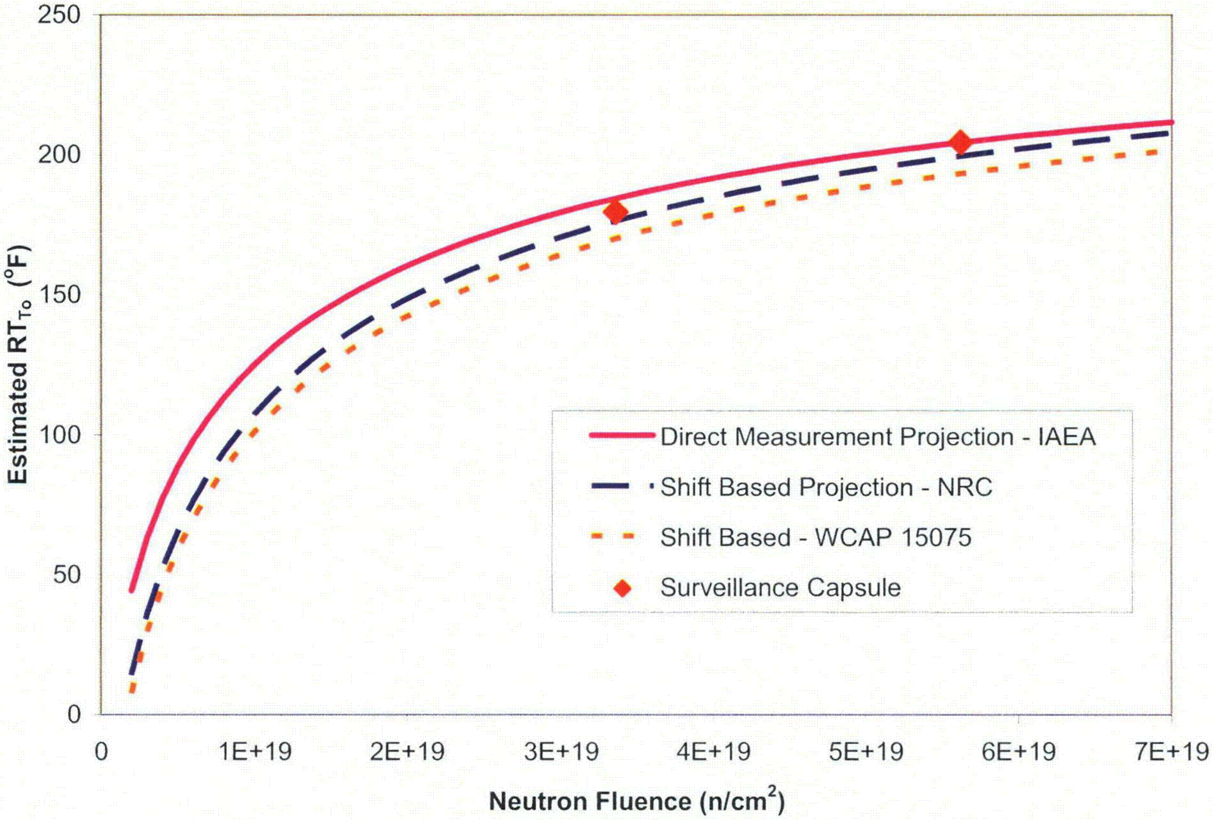

Figure 8-2 Predictions of RT_{To} (No Margins Included) for KPS Weld Metal from Capsules S and T
(Note that RT_{T0} Definition Includes an 8.5°F Bias Adjustment)

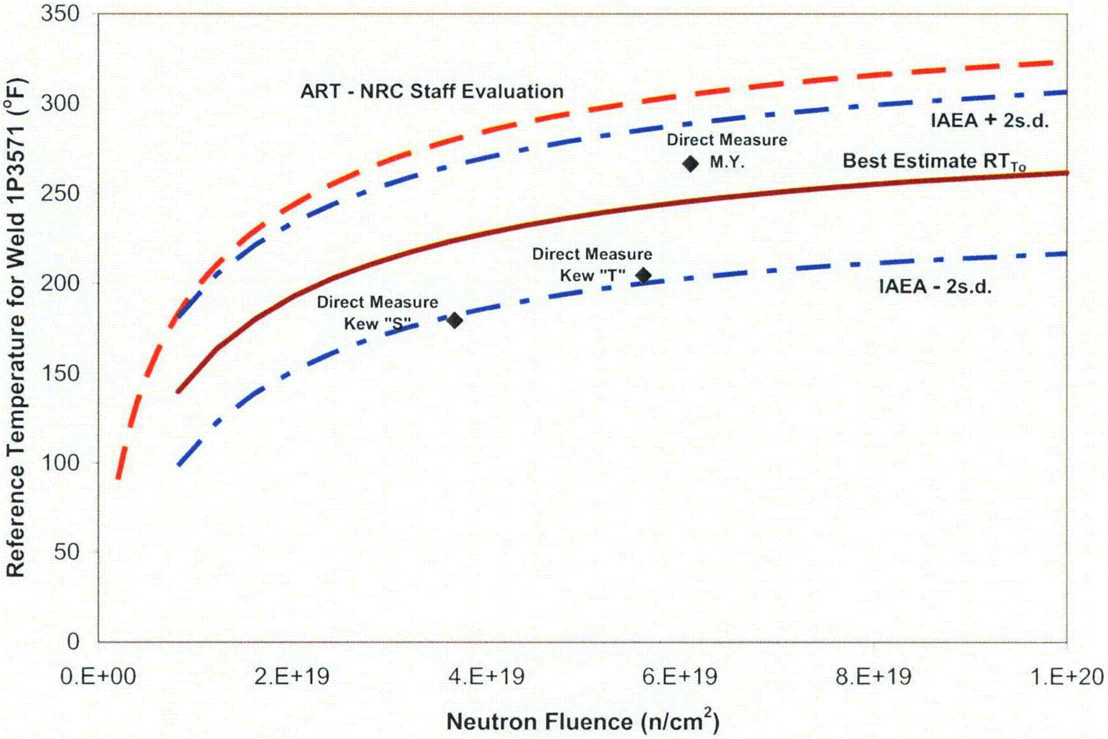

Figure 8-3 Evaluation of ART from the NRC SE Methodology Compared to the IAEA Methodology

9 ART VALUES FOR PTS AND HEAT-UP AND COOL-DOWN CURVES

The value of ART that should be used for PTS (RT_{PTS}) for the limiting circumferential weld should be under 300°F at the fluence expected for EOL and EOLR. EOL fluence estimates for the KPS circumferential weld range from 3.37 x 10^{19} n/cm^2 (80% capacity factor) to 3.44 x 10^{19} n/cm^2 (95.6% capacity factor). Similarly, EOLR fluence estimates for the KPS circumferential weld range from 4.99 x 10^{19} n/cm^2 (80% capacity factor) to 5.37 x 10^{19} n/cm^2 (95.6% capacity factor). Using the SE methodology, the average value of RT_{PTS} is 297.5°F as indicated in Table 9-1 at EOLR using the most optimistic capacity factor. The value of RT_{PTS} associated with an 80% capacity factor is 294.0°F as indicated in Table 9-2. Both values are less than the PTS screening criterion.

For heat-up and cool-down curves, the values of ART to be used corresponding to EOLR can be determined utilizing the SE methodology for the Master Curve results, as well as the IAEA method. The range of results using both approaches for the ¼-T and ¾-T locations in the KPS RPV are listed in Tables 9-1 and 9-2. Similarly the results for EOL are listed in Tables 9-3 and 9-4. Note that the IAEA column in each table includes the 2σ Margin reflecting the sensitivity analysis for the key contributing parameters. Notice that the extrapolation of the NRC SE and the IAEA approaches gives very similar values at the lowest fluences as seen in the last row of Tables 9-3 and 9-4.

Table 9-1. ART Values to be Used for PTS and Heat-up and Cool-down Curves at the 95.6% Capacity Factor EOLR RPV Maximum Fluence

Location	ϕt (at location) (x10^{19} n/cm^2)	FF	Calc #1 (°F)	Calc #2 (°F)	Calc #2a (°F)	NRC SE Average (°F)	IAEA with 2σ (°F)
Inside Surface	5.37	1.4161	284.0	299.7	308.7	297.5	283.3
1/4-T	3.64	1.3352	264.7	279.9	288.4	277.7	265.2
3/4-T	1.67	1.1408	218.3	232.3	239.5	230.0	223.1

Table 9-2. ART Values to be Used for PTS and Heat-up and Cool-down Curves at the 80% Capacity Factor EOLR RPV Maximum Fluence

Location	ϕt (at location) (x10^{19} n/cm^2)	FF	Calc #1 (°F)	Calc #2 (°F)	Calc #2a (°F)	NRC SE Average (°F)	IAEA with 2σ (°F)
Inside Surface	4.99	1.4020	280.7	296.3	305.1	294.0	280.1
1/4-T	3.38	1.3185	260.7	275.8	284.2	273.6	261.5
3/4-T	1.55	1.1209	213.6	227.5	234.6	225.2	218.9

Table 9-3. ART Values to be Used for PTS and Heat-up and Cool-down Curves at the 95.6% Capacity Factor EOL RPV Maximum Fluence

Location	ϕt (at location) ($x10^{19}$ n/cm^2)	FF	Calc #1 (°F)	Calc #2 (°F)	Calc #2a (°F)	NRC SE Average (°F)	IAEA with 2σ (°F)
Inside Surface	3.44	1.3227	261.7	276.8	285.2	274.6	262.5
1/4-T	2.33	1.2284	239.2	253.8	261.5	251.5	241.9
3/4-T	1.07	1.0183	189.1	202.3	208.8	200.1	197.0

Table 9-4. ART Values to be Used for PTS and Heat-up and Cool-down Curves at the 80% Capacity Factor EOL RPV Maximum Fluence

Location	ϕt (at location) ($x10^{19}$ n/cm^2)	FF	Calc #1 (°F)	Calc #2 (°F)	Calc #2a (°F)	NRC SE Average (°F)	IAEA with 2σ (°F)
Inside Surface	3.37	1.3179	260.6	275.7	284.0	273.4	261.4
1/4-T	2.28	1.2231	238.0	252.5	260.2	250.2	240.8
3/4-T	1.05	1.0126	187.7	200.9	207.3	198.7	195.8

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APPENDIX A: PREVIOUS FRACTURE TOUGHNESS TESTS

Table A-1a Unirradiated Precracked Charpy Specimens Tested at -200°F

SPECIMEN ID	wps201	wps202	wps203*	wps204*	wps205	wps206	wps207	wps208	wps209	wps210
Pmax (lbs) - determined from test	1341	1253	1550	1261	1250	1274	1253	1364	1374	1468
LL Compliance (mils/lb)	0.0062	0.0081	0.0071	0.0115	0.0081	0.0068	0.0087	0.0059	0.0079	0.0059
Total Area (in-lbs)	15.40	6.92	9.49	16.60	7.52	6.12	7.76	8.56	10.65	9.66
Plastic Area (in-lbs), calculated	9.87	0.58	0.97	7.43	1.21	0.57	0.95	3.12	3.17	3.33
Ao, Initial Crack length, (in.)	0.2080	0.2060	0.1988	0.1988	0.2100	0.2030	0.2100	0.2050	0.2030	0.1988
bo, Remaining Ligament (in.)	0.1860	0.1880	0.1953	0.1953	0.1840	0.1910	0.1840	0.1890	0.1910	0.1953
Ao/W, Crack/width Ratio	0.528	0.523	0.504	0.504	0.533	0.515	0.533	0.520	0.515	0.504
f(Ao/W)	2.915	2.867	2.700	2.700	2.965	2.796	2.965	2.843	2.796	2.700
Ke (ksi-in^0.5)	63.24	58.09	67.70	55.08	59.95	57.61	60.10	62.71	62.14	64.12
Je (in-lbs/in^2)/1000	0.1333	0.1125	0.1528	0.1011	0.1198	0.1106	0.1204	0.1311	0.1287	0.1371
Jp (in-lbs/in2)/1000	0.2558	0.0149	0.0240	0.1834	0.0317	0.0145	0.0250	0.0795	0.0800	0.0822
Jt (in-lbs/in2)/1000	0.3891	0.1274	0.1768	0.2845	0.1515	0.1251	0.1454	0.2106	0.2087	0.2193
KJC (ksi-in^0.5)	108.0	61.8	72.8	92.4	67.4	61.3	66.1	79.5	79.1	81.1
KJC(1T Adjusted) - (ksi-in^0.5)	89.4	52.8	61.5	77.0	57.2	52.3	56.1	66.8	66.5	68.0

* Invalid precracks

Table A-1b Unirradiated Reconstituted Precracked Charpy Specimens Tested at -200°F

SPECIMEN ID	*rkw1*	*rkw3*	*rkw6*	*rkw7*	*rkw8*	*rkw10*	*rkw11*	*rkw2*
Pmax (lbs) - determined from test	1255	1378	1472	1421	1582	1468	1422	1556
LL Compliance (mils/lb)	0.0045	0.0049	0.0065	0.0059	0.0043	0.0043	0.0057	0.0040
Total Area (in-lbs)	10.12	8.02	6.01	8.54	11.56	14.12	6.32	19.90
Plastic Area (in-lbs), calculated	6.58	3.37	0.00	2.59	6.18	9.49	0.56	15.01
Ao. Initial Crack length, (in.)	0.2040	0.1970	0.1880	0.1940	0.1870	0.1920	0.1910	0.1920
bo, Remaining Ligament (in.)	0.1900	0.1970	0.2060	0.2000	0.2070	0.2020	0.2030	0.2020
Ao/W, Crack/width Ratio	0.5178	0.5000	0.4772	0.4924	0.4746	0.4873	0.4848	0.4873
f(Ao/W)	2.819	2.663	2.480	2.599	2.460	2.558	2.538	2.558
Ke (ksi-in^0.5)	57.22	59.32	59.02	59.72	62.97	60.73	58.37	64.38
Je (in-lbs/in^2)/1000	0.1091	0.1173	0.1161	0.1189	0.1322	0.1229	0.1136	0.1382
Jp (in-lbs/in2)/1000	0.1669	0.0825	0.0000	0.0624	0.1439	0.2266	0.0133	0.3584
Jt (in-lbs/in2)/1000	0.2761	0.1998	0.1161	0.1813	0.2761	0.3495	0.1269	0.4966
KJC (ksi-in^0.5)	91.0	77.4	59.0	73.7	91.0	102.4	61.7	122.1
KJC(1T Adjusted) - (ksi-in^0.5)	75.9	65.1	50.5	62.2	75.9	84.9	52.7	100.5

Table A-1c Unirradiated ½ T Compact Tension Specimens Tested at -187°F

SPECIMEN ID	wps101	wps102	wps103	wps104	wps105	wps106
Pmax (lbs) - determined from test	3869	2867	3750	3445	3433	2416
LL Compliance (mils/lb)	0.0026	0.0029	0.0025	0.0029	0.0027	0.0024
Total Area (in-lbs)	24.02	13.69	22.25	17.49	17.13	7.13
Plastic Area (in-lbs), calculated	4.56	1.77	5.00	0.41	1.14	0.04
Ao, Initial Crack length, (in.)	0.5200	0.5280	0.5230	0.5250	0.5220	0.5170
bo, Remaining Ligament (in.)	0.4800	0.4720	0.4770	0.4750	0.4780	0.4830
Ao/W, Crack/width Ratio	0.5200	0.5280	0.5230	0.5250	0.5220	0.5170
f(Ao/W)	10.134	10.400	10.233	10.299	10.200	10.038
Ke (ksi-in^0.5)	78.42	59.63	76.74	70.96	70.03	48.50
Je (in-lbs/in^2)/1000	0.2050	0.1185	0.1963	0.1678	0.1635	0.0784
Jp (in-lbs/in2)/1000	0.0427	0.0169	0.0471	0.0039	0.0108	0.0004
Jt (in-lbs/in2)/1000	0.2477	0.1354	0.2434	0.1717	0.1742	0.0788
KJC (ksi-in^0.5)	86.2	63.7	85.5	71.8	72.3	48.6
KJC(1T Adjusted) - (ksi-in^0.5)	75.4	56.5	74.8	63.3	63.7	43.8

Table A-2a Irradiated Precracked Capsule S Charpy Specimens Tested at 136°F

SPECIMEN ID	*w24*	*W19*	*h17*	*h18*	*w23*	*h 20**	*h19*	*w17*	*h21*
Pmax (lbs) - determined from test	1514	1349	1433	1285	1490	1319	1273	1323	1076
LL Compliance (mils/lb)	0.0069	0.0070	0.0071	0.0073	0.0071	0.0071	0.0071	0.0071	0.0082
Total Area (in-lbs)	15.80	8.49	25.90	20.36	23.03	29.60	9.97	15.57	15.09
Plastic Area (in-lbs), calculated	7.90	2.12	18.61	14.34	15.13	23.42	4.19	9.35	10.33
Ao, Initial Crack length, (in.)	0.1920	0.1920	0.1960	0.2030	0.1990	0.2000	0.1970	0.1970	0.2100
bo, Remaining Ligament (in.)	0.2020	0.2020	0.1980	0.1910	0.1950	0.1940	0.1970	0.1970	0.1840
Ao/W, Crack/width Ratio	0.4873	0.4873	0.4975	0.5152	0.5051	0.5076	0.5000	0.5000	0.5330
f(Ao/W)	2.5585	2.5585	2.6412	2.7960	2.7059	2.7280	2.6625	2.6625	2.9652
Ke (ksi-in^0.5)	62.65	55.84	61.20	58.10	65.20	58.20	54.81	56.97	51.60
Je (in-lbs/in^2)/1000	0.1308	0.1039	0.1248	0.1125	0.1417	0.1129	0.1001	0.1082	0.0888
Jp (in-lbs/in2)/1000	0.1887	0.0505	0.4534	0.3620	0.3742	0.5821	0.1025	0.2289	0.2707
Jt (in-lbs/in2)/1000	0.3195	0.1545	0.5782	0.4745	0.5159	0.6950	0.2026	0.3371	0.3594
KJC (ksi-in^0.5)	97.9	68.1	131.7	119.3	124.4	144.4	78.0	100.6	103.8
KJC(1T Adjusted) - (ksi-in^0.5)	81.3	57.7	108.1	98.3	102.3	118.2	65.6	83.5	86.1

Table A-2b Irradiated Precracked Capsule S Charpy Specimens Tested at 59°F

SPECIMEN ID	*W21*	*W20*	*W22*
Pmax (lbs) - determined from test	1100	1220	1330
CLL (mils/lb) - determined from initial unloadings of test	0.0071	0.0071	0.0071
Total Area beneath Load-Disp Curve	3.77	3.77	3.85
Plastic Area (in-lbs), calculated	0.00	0.00	-2.43
Ao, Initial Crack length, (in.)	0.2	0.2	0.2
bo, Remaining Ligament (in.)	0.194	0.194	0.194
Ao/W, Crack/width Ratio	0.508	0.508	0.508
f(Ao/W)	2.728	2.728	2.728
Ke (ksi-in^0.5)	48.54	53.83	58.68
Je (in-lbs/in^2)/1000	0.0785	0.0966	0.1148
Jp (in-lbs/in^2)/1000	0.0000	0.0000	-0.0604
Jt (in-lbs/in^2)/1000	0.0785	0.0966	0.0544
KJC (ksi-in^0.5)	48.5	53.8	40.4
KJC(1T Adjusted) - (ksi-in^0.5)	42.2	46.4	35.8

Table A-3 Irradiated Precracked Maine Yankee Specimens Tested at 210°F

SPECIMEN ID	*322*	*36a*	*313*	*371a*	*33u*	*375*	*371b*	*37ua*
Pmax (lbs) - determined from test	1482	1220	1373	1570	1259	1436	1457	1722
LL Compliance (mils/lb)	0.0065	0.0071	0.0071	0.0059	0.0073	0.0071	0.0060	0.0064
Total Area (in-lbs)	9.96	5.28	14.77	35.00	7.26	10.57	9.52	15.82
Plastic Area (in-lbs), calculated	2.82	0.00	8.07	27.70	1.48	3.26	3.18	6.35
Ao, Initial Crack length, (in.)	0.1840	0.2020	0.1930	0.1860	0.2020	0.1960	0.1900	0.1970
bo, Remaining Ligament (in.)	0.2100	0.1920	0.2010	0.2080	0.1920	0.1980	0.2040	0.1970
Ao/W, Crack/width Ratio	0.4670	0.5127	0.4898	0.4721	0.5127	0.4975	0.4822	0.5000
f(Ao/W)	2.4042	2.7731	2.5788	2.4415	2.7731	2.6412	2.5185	2.6625
Ke (ksi-in^0.5)	57.63	54.72	57.27	62.00	56.47	61.34	59.35	74.15
Je (in-lbs/in^2)/1000	0.1107	0.0998	0.1093	0.1281	0.1063	0.1254	0.1174	0.1833
Jp (in-lbs/in2)/1000	0.0648	-0.0001	0.1936	0.6423	0.0372	0.0794	0.0752	0.1553
Jt (in-lbs/in2)/1000	0.1755	0.0997	0.3029	0.7704	0.1435	0.2048	0.1927	0.3386
KJC (ksi-in^0.5)	72.6	54.7	95.3	152.0	65.6	78.4	76.0	100.8
KJC(1T Adjusted) - (ksi-in^0.5)	61.3	47.1	79.3	124.2	55.8	65.9	64.0	83.6

Table A-4 Unirradiated Maine Yankee Weld Specimen Data

SPECIMEN ID	*CO4-4*	*CO4-5*	*CO4-2*	*CO4-7*	*CO4-8*	*CO4-3*	*CO4-6*
Pmax (lbs) - determined from test	1070	1110	1230	1150	1170	1180	1180
LL Compliance (mils/lb)	0.0090	0.0090	0.0089	0.0095	0.0096	0.0088	0.0089
Total Area (in-lbs)	7.01	7.98	12.93	12.29	13.42	13.61	14.09
Plastic Area (in-lbs), calculated	1.86	2.44	6.20	6.00	6.84	7.49	7.89
Ao, Initial Crack length, (in.)	0.2031	0.2040	0.2003	0.2084	0.2032	0.2060	0.2045
bo, Remaining Ligament (in.)	0.1909	0.1900	0.1937	0.1856	0.1908	0.1880	0.1895
Ao/W, Crack/width Ratio	0.5155	0.5178	0.5084	0.5289	0.5157	0.5228	0.5190
f(Ao/W)	2.7984	2.8193	2.7347	2.9252	2.8007	2.8667	2.8310
Ke (ksi-in^0.5)	49.14	51.35	55.20	55.20	53.77	55.51	54.82
Je (in-lbs/in^2)/1000	0.0792	0.0865	0.0999	0.0999	0.0948	0.1011	0.0986
Jp (in-lbs/in2)/1000	0.0469	0.0618	0.1543	0.1560	0.1730	0.1920	0.2008
Jt (in-lbs/in2)/1000	0.126	0.148	0.254	0.256	0.268	0.293	0.299
KJC (ksi-in^0.5)	62.0	67.2	88.0	88.3	90.4	94.5	95.5
KJC(1T Adjusted) - (ksi-in^0.5)	52.9	57.1	73.5	73.8	75.4	78.7	79.5

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