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WCAP-15624

Master Curve Fracture Toughness Application for BVPS-1

Westinghouse Electric Company LLC

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FORWARD

WCAP-15624 summarizes application of the Master Curve fracture toughness data for assuring reactor pressure vessel (RPV) integrity for Beaver Valley Power Station, Unit 1 (BVPS-1). This application represents a lead-plant activity by the nuclear industry for an RPV that is life-limited by a beltline plate material. The fracture toughness data presented in this report were generated in part from the Westinghouse Owners Group (WOG) lead-plant applications program for the life-limiting plate material, and by First Energy Nuclear Operating Company (FENOC) as part of their long range strategic plan for management of the irradiation damage to the reactor vessel. Additionally, FENOC is implementing their program to base their irradiation damage management program on the fracture toughness approach by fracture toughness testing of the other beltline materials in the BVPS-1 RPV.

EPRI has recently published a support document further endorsing the use of the Master Curve approach, EPRI TR-1000707. This document not only further validates ASME Code Cases N-629 and N-631, but proposes a new Code Case in which the alternative reference temperature, RT_{To}, method of indexing the ASME Code K_{IC} curve is replaced by using the measured 5% lower tolerance Master Curve itself. This alternative K_{IC} curve is not used in this BVPS-1 analysis, but if approval through the Code process is reached, future analyses will utilize this approach by requesting use of the Code Case. The RT_{To} methodology has been applied for the BVPS-1 EOLE life-limiting plate material, similar to the approach taken for the Kewaunee EOLE life-limiting weld metal (see WCAP-15075).

WCAP-15624 provides a summary of the RT_{To} methodology used to determine the adjusted reference temperature for an irradiated RPV steel. The investigation in the report focuses on several key areas:

- The technical basis for application of the Master Curve to irradiated RPV steels;
- The basis and accuracy of T_o values measured using ASTM E1921-97 for different size specimens and loading configurations for the BVPS-1 limiting plate material in the unirradiated and irradiated conditions and for the remaining BVPS-1 beltline materials in the unirradiated condition;
- Determination of the T_o-based index reference temperature (RT_{To}) for the K_{IC} curve, which incorporates the latest knowledge of a bias for irradiated materials between small precracked Charpy three-point bend tests versus larger compact tension tests; and
- A margin approach for RT_{To} that meets the intent of accepted regulatory methods (e.g., Reg. Guide 1.99 Rev. 2 procedures); issues related to copper/nickel variability and surrogate weld metal are eliminated in this application since the surveillance limiting material is an exact piece of the RPV plate material.

Due to the low lead factors for the surveillance locations in the BVPS-1 vessel, limited fluence levels are available for the surveillance materials irradiated in the BVPS-1 vessel. Current fluences do not extend out to end-of-life (EOL) or EOL extension (EOLE). A supplemental

capsule has been added to surveillance program for BVPS-1; this capsule has been installed in BVPS-2 where the lead factor is much higher. This higher lead factor, and the fact that previously irradiated specimen inserts are included, means that the time to reach an irradiated EOLE condition is less than a decade. All of the RPV beltline materials for BVPS-1 are included in this supplemental capsule, which is designed for Master Curve fracture toughness testing and evaluation. Thus, the integrity of the entire RPV will be validated with the testing of this capsule. Note that the remaining surveillance capsules in BVPS-1 have been integrated into the revised supplemental surveillance program.

WCAP-15618 has been prepared which provides the new operating pressure-temperature curves for the BVPS-1 vessel based on use of the Master Curve results. These curves reflect the latest projected estimates for power up-rates and the removal of hafnium from the core. The second limiting plate material (B6607-2) now has become controlling plate for these curves, (except for EOLE at 1/4-thickness cool-down) due to their Charpy V-notch (CVN) basis using Regulatory Guide 1.99, Rev. 2. As a result, the improvement in the operating pressure-temperature curves is limited by the CVN correlative approach for the second limiting plate. Although the improvement is currently limited, gains are real for the plant operators. The current increase of 20+ psig in the over-pressure protection system (OPPS) set point allows operators to better control the reactor coolant pump (RCP) seal leak-off. Additionally, when trying to maintain pressure above the minimum for control of RCP seal leak-off and below the OPPS set point, operators must be very careful not to inadvertently actuate the OPPS. Thus, even the small increase in the OPPS set points provides additional margin during plant start-ups and reduces the potential for inadvertent actuation of the OPPS, which enhances plant safety due to fewer challenges to plant systems. This gain of 20+ psig increases the available margin between the RCP seal pressure and the OPPS set pressure by nearly 50% and minimizes operator work around that occur to maintain RCP seal flow at less than design pressures. Both of these actions contribute to improving operator interaction during plant heat-ups. The importance of having future measured irradiated fracture toughness results for this plate and the other beltline materials is paramount, since the move to a fracture toughness basis for all materials is expected to demonstrate that the current limiting plate (B6903-1) will remain the limiting material once all other materials are evaluated on the same testing basis (fracture toughness rather than CVN).

The projections for Pressurized Thermal Shock (PTS) are provided in WCAP-15624 based on applying the Master Curve methodology to the limiting plate, B6903-1. It should be noted that the change in the projected EOL PTS identified in WCAP-15624 is limited by the Charpy based values of the second most limiting plate, B6607-2. When the material from the supplemental surveillance capsule is removed and tested, it is expected that there will be a significant improvement not only in the EOL PTS values but also in the EOLE values. The BVPS-1 RPV stays below the PTS screening criterion of 270°F through and beyond EOLE.

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PREFACE

This report has been reviewed by:

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1 INTRODUCTION

First Energy Nuclear Operating Company (FENOC) currently operates Beaver Valley Nuclear Power Station Unit 1 (BVPS-1). This nuclear power plant has been one that has had an ongoing perceived problem with pressurized thermal shock (PTS) for the reactor pressure vessel (RPV) beltline region plate material. Previous surveillance testing of the limiting vessel plate material, contained in the surveillance capsule program, has shown a higher than expected degree of neutron embrittlement. These Charpy V-notch (CVN) test results have led to projections of end of-life (EOL) reference toughness, termed RT_{PTS}, which are either close to or exceed the screening criterion of 270°F in the Code of Federal Regulations, 10 CFR 50.61 [1]. Section 2 of this report reviews the CVN results for the BVPS-1 surveillance plate material and discusses additional data obtained recently to better quantify all of the materials contained in the beltline region.

As new surveillance data were obtained and the calculation method for RT_{PTS} changed in the early 1990s, the exact PTS status for the BVPS-1 RPV has oscillated and changed. In an attempt to control the embrittlement of the RPV plate material at the peak flux locations, flux reduction methods were employed at BVPS-1 using hafnium rods in the peripheral fuel bundles. These localized flux reduction measures have forced a non-optimum core flux profile and dramatically increased fuel cycle costs.

Recently, FENOC opted to eliminate the hafnium flux reduction, since current embrittlement projections demonstrate that the beltline plate will meet the PTS screening criterion for the current EOL. For current operating life, the use of the Master Curve methodology for the evaluation of material toughness properties is required to provide additional operating margin for the expansion of the pressure-temperature operating windows during heat-up and cool-down evolutions. For an end of license extension (EOLE) operating period, the hafnium flux reduction, if left in the core, would not allow the BVPS-1 RPV to meet the PTS screening criterion using current CVN-based technology. In an attempt to better define the condition of the RPV, and to provide better stability in defining the best estimate of RT_{PTS} for EOL and EOLE, FENOC has tested the two highest fluences of surveillance plate material using actual fracture toughness specimens (reconstituted CVN-size and previously untested 1X-WOLs) using the Master Curve methodology prescribed in ASTM Test Method E 1921-97 [2]. Section 3 of this report describes these measured fracture toughness results, corresponding to less than EOL fluence.

Additionally, FENOC has investigated other RPV mitigation strategies including a simplified Regulatory Guide 1.154 [3] analysis [4, 5] and thermal annealing [6]. Utilizing a simplified Regulatory Guide 1.154 approach would be a first-of-a-kind and involve significant regulatory uncertainty. Additionally, there is high regulatory uncertainty when performing a thermal anneal with respect to establishing re-embrittlement rates and solving plant—specific technical issues for the anneal. The most appealing of the mitigation approaches is the direct measurement of fracture toughness with the Master Curve methodology, since this approach involves much less empiricism and extrapolation. Also, the Master Curve fracture toughness approach has some precedence with the Nuclear Regulatory Commission (NRC) Safety Evaluation (SE) acceptance for the Kewaunee RPV [7] and the indirect application for the Zion

RPVs by the B&W Owners Group [8]. Industry groups have extensively studied the other mitigation methods, but none have been carried forward through the NRC licensing process at this time.

To meet the intent of current regulations using the CVN-based approach, FENOC recognizes that the current testing that has been completed to date is not sufficient to properly project an RT_{PTS} value for EOLE based on the ASTM E 1921-97 transition temperature, T_o [2], and the ASME Code defined transition temperature, RT_{To} based on T_o [9]. Therefore, a supplemental surveillance capsule has been fabricated and installed in Beaver Valley Power Station Unit 2 (BVPS-2). This supplemental capsule contains all of the beltline materials in BVPS-1, and the irradiation in BVPS-2 will allow faster accumulation of fluence than that possible in BVPS-1 (i.e., BVPS-2 has higher lead factor locations than BVPS-1). The testing of the supplemental capsule as part of a revised surveillance program will allow direct measurement of fracture toughness at the fluence corresponding to EOLE, thus eliminating the need to extrapolate using lower fluence data.

Section 3 includes presentation of the baseline Master Curve fracture toughness results for all of the beltline materials. Proof of consistency between the various testing laboratories is shown using round robin results from various sources. The actual methodology used to determine the adjusted reference temperature (ART) using RT_{To} and a suitable margin is presented in Section 4. The projections for RT_{PTS} at EOL and EOLE are made in Section 4, as well as the values of ART at the ¼-thickness (¼-T) and ¾-thickness (¾-T) locations in the vessel at EOL and EOLE. These ¼-T and ¾-T values will be used for calculation of heat-up and cool-down curves in WCAP-15618 [10].

Details of the supplemental surveillance program for BVPS-1 are presented in Section 5. Key integration requirements are reviewed since the supplemental capsule will be irradiated in BVPS-2. It is important to emphasize that this is the first supplemental surveillance program designed for fracture toughness testing and includes all of the RPV beltline materials. The future withdrawal schedule for the remaining BVPS-1 surveillance capsules and the supplemental capsule in BVPS-2 is presented and discussed with regard to future validation.

2 REVIEW OF CVN RESULTS AND PTS STATUS FOR BVPS-1

2.1 REVIEW OF BASELINE CVN DATA

The beltline region of an RPV, per ASTM E185-82 [11], is defined as "the irradiated region of the reactor vessel (shell material including weld regions and plates or forgings) that directly surrounds the effective height of the active core and adjacent regions that are predicted to experience sufficient neutron damage to warrant consideration in the selection of the surveillance material." Figure 2-1 indicates the location of all beltline region materials for the BVPS-1 RPV. The plate and weld materials are designated by manufacturing codes different from the actual heat numbers. Table 2-1 provides a summary of the identified RPV beltline materials and their actual heat numbers.*

The Nuclear Steam Supply System (NSSS) vendor, Westinghouse Electric Company, developed the original surveillance program for the BVPS-1 RPV. The original surveillance program was designed under ASTM E 185-73, but subsequent testing has followed the latest version of ASTM E 185 that has been approved by the NRC, through ASTM E 185-82. A description of the surveillance program and the pre-irradiation mechanical properties of the reactor vessel materials are presented in WCAP-8457, "Duquesne Light Company Beaver Valley Unit 1 Reactor Vessel Radiation Surveillance Program" [12]. Based on the measured chemistry, initial mechanical properties, and projected fluence, Lower Shell Plate B6903-1 (Heat # C6317-1) and the submerged arc weld metal identical to the vessel intermediate shell longitudinal weld seams (Heat # 305424) were selected to be in the reactor vessel surveillance program. Four surveillance capsules have been withdrawn and tested to date with the latest capsule, Capsule Y, having been recently removed at 14.3 EFPY. Table 2-2 presents a summary of the capsules withdrawn from the BVPS-1 reactor vessel along with the most recently calculated capsule fluence values.

Table 2-3 provides a summary of the available CVN data sets for each of the reactor pressure vessel plate and weld materials. Note that additional CVN test results have been generated by Westmoreland Material Research and Testing Inc. (WMTR) for the beltline plate materials to confirm the original baseline results. These results are summarized in Appendix A. The new CVN results are consistent with the original baseline for all of the plate materials within the level of scatter expected. The results for the surveillance plate material are very consistent and do not warrant any change from the existing baseline properties used in previous evaluations. The CVN results for the two welds not in the BVPS-1 surveillance program are also summarized in Appendix A. These welds are footnoted in Table 2-3 as being the welds in the Ft. Calhoun (Heat # 305414) and St. Lucie-1 (Heat # 90136) surveillance programs. Additional testing has

* Note that the manufacturing code and the heat number are similar in format for plates, and some confusion can occur since both formats are referenced in different reports and documents. This report uses both formats as indicated in Table 2-1 where the B format is the manufacturing code and the C format is the heat number. When the C format is used, the wording typically indicates the material as the plate heat or heat number and when the B format is used, the material is simply designated as the plate. The welds are termed by their heat number.

been performed to compare the baseline CVN properties for these two welds [13, 14]. This comparison of the CVN data is presented in Appendix A and illustrates that the baseline results for the Ft. Calhoun and St. Lucie surveillance programs are consistent with the new CVN data.

2.2 SIMILARITY OF PLATES B6607-1 AND B6607-2 (Plate Heats C4381-1 and C4381-2)

The original qualification records indicated that plate materials B6607-1 and B6607-2 exhibited differing material properties in terms of initial RT_{NDT}. These two plate materials correspond to heat numbers C4381-1 and C4381-2, respectively, and are the same melt heat split into two separate plate sections. As identified in Table 2-1, the initial RT_{NDT} values differ by 30°F, due to differences in the measured nil-ductility transition (NDT) temperatures. This difference in NDT temperature is probably insignificant since variability in measured NDT temperatures can be 30°F or higher. In the past, however, these two plate sections have been treated as different plate materials.

Upon the completion of the recent CVN testing identified in Table 2-3, and the comparison review summarized in Appendix A, these two plate sections have been shown to have essentially identical CVN mechanical properties. Figure 2-2 shows the comparison between the latest TL CVN results for the two plate sections. There is no discernable difference in the results. This equivalency, along with the baseline fracture toughness data presented later in Section 3 of this report, validates that these plates can be treated as a single plate material. This treatment as a single material is important since it reduces the number of materials to be tested and evaluated in the supplemental surveillance capsule described in Section 5.

2.3 REVIEW OF IRRADIATED CVN RESULTS AND PTS EVALUATIONS

In 1985, the NRC issued a formal rule on PTS, 10 CFR 50.61. It established the screening criteria for pressurized water reactor (PWR) vessel embrittlement as measured by the reference temperature termed RT_{PTS}. Screening criteria were set corresponding to EOL plant operation for beltline axial welds, forgings, and plates at 270°F, and at 300°F for beltline circumferential weld seams. All PWR vessels in the United States have been required to evaluate vessel embrittlement in accordance with these criteria through EOL or beyond.

The NRC amended its regulations for PWR plants to change the procedure for calculating radiation embrittlement RT_{PTS} values. The revised PTS Rule was published in the Federal Register, May 15, 1991 with an effective date of June 14, 1991. This amendment made the procedure for calculating RT_{PTS} values consistent with the method given in Regulatory Guide 1.99, Revision 2 [15]. The PTS Rule states:

- The screening criteria for the reactor vessel beltline region are:

  270°F for plates, forgings, and axial welds
  300°F for circumferential welds

- The following equations must be used to calculate RT_{PTS} values for each weld, plate or forging in the reactor vessel beltline:

$$RT_{PTS} = I\,RT + \Delta RT_{PTS} + M \quad (1)$$

where IRT is the initial RT_{NDT} and M is a required margin term;

$$\Delta RT_{PTS} = CF * [f]^{(0.28 - 0.1 \log[f])} \quad (2)$$

where CF is the chemistry factor and f is the fluence (10^{19} n/cm^2; E > 1 MeV).

- All values of RT_{PTS} must be verified to be bounding values for the specific reactor vessel. In doing this, each plant should consider plant-specific information that could affect the level of embrittlement.

- Plant-specific PTS safety analyses are required before a plant is within three years of reaching the screening criteria, including analyses of alternatives to minimize the PTS concern.

- NRC approval for operation beyond the screening criteria is required.

2.3.1 Summary of PTS Evaluation Prior to Testing Capsule Y

In complying with the provisions of the PTS Rule, extensive RT_{PTS} analyses have been performed prior to the withdrawal of the most recent surveillance capsule (Capsule Y). These analyses evaluated alternative approaches to address PTS concerns. The last analysis was based on the Safety Evaluation (SE) on PTS for BVPS-1 issued by the NRC in October 1997 [16]. From this SE, the properties for the limiting plate material B6903-1 (Heat # C6317-1) were defined as:

Initial RT_{NDT}:	27°F
Chemistry Factor:	159.9°F
Margin:	34°F

Based on these parameters, it was determined that the limiting plate material B6903-1 (Heat # C6317-1) would reach the PTS screening limit of 270°F at a fluence value of 3.21×10^{19} n/cm^2. Figure 2-3 provides a graphic illustration of the projected RT_{NDT} as a function of fluence based on assumptions prior to the testing of Capsule Y. Note that the SE issued by NRC is very conservative using the Charpy transition temperature shift approach with a chemistry factor based on assumed credible measured shift data and a margin term based on non-credible data (i.e., 2 sigma).

For projection purposes as to when this fluence level would be reached, plant operations were assumed to have the following profile:

- The RPV core configuration would be L4P + hf (low-low leakage core with hafnium inserts) through the end of cycle 14. Hafnium would then be removed at the start of Cycle 15.
- A 1% power uprate at the beginning of cycle 15.
- An additional power uprate of 5% (for a total of 6%) would occur at the beginning of cycle 16.

Based on these plant operating parameters and a 93% capacity factor, the fluence level of 3.21×10^{19} n/cm^2 was estimated to occur around 8/20/2014, well before the current EOL date of 1/1/2016.

2.3.2 Summary of PTS Evaluation Including Capsule Y CVN Data

Capsule Y was recently withdrawn from BVPS-1 at the end of Cycle 13. To more accurately assess the PTS situation at BVPS-1, the CVN and measured fluence data were re-evaluated to include these latest results [17]. Additionally, updated plant operation parameters including core configuration were adjusted.

Impact on Chemistry Factor based on New Capsule Y CVN Data

Table 2-4 summarizes the fluence and RT_{NDT} shift (ΔRT_{NDT}) results for each of the four capsules withdrawn to date. ΔRT_{NDT} results were all determined using symmetric hyperbolic tangent (tanh) curve fits* to the CVN energy data and determining the temperature shift at 30 ft-lb. Utilizing the shift values listed in Table 2-4, the chemistry factor (CF) was determined as shown in Figure 2-4. The inclusion of the Capsule Y data lowers the calculated CF very close to the chemistry table value from Regulatory Guide 1.99, Rev. 2 and 10 CFR 50.61. Spread sheet calculations of the CF values for the plate and weld surveillance materials are presented in Table 2-5.

In summary, the chemistry factors for the surveillance plate material are:

Regulatory Guide 1.99, Rev 2 (based on Cu and Ni content only)	141.8°F
Fitted CF from spreadsheet (Table 2-5) and CVGRAPH 5.0 (Figure 2-4)	149.4°F

*Using CVGRAPH, Version 5.0

Thus, the higher, more conservative CF of 149.4°F, based on the CVN data fit (assuming credibility) for the plate results, will be used for future projections. Note that the weld CF is higher than that for the plate material, but the peak flux location does not occur at the longitudinal weld seams. The projected shift for the axial welds is much less than that for the base metal, and, in addition, the initial RT_{NDT} is considerably lower for the welds.

New Fluence Projections Based on Anticipated Plant Operations

Estimates for flux values come from the latest information presented in WCAP-15571 [17]. Azimuthal variations of neutron exposure at the clad/base metal interface are indicated and the maximum occurs at the 0° locations, as seen in Table 2-6.

The resulting impact to flux and fluence estimates, based on revised plant operations and core configuration, are described below.

- In June 2001 (during Cycle 14), a 1.4% power up-rate is scheduled. From Table 2-6, calculated flux values are available for Cycles 10 – 13 (which all have the same L4P + hf core configuration). The average peak flux value for these cycles is 2.71×10^{10} n/cm^2-s. This flux is used at the beginning of Cycle 14 and continues until the power up-rate occurs in June 2001. The 1.4% power up-rate will result in a calculated peak flux rate of 2.75×10^{10} n/cm^2-s. This value will be applied for the remainder of Cycle 14.

- At the end of Cycle 14, hafnium will be removed from the core resulting in an 'L4P only' core configuration. This configuration is equivalent to that seen during Cycle 8, which was the last time the core was in an 'L4P only' core configuration. A 1.4% power up-rate needs to be applied to the Cycle 8 value. The calculated peak flux for Cycle 8 was 4.07×10^{10} n/cm^2-s. Thus, an additional 1.4% (to compensate for the power up-rate) results in a calculated peak flux of 4.13×10^{10} n/cm^2-s. This will be the flux used at the start of Cycle 15.

- In January 2003, an additional 8% power up-rate (for a total of 9.4%) is scheduled. This timing occurs with about three months left in Cycle 15. So for the first 431 days of Cycle 15, a calculated peak flux rate of 4.13×10^{10} n/cm^2-s will be used. This value will be adjusted by 8% for the remaining 82 days of Cycle 15. This results in a calculated peak flux rate of 4.45×10^{10} n/cm^2-s for the remainder of the cycle.

- Plant operation for all remaining cycles is projected to maintain the 'L4P only' core configuration with the 9.4% power up-rate. The flux will remain at 4.45×10^{10} n/cm^2-s.

A summary of the flux rates used for determining fluence values at EOL and EOLE are presented below in Table 2-7.

Fluence values for the plant operation of BVPS-1 can be projected utilizing the flux values presented in Table 2-7. Table 2-8 presents the fluence projections for plant operation out past EOLE (1/1/2036).

Calculation of RT_{PTS} Values based on Updated Plant Information

Based on the revised fluence, a capacity factor of 90% and new shift data provided by the analysis of the CVN data from Capsule Y, new baseline values for the limiting plate material are used to estimate when the PTS screening criterion is reached:

Initial RT_{NDT}	27°F
Chemistry Factor	149.4°F
Margin	34°F

The conservative CF is used assuming credible data from the surveillance program. The margin term is maintained at 34°F (for non-credible data) since the data scatter [13] is still greater than that allowed by Regulatory Guide 1.99, Rev. 2 or 10 CFR 50.61. With these values and Equations 1 and 2, a new fluence value can be determined when RT_{NDT} = 270°F. The fluence value corresponding to these input parameters is 4.91×10^{19} n/cm^2. From the information provided in Table 2-8, the RT_{PTS} limit of 270°F is estimated to occur around 10/30/2027, well after the EOL (1/1/2016). Figure 2-5 compares the projections of temperature shift for both evaluations, with and without including the results from Capsule Y. Thus, the lowering of the chemistry factor with the addition of Capsule Y data allows plant operation to continue out past EOL. However, at EOLE (1/1/2036), the fluence value is estimated to be 5.87×10^{19} n/cm^2. This fluence equates to an RT_{PTS} value of 275.1°F. Therefore, to reach EOLE, alternatives such as the Master Curve approach must be explored and implemented.

Application of the Master Curve approach is being sought now (during current operating life) to provide additional operating margin during heatup/cooldown activities, which lowers the risk associated with an inadvertent actuation of the low temperature over pressure protection system and minimizes the need for operator work around. Additionally, testing and evaluating the properties of the RPV materials using the Master Curve approach provides a technically superior method for assessing radiation damage now and into extended license life.

Table 2-1 Summary of the BVPS-1 RPV Beltline Materials

Material	Material Type	Heat Number	Cu Content (wt %)	Ni Content (wt %)	Initial RT_{NDT} [(a)] (°F)
Intermediate Shell Plate B6607-1	SA533B-1	C4381-1	0.14	0.62	43
Intermediate Shell Plate B6607-2	SA533B-1	C4381-2	0.14	0.62	73
Lower Shell Plate B6903-1[(b)]	SA533B-1	C6317-1	0.205[(c)]	0.535[(c)]	27
Lower Shell Plate B7203-2	SA533B-1	C6293-2	0.14	0.57	20
Intermediate Shell Longitudinal Welds 19-714A/B[(b)]	Linde 1092	305424	0.282[(c)]	0.630[(c)]	-56
Lower Shell Longitudinal Welds 20-714A/B	Linde 1092	305414	0.337	0.609	-56
Circumferential Weld 11-714	Linde 0091	90136	0.269	0.070	-56

(a) Initial RT_{NDT} values of the plate materials are measured values, while those for the weld materials were not measured and generic values are used.
(b) These materials are contained in the BVPS-1 surveillance program.
(c) Adjusted based on latest Capsule Y measurements [17].

Table 2-2 Summary of Capsules Withdrawn in the BVPS-1 Surveillance Program

Capsule	Reference	Calculated Capsule Fluence [(a)] ($\times 10^{19}$ n/cm^2)
Unirradiated Baseline	WCAP-8457 [12]	---
V	WCAP-9860 [18]	0.323
U	WCAP-10867 [19]	0.646
W	WCAP-12005 [20]	0.986
Y	WCAP-15571 [17]	2.15

(a) The most recent fluence calculations are contained in WCAP-15571 [17].

Table 2-3 Available CVN Data for BVPS-1 Materials

RPV Material	CVN Data Source						
	Original Qualification Data[a]	Baseline Surv. Program	Add'l WMTR[b] Testing	Capsule U	Capsule V	Capsule W	Capsule Y
Plate B6903-1	LT[c]	TL[d] & LT	TL & LT	TL & LT	TL & LT	TL & LT	TL & LT
Plate B6607-1	TL & LT	---	TL & LT	---	---	---	---
Plate B6607-2	TL & LT	---	TL & LT	---	---	---	---
Plate B7203-2	LT	---	TL	---	---	---	---
Weld 305424	---	T[e]	---	T	T	T	T
Weld 305414	---	T[f]	T	---	---	---	---
Weld 90136	---	T[g]	T	---	---	---	---

(a) Original qualification CVN data from either material certifications or additional CVN testing performed by Westinghouse for the surveillance program in 1973.
(b) Westmoreland Mechanical Testing & Research Inc. (WMTR).
(c) LT indicates longitudinal orientation.
(d) TL indicates transverse orientation.
(e) T indicates transverse orientation equivalent for all the welds with the crack running in the welding direction.
(f) This weld is the surveillance material in the Ft. Calhoun program; surveillance CVN data are available at 0.553, 0.771, and 1.28×10^{19} n/cm^2.
(g) This weld is the surveillance weld in the St. Lucie-1 program; surveillance CVN data are available at 0.550 and 0.716×10^{19} n/cm^2.

Table 2-4 Summary of Fluence and RT_{NDT} Shift Values for BVPS-1 Radiation Surveillance Program

Surveillance Material	Capsule	Fluence, f ($x10^{19}$ n/cm^2)	FF[a]	ΔRT_{NDT} (°F)
Lower Shell Plate B6903-1 (LT)	V	0.323	0.689	128.49
	U	0.646	0.878	118.93
	W	0.986	0.996	148.52
	Y	2.15	1.208	142.18
Lower Shell Plate B6903-1 (TL)	V	0.323	0.689	137.81
	U	0.646	0.878	131.84
	W	0.986	0.996	179.99
	Y	2.15	1.208	166.93
Surveillance Weld Metal 19-4A/B (Heat # 305424)	V	0.323	0.689	159.72
	U	0.646	0.878	166.32
	W	0.986	0.996	187.73
	Y	2.15	1.208	179.69

(a) $FF = [f]^{(0.28 - 0.1 \log [f])}$

Table 2-5 Determination of Chemistry Factor for BVPS-1 Following Regulatory Guide 1.99, Revision 2

Material	Capsule	f[a]	FF[b]	ΔRT_{NDT}[c]	FF x ΔRT_{NDT}	FF^2
Lower Shell Plate B6903-1 (Longitudinal)	V	0.323	0.689	128.49°F	88.53°F	0.475
	U	0.646	0.878	118.93°F	104.42°F	0.771
	W	0.986	0.996	148.52°F	147.93°F	0.992
	Y	2.15	1.208	142.18°F	171.75°F	1.459
Lower Shell Plate B6903-1 (Transverse)	V	0.323	0.689	137.81°F	94.95°F	0.475
	U	0.646	0.878	131.84°F	115.76°F	0.771
	W	0.986	0.996	179.99°F	179.27°F	0.992
	Y	2.15	1.208	166.93°F	201.65°F	1.459
				SUM	1104.26°F	7.394
	$CF_{Plate\ B6903-1} = \Sigma(FF \times \Delta RT_{NDT}) \div \Sigma(FF^2) = 1104.26°F \div 7.394 = 149.4°F$					
Weld Metal (Heat 305424)	V	0.323	0.689	159.72°F	110.05°F	0.475
	U	0.646	0.878	166.32°F	146.03°F	0.771
	W	0.986	0.996	187.73°F	186.98°F	0.992
	Y	2.15	1.208	179.69°F	217.07°F	1.459
				SUM	660.13°F	3.697
	$CF_{Weld\ Metal} = \Sigma(FF \times \Delta RT_{NDT}) \div \Sigma(FF^2) = 660.13°F \div 3.697 = 178.6°F$					

(a) f = Calculated fluence from capsule Y evaluation, (x 10^{19} n/cm², E > 1 MeV).
(b) FF = fluence factor = $[f]^{(0.28 - 0.1 * \log[f])}$
(c) ΔRT_{NDT} values are the measured 30 ft-lb temperature shift values.

Table 2-6 Calculated Azimuthal Variation of Fast Neutron Flux at the RPV Clad/Base Metal Interface

Cycle No.	φ (E > 1 MeV) (x 10^{10} n/cm²-s)			
	0°	15°	30°	45°
8	4.07	2.21	1.17	0.754
9	3.64	2.03	1.19	0.838
10	2.79	1.56	1.05	0.750
11	2.59	1.39	1.09	0.819
12	2.70	1.53	1.13	0.723
13	2.76	1.50	1.08	0.752

Table 2-7 Calculated Fluxes for Cycles 13 - 17

Cycle	Start Date	End Date	Cycle Days	φ (E > 1 MeV) (x 10^{10} n/cm^2-s)
13	01/21/98	02/11/00		2.76
14a	04/21/00	06/01/01	406	2.71
14b	06/01/01	09/14/01	105	2.75
15a	10/24/01	01/01/03	431	4.13
15b	01/01/03	03/21/03	82	4.45
16	04/30/03	09/17/04	506	4.45
17	10/27/04	03/17/06	506	4.45

Table 2-8 Maximum Fluence Projections for BVPS-1 Beltline Inside Diameter Surface

CYCLE	START	END	CYCLE EFPY 0.90 Capacity Factor	TOTAL EFPY	CORE CONFIG	Flux Rate $x10^{10}$ n/cm^2-s	CYCLE Accum Fluence $x10^{18}$ n/cm^2	TOTAL RV FLUENCE $x10^{19}$ n/cm^2
13	1/21/1998	2/11/2000		14.30	L4P+Hf	2.76		1.76
14a	4/21/2000	6/1/2001	1.00	15.30	L4P+Hf	2.71	0.856	1.85
14b[1]	6/1/2001	9/14/2001	0.26	15.56	L4P+Hf	2.75	0.225	1.87
15a	10/24/2001	1/1/2003	1.06	16.62	L4P	4.13	1.38	2.01
15b[2]	1/1/2003	3/21//2003	0.20	16.82	L4P	4.45	0.284	2.03
16	4/30/2003	9/17/2004	1.25	18.07	L4P	4.45	1.75	2.21
17	10/27/2004	3/17/2006	1.25	19.32	L4P	4.45	1.75	2.38
18	4/26/2006	9/14/2007	1.25	20.57	L4P	4.45	1.75	2.56
19	10/27/2007	3/20/2009	1.26	21.83	L4P	4.45	1.75	2.74
20	4/29/2009	9/17/2010	1.25	23.07	L4P	4.45	1.75	2.91
21	10/27/2010	3/16/2012	1.25	24.32	L4P	4.45	1.75	3.09
22	4/25/2012	9/20/2013	1.26	25.59	L4P	4.45	1.78	3.26
23	10/30/2013	3/20/2015	1.25	26.83	L4P	4.45	1.75	3.44
24	4/29/2015	9/16/2016	1.25	28.08	L4P	4.45	1.75	3.61[3]
25	10/26/2016	3/23/2018	1.26	29.35	L4P	4.45	1.78	3.79
26	5/2/2018	9/20/2019	1.25	30.59	L4P	4.45	1.75	3.97
27	10/26/2019	3/15/2021	1.25	31.84	L4P	4.45	1.75	4.14
28	4/25/2021	9/20/2022	1.26	33.11	L4P	4.45	1.78	4.32
29	10/26/2022	3/15/2024	1.25	34.35	L4P	4.45	1.75	4.49
30	4/25/2024	9/13/2025	1.25	35.60	L4P	4.45	1.75	4.67
31	10/26/2025	3/23/2027	1.26	36.87	L4P	4.45	1.78	4.85
32	4/25/2027	9/12/2028	1.25	38.11	L4P	4.45	1.75	5.02
33	10/26/2028	3/16/2030	1.25	39.36	L4P	4.45	1.75	5.20
34	4/25/2030	9/20/2031	1.26	40.63	L4P	4.45	1.78	5.38
35	10/26/2031	3/15/2033	1.25	41.87	L4P	4.45	1.75	5.55
36	4/25/2033	9/13/2034	1.25	43.12	L4P	4.45	1.75	5.73
37	10/26/2034	3/22/2036	1.26	44.39	L4P	4.45	1.78	5.90[4]
38	4/25/2036	9/13/2037	1.25	45.63	L4P	4.45	1.75	6.08
39	10/26/2037	3/16/2039	1.25	46.88	L4P	4.45	1.75	6.25
40	4/25/2039	9/19/2040	1.26	48.15	L4P	4.45	1.78	6.43

[1] Hafnium inserts will be removed from the BVPS-1 fuel management strategy at the end of Cycle 14. In addition, a power uprate of 1.4% will also be implemented at that time.

[2] A second power uprate of 8% is implemented during Cycle 15, for a total power uprate of 9.4%.

[3] The estimated EOL fluence is calculated based on an EOL date of 1/1/2016. This is approximately 49% through Cycle 24 and corresponds to a total peak fluence of 3.52×10^{19} n/cm^2 and 27.44 EFPY.

[4] The estimated EOLE fluence is calculated based on extended license expiration on 1/1/2036. This is approximately 84% through Cycle 37 and corresponds to a total peak fluence of 5.87×10^{19} n/cm^2 and 44.18 EFPY.

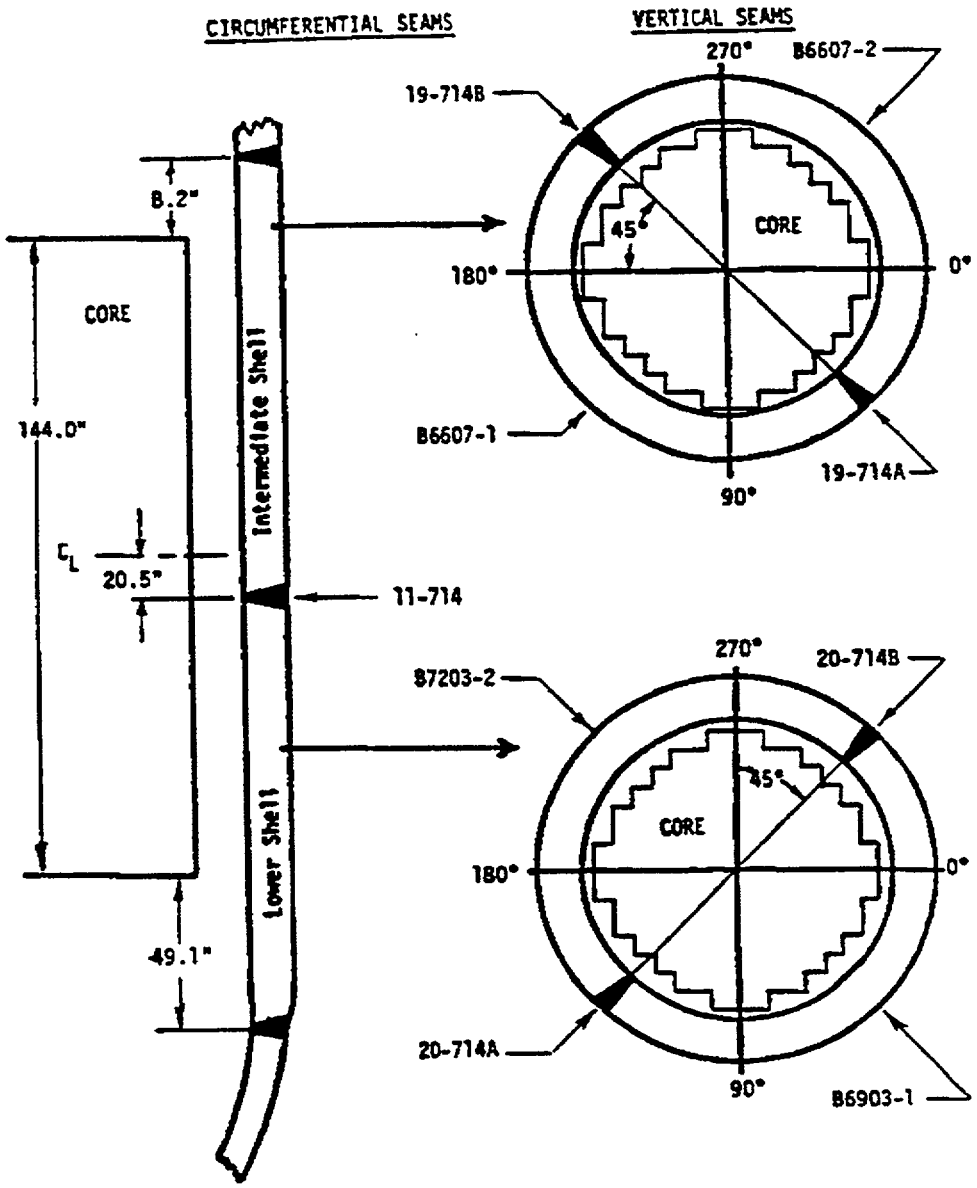

Figure 2-1 Location of BVPS-1 Beltline Region Materials

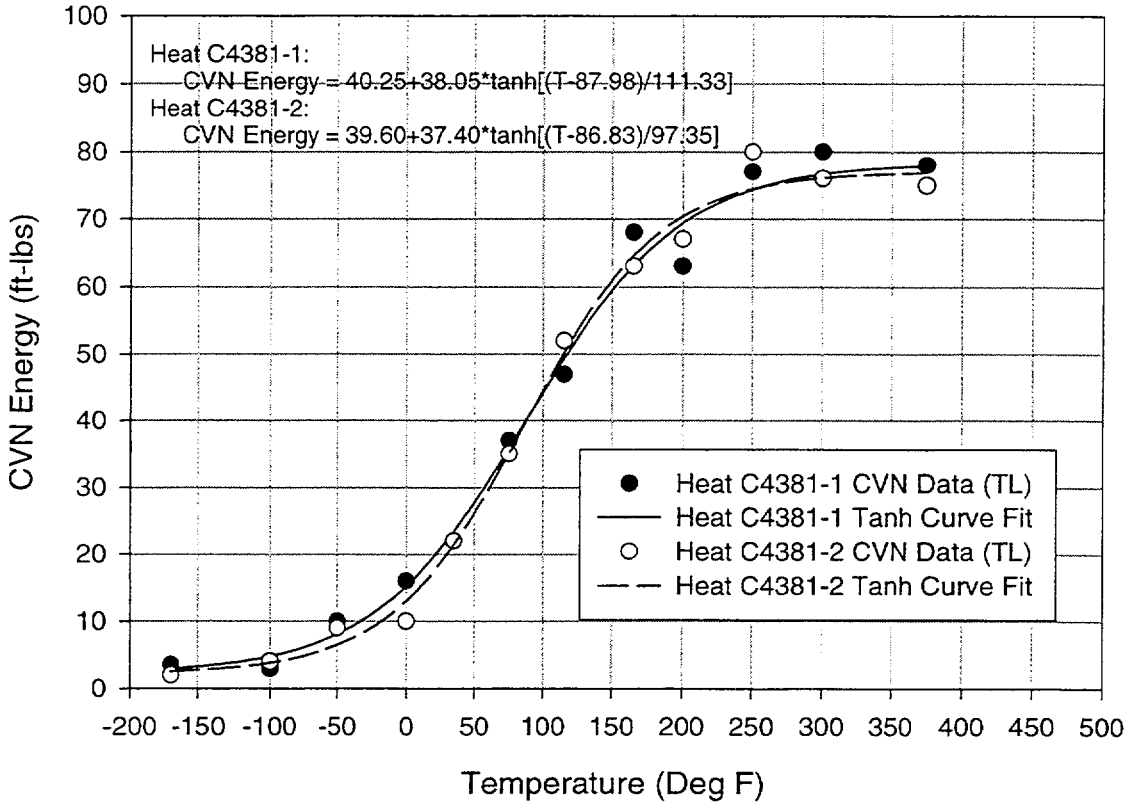

Figure 2-2 Tanh Plots for WMTR Data for Plate Heats C4381-1 and C4381-2 (TL Orientation)

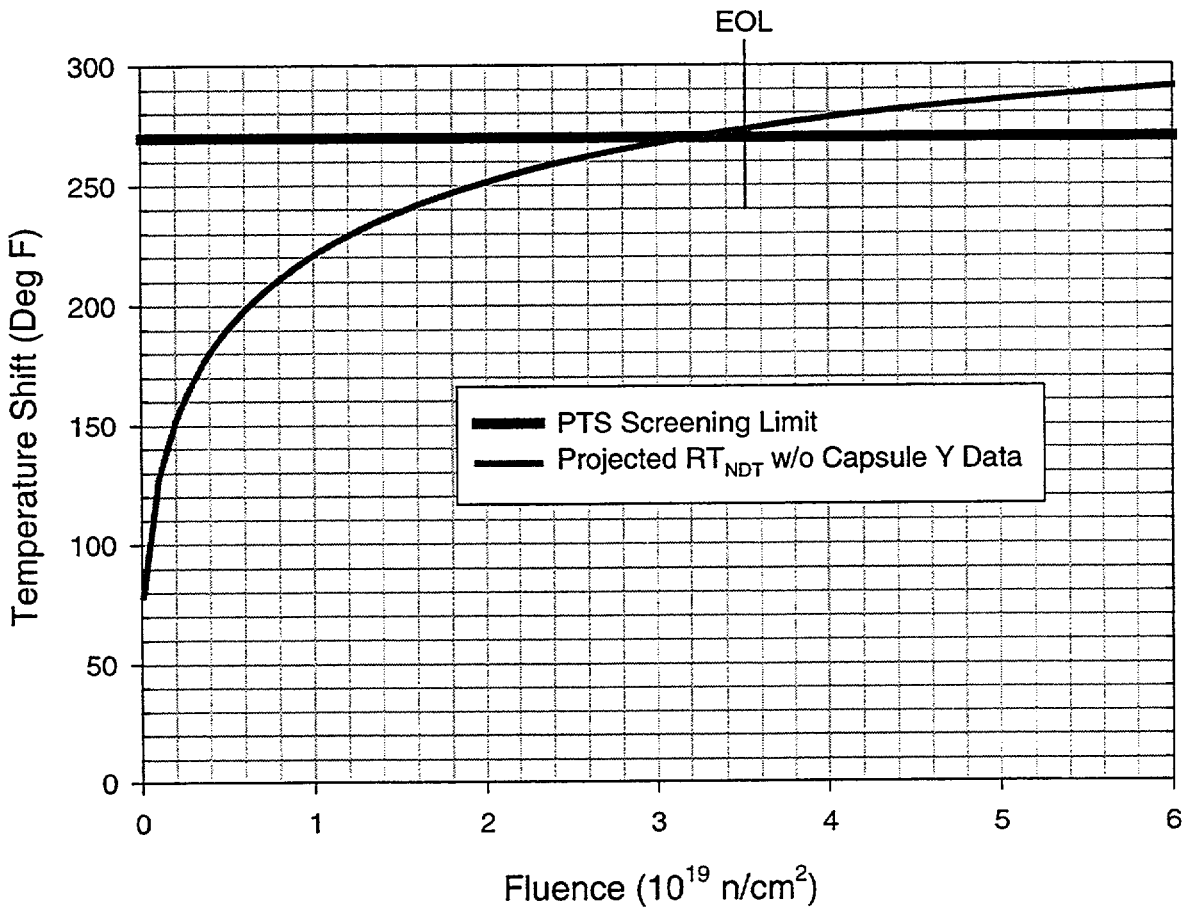

Figure 2-3 ΔRT_{NDT} Projections Prior to Testing Capsule Y

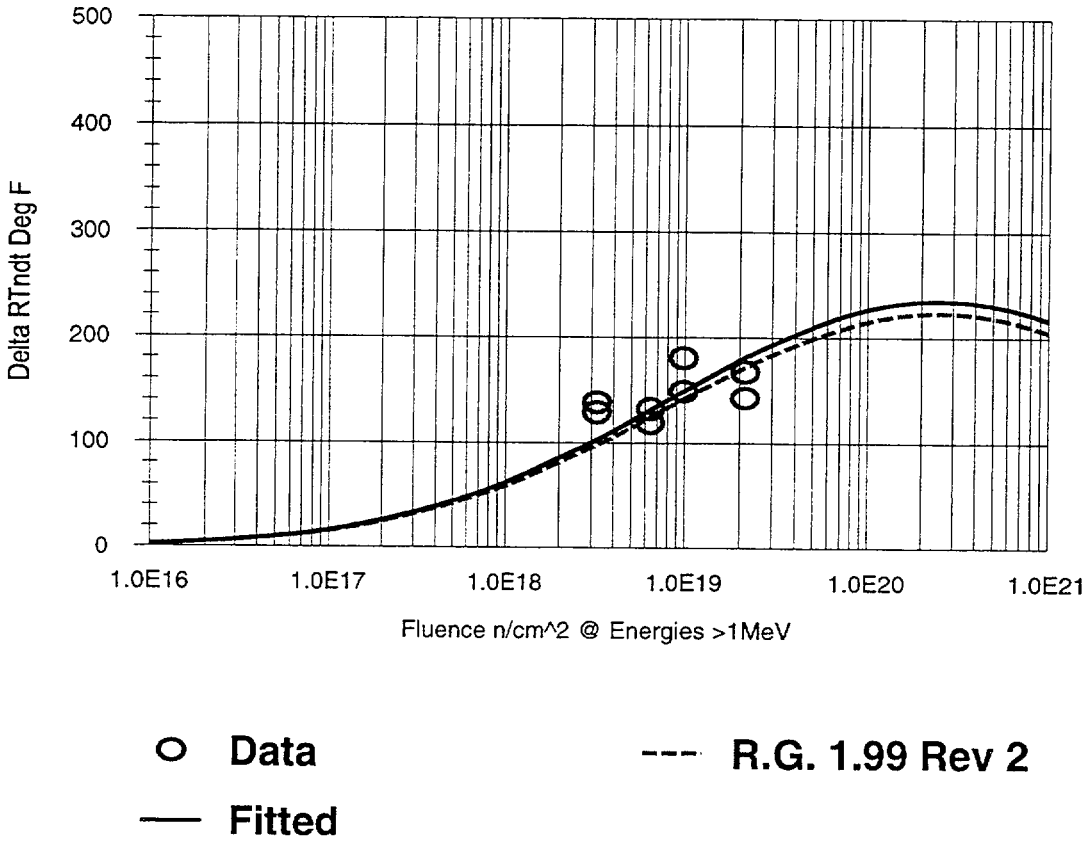

Figure 2-4 Determination of Chemistry Factor for BVPS-1 Using CVGRAPH 5.0

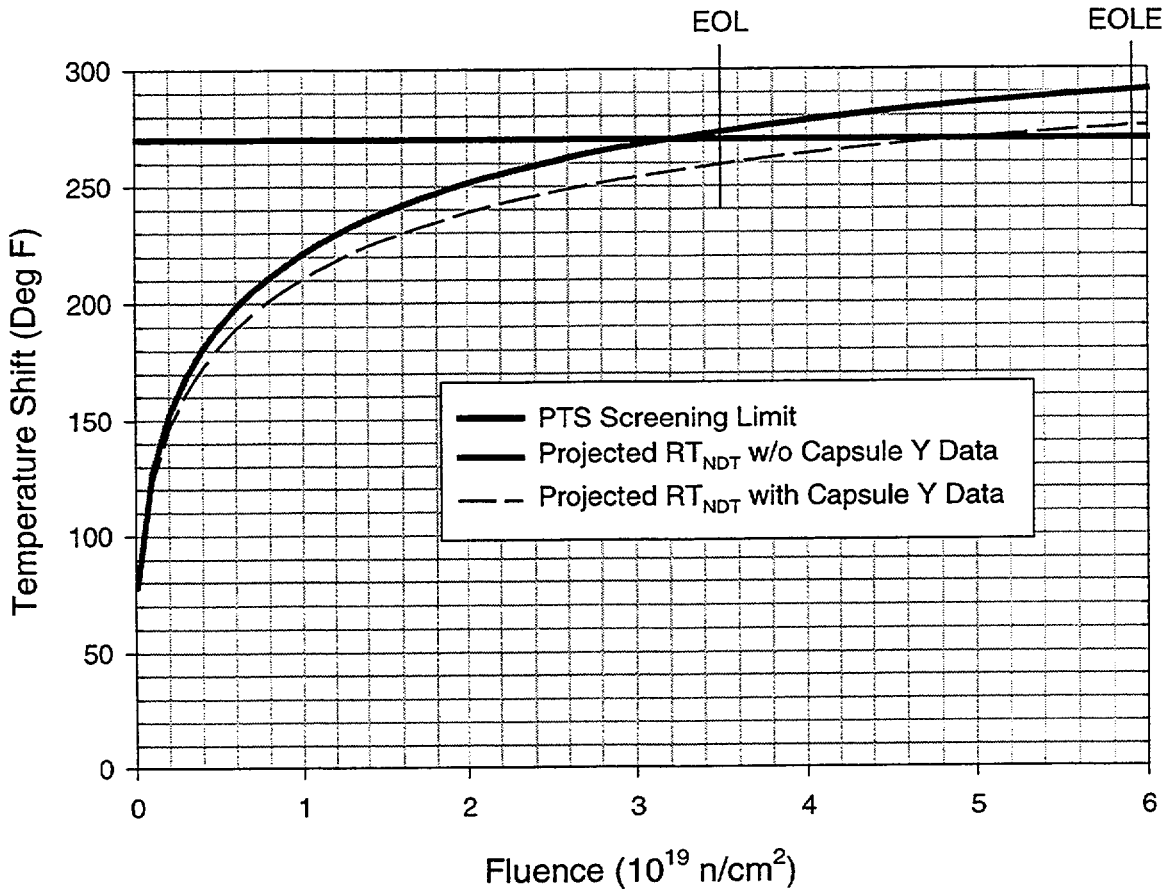

Figure 2-5 ΔRT_{NDT} Projections Following the Withdrawal of Capsule Y

3 FRACTURE TOUGHNESS TESTING AND RESULTS

This section presents the measured fracture toughness data for the BVPS-1 beltline plate, weld, and surveillance materials. These materials were previously identified in Table 2-1.

3.1 TESTING METHODOLOGY AND LABORATORIES USED

Testing methodology met the requirements of ASTM E 1921-97 [2], and includes additional information from 1X-WOL specimens that were also tested and evaluated. The multi-temperature evaluation methods were also used as proposed in a new version of ASTM E 1921-97 that is currently being balloted to utilize the most current evaluation methods to assess the data.

The BVPS-1 materials have been tested by several different laboratories:

- Westmoreland Mechanical Testing & Research, Inc. (WMTR)
- McDermott Technology, Inc. (MTI)
- Korea Atomic Energy Research Institute (KAERI),
- Westinghouse Science & Technology Center (WSTC), and
- ABB Combustion Engineering, Windsor (CE).

3.2 PROOF OF CONSISTENCY BETWEEN LABORATORIES

The testing program for the BVPS-1 RPV materials involves several different laboratories as presented above. All of these laboratories have been involved in various US nuclear industry and international programs for the assessment of fracture toughness of RPV materials. These various programs and some of the pertinent results are described in the subsection that follows. Although different test laboratories are used in this program, the differences in measured values of T_o from different test laboratories are not significant and therefore support the independence of the data generated by different testing organizations.

3.2.1 NSSS Vendor Testing of Shoreham Weld Metal

In an effort to move the Master Curve method forward in the nuclear industry prior to the final approval of ASTM E 1921-97, the three PWR NSSS vendors - Westinghouse (testing by STC), Framatome Technologies, Inc. (with testing by MTI), and ABB-Combustion Engineering (CE) - participated in an internal round robin testing program using the Shoreham Linde 1092 weld metal. The results are shown in Table 3-1.

There is acceptable agreement between the three testing laboratories. ASTM E 1921-97 indicates that results within 18°F (10°C) are to be expected.

3.2.2 MPC Round Robin Testing of 73W Weld Metal

The Materials Property Council (MPC) has sponsored a round robin test program that involves ten different laboratories, including Westinghouse (WMTR), Framatome Technologies, Inc. (with testing performed by MTI), CE, and KAERI. The material being evaluated is a Linde 124 weld metal (73W) specially fabricated for the NRC-sponsored Heavy Section Steel Irradiation (HSSI) program conducted at Oak Ridge National Laboratory (ORNL). All of the round robin testing and data analysis have not been completed, but some preliminary results are shown in Table 3-2. The 73W weld metal has been tested extensively at ORNL, but the specific weldment used for the round robin program is different than the weldment used in the previous fracture toughness testing. Therefore, additional one-inch thickness (1T) compact tension (1T-CT) tests are planned for the round robin weldment to further document its pedigree and its relationship to the previous weldment characterization. The round robin results show reasonable agreement between the laboratories.

3.2.3 IAEA Results on A533B-1 Plate JRQ

Heat JRQ was supplied by the Japanese as an international reference material under sponsorship of the International Atomic Energy Agency (IAEA). This heat was tested extensively in a Coordinated Research Program (CRP) on Neutron Irradiation Effects on Advanced Pressure Vessel Steels. This IAEA program was focused on fracture toughness testing of several different RPV steel heats. Several different laboratories in different countries tested heat JRQ in both the LT and TL orientations. The results from these tests have been analyzed and evaluated [21]. Several key points can be made:

- The LT orientation data show a marked effect of plate thickness location, while the TL data do not display this difference.

- The estimated T_o value for the LT data at ¼-thickness (¼-T) of 2.2 in (56 mm) is -94°F (–70°C) based on both compact tension and three-point bend specimen tests; no real differentiation in test specimen type or size is evident from the data.

- The estimated T_o value for the TL data at ¼-T is –67°F (-55°C), where some data show a bias between compact tension and three-point bend precracked Charpy tests, whereas the rest of the data do not show any bias effects due to specimen type or size.

Note that this evaluation was performed before ASTM E 1921-97 was available, and some of the T_o values may not be valid following current practice. None of the laboratories participating in the BVPS-1 testing program participated in this initial CRP.

The IAEA then conducted another CRP on Master Curve Application to Reactor Pressure Vessel Material Testing. This CRP was completed at the end of 1999, but the data have not been fully analyzed and published. A preliminary evaluation [22] of the extensive three-point bend precracked Charpy testing of the JRQ material (TL orientation) revealed:

- The best estimate T_o value for precracked Charpy specimens is –94°F (–70°C); note that the material for this later CRP was taken from a different section of the large reference plate.

- For the ASTM E 1921-97 approach, the lower the test temperature relative to –94°F (–70°C), the lower the measured value of T_o, although the measured values of T_o are still within 18°F (10°C) down to a test temperature of –148°F (–100°C).

- No difference between T_o values can be found with regard to test laboratory (over twenty participated) or single- and multi-temperature assessment methods.

Three of the laboratories participating in the BVPS-1 testing program participated in this CRP: MTI, STC, and KAERI. Results from these three laboratories appear to be consistent.

Another CRP has been initiated in 2000 by the IAEA on Surveillance Programmes Results Application to RPV Integrity Assessment [23]. This CRP will initially involve further extensive 1T-CT and precracked Charpy testing of the JRQ material. The final results for heat JRQ from this CRP should define any bias that exists between 1T-CT and three-point bend precracked Charpy specimens. This IAEA CRP also is chartered to develop international guidelines for using the Master Curve approach in defining RPV embrittlement relative to PTS and heat-up and cool-down curves. BVPS-1 personnel are active participants in the CRP and will assist in coordinating testing (along with EPRI) of the JRQ material. BVPS-1 personnel will also act as overall evaluators of the project.

The relevance of this IAEA program with regard to the BVPS-1 testing is three-fold:

- The life-limiting material for the BVPS-1 vessel is a plate material, A533B-1 steel, and the reference material for the IAEA program is heat JRQ, A533B-1 steel plate.

- The potential bias effect for heat JRQ is being investigated systematically in the new IAEA CRP experimental program, which was initiated this year; previous data are not adequate to define a bias effect.

- Laboratory variability in measuring and assessing T_o values following ASTM E 1921-97 and the multi-temperature methodology has been assessed for heat JRQ: no appreciable variability has been identified.

3.3 LAYOUT OF TESTING PROGRAM FOR BVPS-1 MATERIALS

This section presents the layout of the fracture mechanics test program for BVPS-1 materials. It describes and presents the data for testing performed to date.

Table 3-3 shows the layout of BVPS-1 materials fracture toughness testing to date. The TL orientation test data for each specimen type are given in Appendix B (Plate) and Appendix C (Weld). The LT orientation test data are provided for information in Appendix D. The data are presented in SI units because the testing standard, ASTM E 1921-97, was written in SI units. The T_o results (see Sections 3.4 and 3.5) will be presented in both SI and English units.

The testing program has included the following test specimen types: standard compact tension (CT) (both 1T and ½T sizes); precracked Charpy three point bend (PCVN); reconstituted precracked Charpy (RPCVN); and 1X-WOL specimens. The 1X-WOL specimen geometry is one that was used in the early days of fracture mechanics before the compact tension geometry was fully developed and standardized, and some of the BVPS-1 surveillance capsules contain 1X-WOL specimens.

Appendix E contains fracture toughness results for a weld similar to Heat 90136, a Linde 0091 flux weld. This weld was from the Farley-1 surveillance program and represents the only Linde 0091 weld evaluated in both the unirradiated and irradiated conditions using both CT and PCVN specimens. These results, although not directly applicable to the BVPS-1 RPV, are added to this report for comparison of general trends for this different flux type weld.

3.4 RESULTS FOR BVPS-1 PLATES

Table 3-4 shows both unirradiated and irradiated T_o results for the surveillance plate (Heat C6317-1). Tables 3-5 and 3-6 show the T_o results for the second and third most limiting plates (C4381-2 and C6293-2, respectively).

Unirradiated values of T_o for the BVPS-1 surveillance plate material in the TL orientation were determined using three different specimen sizes and geometry. 1T-CT and ½T-CT specimens were tested in accordance with ASTM E 1921-97 using the single temperature method. Precracked Charpy three-point bend (PCVN) specimens were also tested and T_o values determined using both ASTM E 1921-97 and the multi-temperature methodology being voted by the ASTM Committee that wrote E 1921-97*. For the PCVN tests, there was only one additional specimen tested at a temperature higher than that used for the E 1921-97 determination, and not surprisingly the results are only 4.3°F different. The use of the multi-temperature method is considered appropriate since all data should be considered if the fracture toughness tests are valid.

The results of fracture toughness tests on the surveillance plate (Heat C6317-1) and the second most limiting plate (Heat 4381-2) in the LT orientation are given in Appendix D. These tests were conducted using: PCVN and reconstituted PCVN (RPCVN) specimens to validate the reconstitution process for the broken irradiated surveillance capsule CVN specimens; 1T-CT specimens; and 1X-WOL specimens that were modified to simulate compact tension-type specimens. The results from some of these tests in the LT orientation are discussed later in Section 4.

*The single-temperature calculation of T_o using ASTM E 1921-97 and the revised version being balloted are slightly different and can lead to a difference in the T_o values of about 1°F.

3.5 RESULTS FOR BVPS-1 WELDS (UNIRRADIATED ONLY)

Table 3-7 shows unirradiated T_o results for the surveillance weld (Heat 305424). Tables 3-8 and 3-9 show the T_o results for weld heats 305414 and 90136, respectively.

Table 3-1 Round Robin Testing Program Results for Shoreham Linde 1092 Weld

Laboratory	Heat	Flux Type	Test Temperature °F (°C)	K_{Jc} (Med) ksi√in (MPa√m)	T_o °F (°C)
CE	20291/12008	Linde 1092	-200 (-129)	91.7 (100.7)	-201 (-129)
MTI	20291/12008	Linde 1092	-200 (-129)	85.5 (93.9)	-191 (-124)
WMTR	20291/12008	Linde 1092	-200 (-129)	74.2 (81.5)	-184 (-120)

Table 3-2 Preliminary MPC Round Robin T_o Results from PCVN Three-Point Bend Tests of Weld 73W

Laboratory	Test Temperature, °c			Laboratory Average, °C
	-100	-85	-75	
WMTR	-87	-86	--	-86
MTI	-77	-75	--	-76
KAERI	-84	--	-69	-77
CE	-85	-75	-83	-81
AVERAGE, °C	-83	-79	-76	-79

Table 3-3 Available Fracture Toughness Data for BVPS-1 Materials			
RPV Material Heat Number	**Specimen Orientation**	**Specimen Type**	**Table Numbers Corresponding to Specimen Type**
Plate Heat C6317-1 (Unirradiated)	TL	PCVN, ½T-CT, 1T-CT	B-2, B-3, B-1
	LT	PCVN, RPCVN, 1T-CT, 1X-WOL	D-2, D-3, D-1, D-4
Plate Heat C6317-1 (Irradiated)	TL	RPCVN for Capsules Y and W, 1X-WOL for Capsule W	B-5, B-4, B-6
	LT	None	--
Plate Heat C4381-2 (Unirradiated)	TL	PCVN, 1T-CT	B-9, (B-7, B-8)
	LT	1T-CT[a]	(D-5, D-6)
Plate Heat C6293-2 (Unirradiated)	TL	PCVN, 1T-CT	B-11, B-10
	LT	None	--
Weld 305414 (Unirradiated)	T[b]	PCVN, 1T-CT	C-2, C-1
Weld 305424 (Unirradiated)	T[b]	PCVN	(C-3, C-4)
Weld 90136 (Unirradiated)	T[b]	PCVN	C-5

(a) Tests performed on both sections of plate heat C4381 (e.g., C4381-1 and C4381-2), also designated B6607-1 and B6607-2, respectively.

(b) Transverse equivalent in a weldment in which the crack propagates in the welding direction.

Table 3-4 T_o Results for Plate Heat C6317-1

Material	Fluence, n/cm²	Test Laboratory	Orientation	Specimen Type	ASTM E 1921-97 Test Temp., °C (°F)	ASTM E 1921-97 T_o, °C (°F)	Multi-Temp. T_o, °C (°F)
A533B-1	0	WMTR	TL	1T-CT	-76 (-105)	-52 (-61)	NA
A533B-1	0	MTI	TL	1/2T-CT	-80 (-112)	-40 (-40)	NA
A533B-1	0	WMTR	TL	PCVN	-85 (-121)	-68 (-91)	-66 (-87)
A533B-1 (W)	9.86×10^{18}	STC	TL	RPCVN	18 (64)	47 (117)	46 (115)[b]
A533B-1 (W)	9.86×10^{18}	STC	TL	1X-WOL	47 (117)	40 (104)[a]	
A533B-1 (Y)	2.15×10^{19}	STC	TL	RPCVN	38 (100)	75 (167)	72 (162)

(a) Invalid T_o measurement, insufficient number of specimens tested (4)

(b) Combined specimen type/size for comparison only

Table 3-5 T_o Results for Plate Heat C4381-2

Material	Fluence, n/cm²	Test Laboratory	Orientation	Specimen Type	ASTM E 1921-97 Test Temp., °C (°F)	ASTM E 1921-97 T_o, °C (°F)	Multi-Temp. T_o, °C (°F)
A533B-1	0	WMTR	TL	PCVN	-76 (-105)	-58 (-73)	NA
A533B-1	0	WMTR	TL	1T-CT	-76 (-105)	-33 (-27)	NA
A533B-1	0	MTI	TL	1T-CT	-76 (-105)	-33 (-27)	NA

Table 3-6 T_o Results for Plate Heat C6293-2

Material	Fluence, n/cm²	Test Laboratory	Orientation	Specimen Type	ASTM E 1921-97 Test Temp., °C (°F)	ASTM E 1921-97 T_o, °C (°F)	Multi-Temp. T_o, °C (°F)
A533B-1	0	WMTR	TL	PCVN	-76 (-105)	-72 (-97)	NA
A533B-1	0	WMTR	TL	1T-CT	-76 (-105)	-53 (-63)	NA

Table 3-7 T_o Results for Weld Heat 305424

Material	Fluence, n/cm²	Test Laboratory	Orientation	Specimen Type	ASTM E 1921-97 Test Temp., °C (°F)	ASTM E 1921-97 T_o, °C (°F)	Multi-Temp. T_o, °C (°F)
Linde 1092 Flux Weld	0	CE	T	PCVN	-129 (-200)	-138 (-216)	-135 (-211)
Linde 1092 Flux Weld	0	CE	T	PCVN	-129 (-200)	-126 (-194)	NA
Linde 1092 Flux Weld	0	CE	T	Combined PCVN	-129 (-200)	-131 (-204)	-129 (-201)

Table 3-8 T_o Results for Weld Heat 305414

Material	Fluence, n/cm^2	Test Laboratory	Orientation	Specimen Type	ASTM E 1921-97 Test Temp., °C (°F)	ASTM E 1921-97 T_o, °C (°F)	Multi-Temp. T_o, °C (°F)
Linde 1092 Flux Weld	0	KAERI	T	PCVN	-90 (-130)	-79 (-110)	-77 (-106)
Linde 1092 Flux Weld	0	KAERI	T	1T-CT	-70 (-94)	-78 (-108)	NA

Table 3-9 T_o Results for Weld Heat 90136

Material	Fluence, n/cm^2	Test Laboratory	Orientation	Specimen Type	ASTM E 1921-97 Test Temp., °C (°F)	ASTM E 1921-97 T_o, °C (°F)	Multi-Temp. T_o, °C (°F)
Linde 0091 Flux Weld	0	WMTR	T	PCVN	-90 (-130)	-94 (-138)	NA

4 APPLICATION OF BVPS-1 FRACTURE TOUGHNESS RESULTS

4.1 LICENSING ACTIONS NEEDED

The objective of the FENOC application for the BVPS-1 RPV is to obtain NRC concurrence on the viability of the RPV to the EOL and EOLE periods. The use of the Master Curve methodology for the evaluation of material fracture toughness properties during the current operating license life is required to provide additional operating margin for the expansion of the P-T operating windows. The expansion of this operating window will allow increased operator flexibility during heat-up and cool-down activities, which will minimize the risk of system challenges and operator action. The concurrence for the use of this methodology for the assessment of RPV material, as it relates to EOLE, is required to allow the utility to proceed with planning and improvements for the License Extension period during the current licensing life. The primary concern for attaining EOLE is the fracture toughness of the RPV. To that end, this report employs Master Curve technology to make direct measurements of fracture toughness in irradiated materials. In order to utilize the measured fracture toughness results to determine a revised RT_{PTS} value at EOLE and new heat-up and cool-down pressure-temperature (P-T) curves out to EOLE, several exemptions to current NRC regulations will be required. There are three primary exemptions:

1. Exemption to allow use of Master Curve to determine RT_{PTS} value in accordance with 10 CFR 50.61. Current regulations base determination of RT_{PTS} on measurements of the initial ASME reference temperature, RT_{NDT}, and the irradiation-induced shift in Charpy transition temperature. This exemption would allow direct determination of the fracture toughness reference transition temperature, RT_{To}, to be used to determine RT_{PTS}.

2. Exemption to allow use of Master Curve to determine ART value in 10 CFR 50, Appendix G. Current regulations use an Adjusted Reference Temperature, ART, to set the pressure-temperature limits for plant heat-up and cool-down. This exemption would allow direct determination of the fracture toughness reference transition temperature, RT_{To}, to be used to determine ART.

3. Exemption to allow use of the Master Curve to determine RT_{PTS} value during extended operating license life – 10 CFR 50.54.

These exemptions are both based on ASME Code Cases N-629 and N-631[24], which define the reference temperature, RT_{To}, which may be used as an alternative to RT_{NDT}. The ASME Code Cases anticipate the use of RT_{To} for PTS and P-T curve applications. However, the use of this alternative definition within current regulations poses additional issues that go beyond the scope of the Code Cases. These additional issues are addressed in the following sections.

Two additional exemptions are required to expand the P-T operating window for heat-up and cool-down.

4. Exemption based on ASME Code Case N-641 [25] to allow use of:

   - the K_{IC} curve rather than the K_{IR} curve,
   - a circumferential flaw in the girth weld of the beltline, and
   - new criteria for establishing low temperature over-pressure protection (LTOP) settings.

   This Code Case eliminates the need to use three separate Code Cases (N-514 [26], N-588 [27], and N-640 [28]), but accomplishes the same benefits.

5. Exemption to eliminate the RT_{NDT} + 120°F flange requirement. Eliminating the flange requirement can reduce challenges at low temperatures for reactor coolant pump seal failure, thus increasing plant safety. The removal of the flange requirement also makes it easier for operators to heat-up and cool-down the plant. WCAP-15315 [29] documents the technical basis for eliminating the RT_{NDT} + 120°F flange requirement currently required by 10 CFR 50.61.

The use of fracture toughness data to establish the long-term integrity of the BVPS-1 RPV requires an additional exemption to allow continued surveillance:

6. Exemption to include Master Curve testing as part of RPV surveillance program. Since a fracture toughness methodology will be used for establishing RT_{PTS} and P-T curves, future surveillance must be focused on measurement of fracture toughness instead of current Charpy V-notch surveillance capsule testing. The addition of a supplemental fracture toughness capsule in BVPS-2, containing BVPS-1 beltline materials, will require approval of a type of integrated surveillance program per 10 CFR 50, Appendix H. The need to primarily focus on direct measurement of fracture toughness also will require an exemption to Appendix H to allow the surveillance program to be modified in EOL such that EOLE monitoring can be effectively accomplished. The BVPS-1 surveillance program will be modified as discussed in Section 5 of this report.

4.2 MASTER CURVE METHODOLOGY

The methodology used to examine the integrity of the BVPS-1 RPV is based on ASME Code Cases N-629 and N-631. Current regulations are based on the ASME reference fracture toughness curves (K_{IC} and K_{IR}), which index the toughness to RT_{NDT}. Because direct determinations of RT_{NDT} at all projected fluences are not feasible for irradiated materials at this time, current regulations employ estimates based on a combination of unirradiated RT_{NDT} values and irradiation-induced shifts in Charpy 30 ft-lb transition temperatures. The regulatory parameters, RT_{PTS} and ART are determined by adding an additional margin to these estimated RT_{NDT} values to assure that the resulting indexed fracture toughness curve provides a lower bound to the fracture toughness data. The two ASME Code Cases provide an alternative method for indexing the ASME reference fracture toughness curves, based directly on fracture toughness measurements. These curves also can be applied to irradiated materials after direct measurement of irradiated surveillance capsule materials. However, an additional methodology is required to determine the regulatory parameters, RT_{PTS} and ART at the EOLE

fluence using measured values of RT_{To}. An approach for the determination of these parameters was originally presented in the submittal for the Kewaunee RPV [31]. An EPRI report [30] was written in December 2000 providing an industry review of application issues for the Master Curve methodology.

Application of direct measurements of fracture toughness to RPV analysis often requires a method for transforming the measured values to equivalent values at the fluence of interest. Current regulations employ trend equations for the Charpy transition temperature shifts, which are provided in 10 CFR 50.61 and NRC Regulatory Guide 1.99, Revision 2 [15] to accomplish these transformations. However, there is no equivalent trend curve for Master Curve measurements. In the submittal for the Kewaunee RPV, the available data spanned the fluence of interest and the transformation required only a small interpolation. However, application to the BVPS-1 requires an extrapolation to the EOLE fluence to demonstrate the ability to remain the current regulatory screening limit, since the current available surveillance material is irradiated to a maximum fluence of 2.15×10^{19} n/cm^2. The EOLE fracture toughness trend must be inferred by fitting RT_{To} data from the two highest fluence capsules. These results will be confirmed by future fracture toughness surveillance testing, which includes the newly inserted capsule in BVPS-2.

Application of the Master Curve technology also requires the development of a margin strategy. Although the ASME Code Cases provide a reference temperature (RT_{To}), which can be used as an alternative to RT_{NDT}, they do not provide guidance on the margins (if any) required to determine corresponding values of RT_{PTS} or ART. The methodology being applied for the BVPS-1 RPV is similar in intent to that developed for the Kewaunee RPV [30]. However, there is a significant difference between the two applications. The limiting material for the BVPS-1 RPV is a plate material with lower copper content and less potential irradiation variability than the weld metal evaluated for the Kewaunee RPV. Thus, uncertainties in applying the Master Curve approach for BVPS-1 will be less than those for Kewaunee.

4.2.1 Reference Temperature Definitions

The reference temperature, RT_{NDT}, is designed to describe the ductile-to-brittle transition of ferritic steels. By itself, RT_{NDT} defines a degree of unspecified inherent conservatism in the ductile-to-brittle transition temperature since it is based on bounding values of nil-ductility transition temperature and 50 ft-lb / 35 mils (lateral expansion) CVN temperature. In terms of actual fracture toughness, RT_{NDT} is merely an indicator of underlying material properties. However, the relationship defined in the ASME Code between RT_{NDT} and the reference toughness curves does imply real inherent conservatism. By choosing to index the reference toughness curves in a manner such that they provide lower bounds to the existing fracture toughness data, the ASME Code has sought to provide a conservative method for estimating fracture toughness values to be used in RPV integrity analysis. When used for unirradiated properties, where RT_{NDT} is measured directly following the ASME Code procedure, no additional margin is generally required in the analytical process.

Although the definition of RT_{NDT} is not limited in application to unirradiated materials, the amount of material required makes direct determinations of RT_{NDT} in irradiated materials

impractical. Therefore, current regulations employ ART to index the reference toughness curves.* The ART value is defined for a specific neutron fluence, which is generally taken as the EOL or EOLE fluence. However, the general form of the definition may be described as:

$$ART = RT(f) + Margin \tag{3}$$

where,

RT(f) is the estimated RT_{NDT} value as a function of fluence, and

Margin is the uncertainty related to the estimation process.

In current regulation, the reference temperature is estimated as:

$$RT(f) = RT_{NDT(U)} + \Delta RT(f) \tag{4}$$

where,

$RT_{NDT(U)}$ is the unirradiated RT_{NDT} value, and $\Delta RT(f)$ is the Charpy 30 ft-lb transition temperature shift from Regulatory Guide 1.99, Revision 2.

Under current regulations, generic values of $RT_{NDT(U)}$ may be used, but the Margin must be adjusted appropriately. An alternative formulation of Equation 4 is required for Master Curve applications.

ASME Code Case N-629 provides a means of measuring an alternative reference temperature, RT_{To}, for irradiated materials. Code Case N-631 is very similar to Code Case N-629 and is applicable to unirradiated materials. This reference temperature is defined as:

$$RT_{To} = T_o + 35°F \tag{5}$$

where T_o is defined using the ASTM E 1921-97 test procedure.

The Code Cases are constructed to allow RT_{To} to be used in place of RT_{NDT} as an indexing temperature for the ASME reference toughness curves. These Code Cases clearly anticipate that this alternative reference temperature acts in a manner similar to that defined in Equation 4 for determining ART. This report section shows the implementation of that practice.

*Although the definitions for ART and RT_{PTS} appear in different places in NRC regulations, they are identical in computation. For simplicity ART is employed here to describe both values.

4.2.2 Fluence Dependence of Reference Temperature

Measurements of irradiated specimens in accordance with Code Case N-631 represent direct determinations of the function RT(f) at specific fluences. Because they are direct measurements, they provide far more accurate values than the indirect estimation procedure used in current regulation. However, most reactor vessel integrity analyses require the evaluation of RT(f) at EOL and EOLE fluences, which can only be accomplished by fitting a curve to the measured data.

The Regulatory Guide 1.99, Revision 2 [15] prediction curve fits CVN 30 ft-lb transition temperature (ΔT_{30}) data to a function of the form:

$$\Delta T_{30} = CF * FF(f) \tag{6}$$

where,

ΔT_{30} is the Charpy 30 ft-lb temperature shift assumed equal to ΔRT,

CF is the Chemistry Factor, and

FF(f) = Fluence Factor

While the magnitude of the shift is determined by CF, the shape of the curve is determined by FF(f). FF(f) is the same for all materials; any material specific information is contained in the chemistry factor. Although Regulatory Guide 1.99, Revision 2 provides tables that allow determination of CF on the basis of the material form and composition, when credible surveillance data are available (or if the data exhibit abnormally high shift results, even if considered non-credible), CF can be determined by a fit to the data.

The use of CVN shifts to adjust the reference temperature is implicitly based on the assumption that there is equivalence between the fracture toughness shift and the CVN shift. It is, therefore, reasonable to apply the same form of equation (6) to assess in the fracture toughness transition temperature, ΔRT_{To} will also have the form:

$$\Delta RT_{To} = CF_{To} * FF(f) \tag{7}$$

where CF_{To} is the effective chemistry factor for fracture toughness shifts.

When the Regulatory Guide 1.99, Revision 2 Fluence Factor is used, CF_{To} may be determined by fitting ΔRT_{To} measurements. In this case, the reference temperature may be estimated as:

$$RT(f) = RT_{To(U)} + \Delta RT_{To} = RT_{To(U)} + CF_{To} * FF(f) \tag{8}$$

Substitution of this relationship into Equation 3, defines that for the Master Curve application, the ART value is:

$$ART = RT_{To(U)} + CF_{To} * FF(f) + Margin \quad (9)$$

This equation may then be evaluated at the EOL and EOLE fluences to provide the final ART values at EOL and EOLE. Evaluation of this equation requires determination of three basic parameters, $RT_{To(U)}$, CF_{To}, and Margin, which are discussed next. Because the data are all describing a single set of data, there are significant interactions between these parameters.

4.2.3 $T_{o(u)}$ and Conversion to $RT_{To(U)}$

Unirradiated values of T_o ($T_{o(u)}$) for the BVPS-1 surveillance plate material in the TL orientation were determined using three different specimen sizes and geometry, as presented in Section 3 (Table 3-4). 1T-CT and ½T-CT specimens were tested in accordance with ASTM E 1921-97 using the single temperature method. Precracked Charpy three-point bend (PCVN) specimens were also tested, and T_o values were determined using both ASTM E 1921-97 and the multi-temperature methodology currently being voted by the ASTM Committee that wrote E 1921-97. For the PCVN tests, there was only one additional specimen tested at a temperature higher than that used for the E 1921-97 determination, and not surprisingly the results were only 4°F different. The use of the multi-temperature method for the PCVN specimens is considered appropriate since all data should be considered if valid. The data for the three different data sets are compared to the Master Curve derived for the ½T-CT specimens in Figure 4-1. While both the 1T-CT and ½T-CT data appear to be consistent with the ½T-CT Master Curve, the PCVN data appear to exhibit a higher toughness.

The Master Curve test technique is designed to eliminate specimen size and configuration effects from the result. This specimen size independence was verified by fracture toughness tests on the surveillance plate in the LT orientation (see Appendix D). These tests were conducted using: PCVN and reconstituted PCVN (RPCVN) specimens to validate the reconstitution process for the broken irradiated surveillance capsule CVN specimens; 1T-CT specimens; and 1X-WOL specimens that were modified to simulate compact tension-type specimens. The 1X-WOL specimen geometry is one that was used in the early days of fracture mechanics before the CT geometry was fully developed and standardized, and some of the BVPS-1 surveillance capsules contain 1X-WOL specimens. The $T_{o(u)}$ results from these LT orientation tests are only slightly varied, and three key points can be made:

(1) the reconstitution process produces acceptable specimens, and RPCVN test results closely match those from traditional PCVN specimens,

(2) 1X-WOL test results closely match the results from 1T-CT specimen tests, and

(3) the LT orientation T_o results are lower than those for the TL orientation.

Since the emphasis is focused on weak (TL) orientation results for the reference temperature approach in the ASME Code, the data used for application of the Master Curve in determining an alternative reference temperature, RT_{To}, also will utilize TL orientation fracture toughness results.

There has been significant recent discussion of a possible bias in T_o values based on results from PCVN tests. This bias is discussed in more detail in the section 4.2.5.

An appropriate value of $T_{o(u)}$ must be selected for the analysis. This process should parallel the path taken to determine the $RT_{NDT(U)}$ value under current regulations. The definition of $RT_{NDT(U)}$ following the ASME Code involves a bounding drop-weight nil-ductility transition temperature measurement and a bounding determination of a 50 ft-lb CVN temperature. ASME Code Cases N-629 and N-631 define an alternative reference temperature, $RT_{To} = T_o + 35°F$, based on testing actual fracture toughness specimens. This RT_{To} value is also considered a bounding value, and no margin would be applied, if the same logic in 10 CFR 50.61 were applied. The NRC staff has argued that there may still be some material uncertainty in initial RT_{To} as measured using fracture toughness tests, and the Margin term used to define ART should include an uncertainty term for unirradiated fracture toughness.

Given the large scatter in the measured $T_{o(u)}$ values, it is difficult to appropriately evaluate this initial material uncertainty with regard to the Margin term. An alternative approach would be to eliminate the initial material property uncertainty in the Margin, choosing a clearly conservative measure of $RT_{To(U)}$. For BVPS-1 surveillance plate in the TL orientation, the highest measured value of $T_{o(u)}$ was obtained for the ½T-CT specimens. As indicated by Figure 4-1, the ½T-CT Master Curve provides a reasonable representation of the 1T-CT data as well and underestimates the toughness of the PCVN specimens. The ½T-CT specimen results give a value of $T_{o(u)}$ of –40°F, which translates to an RT_{To} value of –5°F. This conservative value includes any uncertainty in initial material properties, and no additional uncertainty will be added to the final Margin term.

4.2.4 Calculation of Chemistry Factor, Shift in RT_{To}

Although the Master Curve provides a means of determining fracture toughness transition temperature in irradiated materials without reference to the unirradiated state, current embrittlement models are generally designed to predict irradiation-induced shifts in transition temperature. Two measurements of T_o have been made for the plate material in the irradiated condition. Capsules W and Y contained the surveillance plate material, and RPCVN specimens were fabricated and tested. Additionally, Capsule W contained a limited number of 1X-WOL specimens that were also tested. The limited number (four) of the 1X-WOL specimens makes it impossible to measure a valid T_o, but a good indication can be inferred for comparison purposes. These measurements provide a direct measurement of the transition temperatures at the two capsule fluences. However, in order to evaluate Equation (8), shifts in transition temperature are required.

The change in T_o (or RT_{To}, since they are offset by 35°F) are determined by subtracting the unirradiated T_o (or RT_{To}) values, as evaluated in the Section 3, from the irradiated values. The T_o chemistry factor, CF_{To}, can then be determined using a methodology analogous to the CVN-based approach in 10 CFR 50.61 and Regulatory Guide 1.99, Revision 2. Determinations of ΔT_o based on the RPCVN data from Capsules Y and W were used to estimate CF_{To} for the surveillance plate material. The CF_{To} is 163.2°F, which is not that much higher than the CF for CVN data (149.4°F). Although the T_o analysis apparently exhibits a higher irradiation

sensitivity than the CVN analysis, the predicted final reference temperatures are similar due to differences in the initial values.

The initial reference temperature is lower for the Master Curve fracture toughness approach, RT_{To} = -5°F, as compared to RT_{NDT} = 27°F. It should also be noted that there are similar compensating effects with respect to the choice of the unirradiated RT_{To} value. Had a lower initial value been selected, CF_{To} would have been larger, but the net effect would still be matched to the RT_{To} measurements in Capsules Y and W.

4.2.5 Bias Term

The chemistry factor, CF_{To}, was determined in the previous section by matching the trend equations to RT_{To} values determined by testing RPCVN specimens. The tests produced T_o values that meet the validity requirements of ASTM Standard E 1921-97. However, it has been suggested that there is a possible bias in T_o values determined by testing CVN-size specimens in three-point bending. In their response to the Kewaunee submittal, the NRC required an additional margin term to cover this potential bias [7]. There are subtle differences between a bias in a measurement and the margin applied to a measurement. A margin implies that a best estimate of the value exists, and a margin is included to cover uncertainty in the measurement. A bias occurs when the measured value is not actually the best estimate value; in this case, the bias must be added (or subtracted) to get the best estimate value. If a bias is presumed in the RT_{To} values determined using PCVN three-point bend specimen tests, RT_{PCVN}, then the best estimate of the reference temperature, RT_{BE}, would be:

$$\begin{aligned} RT_{BE}(f) &= RT_{PCVN}(f) + \text{Bias} \\ &= RT_{To(U)} + CF_{To} * FF(f) + \text{Bias} \end{aligned} \qquad (10)$$

The adjusted reference temperature would then be:

$$\begin{aligned} ART &= RT_{BE}(f) + \text{Margin} \\ &= RT_{To(U)} + CF_{To} * FF(f) + \text{Bias} + \text{Margin} \end{aligned} \qquad (11)$$

This form of the equation allows separate considerations of the Bias and Margin effects.

The need for a Bias term appears to be dependent upon the degree of loss of constraint from testing small three-point bend specimens versus CT specimens. Evidently, the CT specimen maintains a higher level of constraint than the three-point bend specimen. This difference appears to be due to the difference in pure bending for the CT-type specimen versus the combined bending plus a small amount of shear loading for three-point bending. The effect of specimen size* appears to be reconciled through the Master Curve normalization to 1T size, but the loss of constraint from the specimen loading geometry is not. Recent finite element studies have compared the three-point bend versus the CT loading for unirradiated ferritic material

*0.394T-bend (PCVN), ½T-CT, 1T-CT, and 1X-WOL specimens were evaluated for the BVPS-1 materials.

flow properties and found that a difference of 18°F (10°C) can be expected in measured values of T_o [32]. Note that this difference is expected to decrease with increased yield strength and a different strain hardening exponent [n = 0.1 (N = 10) for unirradiated compared to n = 0.07 (N=14.3) for irradiated material], but the calculations have not been performed for the irradiated case. Additionally, there are very limited experimental data for making a comparison in the irradiated case. Unirradiated experimental data developed for the BVPS-1 materials support the need for a Bias adjustment for unirradiated T_o results, if only PCVN three-point bend testing is performed.

From the test program conducted for the BVPS-1 plate material, the 1X-WOL and RPCVN test results from Capsule W suggest that the Bias may actually be negative (-12°F), but only four 1X-WOL geometry specimens were tested. Two other comparisons can be made based upon testing conducted by the Westinghouse Owners Group (WOG) in support of the Master Curve technology. The Kewaunee weld metal from Capsule S had RPCVN and two 1X-WOL specimens tested. The resultant difference in T_o between multi-temperature RPCVN results (139°F) and the combined RPCVN and 1X-WOL specimen results (148°F) was 9°F. The WOG program also included tests in the irradiated condition for a Linde 0091 weld metal. The tests included RPCVN and ½T-CT specimens tests, with only four ½T-CT specimens for a determination of T_o (invalid per ASTM E 1921-97). As shown in Appendix E, the resultant difference between the CT and three-point results was –3°C (-6°F), again showing a negative bias. The only other source of irradiated data comparison relevant to defining bias is from the IAEA CRP3 program [21]. In the tables of irradiated data for the JRQ plate and the FFA forging materials, the results from Finland (VTT) show a Bias of about –20°F for the JRQ steel (fourteen PCVN versus twenty-five ½T-CT round specimens) and a Bias of +20°F for the FFA steel (twenty-two PCVN versus twenty-six ½T-CT round specimens). Results from Japan are also listed, but there were far fewer tests conducted and questions regarding the reliability of measurements (particularly for the JRQ steel) were raised.

It appears that a small Bias term may be needed for irradiated PCVN determination of T_o and RT_{To}, but this Bias term should be less than for unirradiated RPV materials. The value of Bias for irradiated test results used by the NRC in their SE for the Kewaunee RPV was 8.5°F [7]. Based on the above discussion, the value selected for the irradiated BVPS-1 surveillance plate material is 8°F.

4.2.6 Margin

The appropriate Margin to be applied is dependent upon assumptions used in the assessment of other parameters. To eliminate concern in the Margin term for initial material property variability, the highest measurement of T_o was chosen based upon CT, high constraint, data. Other issues needing consideration are chemistry (copper/ nickel) variability and fluence uncertainty. Because the BVPS-1 limiting material is a plate, the variability in chemistry is much less than for a high copper weld. The nominal copper and nickel content for the BVPS-1 surveillance plate was measured in the 1970s as 0.20 wt% copper and 0.54 wt% nickel; chemistry measurements were made on one of the broken CVN specimens taken from Capsule Y (just tested), and the resultant measured copper was 0.21 wt% and the nickel was measured as 0.53 wt%. These values are essentially equivalent to the nominal values assumed for this plate.

for this plate. The uncertainty in chemistry is therefore small and has been randomly sampled by the large number of CVN and fracture toughness tests conducted on the BVPS-1 surveillance plate.

The fluence projections for the BVPS-1 plate are based upon calculated values of fluence, not adjusted for dosimetry measurements. The measured values of fluence are less than those calculated; therefore, the projections of fluence are felt to be conservative. Additionally, the scheduled power up-rates are maximum values, and actual levels of increased flux may be less than those assumed here. As indicated in Section 2, a capacity factor of 90% has been assumed for all projections.

The most appropriate measure of uncertainty in irradiated ΔRT_{To}, is the uncertainty associated with the measurement of irradiated T_o, σ_{To}. This uncertainty comes directly from ASTM E 1921-97 as $\beta/N^{1/2}$, where N is the number of test specimens used to determine T_o and β is the statistical quantity from ASTM E 1921-97. Since a minimum number of 6-8 tests are required for determining T_o using a PCVN size specimen, σ_{To} is about 12°F. Following typical engineering practice of assigning a margin equal to 2σ, or approximately a 95% confidence limit, the Margin to cover uncertainty in determining T_o is $2\sigma_{To}$ = 24°F. This value of 24°F is large enough to cover all uncertainties associated with chemistry variability and fluence uncertainty, as discussed above. The definition of $RT_{To} = T_o$ +35°F also includes some extra coverage for these uncertainties. The margin was thus selected as the $2\sigma_{To}$ valve for a typical determination of RT_o in the irradiated condition using 6-8 test specimens.

4.2.7 Evaluation of the Adjusted Reference Temperature, ART

The best estimate value for the fracture toughness transition temperature as determined by testing of RPCVN specimens may be determined by evaluating Equation 8:

$$RT_{PCVN}(f) = -5 + 163.2 * FF(f) \qquad (8a)$$

At the vessel inside diameter peak EOL fluence of 3.52×10^{19} n/cm^2 and EOLE fluence of 5.87×10^{19} n/cm^2, $RT_{PCVN}(f)$ corresponds to reference temperatures of 212°F and 229°F, respectively. These values are the best estimate of the reference temperature based on measurements from three-point bend RPCVN-size specimens. Adjusting for the 8°F Bias, the best estimate reference temperature prediction equation would then be:

$$RT_{BE}(f) = 3 + 163.2 * FF(f) \qquad (10a)$$

which corresponds to 220°F at EOL and 237°F at EOLE. The best estimate curve based on this predictive equation is compared to the RT_{To}- and RT_{NDT}-derived values from the measured surveillance capsule data in Figure 4-2. In order to provide a means of direct comparison, all RPCVN-based determinations exhibited in Figure 4-2 have been adjusted upwards by the Bias factor of 8°F. Both the CVN-based RT_{NDT} and fracture toughness RT_{To} data are in good agreement except for the RT_{NDT} results for the lowest fluence capsule. Primarily due to this low fluence capsule, the scatter in the CVN data is greater than that allowed in 10 CFR 50.61 and Regulatory Guide 1.99, Rev. 2 for defining credible data.

The apparent agreement between the CVN-based RT_{NDT} values and the RT_{To} values contrasts with previous observations indicating that RT_{NDT} can provide an overly conservative estimate of the fracture toughness transition temperature. Indeed numerous studies have indicated that RT_{NDT} is a relatively poor measure of the fracture toughness transition temperature. In order to assure that the ASME reference toughness curves provided a lower bound for all materials, the curve was set by a relatively small number of limiting materials. The RT_{NDT} methodology produces excessively conservative toughness values for the non-limiting materials. The ASME Code Cases provide reference toughness curves that provide a more reliable predictor of toughness and eliminate the excess conservatism. The agreement between RT_{NDT} values and the RT_{To} values indicate that the BVPS-1 surveillance plate material is approaching the behavior of the ASME Code limiting materials. It should be noted that for the limiting material in the original K_{IC} database (HSST Plate 02), the ASME Code Case provides an RT_{To} value that is more conservative than the corresponding RT_{NDT} value by 18°F. This extra margin in the RT_{To} values is not explicitly used in this evaluation and therefore, is not apparent in Figure 4-2.

Including the Margin term of 24°F results in an adjusted reference temperature of the form:

$$ART = 3 + 163.2 * FF(f) + 24 \qquad (11a)$$

The ART value on the vessel inside surface are 244°F at EOL and 261°F at EOLE. The predicted ART is also compared to the RT_{NDT} and RT_{To} based on surveillance capsule data in Figure 4-2. The ART curve bounds all of the RT_{To} values and the bulk of the RT_{NDT} values. If the RT_{NDT} values included a large degree of excess conservatism, a larger portion of the values would be expected to fall above the ART curve. The anomalous data appears to be the CVN data from the lowest fluence surveillance capsule.

It is also interesting to compare the predictions of the Master Curve methodology to existing CVN-based methodologies. The current CVN methodology, as described in Regulatory Guide 1.99, Revision 2 and 10 CFR 50.61, provides both an RT(f) prediction and a margin term as illustrated in Figure 4-3. The prediction curve provided in this figure was derived by fitting the CVN data as described in Section 2. The shaded areas in Figure 4-3 indicate the 1σ and 2σ bands around the standard CVN prediction curve. There is close agreement between this curve and the best estimate curve derived from the Master Curve Data (Equation 8a). It is also prudent to consider regulatory changes that may occur during the life of this plant. The NRC is currently considering revisions to the PTS Rule and Regulatory Guide 1.99 that would revise CVN shift predictions. As illustrated in Figure 4-3, the currently proposed curve [32] predicts a lower reference temperature at EOLE. The step change shown at about 1.5×10^{19} n/cm^2 is due to the introduction of a time bids term in the proposed correlation.

The fracture toughness results support the overall trend of the CVN shift data. The RT_{To}-based prediction curve falls well within the 1σ band surrounding the current regulatory curve. This support, using measured fracture toughness data from two surveillance capsule irradiations, suggests that the CVN data could be considered credible, and the margin reduced accordingly. The CVN Margin term would then be 17°F, and the projected RT_{PTS} at EOLE based on the CVN results would be 258°F. This value is comparable to the value of 261°F determined from fracture toughness data and well below the PTS screening criterion of 270°F.

4.3 CALCULATION OF ART FOR THE INNER SURFACE, ¼-THICKNESS AND ¾-THICKNESS POSITIONS

The EOL and EOLE inside surface fluence are 3.52×10^{19} n/cm^2 and 5.87×10^{19} n/cm^2, respectively. These correspond to EOL and EOLE ART = RT_{PTS} values of 244° and 261°F, respectively, based on Master Curve fracture toughness data (Table 4-1). Table 4-2 lists the EOL and EOLE RT_{PTS} values for the other beltline materials based on CVN technology. The limiting material is still the surveillance heat C6903-1, but the value of RT_{PTS} is now based on the Master Curve approach.

The calculation of heat-up and cool-down pressure-temperature (P-T) curves requires ART values at the ¼-thickness and ¾-thickness through wall locations corresponding to the peak fluence. The ART values were determined following the process in Regulatory Guide 1.99, Revision 2, which relies upon the fluence function defined as:

$$FF(f) = f^{[0.28 - 0.1 \log (f)]} \tag{12}$$

and the CF_{To} = 163.2°F determined for the Master Curve approach.

The fluence (f) is attenuated according to the exponential decrease through the RPV wall as:

$$f_x = f_o \exp(-0.24\, x) \tag{13}$$

where x is the distance into the vessel wall from the inside surface in units of inches. This attenuation formula for fluence is based upon dpa and not E > 1 MeV. Equation 12 was applied for determining the fluences at ¼-thickness and ¾-thickness in the 7.88 in BVPS-1 RPV. The ART values were determined using the process leading to equation 11, in the same manner as for the inside surface ART = RT_{PTS}. Table 4-3 lists the results of these calculations for the ¼-thickness location and Table 4-4 list the ¾-thickness results. The same Bias and Margin terms were used as indicated in the tables.

Appropriate heatup and cooldown curves have been calculated using these ART values in WCAP-15618 [10]. Note that the limiting material for heatup and cooldown is generally the second limiting plate (Heat C4381) based on the CVN method of Regulatory Guide 1.99, Rev. 2 [15]. Once irradiated fracture toughness data are available for this heat, additional benefit is expected for pressure-temperature curves.

Table 4-1 Calculation of the Inner Surface ART Values (RT_{PTS}) for the BVPS-1 Plate Heat C6317-1 for EOL and EOLE

	CF_{To} deg. F	f(surface) x 10^{19} n/cm^2	FF @ Surface	$RT_{To(U)}$ deg. F	Bias deg. F	Margin deg. F	ΔRT_{PCVN} deg. F	ART deg. F
EOL	163.2	3.52	1.327887	-5	8	24	217	244
EOLE	163.2	5.87	1.432644	-5	8	24	234	261

Table 4-2 Inner Surface ART Values (RT_{PTS}) for the BVPS-1 Beltline Materials [CVN-based ART = IRT + ΔRT + Margin]

Material/ Heat	CF* deg. F	Time Limit	f(surface) x 10^{19} n/cm^2	FF @ Surface	IRT deg. F	Margin deg. F	ΔRT deg. F	ART deg. F
Plate C4381-2	100.5	EOL	3.52	1.327887	73	34	133.5	240
Plate C4381-2	100.5	EOLE	5.87	1.432644	73	34	144.0	251
Plate C4381-1	100.5	EOL	3.52	1.327887	43	34	133.5	210
Plate C4381-1	100.5	EOLE	5.87	1.432644	43	34	144.0	221
Plate C6293-2	98.65	EOL	3.52	1.327887	20	34	131.0	185
Plate C6293-2	98.65	EOLE	5.87	1.432644	20	34	141.3	195
Weld 305414	209.1	EOL	0.704	0.901565	-56	65.5	188.5	198
Weld 305414	209.1	EOLE	1.174	1.044772	-56	65.5	218.5	228
Weld 305424	192.5	EOL	0.704	0.901565	-56	65.5	173.6	183
Weld 305424	192.5	EOLE	1.174	1.044772	-56	65.5	201.1	211
Weld 90136	124.4	EOL	3.52	1.327887	-56	65.5	165.2	175
Weld 90136	124.4	EOLE	5.87	1.432644	-56	65.5	178.2	188

*Calculations used three significant figures for chemistry values

Table 4-3 Calculation of the ¼-Thickness ART Values for the BVPS-1 Plate Heat C6317-1 for EOL and EOLE

CF_{To} deg. F	f(surface) x 10^{19} n/cm^2	f(1/4-T) x 10^{19} n/cm^2	FF @1/4-T	$RT_{To(U)}$ deg. F	Bias deg. F	Margin deg. F	ΔRT_{PCVN} deg. F	ART deg. F
163.2	3.52	2.193857	1.213098	-5	8	24	198	225
163.2	5.87	3.658505	1.336577	-5	8	24	218	245

Table 4-4 Calculation of the ¾-Thickness ART Values for the BVPS-1 Plate Heat C6317-1 for EOL and EOLE

CF_{To} deg. F	f(surface) x 10^{19} n/cm^2	f(3/4-T) x 10^{19} n/cm^2	FF @3/4-T	$RT_{To(U)}$ deg. F	Bias deg. F	Margin deg. F	ΔRT_{PCVN} deg. F	ART deg. F
163.2	3.52	0.852196	0.955143	-5	8	24	156	183
163.2	5.87	1.421133	1.097509	-5	8	24	179	206

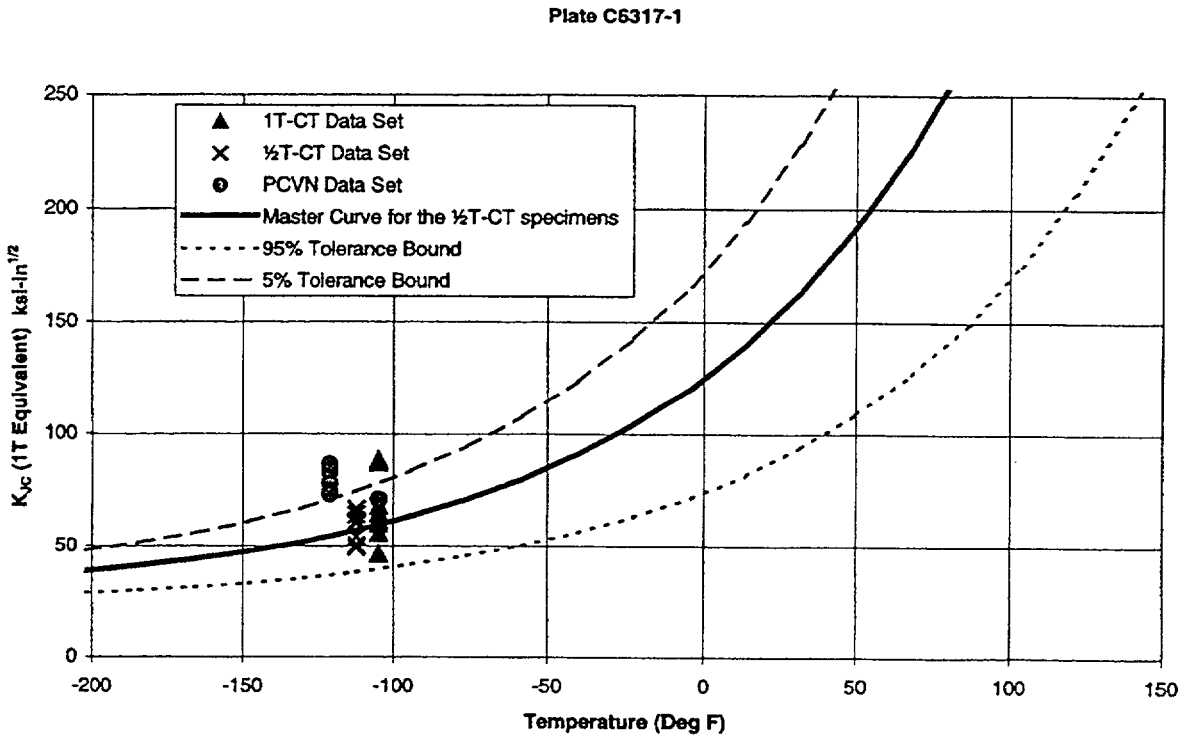

Figure 4-1 Master Curve for Unirradiated Surveillance Plate Material

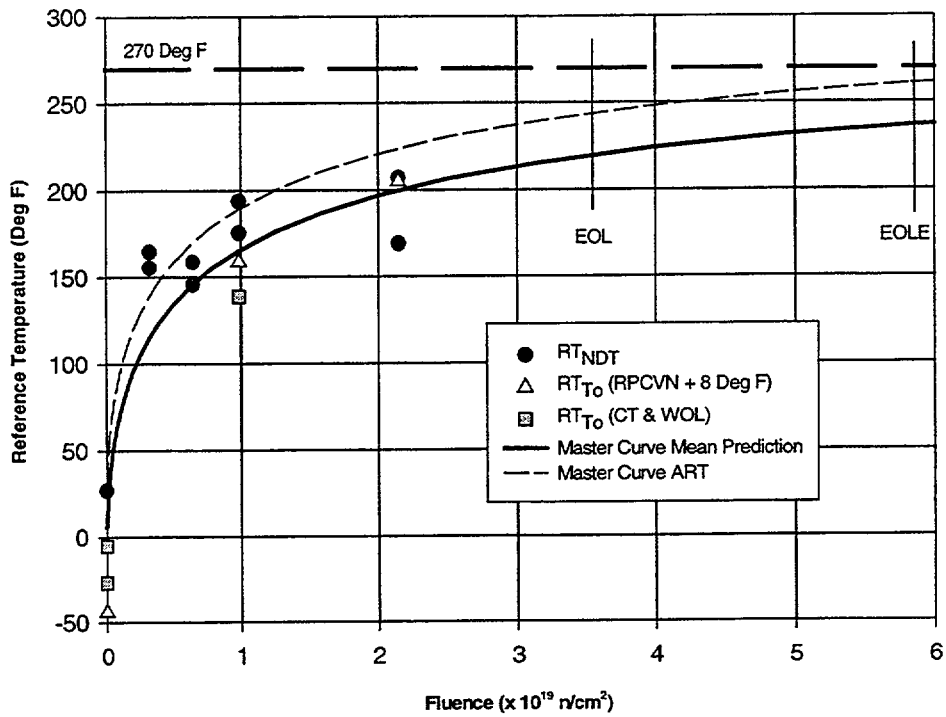

Figure 4-2 Comparison of Reference Temperatures Determined by CVN and Master Curve Testing

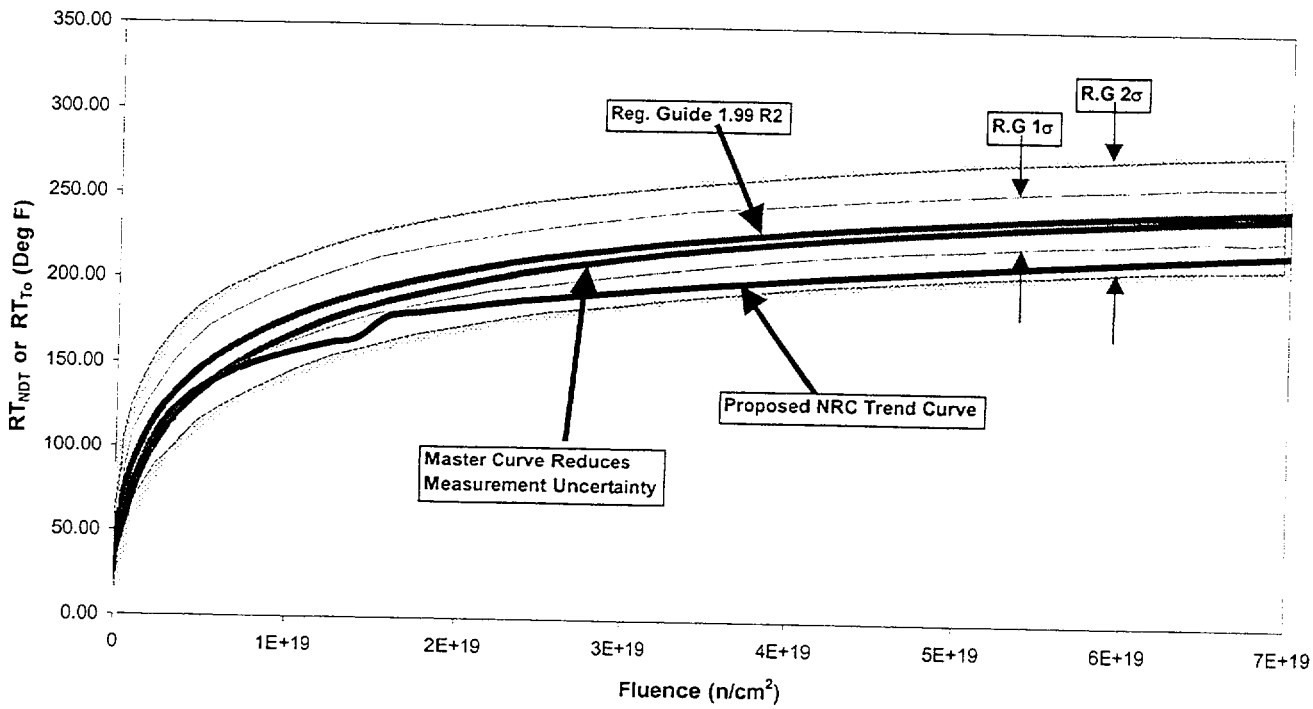

Figure 4-3 Comparison of Trend Curve Predictions for BVPS-1 Surveillance Plate

5 FUTURE SURVEILLANCE PROGRAM

5.1 HISTORY OF EXISTING PROGRAM

The original BVPS-1 surveillance program was prepared in accordance with ASTM E 185-73 and consists of eight surveillance capsules attached to the outside of the reactor internals thermal shield. Each capsule contains mechanical specimens, dosimetry, and thermal monitors. The mechanical specimens (CVN, 1X-WOL, and tensile specimens) were fabricated from material considered representative of the BVPS-1 RPV. A pre-irradiation (baseline) evaluation of the strength and Charpy toughness of the surveillance materials was performed.

ASTM E 185-73 recommended the surveillance program materials be prepared from materials considered representative of the beltline of the reactor vessel. The criterion suggested using the plate with the highest NDTT, as determined by the drop-weight test, as the source for base metal and heat-affected-zone (HAZ) materials. ASTM E 185-73 further specifies that the beltline materials be evaluated on the basis of initial reference temperature (RT_{NDT}), the predicted changes in initial properties as a function of chemical composition, and the neutron fluence during reactor operation.

Westinghouse Electric Company developed the original surveillance program for the BVPS-1 reactor vessel. Although the original program was in accordance with ASTM E 185-73, subsequent testing has followed the latest version of ASTM E 185 that was been approved by the NRC, through ASTM E 185-82. A description of the surveillance program and the pre-irradiation mechanical properties of the reactor vessel materials are presented in WCAP-8457, "Duquesne Light Company Beaver Valley Unit 1 Reactor Vessel Radiation Surveillance Program" [12]. Based on the measured chemistry, initial mechanical properties, and projected fluence, lower shell plate B6903-1 (heat # C-6317-1) and the submerged arc weld metal identical to the vessel intermediate shell longitudinal weld seams (heat # 305424) were selected to be in the reactor vessel surveillance program. Four surveillance capsules have been withdrawn and tested to date, with the latest capsule, Capsule Y, having been removed at 14.3 EFPY. Table 5-1 presents a summary of the BVPS-1 surveillance program along with the most recently calculated fluence values for all capsules. A detailed discussion of surveillance test results is provided in Section 2. Note that the new surveillance capsule, MC, containing Master Curve test specimens for all of the beltline materials is also listed in Table 5-1, even though it is being irradiated in BVPS-2.

The surveillance materials are contained in capsules positioned in the reactor between the thermal shield and vessel as shown in Figure 5-1. This figure also includes the numbering system for the capsule specimens and their locations. The irradiation conditions (temperature, neutron spectrum, and flux) for the capsule are very similar to those of the reactor vessel. Each capsule contains 44 CVN specimens, 4 tensile specimens, and 4 1X-WOL specimens. The relationship of the test material to the type and number of specimens in each capsule is shown in Table 5-2.

Dosimeters of iron, copper, aluminum-cobalt, cadmium-shielded aluminum-cobalt, and nickel wires are included in the capsules. Each capsule also contains a dosimeter block which is located in the center of the capsule. Two cadmium-oxide-shielded capsules, each containing isotopes of U^{238} or Np^{237} are located in the dosimeter block. The double containment afforded by the dosimeter assembly prevents loss and contamination by U^{238} or Np^{237} and their activation products. Each dosimeter block contains approximately 12 milligrams of U^{238} in a 3/8-inch long by ¼-inch-OD sealed brass tube and 20 milligrams of Np^{237} in a 3/8-inch long by ¼-inch-OD sealed stainless steel tube. Each tube is placed in a ½-inch diameter hole in the dosimeter block (one U^{238} and one Np^{237} tube per block) and the space around the tube is filled with cadmium oxide. After placement of this material, each hole is blocked with two 1/16-inch thick aluminum spacer discs and an outer 1/8-inch thick steel cover disc welded in place.

The specimens are seal-welded into a square austenitic stainless steel capsule to prevent corrosion of specimen surfaces during irradiation. The capsules were hydrostatically compacted in demineralized water to collapse the capsule on the specimens so that optimum thermal conductivity between the specimens and the reactor coolant is obtained. The capsules were helium leak tested as a final inspection procedure.

5.2 REVIEW OF REMAINING STANDBY CAPSULES

Specimen capsules S, T, and Z were originally installed as standby capsules in non-lead factor (lagging) fluence locations. These capsules are supplemental to the surveillance program capsules required in accordance with ASTM E185-73. Capsules S, T, and Z are identical to other capsules in the BVPS-1 surveillance program and the type and number of specimens in each capsule is listed in Table 5-2.

Capsules S, T, and Z were originally located in positions with lead factors of 0.41, 0.54 and 0.54, respectively. However, due to fuel management strategies that have been implemented at BVPS-1, the lead factor for the capsules following Cycle 10 were 0.63 for Capsule S, and 0.77 for Capsule T and Z. Following Cycle 10, the Capsules T and Z were relocated to higher fluence locations, such that their lead factors will increase with subsequent operating cycles. Table 5-3 illustrates the projected lead factors for Capsules S, T, and Z at various EFPY levels.

Based on the projected EOLE lead factor for Capsule S of 0.60, it is recommended that the capsule be relocated to a position with a higher lead factor. The current capsule location provides no leading information on reactor vessel material embrittlement, and therefore does not contribute to the surveillance program. The locations where Capsules W and Y were previously located have lead factors of 1.09 and 1.22, respectively. Relocation of Capsule S to one of these locations provides the opportunity to irradiate additional specimens to higher fluence levels reflecting irradiation during the license renewal period.

Capsule S, T, and Z are standby capsules and are not required to be tested in accordance with ASTM E85-73. Because they are supplemental in nature, the specimens in these capsules may be used to obtain direct fracture toughness measurements using the Master Curve. Because of the flexibility regarding the lead factors and withdrawal dates for these capsules, it is recommended that they be removed and tested at fluence levels which fill gaps in the fracture

toughness information currently available for BVPS-1 reactor vessel materials. Intermediate fluence levels in the range of 3 to 4 x 10^{19} n/cm^2 can be obtained before the end of the current BVPS-1 operating license, which can supplement the other available toughness data and verify the projected trend/shift curve through direct measurement. This additional data may possibly enable the generation of a fracture toughness relationship for BVPS-1 and could be valuable to industry efforts to generate a fracture toughness trend relationship for reactor vessel steels.

5.3 DESCRIPTION OF NEW SUPPLEMENTAL SURVEILLANCE CAPSULE

The new BVPS-1 surveillance capsule that is being irradiated in BVPS-2 contains surveillance specimens that will be used to directly measure the fracture toughness of the BVPS-1 beltline materials. The supplemental capsule contains specimens from each of the BVPS-1 beltline materials, with CVN, (1/2)T-CT compact, and tensile specimens included for materials that have not been previously irradiated and tested (Plates B7203-2 and B6607-2, and weld heat #305414). Materials that were previously irradiated (Plate B6903-1, and weld heats #90136 and #305424) are included as CVN inserts in the new capsule to supplement previously generated data. A complete list of specimens included in the supplemental surveillance capsule is presented in Table 5-4.

The target fluence for the BVPS-1 supplemental surveillance materials will correspond to the peak reactor vessel fluence at EOLE. Surveillance data obtained from this capsule will provide direct fracture toughness measurements for all BVPS-1 materials near the maximum fluence of the end of license extension. This data will provide direct evidence to validate previous reactor vessel life assessments and a measure of the actual margins available for the BVPS-1 RPV.

5.4 SUPPLEMENTAL CAPSULE IRRADIATION AND WITHDRAWAL SCHEDULE

The supplemental surveillance capsule for BVPS-1 will be irradiated to a target fluence equivalent to the extended end of operating license life (EOLE) fluence for the limiting BVPS-1 material, lower shell plate B6903-1. Irradiation to this fluence will allow fracture toughness measurements to be directly obtained to demonstrate adequate reactor vessel toughness throughout the license renewal term.

As discussed in Section 2, the peak BVPS-1 reactor vessel fluence will change significantly from previous estimates because of the FENOC decision to eliminate the hafnium flux reduction program following Fuel Cycle 14, and to implement power up-rates totaling 9.4% in Cycle 15. The revised EOLE peak fluence estimate for BVPS-1 is 5.87 x 10^{19} n/cm^2 and considers the affects of hafnium removal and power up-rate. This fluence value is applicable to the BVPS-1 intermediate and lower shell plate materials. Due to core geometry and previous shielding with hafnium, the BVPS-1 beltline circumferential and longitudinal welds will receive a lower EOLE fluence.

The supplemental surveillance capsule for BVPS-1 has been fabricated and was installed in BVPS-2 at the beginning of BVPS-2 Cycle 9. During BVPS-2 Cycles 9 and 10, power up-rates will be implemented, with the total up-rate amounting to 9.4%. The BVPS-1 limiting material

(lower shell plate B6903-1) was previously irradiated in BVPS-1 surveillance capsule Y to a fluence of 2.15×10^{19} n/cm^2. This surveillance material is calculated to reach the vessel EOLE fluence during BVPS-2 Cycle 16, and should be removed during the refueling outage following Cycle 16. Table 5-5 provides details of the BVPS-1 supplemental surveillance capsule fluence projections from irradiation in BVPS-2.

At the time of surveillance capsule removal, other BVPS-1 surveillance materials included in the capsule will be at different fluence values because of differences in prior specimen irradiation. Table 5-6 provides a comparison between the estimated total specimen irradiation and the EOLE fluence projections for all BVPS-1 materials. These projections demonstrate that most BVPS-1 supplemental surveillance specimens will be above the EOLE projected fluence.

Based on the fuel management strategies and power up-rates planned for the BVPS Units, the BVPS-1 supplemental surveillance capsule should be removed and tested following BVPS-2 Cycle 16. This refueling outage is estimated to occur sometime during the year 2011. It is recommended that the BVPS-1 peak reactor vessel fluence and the fluence to the supplemental surveillance capsule fluence in BVPS-2 be re-evaluated in the future to reflect actual reactor operation. As further reactor operation occurs, better vessel and capsule fluence estimates can be made and a more definitive capsule withdrawal schedule may be established.

5.5 REVIEW OF SUPPLEMENTAL SURVEILLANCE PROGRAM COMPLIANCE WITH APPENDIX H TO 10 CFR 50

The requirements for implementation of an integrated surveillance program are delineated in Appendix H to 10 CFR 50, "Reactor Vessel Material Surveillance Program Requirements." Appendix H defines an integrated surveillance program as a reactor vessel material surveillance program where "the representative materials chosen for surveillance for a reactor are irradiated in one or more other reactors that have similar design and operating features." Integrated surveillance programs may be approved on a case-by-case basis by the Director, Office of Nuclear Reactor Regulation (NRR).

The criteria for approval of an integrated surveillance program from Appendix H are listed below, followed by a description of compliance for BVPS-1.

a. Criterion: The reactor in which the materials will be irradiated and the reactor for which the materials are being irradiated must have sufficiently similar design and operating features to permit accurate comparisons of the predicted amount of radiation damage.

   Discussion: The host reactor, BVPS-2, is of substantially equivalent design to the BVPS-1 reactor. Each reactor was designed by Westinghouse Electric Company and are of the same design and power rating. The BVPS units are each operated by FENOC and have similar fuel designs and fuel management strategies. BVPS-1 and BVPS-2 are of sufficiently similar design and operation to permit accurate comparisons of the predicted amount of radiation damage.

b. Criterion: Each reactor must have an adequate dosimetry program.

Discussion: The integrated surveillance program for BVPS-1 is a supplement to the existing surveillance program. There will be no reduction in the testing of capsules from the BVPS-1 and 2 plant specific surveillance programs, each of which adequately monitors neutron fluence on the respective reactor vessel. Therefore, each reactor has an adequate dosimetry program.

c. Criterion: There must be adequate arrangement for data sharing between plants.

Discussion: Both the BVPS Unit 1 and Unit 2 reactors are owned and operated by FENOC. No special data sharing arrangements are needed. This provision of Appendix H is concerned with data sharing between two or more operating companies. Therefore there is an adequate arrangement for data sharing between the two units.

d. Criterion: There must be a contingency plan to assure that the surveillance program for each reactor will not be jeopardized by operation at reduced power level or by an extended outage of another reactor from which data are expected.

Discussion: The integrated surveillance program for BVPS-1 supplements the existing plant specific surveillance program and is being implemented to obtain direct fracture toughness surveillance data for a license extension term. Because of the long time period until the data is needed for BVPS-1, operation of the BVPS-2 host reactor at a reduced power level or by an extended outage will not jeopardize the surveillance program. Based on current cycle projections, the capsule is projected to be removed in approximately 2011. The BVPS-1 license renewal term does not end until 2036, therefore, the surveillance program for BVPS-1 will not be jeopardized by operation at reduced power level or by an extended outage of BVPS-2.

e. Criterion: There must be substantial advantages to be gained, such as reduced power outages or reduced personnel exposure to radiation, as a direct result of not requiring surveillance capsules in all reactors in the set.

Discussion: The supplemental surveillance capsule for BVPS-1 does not reduce the number of capsules scheduled to be withdrawn and tested from the existing surveillance programs for BVPS-1 or BVPS-2. Therefore, the original surveillance program is not affected and surveillance capsules are still required in each reactor.

Appendix H further requires that no reduction in the requirements for number of materials to be irradiated, specimen types, or number of specimens per reactor is permitted; and that no reduction in the amount of testing is permitted unless previously authorized by the Director, NRR. The integrated surveillance program for BVPS-1 is supplemental in nature and does not reduce the number or type of specimens being tested. BVPS-1 is in compliance with the requirements of Appendix H to 10 CFR 50, but the program does change the proposed withdrawal schedule to optimize the management of RPV radiation damage.

Table 5-1 BVPS-1 Surveillance Program			
Capsule	**Lead Factor**	**Equivalent Removal Fluence**	**Comments**
V	1.60	1.16 EFPY (End of First Core Cycle)	Fluence achieved was 3.23×10^{18} n/cm^2, E > 1 MeV
U	1.05	3.59 EFPY	Fluence achieved was 6.46×10^{18} n/cm^2, E > 1 MeV
W	1.09	5.89 EFPY	Fluence achieved was 9.86×10^{18} n/cm^2, E > 1 MeV
Y	1.22	14.3 EFPY	Fluence achieved was 2.15×10^{19} n/cm^2, E > 1 MeV
X	1.76	25.7 EFPY	Target fluence is 5.82×10^{19} n/cm^2, E > 1 MeV
Z	0.77 / 1.60	Standby	Capsule reinserted in capsule V location at the end of Cycle 10 (10.8 EFPY).
T	0.77/ 1.05	Standby	Capsule reinserted in capsule U location at the end of Cycle 10 (10.8 EFPY).
S	0.63	Standby	Consider moving to either capsule W or Y locations at the end of Cycle 14.
MC	N/A	2011 (> 48 EFPY for plate heat C6293-2)	Irradiated in BVPS-2; target fluence for BVPS-1 limiting plate of 5.96×10^{19} n/cm^2 at the end of BVPS-2 Cycle 16

Table 5-2 Type and Number of Specimens in the BVPS-1 Surveillance Test Capsules						
	Capsules W, V, S, and Z			**Capsules Y, X, U, and T**		
Material	**CVN**	**Tensile**	**1X-WOL**	**CVN**	**Tensile**	**1X-WOL**
Plate B6903-1 (Longitudinal Orientation)	8	-	-	8	-	-
Plate B6903-1 (Transverse Orientation)	12	2	4	12	2	-
Weld 305424	12	2	-	12	2	4
HAZ	12	-	-	12	-	-

Table 5-3 BVPS-1 Capsule S, T and Z Projected Lead Factors				
		Capsule (Location)		
EFPY	Cycle	S (45°)	T (25°)	Z (15°)
10.8	10	0.60	0.77	0.77
11.8	11	0.62	0.81	0.83
12.9	12	0.63	0.86	0.90
14.3	13	0.65	0.91	0.97
15.7	14	0.66	0.95	1.03
17.0	15	0.66	0.97	1.10
28.0	-	0.62	1.05	1.39
45.0	-	0.60	1.10	1.55

Table 5-4 BVPS-1 Material and Specimen Types in Supplemental Capsule being Irradiated in BVPS-2				
	Number and Type of Specimens			
Material	CVN	½T-CT	Tensile	CVN Insert
Lower Shell Plate B6903-1 (Ht # C6317-1)	--	--	--	10[a]
Lower Shell Plate B7203-2 (Ht # C6293-2)	14	8	3	--
Intermediate Shell Plate B6607-2 (Ht # C4381-2)	14	8	3	--
Weld Metal Heat # 305414	14	8	3	10[b]
Weld Metal Heat #90136	--	--	--	10[c]
Weld Metal Heat # 305424	--	--	--	10[a]

(a) Specimen previously irradiated in BVPS-1 Capsule Y to a fluence of 2.15×10^{19} n/cm^2
(b) Specimen previously irradiated in Fort Calhoun Surveillance program to a fluence of 1.28×10^{19} n/cm^2
(c) Specimen previously irradiated in St. Lucie-1 Surveillance program to a fluence of 7.16×10^{18} n/cm^2

Table 5-5 BVPS-2 Fuel Cycles and Estimated BVPS-1 Surveillance Capsule Fluence				
CYCLE	Total EFPY	Cycle Accumulated Fluence, x 10^{18} n/cm^2	Total Capsule Fluence, x 10^{19} n/cm^2	Total Fluence to Lower Shell Specimens[a], x 10^{19} n/cm^2
9a	0.53	2.06	0.206	2.36
9b[b]	1.14	2.41	0.446	2.60
10a	1.86	2.84	0.730	2.88
10b[c]	2.28	1.78	0.908	3.06
11	3.42	4.84	1.39	3.54
12	4.57	4.84	1.88	4.03
13	5.71	4.84	2.36	4.51
14	6.85	4.84	2.85	5.00
15	7.99	4.84	3.33	5.48
16	9.13	4.84	3.81	5.96[d]
17	10.27	4.84	4.30	6.45
18	11.42	4.84	4.78	6.93
19	12.56	4.84	5.27	7.42
20	13.70	4.84	5.75	7.90
21	14.84	4.84	6.24	8.39
22	15.98	4.84	6.72	8.87
23	17.12	4.84	7.21	9.36
24	18.27	4.84	7.69	9.84

(a) The lower shell material specimens were previously irradiated in BVPS-1 Capsule Y to a fluence of 2.15 x 10^{19} n/cm^2.

(b) A power uprate of 1.4% is being implemented during Cycle 9.

(c) A second power uprate of 8% is implemented during Cycle 10, for a total power uprate of 9.4%.

(d) The surveillance capsule is estimated to receive the BVPS-1 EOLE fluence during BVPS-2 Cycle 16. The capsule should be withdrawn following BVPS-2 Cycle 16, during approximately 2011.

Table 5-6 BVPS-1 Material and Specimen Estimated Fluence

Material	Prior Specimen Irradiation Fluence, n/cm^2	Capsule Irradiation, n/cm^2	Total Specimen Irradiation, n/cm^2
Lower Shell Plate B6903-1 (Ht # C6317-1)[1]	2.15×10^{19}	3.81×10^{19}	5.96×10^{19}
Lower Shell Plate B7203-2 (Ht # C6293-2)	0	3.81×10^{19}	3.81×10^{19}
Intermediate Shell Plate B6607-2 (Ht # C4381-2)	0	3.81×10^{19}	3.81×10^{19}
Weld Metal Heat # 305414[2]	1.28×10^{19}	3.81×10^{19}	5.09×10^{19}
Weld Metal Heat #90136[3]	0.716×10^{19}	3.81×10^{19}	4.53×10^{19}
Weld Metal Heat # 305424[1]	2.15×10^{19}	3.81×10^{19}	5.96×10^{19}

[1] Specimen previously irradiated in BVPS-1 Capsule Y.
[2] Specimen previously irradiated in Fort Calhoun-1 surveillance program.
[3] Specimen previously irradiated in St. Lucie-1 surveillance program.

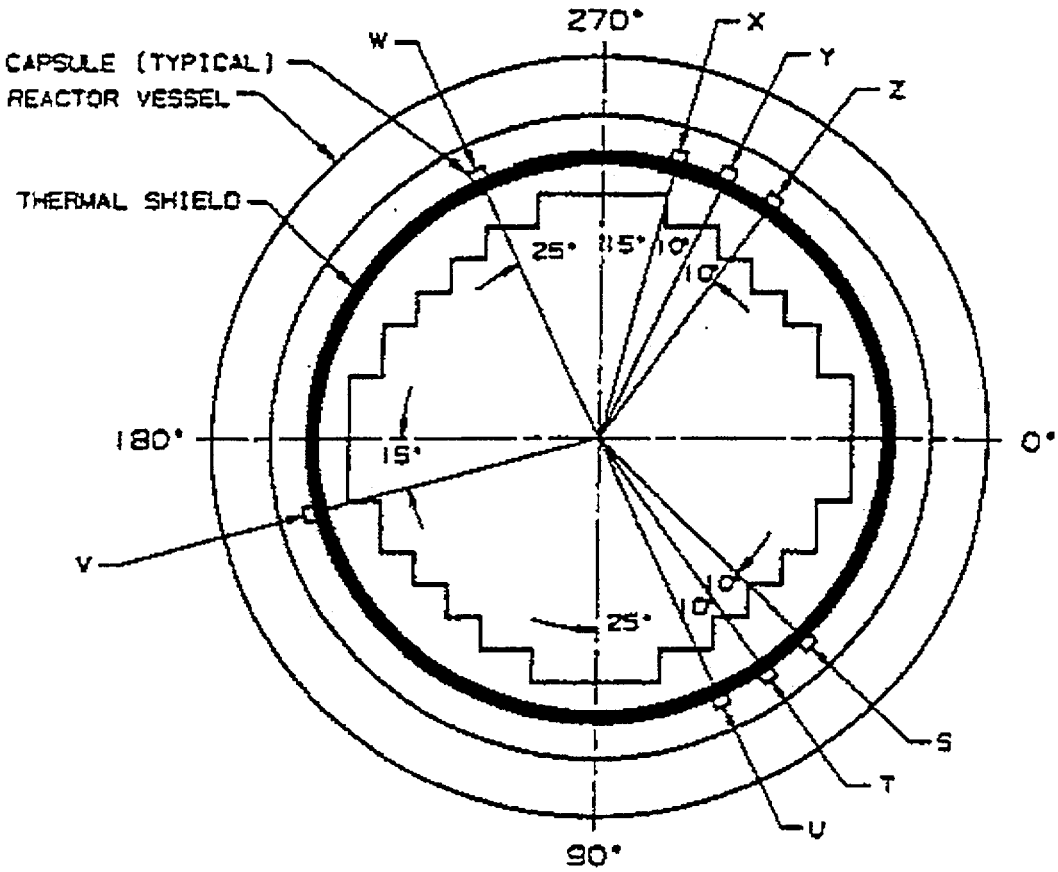

Figure 5-1 Arrangement of Surveillance Capsules in the Reactor Vessel

6 SUMMARY AND CONCLUSIONS

This report summarizes the fracture toughness testing that has been conducted to date on the BVPS-1 RPV beltline materials. The most limiting RPV material is the beltline plate material from the lower shell course. This plate material is included in the current surveillance program for BVPS-1, and now four surveillance capsules have been tested and evaluated using traditional CVN-based technology. The latest results, when analyzed following past NRC guidelines, indicate that the RPV material may reach the PTS screening criterion limit before EOLE. Therefore, testing of the broken surveillance specimens from the two highest dose capsules has been performed primarily using reconstituted precracked Charpy specimens (RPCVN) and analyzed using the Master Curve methodology following ASME Code Case N-629. Use of the Master Curve methodology involves engineering judgment in applying ASME Code Case N-629 to an actual RPV evaluation. The evaluation performed here involves extrapolation to EOLE fluence, but indicates that the RPV limiting plate material has adequate toughness out to EOLE and beyond. A supplemental surveillance program has been designed and implemented that includes not only the limiting plate material, but also all of the BVPS-1 beltline materials for future evaluation using the Master Curve methodology. The testing of this supplemental capsule at a fluence corresponding close to EOLE or greater will confirm the toughness condition for the BVPS-1 RPV materials near the time when current EOL is reached. Baseline (non-irradiated) testing of all of the BVPS-1 RPV beltline materials is presented in this report.

The following conclusions were reached from this current analysis of the limiting beltline plate material:

- The latest Charpy-based toughness evaluation for the BVPS-1 limiting plate material indicates that the PTS screening criterion of 270°F will be reached before EOLE when future plant operation is considered (removal of hafnium core suppression and planned power up-rates). This evaluation assumes lack of credibility in the CVN data with the NRC-defined attendant use of a two sigma margin due to data scatter for the lowest fluence CVN shift results. The fact that the Master Curve fracture toughness data show a consistent trend in behavior with the CVN results for the two highest fluence capsule fluences suggests that the lack of credibility should be questioned, and a smaller margin should be applied. If the CVN-based margin was reduced, the limiting plate material would show adequate toughness to EOLE and beyond.

- Current application of the Master Curve methodology for the BVPS-1 plate material requires extrapolation from the two highest capsule fluences to the RPV EOLE fluence. This extrapolation therefore requires use of the measured unirradiated fracture toughness properties, as well as the measured fracture toughness at the two capsule fluence levels. The unirradiated fracture toughness was evaluated using PCVN, ½T-CT, and 1T-CT specimens. The results between these specimen sizes showed a high degree of scatter with the 1T and ½T specimens giving the highest measure of initial RT_{To}. The ½T specimen RT_{To} value was also higher than the 1T specimen RT_{To} result by 21°F; instead of defining some average value, it was decided to use the highest value from the ½-T specimens avoiding the need to consider any uncertainty margin associated with initial properties.

- The issue of bias between PCVN specimen tests and larger compact tension tests was included in the evaluation. Based on limited irradiated results in which PCVN and CTs (or 1X-WOLs) were tested, a value of 8°F was chosen that is consistent with the value of 8.5°F that the NRC chose for evaluating the Kewaunee weld fracture toughness results.

- The appropriate margin term that was chosen was based upon the measurement process of determining T_o and RT_{To} following ASTM E 1921-97. Remaining consistent with industry practice, a two sigma margin related to the maximum uncertainty in a measured RT_{To} value was chosen, which equates to 24°F. This margin is large enough to cover any uncertainties associated with the plate copper and nickel chemistry and fluence. Uncertainties associated with initial properties were conservatively included in the selection of the initial RT_{To} value.

- Since there was a need to extrapolate to higher fluence levels to assess PTS, plus the need to interpolate back for estimating ¼-thickness and ¾-thickness ART values for P-T curves, the current Regulatory fluence function for CVN-based predictions was used for the Master Curve approach. All available irradiated data indicate that this assumption is appropriate.

- The RT_{PTS} estimate from the Master Curve methodology for the limiting plate corresponding to the EOLE fluence is 261°F, which is less than the PTS screening criterion.

- The supplemental surveillance program utilizes the original remaining surveillance capsules in addition to the new capsule inserted in the BVPS-2 RPV at a higher lead factor location than that possible in the BVPS-1 RPV. This capsule contains all of the BVPS-1 beltline materials, and will be available for testing in about 10 years. The direct measurement of fracture toughness for all of the beltline materials will be evaluated at fluence levels close to or greater than projected EOLE.

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APPENDIX A

ADDITIONAL CVN DATA FOR BEAVER VALLEY UNIT 1 RPV MATERIALS

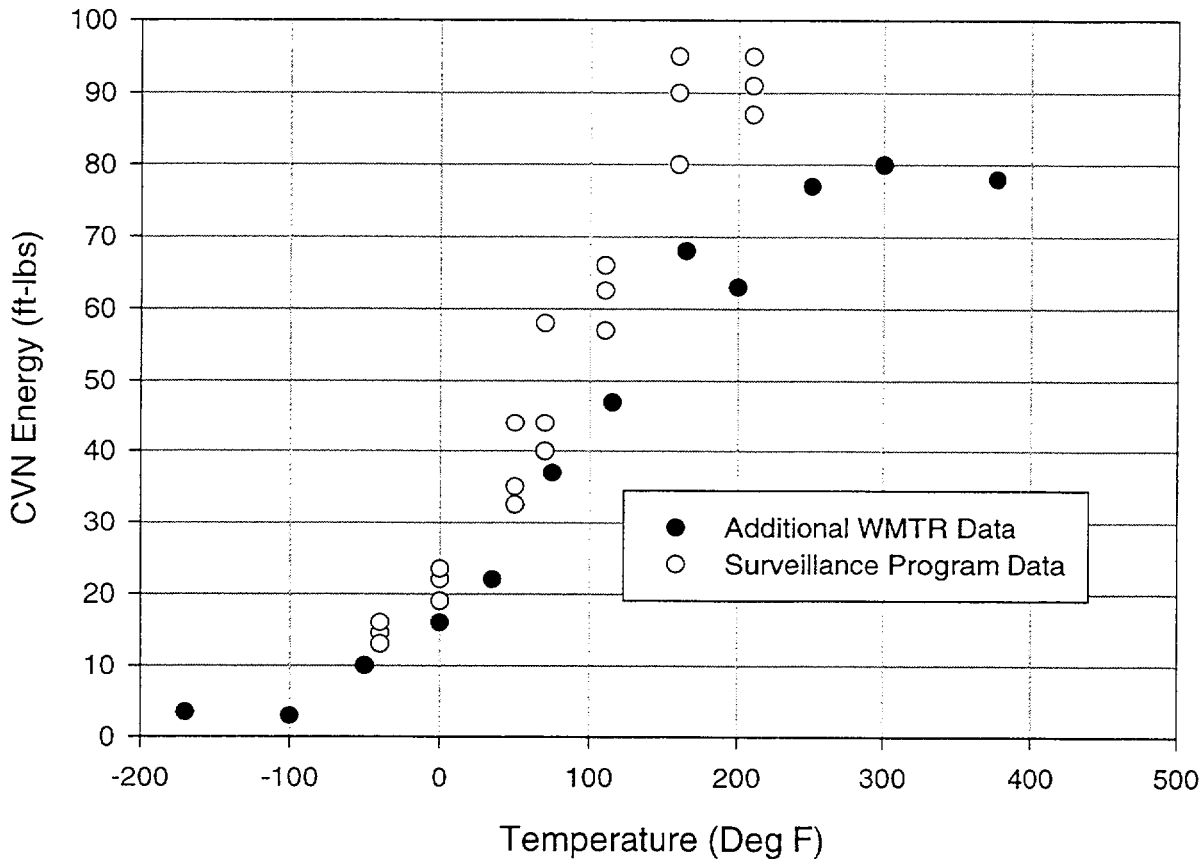

Figure A-1 Additional CVN Data for Plate 6607-1 (TL Orientation)

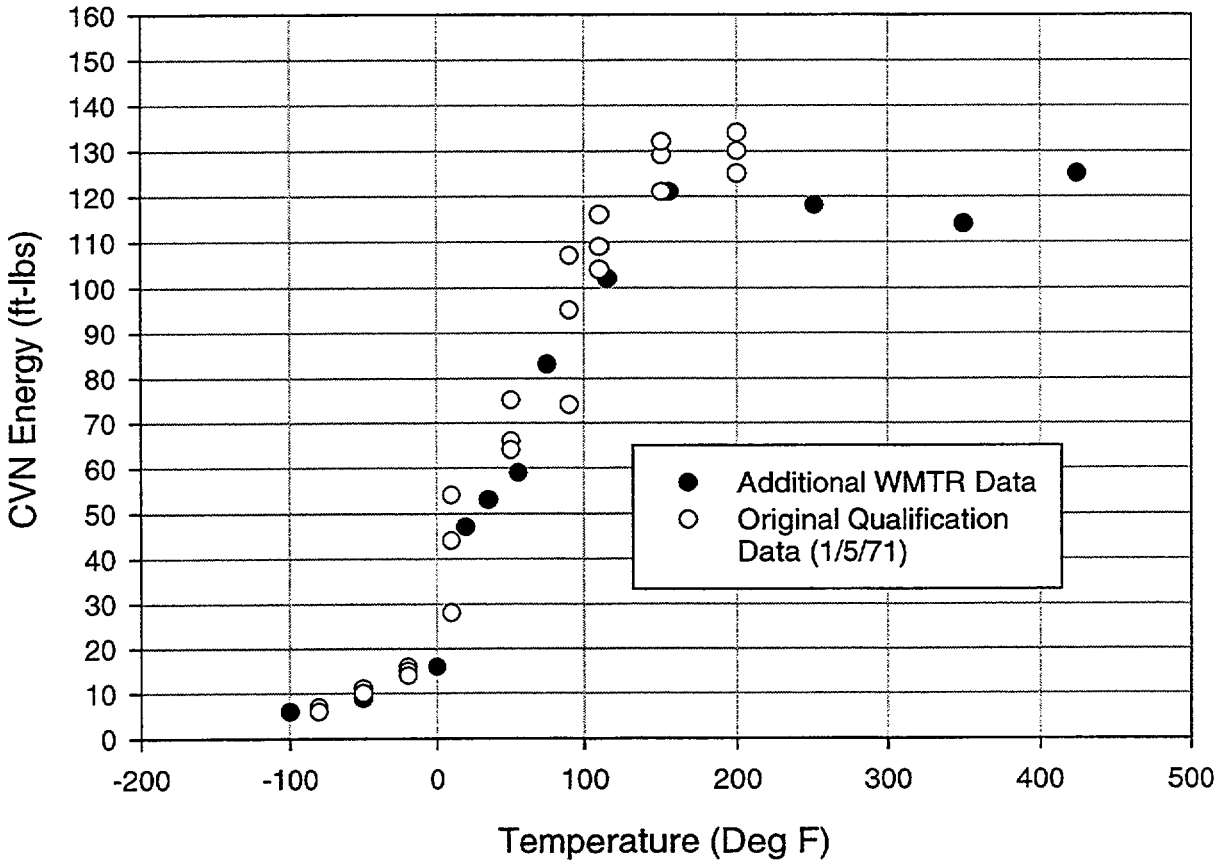

Figure A-2 Additional CVN Data for Plate 6607-1 (LT Orientation)

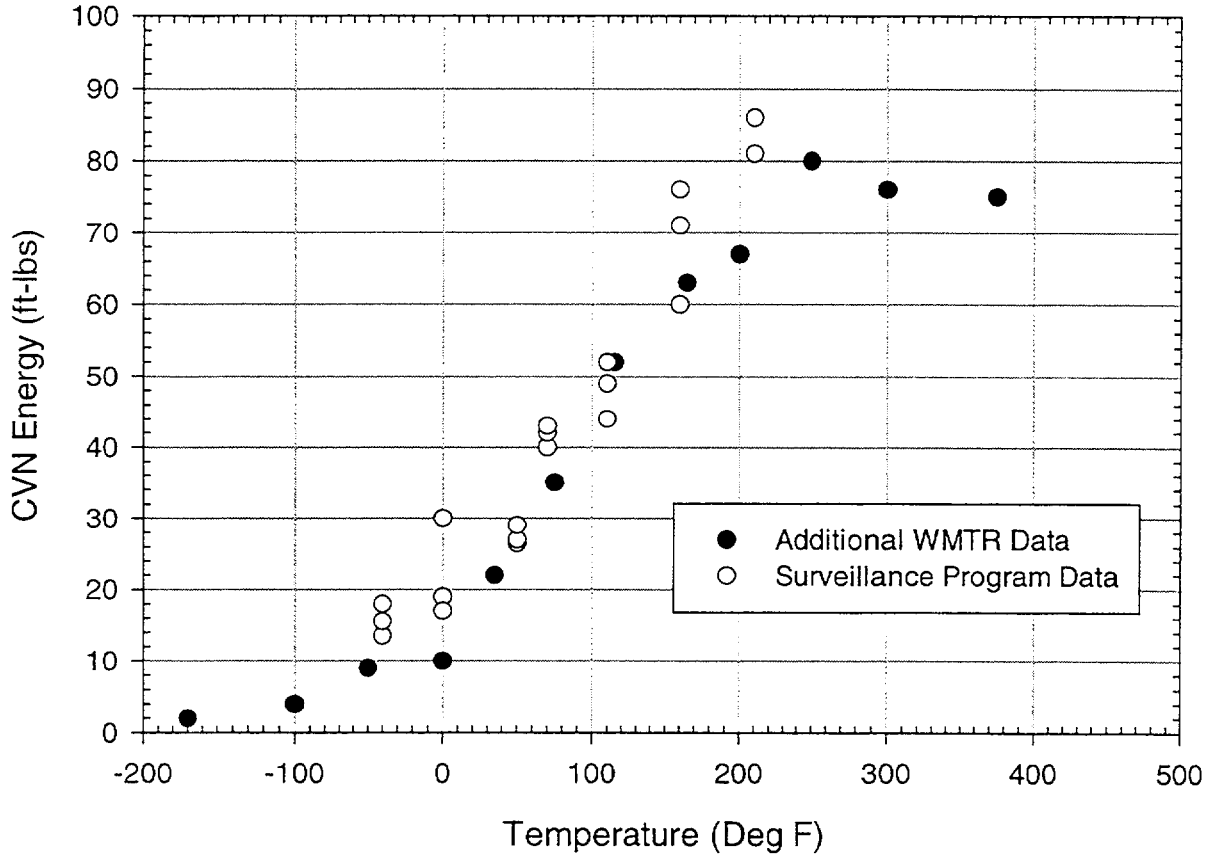

Figure A-3 Additional CVN Data for Plate 6607-2 (TL Orientation)

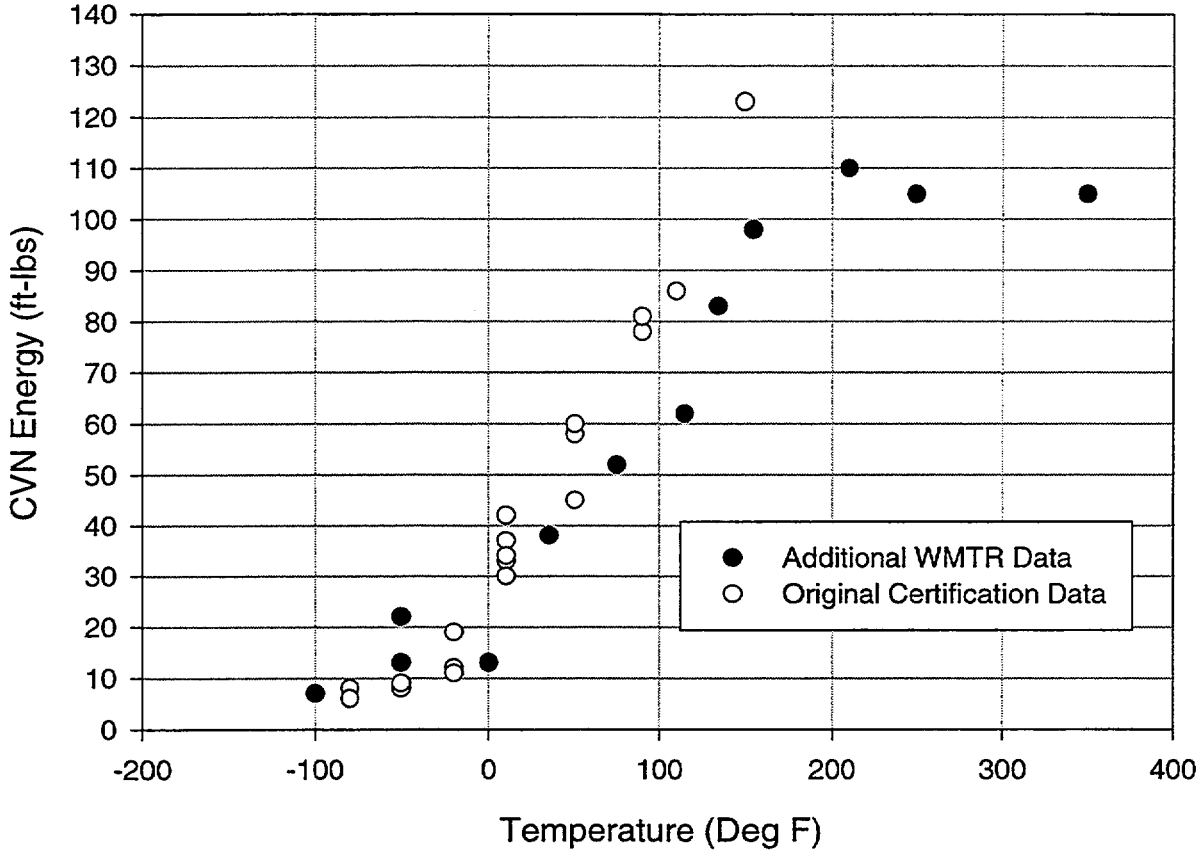

Figure A-4 Additional CVN Data for Plate 6607-2 (LT Orientation)

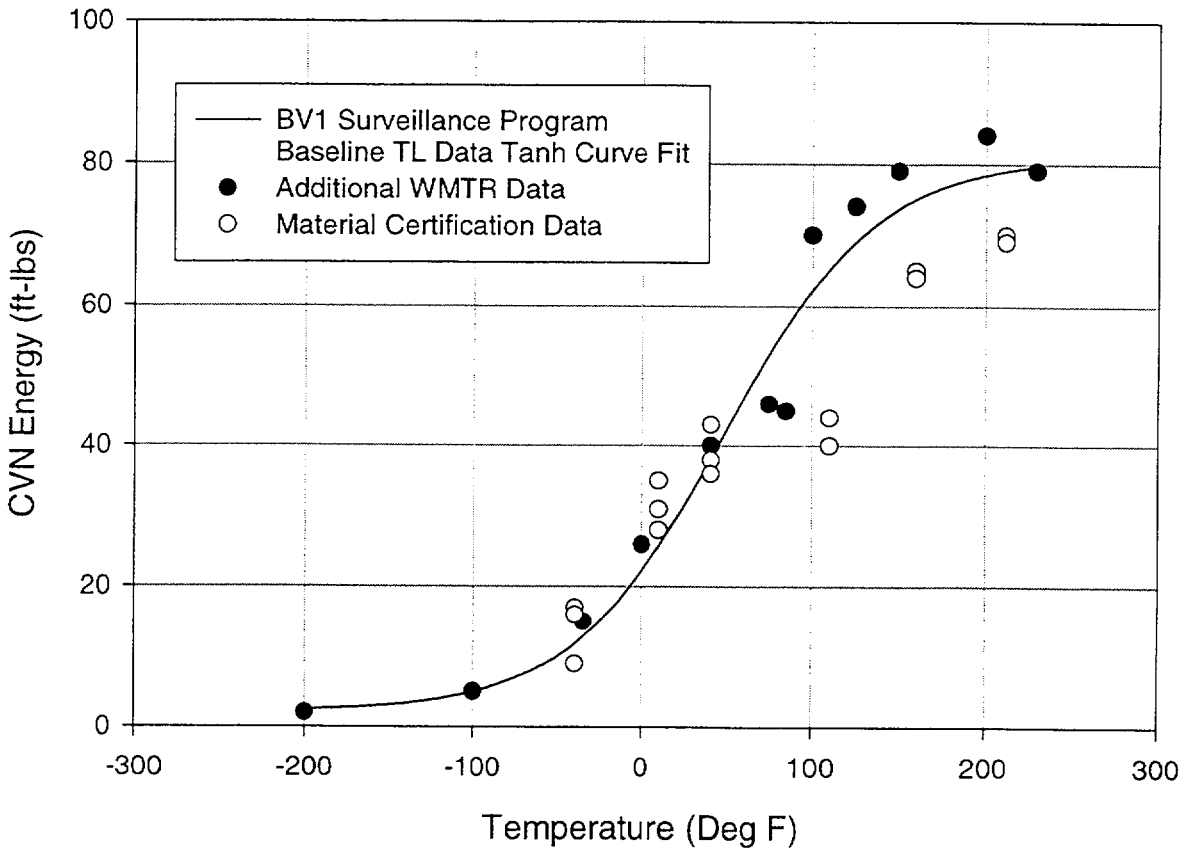

Figure A-5 Additional CVN Data for Plate 6903-1 (TL Orientation)

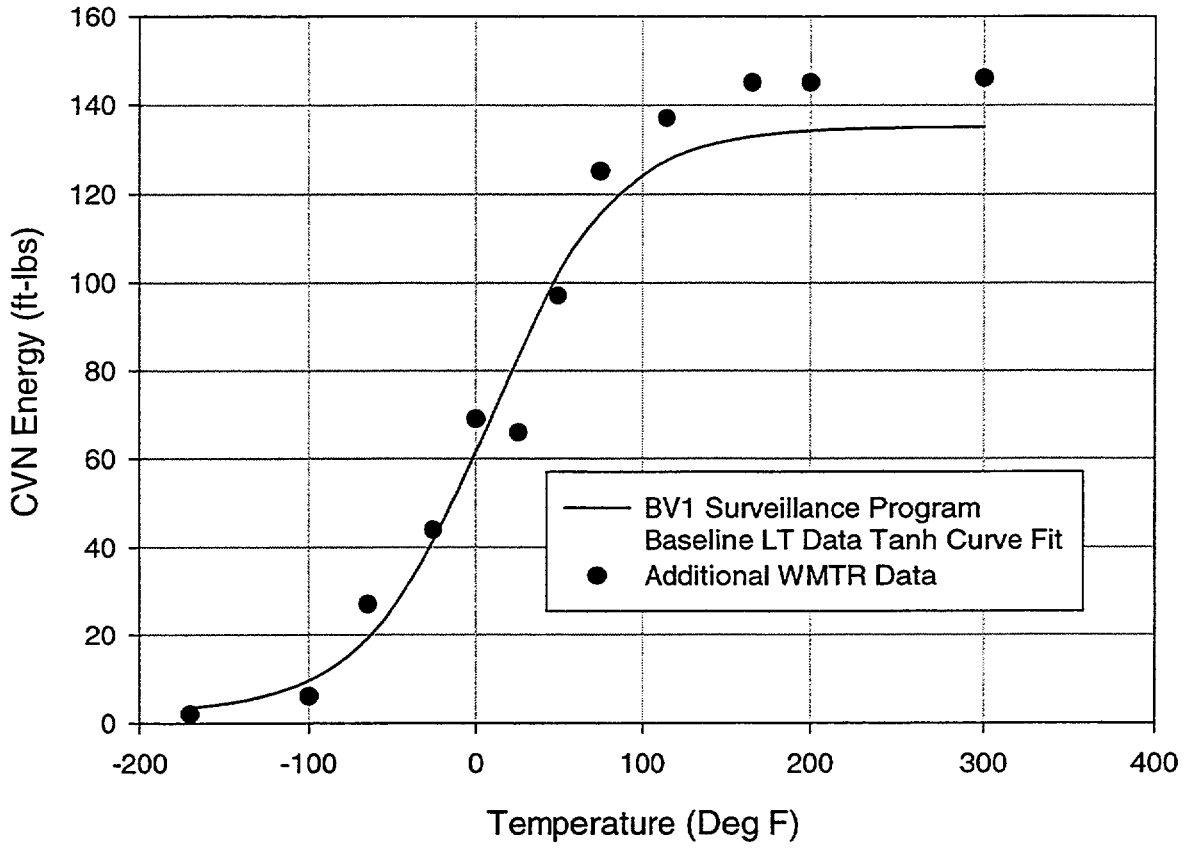

Figure A-6 Additional CVN Data for Plate 6903-1 (LT Orientation)

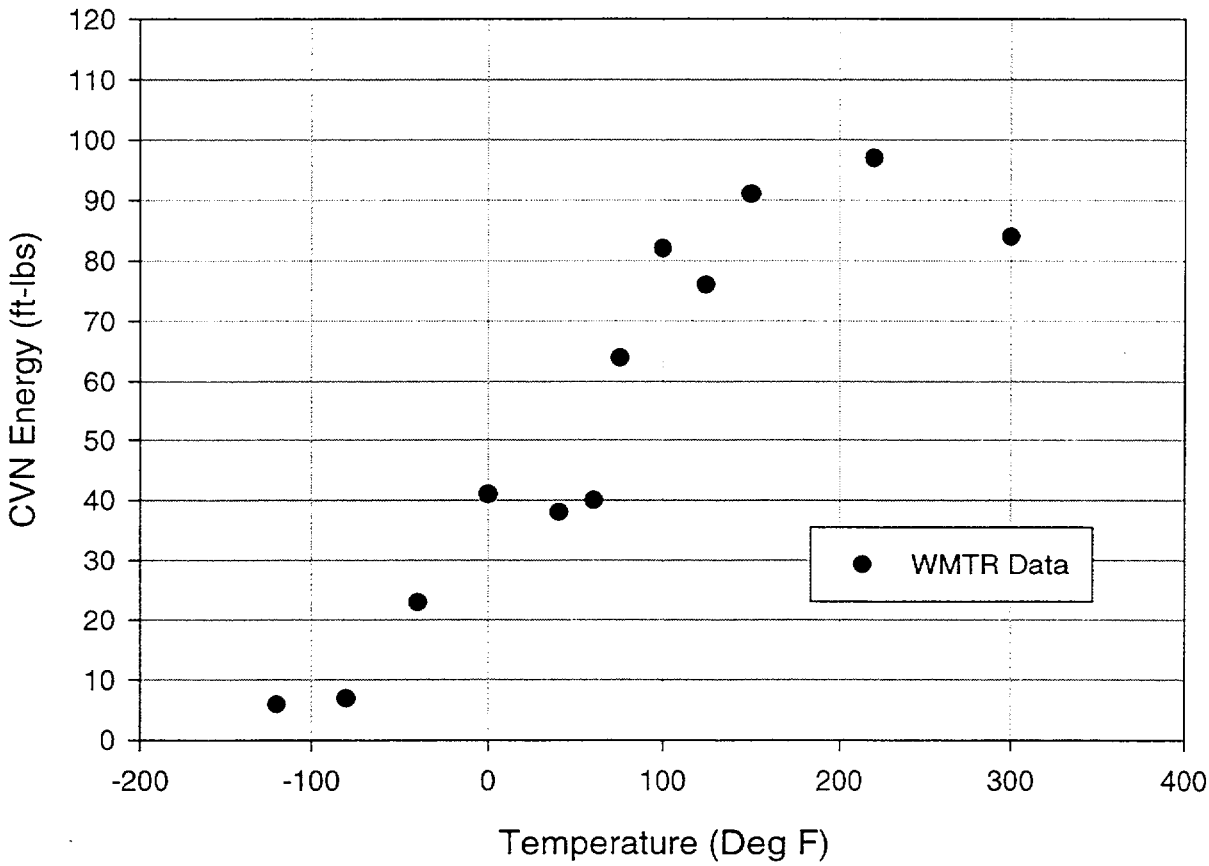

Figure A-7 Additional CVN Data for Plate 7203-2 (TL Orientation)

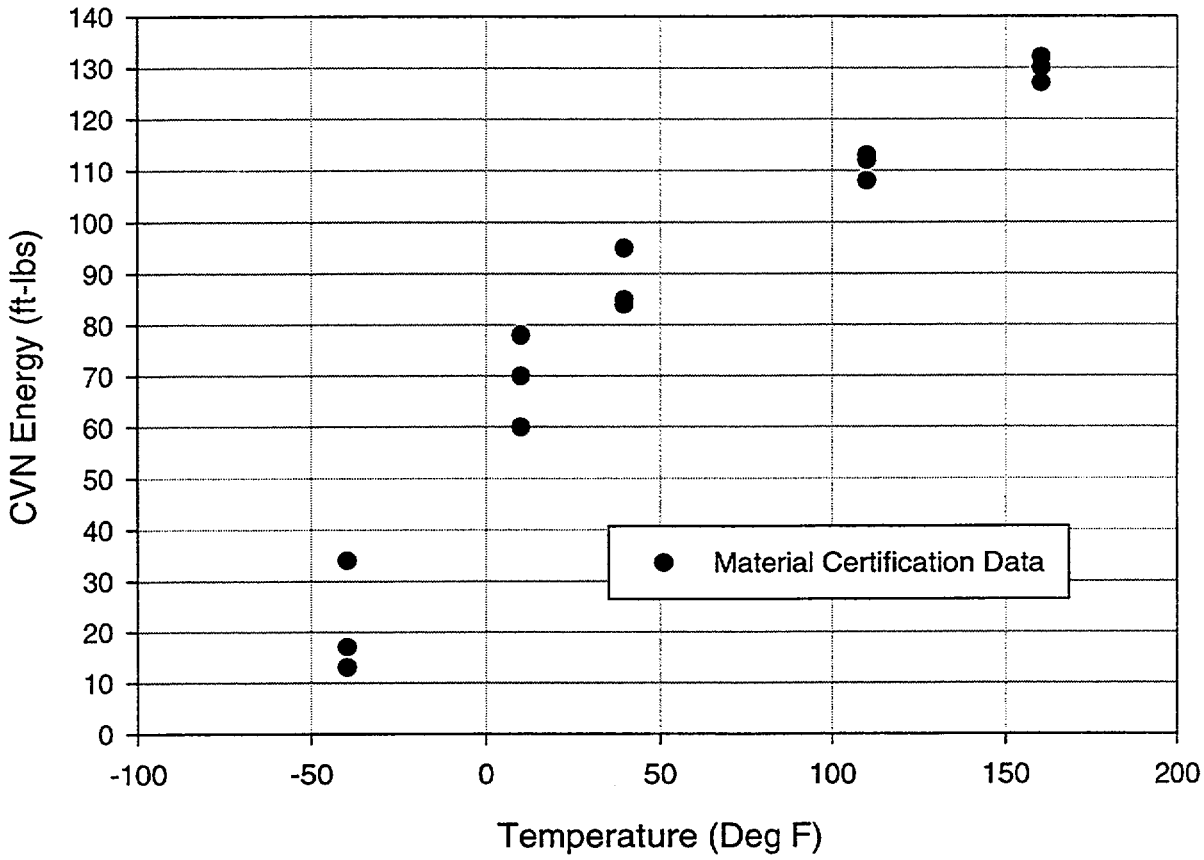

Figure A-8 Additional CVN Data for Plate 7203-2 (LT Orientation)

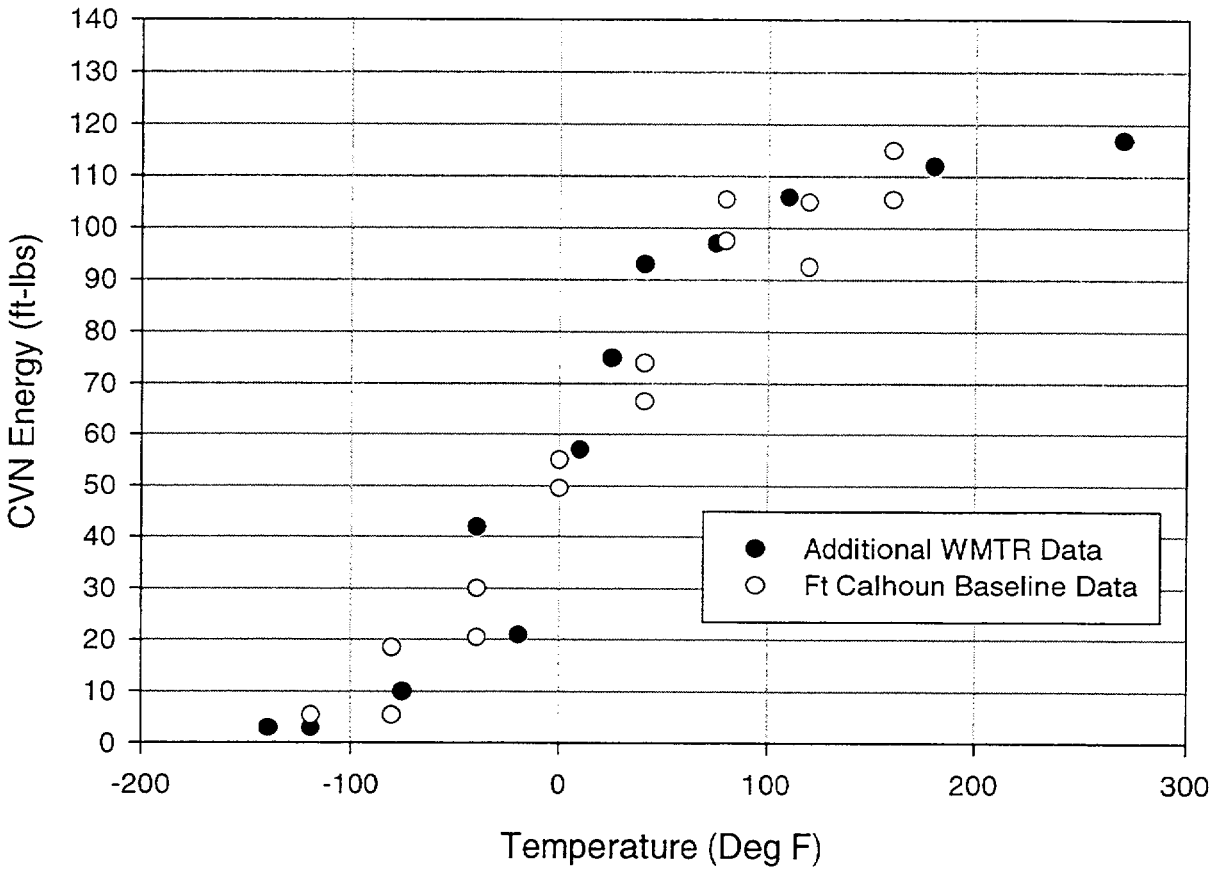

Figure A-9 Additional CVN Data for Weld Heat 305414

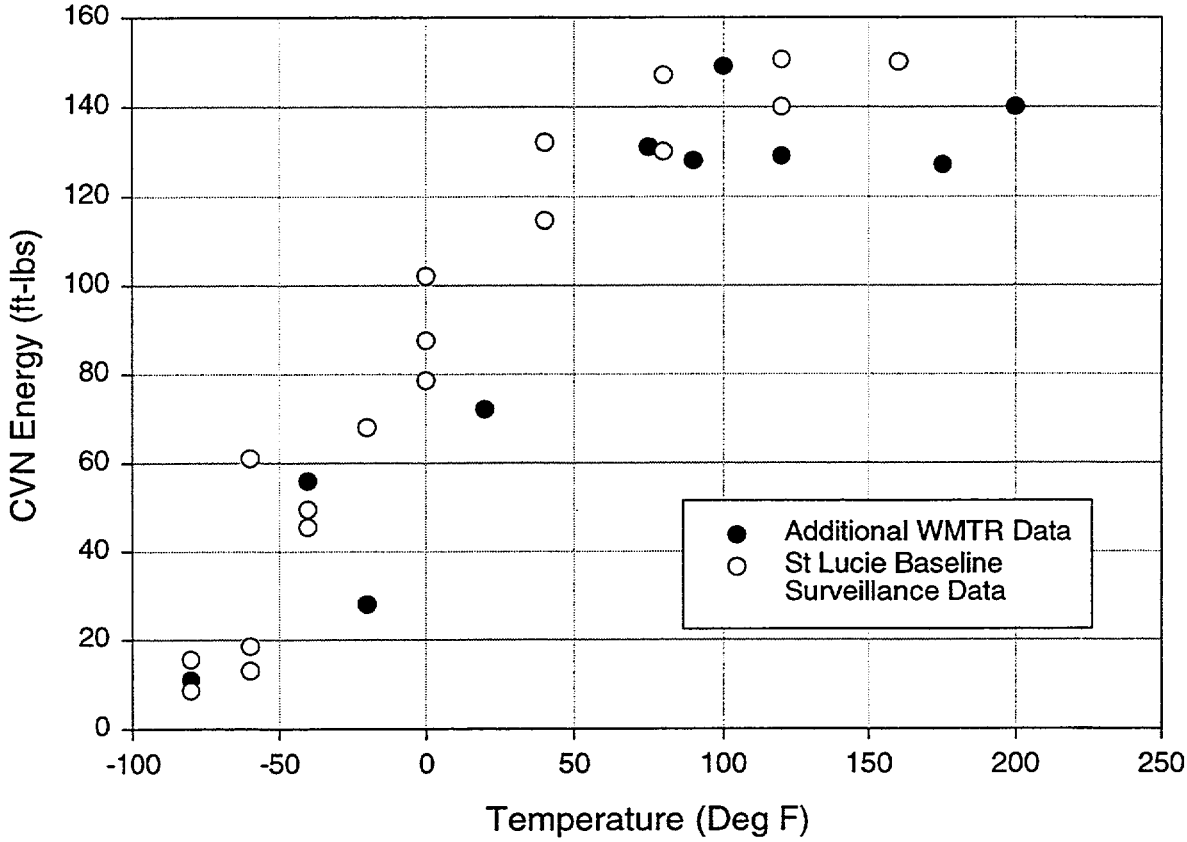

Figure A-10 Additional CVN Data for Weld Heat 90136

APPENDIX B

FRACTURE TOUGHNESS TEST DATA FOR BVPS-1 PLATE MATERIALS (TL ORIENTATION)

Table B-1 Plate Heat C6317-1 (TL) 1T-CT Specimen Test Data				
Plate C6317-1/ I.D. B6903-1				
Specimen:	1T-CT		Yield Strength:	73 ksi (-76°C)
Lab / Test Number:	WMT&R NO. 0-04088		KJC Limit (MPa √m):	289.3
Specimen ID	**Test Temperature (°C)**	**KJC (MPa √m)**	**Valid**	**KJC(1T) (MPa √m)**
03-1-1	-76	95.6	YES	95.7
03-1-2	-76	67.5	YES	67.5
03-1-3	-76	65.9	YES	66.0
03-1-4	-76	96.9	YES	97.0
03-1-5	-76	51.0	YES	51.0
03-1-6	-76	74.6	YES	74.6
03-1-7	-76	61.4	YES	61.5
03-1-8	-76	71.1	YES	71.1

Table B-2 Plate Heat C6317-1 (TL) PCVN Specimen Test Data				
Plate C6317-1/ I.D. B6903-1				
Specimen:	PCVN		Yield Strength:	73 ksi (-76°C)
Lab / Test Number:	WMT&R NO. 0-06759		$K_{JC\ Limit}$ (MPa √m):	129.8
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
03-1-25	-85	103.2	YES	85.90
03-1-26	-85	109.5	YES	90.94
03-1-27	-85	102.5	YES	85.37
03-1-29	-85	114.4	YES	94.82
03-1-30	-85	97.7	YES	81.61
03-1-31	-85	96.3	YES	80.47
03-1-32	-85	96.3	YES	80.49
03-1-28	-76	93.0	YES	77.88

Table B-3 Plate Heat C6317-1 (TL) ½T Specimen Test Data				
Plate C6317-1/ I.D. B6903-1				
Specimen:	½T-CT		Yield Strength:	73 ksi (-76°C)
Lab / Test Number:	MTI NO. 47781		$K_{JC\ Limit}$ (MPa √m):	203.05
Specimen ID	**Test Temperature (°C)**	**KJC (MPa √m)**	**Valid**	**KJC(1T) (MPa √m)**
6317-1	-80	66.96	YES	59.49
6317-2	-80	82.82	YES	72.82
6317-3	-80	75.12	YES	66.35
6317-4	-80	62.11	YES	55.41
6317-5	-80	75.91	YES	67.02
6317-6	-80	60.86	YES	54.36
6317-7	-80	82.90	YES	72.89
6317-8	-80	63.93	NO*	56.94
6317-9	-80	79.79	YES	70.28
6317-10	-80	76.39	YES	67.41

* Invalid fatigue crack

Table B-4 Plate Heat C6317-1 (TL) Irradiated (Capsule W) RPCVN Specimen Test Data				
Plate C6317-1/ I.D. B6903-1				
Specimen:	RPCVN		Yield Strength:	78 ksi (135°C)
Lab / Test Number:	STC 98-9TC5-WOGFT-R1		$K_{JC\ Limit}$ (MPa √m):	134.3
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
IBV 32	18	68.7	YES	58.6
IBV 29	18	94.7	YES	79.2
IBV 27	18	68.5	YES	58.5
IBV 35	18	78.6	YES	66.4
IBV 36	18	84.9	YES	71.4
IBV 28	18	81.8	YES	69.0
IBV 31	18	87.9	YES	73.8
IBV 25	18	83.9	YES	70.6
IBV 30	18	115.7	YES	95.8

Table B-5 Plate Heat C6317-1 (TL) Irradiated (Capsule Y) RPCVN Specimen Test Data				
Plate C6317-1/ I.D. B6903-1				
Specimen:	RPCVN		Yield Strength:	78 ksi (135°C)
Lab / Test No.:	WCAP-15624		$K_{JC\ Limit}$ (MPa √m):	134.3
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
DT90	51.7	124.7	YES	102.9
DT89	37.8	96.3	YES	80.5
DT95	37.8	66.9	YES	57.2
DT89a	37.8	71.7	YES	60.9
DT88a	37.8	87.5	YES	73.5
DT95a	37.8	81.5	YES	68.8
DT87a	37.8	68.4	YES	58.3
DT88	37.8	88.7	YES	74.4
DT90a	37.8	60.7	YES	52.2
DT87	23.9	60.0	YES	51.7

Table B-6 Plate Heat C6317-1 (TL) Irradiated (Capsule W) 1X-WOL Specimen Test Data				
Plate C6317-1/ I.D. B6903-1				
Specimen:	1X-WOL		Yield Strength:	78 ksi (135°C)
Lab / Test No.:	STC 98-9TC5-WOGFT-R1		$K_{JC\ Limit}$ (MPa √m):	204.3
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
dt9	47	130.9	YES	130.9
dt10	47	92.6	YES	92.6
dt11	47	106.9	YES	106.9
dt12	47	112.4	YES	112.4

Table B-7 Plate Heat C4381-2 (TL) Unirradiated 1T-CT Specimen Test Data (WMTR)				
Plate C4381-2/ I.D. B6607-2				
Specimen:	1T-CT		Yield Strength:	73 ksi (-76°C)
Lab / Test No.:	WMT&R NO. 0-06754		$K_{JC\ Limit}$ (MPa √m):	289.3
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
07-2-21	-76	64.9	YES	64.9
07-2-22	-76	77.3	YES	77.2
07-2-23	-76	79.0	YES	79.0
07-2-24	-76	53.1	YES	53.0
07-2-25	-76	49.5	YES	49.4
07-2-26	-76	44.7	YES	44.7
07-2-27	-76	51.2	YES	51.2
07-2-28	-76	41.7	YES	41.8

Table B-8 Plate Heat C4381-2 (TL) Unirradiated 1T-CT Specimen Test Data (MTI)				
Plate C4381-2/ I.D. B6607-2				
Specimen:	1T-CT		Yield Strength:	73 ksi (-76°C)
Lab / Test No.:	MTI NO. 47781		$K_{JC\ Limit}$ (MPa √m):	289.3
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
4381-1	-75	37.99	YES	37.99
4381-2	-76	66.34	YES	66.34
4381-3	-76	54.73	YES	54.73
4381-4	-76	51.74	YES	51.74
4381-5	-76	79.63	YES	79.63
4381-6	-76	35.83	YES	35.83
4381-7	-76	48.99	YES	48.99
4381-8	-76	68.68	YES	68.68
4381-9	-76	60.47	YES	60.47
4381-10	-76	76.40	YES	76.40

Table B-9 Plate Heat C4381-2 (TL) Unirradiated PCVN Specimen Test Data				
Plate C4381-2/ I.D. B6607-2				
Specimen:	PCVN		Yield Strength:	73 ksi at –76°C
Lab / Test No.:	WMT&R NO. 0-04087 Dated 10-30-00		$K_{JC\ Limit}$ (MPa √m):	129.8
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
07-2-25	-76	111.0	YES	92.1
07-2-26	-76	107.2	YES	89.1
07-2-27	-76	93.5	YES	78.3
07-2-28	-76	70.2	YES	59.8
07-2-29	-76	112.1	YES	93.0
07-2-30	-76	115.2	YES	95.4
07-2-31	-76	106.1	YES	88.2
07-2-32	-76	107.1	YES	89.0
07-2-33	-76	74.9	YES	63.5
07-2-34	-76	92.9	YES	77.7

Table B-10 Plate Heat C6293-2-1 (TL) Unirradiated 1T-CT Specimen Test Data				
Plate C6293-2-1/ I.D. B7203				
Specimen:	1T-CT		Yield Strength:	73 ksi at -76 (°C)
Lab / Test No.:	WMT&R NO. 0-11648		$K_{JC\ Limit}$ (MPa √m):	289.3
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
93-1	-76	68.4	YES	68.4
93-2	-76	71.5	YES	71.5
93-3	-76	43.6	YES	43.6
93-4	-76	75.7	YES	75.8
93-5	-76	87.9	YES	87.9
93-6	-76	80.4	YES	80.4
93-7	-76	92.4	YES	92.5
93-8	-76	73.1	YES	73.1
93-9	-76	97.5	YES	97.5
93-10	-76	62.7	YES	62.7

Table B-11 Plate Heat C6293-2 (TL) Unirradiated PCVN Specimen Test Data				
Plate C6293-2-1/ I.D. B7203				
Specimen:	PCVN		Yield Strength:	73 ksi at -76 (°C)
Lab / Test No.:	WMT&R 0-12252		$K_{JC\ Limit}$ (MPa √m):	128.6
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
93-1	-76	83.7	YES	70.5
93-2	-76	109.2	YES	90.7
93-3	-76	139.3*	YES	103.9
93-4	-76	109.9	YES	91.2
93-5	-76	125.6*	YES	103.5
93-6	-76	107.9	YES	89.7
93-7	-76	98.4	YES	82.1
93-8	-76	115.4	YES	95.6
93-9	-76	140.2*	YES	102.8
93-10	-76	113.3	YES	93.9

* Over the K_{Jc} limit and censored

APPENDIX C

FRACTURE TOUGHNESS TEST DATA FOR BVPS-1 WELD MATERIALS

Table C-1 Weld Heat 305414 Unirradiated 1T-CT Specimen Test Data				
Weld 305414				
Specimen:	1T-CT		Yield Strength:	86.4 ksi at -70°C
Lab / Test No.:	KAERI/TR-1684/2000		$K_{JC\ Limit}$ (MPa √m):	321.6
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
414-1	-70	86.3	YES	86.3
414-2	-70	145.2	YES	145.2
414-3	-70	115.8	YES	115.8
414-4	-70	144.1	YES	144.1
414-5	-70	95.3	YES	95.3
414-6	-70	89.8	YES	89.8
414-7	-70	110.9	YES	110.9
414-8	-70	134.3	YES	134.3
414-9	-70	102.5	YES	102.5
414-10	-70	103.7	YES	103.7

Table C-2 Weld Heat 305414 Unirradiated PCVN Specimen Test Data				
Weld 305414				
Specimen:	PCVN		Yield Strength:	90.4 ksi at -90°C
Lab / Test No.:	KAERI/TR-1684/2000		$K_{JC\ Limit}$ (MPa √m):	144.8
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
414-1	-100	60.9	YES	52.4
414-3	-90	61.6	YES	53.0
414-4	-90	107.1	YES	89.0
414-5	-90	124.9	YES	103.1
414-6	-90	106.8	YES	88.7
414-7	-90	87.0	YES	73.0
414-8	-90	134.1	YES	110.4
414-9	-90	125.4	YES	103.5
414-10	-90	80.2	YES	67.7

Table C-3 Weld Heat 305424 Unirradiated PCVN Specimen Test Data				
Weld 305424				
Specimen:	PCVN		Yield Strength:	93.1 ksi at -129°C
Lab / Test No.:	CEOG NPSD-1118		$K_{JC\ Limit}$ (MPa √m):	144.8
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
CZ-95	-129	74.8	YES	63.4
CZ-93	-129	95.8	YES	80.0
CZ-94	-129	107.7	YES	89.5
CZ-97	-129	123.9	YES	102.3
CZ-96	-129	147.4*	YES	120.9
CZ-98	-129	147.4*	YES	120.9
CZ-99	-129	147.4*	YES	120.9
CZ-91	-121	138.8	YES	114.1
CZ-90	-121	140.7	YES	115.6
CZ-92	-121	147.4*	YES	143.6

* Over the K_{Jc} limit and censored

Table C-4 Weld Heat 305424 Unirradiated PCVN Specimen Test Data				
Weld 305424				
Specimen:	PCVN		Yield Strength:	93.1 ksi at -129°C
Lab / Test No.:	CEOG NPSD-1118		$K_{JC\ Limit}$ (MPa √m):	144.8
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
1-2/2-2	-129	85.8	YES	72.1
1-3/2-3	-129	105.3	YES	87.6
1-6/2-6	-129	106.7	YES	88.7
1-5/2-5	-129	110.4	YES	91.6
1-4/2-4	-129	113.5	YES	94.1
1-12/2-12	-129	119.8	YES	99.1
1-1/2-1	-129	120.6	YES	99.7
1-10/2-10	-129	130.5	YES	107.6
1-9/2-9	-129	131.3	YES	108.2
1-11/2-11	-129	135.6	YES	111.6
1-7/2-7	-129	143.4	YES	117.7
1-8/2-8	-129	143.8	YES	118.1

Table C-5 Weld Heat 90136 Unirradiated PCVN Specimen Test Data				
Weld 90136				
Specimen:	PCVN		Yield Strength:	87.5 ksi at -90°C
Lab / Test No.:			$K_{JC\ Limit}$ (MPa √m):	140.0
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
M1	-90	141.6*	YES	114.0
M2	-90	154.2*	YES	114.6
M3	-90	120.4	YES	99.5
M4	-90	149.6*	YES	115
M5	-90	114.4	YES	94.8
M6	-90	133.8	YES	110.1
M7	-90	130.2	YES	107.3
M8	-90	124.6	YES	102.8
M9	-90	89.2	YES	74.8
M10	-90	119.6	YES	98.9

* Over the K_{Jc} limit and censored

APPENDIX D

FRACTURE TOUGHNESS DATA FOR BVPS-1 PLATE MATERIALS (LT ORIENTATION)

Table D-1 Plate Heat C6317-1 (LT) Unirradiated 1T-CT Specimen Test Data				
Plate C6317-1/ I.D. B6903-1				
Specimen:	1T-CT		Yield Strength:	73 ksi (-76°C)
Lab / Test Number:	STC:98-9TC5-WOGFT-R1		$K_{JC\ Limit}$ (MPa √m):	289.3
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
DLW2	-76	135.9	YES	135.9
DLW3	-76	119.0	YES	119.0
DLW4	-76	78.5	YES	78.5
DLW5	-76	119.3	YES	119.3
DLW6	-76	89.3	YES	89.3
DLW7	-76	69.8	YES	69.8

Table D-2 Plate Heat C6317-1 (LT) Unirradiated PCVN Specimen Test Data				
Plate C6317-1/ I.D. B6903-1				
Specimen:	PCVN		Yield Strength:	73 ksi (-76°C)
Lab / Test Number:	STC:98-9TC5-WOGFT-R1		$K_{JC\ Limit}$ (MPa √m):	129.8
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
DLW7C	-129	62.5	YES	53.6
DLW10C	-129	63.2	YES	54.3
DLW11C	-129	69.5	YES	59.2
DLW12C	-129	74.5	YES	63.2
DLW6C	-129	83.4	YES	70.2
DLW9C	-129	89.8	YES	75.3
DLW8C	-129	89.5	YES	74.7
DLW4C	-129	95.0	YES	79.4
DLW5C	-129	108.8	YES	90.3

Table D-3 Plate Heat C6317-1 (LT) Unirradiated RPCVN Specimen Test Data				
Plate C6317-1/ I.D. B6903-1				
Specimen:	RPCVN		Yield Strength:	73 ksi (-76°C)
Lab / Test Number:	STC:98-9TC5-WOGFT-R1		$K_{JC\ Limit}$ (MPa √m):	129.8
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
DLW2B	-129	80.1	YES	67.6
DLW3A	-129	46.4	YES	40.9
DLW4A	-129	71.4	YES	60.6
DLW4B	-129	98.2	YES	81.8
DLW5A	-129	107.9	YES	89.5
DLW6A	-129	62.5	YES	53.7
DLW7A	-129	65.8	YES	80.0
DLW8A	-129	71.0	YES	60.4

Table D-4 Plate Heat C6317-1 (LT) Unirradiated 1X-WOL Specimen Test Data				
Plate C6317-1/ I.D. B6903-1				
Specimen:	1X-WOL		Yield Strength:	73 ksi (-76°C)
Lab / Test No.:	STC:98-9TC5-WOGFT-R1		$K_{JC\ Limit}$ (MPa √m):	197.7
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
DLW1	-76	180.1	YES	180.1
DLW2	-76	119.4	YES	119.4
DLW3	-76	102.6	YES	102.6
DLW4	-76	102.8	YES	102.8
DLW5	-76	71.7	YES	71.7
DLW6	-76	71.1	YES	71.1

Table D-5 Plate Heat C4381-2 (LT) Unirradiated 1T-CT Specimen Test Data				
Plate C4381-2/ I.D. B6607-2				
Specimen:	1T-CT		Yield Strength:	73 ksi (-76°C)
Lab / Test No.:	WMT&R NO.9-14654		$K_{JC\ Limit}$ (MPa √m):	289.3
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
07-2-11	-76	57.2	YES	57.2
07-2-12	-76	77.1	YES	77.1
07-2-13	-76	66.5	YES	66.5
07-2-15	-76	70.5	YES	70.5
07-2-16	-76	59.4	YES	59.4
07-2-17	-76	65.9	YES	65.9
07-2-18	-76	68.3	YES	68.3
07-2-19	-76	66.3	YES	66.3
07-2-20	-60	82.8	YES	82.8

Table D-6 Plate Heat C4381-2 (LT) Unirradiated 1T-CT Specimen Test Data				
Plate C4381-1/ I.D. B6607-1				
Specimen:	1T-CT		Yield Strength:	73 ksi (-76°C)
Lab / Test No.:	WMT&R NO.9-14653		$K_{JC\ Limit}$ (MPa √m):	289.3
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
07-1-11	-76	58.7	YES	58.7
07-1-12	-76	69.2	YES	69.2
07-1-13	-76	63.9	YES	63.9
07-1-14	-76	54.8	YES	54.8
07-1-15	-76	74.8	YES	74.8
07-1-16	-76	84.8	YES	84.8
07-1-17	-60	66.8	YES	66.8
07-1-18	-76	86.6	YES	86.6
07-1-19	-60	81.1	YES	81.1
07-1-20	-60	57.4	YES	57.4

Table D-7 T_o Results for Plate Heat C6317-1 (LT)							
Material	Fluence, n/cm^2	Test Laboratory	Orientation	Specimen Type	ASTM E 1921-97 Test Temp., °C	ASTM E 1921-97 T_o, °C	Multi-Temp. T_o, °C
A533B-1	0	STC	LT	PCVN	-129	-96	NA
A533B-1	0	STC	LT	RPCVN	-129	-95	NA
A533B-1	0	STC	LT	1T-CT	-76	-79	NA
A533B-1	0	STC	LT	1X-WOL	-76	-90	NA

Table D-8 T_o Results for Plate Heat C4381							
Material	Fluence, n/cm^2	Test Laboratory	Orientation	Specimen Type	ASTM E 1921-97 Test Temp., °C	ASTM E 1921-97 T_o, °C	Multi-Temp. T_o, °C
A533B-1 (C4381-2)	0	WMTR	LT	1T-CT	-76	-38	-37
A533B-1 (C4381-1)	0	WMTR	LT	1T-CT	-76	-46	-41

APPENDIX E

FRACTURE TOUGHNESS DATA FOR THE FARLEY WELD HEAT NUMBER 33A277

This appendix presents the measured fracture toughness data for the Farley weld heat 33A277, a weld similar to BVPS-1 heat 90136, a Linde 0091 flux weld. This weld was from the Farley-1 surveillance program and represents the only Linde 0091 weld evaluated in both the unirradiated and irradiated conditions using both CT and PCVN specimens. These results, although not directly applicable to the BVPS-1 RPV, are added to this report for comparison of general trends for this different flux type weld.

Table E-1 Weld Heat 33A277 Unirradiated 1T-CT Specimen Test Data				
Weld 33A277				
Specimen:	1T-CT		Yield Strength:	82 ksi At –96 (°C)
Lab / Test Number:	CEOG NPSD-1118		$K_{JC\ Limit}$ (MPa √m):	311.0
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
C19-8	-96	52.3	YES	52.3
C19-9	-96	75.0	YES	75.0
C19-1	-96	77.2	YES	77.2
C19-2	-96	77.8	YES	77.8
C19-3	-96	83.8	YES	83.8
C19-6	-96	83.9	YES	83.9
C19-7	-96	85.7	YES	85.7
C19-5	-96	96.4	YES	96.4
C19-4	-96	106.6	YES	106.6

Table E-2 Weld Heat 33A277 Unirradiated PCV Specimen Test Data				
Weld 33A277				
Specimen:	PCVN		Yield Strength:	82 ksi At –96 (°C)
Lab / Test Number:	CEOG NPSD-1118		$K_{JC\ Limit}$ (MPa √m):	132.9
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
C19-3	-96	90.3	YES	75.7
C19-5	-96	97.9	YES	81.7
C19-7	-96	100.3	YES	83.6
C19-10	-96	102.0	YES	84.9
C19-4	-96	112.9	YES	93.6
C19-2	-96	115.0	YES	95.3
C19-6	-96	124.8	YES	103.0
C19-9	-96	132.9*	NO	109.4
C19-1	-96	132.9*	NO	109.4
C19-8	-96	132.9*	NO	109.4

* Over the K_{Jc} limit and censored

Table E-3 Weld Heat 33A277 Irradiated RPCV Specimen Test Data				
Weld 33A277: Irradiated Fluence 2.8 x 10^{19} (Farley Cap X)				
Specimen:	RPCVN		Yield Strength:	85 ksi at RT
Lab / Test Number:	STC:98-9TC5-WOGFT-R1		$K_{JC\ Limit}$ (MPa √m):	144.8
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
Ah47	-65	78.2	NO*	66.1
Ah50	-65	83.5	YES	70.3
Aw50	-65	118.7	YES	98.2
Ah53	-65	51.3	NO*	44.8
Ah55	-65	62.0	YES	53.2
Ah46	-65	67.6	YES	57.7
Aw56	-65	101.6	NO*	84.7
Aw58	-65	68.6	YES	58.4
Aw55	-65	67.6	NO*	57.7
Aw53	-65	116.9	YES	96.7

*Precrack length did not meet the requirements

Table E-4 Weld Heat 33A277 Irradiated 1/2T-CT Specimen Test Data				
Weld 33A277: Irradiated Fluence 2.8 x 10^{19} n/cm^2 (Farley Cap X)				
Specimen:	½ T-CT		Yield Strength:	85 ksi at RT
Lab / Test Number:	STC:98-9TC5-WOGFT-R1		$K_{JC\ Limit}$ (MPa √m):	195
Specimen ID	**Test Temperature (°C)**	**K_{JC} (MPa √m)**	**Valid**	**K_{JC}(1T) (MPa √m)**
Aw9	-65	90.9	YES	79.7
Aw10	-65	82.2	YES	72.3
Aw11	-65	112.4	YES	97.8
Aw12	-65	89.4	YES	78.4

Table E-5 T_o Results for Weld 33A277

Material	Fluence, n/cm²	Test Laboratory	Orientation	Specimen Type	ASTM E 1921-97 Test Temp., °C	ASTM E 1921-97 T_o, °C	Multi-Temp. T_o, °C
Linde 0091 Flux Weld	0	CE	T	1T-CT	-96	-79	NA
Linde 0091 Flux Weld	0	CE	T	PCVN	-96	-94	NA
Linde 0091 Flux Weld	2.8×10^{19}	STC	T	RPCVN	-65	-44	-44[b]
Linde 0091 Flux Weld	2.8×10^{19}	STC	T	1/2T-CT	-65	-47[a]	