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Initial RT_{NDT} Re-evaluation of WF-233 Weld of Kori Unit 1 using Master Curve Technology

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Abstract

The RPV of the oldest PWR in Korea has a Linde 80 weld in the beltline region. It has been subjected to the variety of integrity assessment such as, low upper-shelf toughness analysis and the plant specific PTS analysis. As a part of the activities to attain the integrity of the RPV for the period of the extended operation beyond the design life, the initial RT_{NDT} of the WF233 weld was reevaluated by applying the Master Curve technique to the archive weld material. By removing some of the excess conservatism, the initial RT_{NDT} was redefined as -32.2℃ instead of -23.3℃ that is currently used. The details of the RT_{NDT} determination are explained in this paper. Also, the potential benefits of the lower initial RT_{NDT} to the operating window during plant heatup/cooldown and pressurized thermal shock were discussed from the viewpoint of the life extension.

I. INTRODUCTION

During the operation of the nuclear power plants, fast neutrons are bombarded onto the reactor pressure vessel, causing the degradation of the material properties. This phenomenon is called as radiation embrittlement, and is characterized as increase in strength and decrease in fracture toughness. One of the key parameters of the radiation embrittlement is the reference temperature-nil ductility transition(RT_{NDT}) that is closely related to the fracture toughness of the materials[1]. The RT_{NDT} of the embrittled materials are calculated as the sum of the RT_{NDT} of the unirradiated materials(initial RT_{NDT}), shift of the index temperature measured from Charpy test in the surveillance program[2], and margins. The adjusted RT_{NDT}s are calculated according to the Reg. Guide 1.99 Rev. 2[3], and as shown in figure 1, the RT_{NDT} values are used in pressurized thermal shock(PTS) evaluation[4] and P-T limit curve[5] construction of the RPV.

When embrittled RPVs are subjected to pressurized thermal shock(PTS), the combination of thermal stress and pressure stress can considerably increase the possibility of through-wall propagation of existing cracks. To assure the integrity of RPVs at the event of PTS, PTS rule requires that the reference temperature-pressurized thermal shock(RT_{PTS}) of RPV beltline materials including base and welds should be lower than the PTS screening criteria[4]. The rule further requires that if

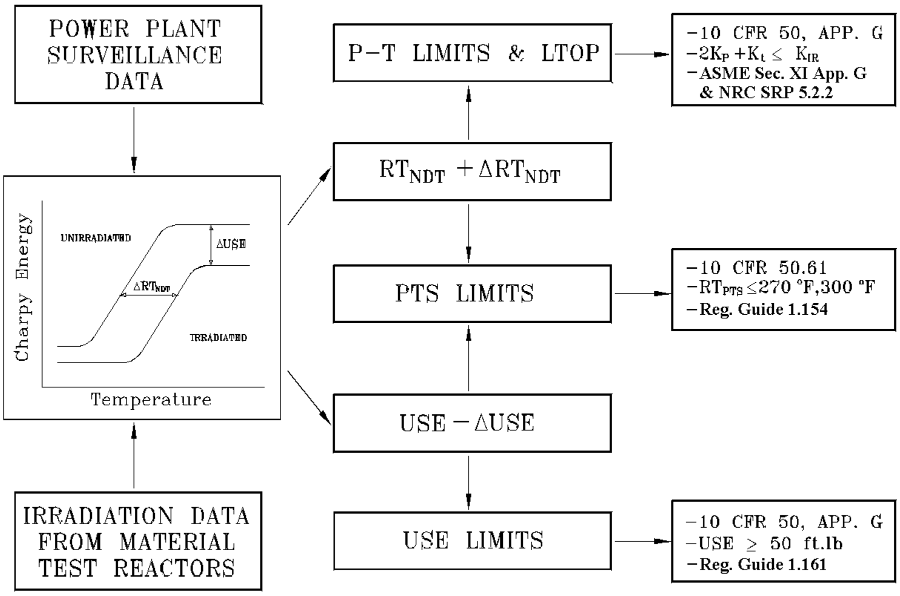


Figure 1. Rules, regulations, and codes relevant to RPV integrity

RT_{PTS} is expected to exceed screening criteria before the end of life, additional actions should be taken to maintain the integrity of the RPV.

Additionally, radiation embrittlement affects the operability of the plant by shifting the P-T limit curves. The P-T limit curves are determined such that, for given heatup/cooldown rates, pressures are lower than the certain temperatures to assure sufficient margin against brittle fracture[5]. Lower-bound fracture toughness curve, K_{IR} curve determined as a function of RT_{NDT} is used in the calculation. Therefore, available operating windows during heatup/cooldown processes are squeezed down to the narrow region between the P-T limit curves and pump cavitation curve. As the radiation embrittlement progresses, the operation window becomes narrower and narrower, causing difficulties for operators to heatup/cooldown the reactor.

The initial RT_{NDT} of RPV materials have been determined following the ASME Sec. III NB-2331[6]. However, the appropriateness of the method in accurately representing the fracture characteristics of the RPV materials has been questioned, in part, due to the indirect nature of Charpy test and resulting large scatter in the measured RT_{NDT} within the same group of materials. To resolve these problems, the Master Curve Technique[7] has been developed as an alternative way to measure the fracture toughness characteristics in the transition region directly from the precracked Charpy sized specimens using fracture toughness testing.

Kori Unit 1 is a typical Westinghouse 2-loop plant with gross capacity of 587 MWe. It is the first commercial nuclear power plant in Korea and has been in operation since 1978. In the life extension feasibility study, its RPV was selected as the most critical component for Plant Lifetime Management(PLiM) by systematic scoping of all the components of Kori Unit 1[8]. One of the most significant aging effects of the RPV was identified as radiation embrittlement. The circumferential weld in the beltline region showed significant radiation embrittlement and has been subjected to extensive integrity assessment. Especially, the initial RT_{NDT} of the weld is relatively high compared to those of the similar materials. As a part of nuclear PLiM program, it was decided to redefine the initial RT_{NDT} of the weld by applying the Master Curve Technique.

In this paper, the status of the RPV of Kori Unit 1 is introduced and the results of the Master Curve application are summarized. Also the impact of the newly defined initial RT_{NDT} on the various aspect of the RPV integrity assessments from viewpoint of the extended operation are reviewed.

II. STATUS OF KORI-1 RPV

2.1 Design and Weld Characteristics

The RPV of Kori Unit 1 is one of the typical Westinghouse 2-loop design and fabricated by B&W, with inner diameter of 132 inches and thickness of 6.5 inches. The schematic of the RPV is shown in figure 2. Its cylindrical shells were made of SA 508 Cl. 2 ring forging and internally clad with stainless steel 308 type weld. There are three circumferential welds near the reactor core, those are WF259, WF232/233, and WF267. The chemical compositions of the welds are summarized in table 1.

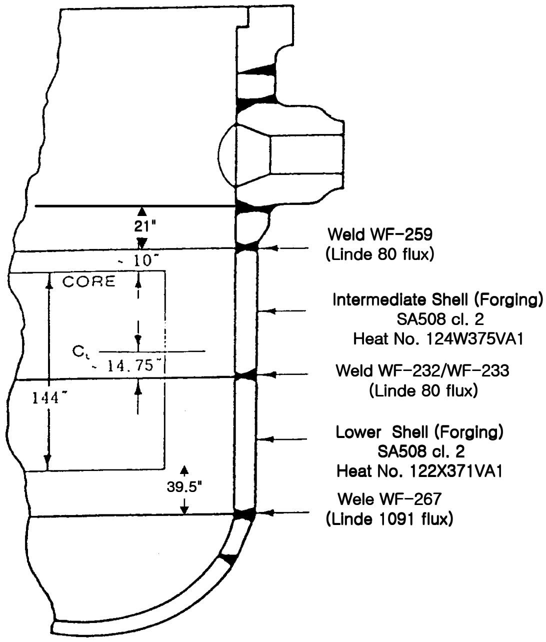


Figure 2 Schematics of Kori Unit 1 RPV and materials of construction

Like many of the early RPVs fabricated by B&W, Linde 80 flux was used in the beltline region welds of Kori Unit 1 RPV. The WF232/233 weld close to the midplane of the core consists of two weld materials. The inner portion of the weld is WF232, which contains less copper and nickel, and the outer portion of the weld is WF233. In surveillance program, more susceptible WF233 is included as the limiting

Table 1. Composition and initial RT_{NDT}s of welds near the beltline region.

Weld ID	WF-259	WF-232	WF-233	WF-267
Location	Nozzle Shell/ Inter. Shell	Inter. Shell/ Low. Shell(ID)	Inter. Shell/ Low. Shell(OD)	Lower Shell/ Lower Head
Filler wire heat no.	T29744	8T3914	T29744	T49544
Flux type & lot no.	Linde80, lot 8806	Linde80, lot 8790	Linde80, lot 8790	Linde 0091, lot3490
Cu in Weld Qual. Test	0.21%	0.14%	0.23%	0.24%
Ni in Weld Qual. Test	0.66%	0.69%	0.61%	0.52%
Cu in BAW-1799 [9]	-	0.18% (retest)	0.29%	-
Ni in BAW-1799 [9]	-	0.64% (retest)	0.68%	-
initial RT_{NDT}, ℃	-20.6 (generic)	-20.6 (generic)	-23.3 (measured)	-48.9 (generic)

material. The concern over the high copper content in the welds with Linde 80 flux and its effects on radiation embrittlement prompted the extensive reanalysis of the weld chemistry[9].

2.2 Initial RT_{NDT} of Beltline Weld

The fracture toughness of RPV materials is strongly dependent on temperature. From low temperature to high temperature, the lower-shelf energy region, transition region, and the upper-shelf energy region are defined. Reference temperature-nil ductility transition(RT_{NDT}) is the conceptual threshold temperature below which the material shows fully brittle fracture characteristics. It is determined according to ASME NB-2331 in which the initial RT_{NDT} be the higher of the nil-ductility transition temperature(NDTT) from drop weight test or 33.3℃ (60˚F) below the index temperature for 68 J (50 ft-lb) of absorbed energy in Charpy impact test. The intent of the NB-2331 is to define the conservative reference temperature in assessing fracture toughness of RPV materials. For WF233 weld of Kori Unit 1 RPV, NDTT was measured as –28.9℃, and the index temperature for 68 J of absorbed energy was measured as 10℃. Then the initial RT_{NDT} was defined as -23.3℃ which is the higher of -28.9℃ and -23.3℃(10℃- 33.3℃) [10].

Table 2. Summary of surveillance tests of circumferential weld in beltline region

Capsule	Fluence (10^{19} n/cm^2)	Measured Shift in RT_{NDT}, ℃	Adjusted RT_{NDT}, ℃	Upper shelf energy, J
Unirradiated	-	-	-23.3	90.2
V	0.509	90.1	115.7	65.0
T	1.115	87.8	113.4	56.9
S	1.228	99.9	125.5	63.3
R	2.988	115.0	140.1	54.6
R	3.938	115.1	140.2	55.2

2.3 Surveillance Test Results

In surveillance capsules, forging materials, weld, heat affected zone materials are included. Upto now, five out of six capsules have been withdrawn and tested. The results of the surveillance test are summarized in table 2. As shown in table 2, the reduction of USE and the increase in RT_{NDT} have been progressed considerably. Especially, USE of WF233 weld has been below the minimum requirement of 68 J since the first surveillance test. RT_{PTS} was also projected to exceed the screening criteria of 148.9℃ (300˚F) at about 27EFPY[11].

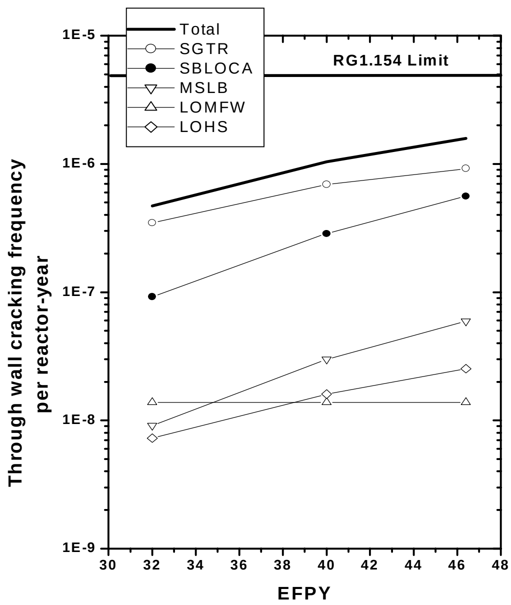


Figure 3. Calculated through-wall-cracking frequency

2.4 Plant-Specific PTS Evaluation

Following the procedure and methodology of Reg. Guide 1.154[12], the integrated PTS risk was calculated to determine the integrity of the RPV at the events of potential PTS transients and compared with the acceptance limit of 5.0×10^{-6} per reactor-year. As shown in figure 3, the through wall cracking probability of Kori Unit 1 RPV due to PTS events was estimated as less than 5.0×10^{-6} per reactor-year even after 46.4 EFPY, equivalent to 60 operating years. Therefore, it is now expected that RPV can maintain enough safety margin against pressurized thermal shock during its design life and extended operation period.

III. APPLICATION OF MASTER CURVE TECHNIQUE

In this section, the detailed procedure to determine the initial RT_{NDT} of the WF233 weld is presented. First, the fracture properties of WF-233 weld are evaluated for the pre-cracked Charpy specimens by a master curve method defined in ASTM E1921-97[7]. For the sake of comparison, the 72W weld, which was specially made for simulating the low USE Linde 80 welds for the HSST program, was tested using the same method. The chemistry of WF-233 is thoroughly analyzed in location bases in the weld and the chemistry factor of the WF-233 weld is evaluated with the resultant data. Then the initial RT_{NDT} of WF233 weld was determined by comparing with the fracture toughness test database of other Linde 80 weld.

3.1 Fracture toughness evaluation

The recently developed Master Curve technique provides the method to determine the characteristic temperature T_o from the fracture toughness test in the transition region. Compared to RT_{NDT} measured from the Charpy impact test, it has more sound technical basis and provide more reliable and statistically significant fracture toughness characteristics. The reference fracture toughness curve based on the Master Curve methods can be represented as follows;

$$K_{JC(med)} = 30 + 70 \cdot \exp[0.019 \cdot (T - T_o)] \qquad \text{in MPa}\sqrt{\text{m}} \qquad (1)$$

Where, T_o is the index temperature at which the mean K_{JC} equals to 100MPa√ m measured on the 1T-CT specimens.

The above method was reflected on the ASME Nuclear Code Cases N-629[13] and N-631[14], in which RT_{NDT} was replaced with RT_{To} while maintaining current framework of reference fracture toughness curve of ASME Code. According to the code cases, RT_{To} and RT_{NDT} were defined as follows;

$$RT_{NDT} \approx RT_{To} = T_o + 19.4^o C \qquad (2)$$

With this relationship, the 5% lower-bound K_{JC} curve is comparable to the reference fracture toughness curve of the ASME Code.

The fracture toughness of the welds was evaluated using the master curve method in accordance with ASTM standard E1921-97. The testing specimens were pre-cracked Charpy size 3- point bend type. The main test temperature was -90ºC. Figure 4 represents the K_{JC} curve for WF233 and the resulting reference temperature(T_o) was -83.3ºC. The standard deviation associated with the

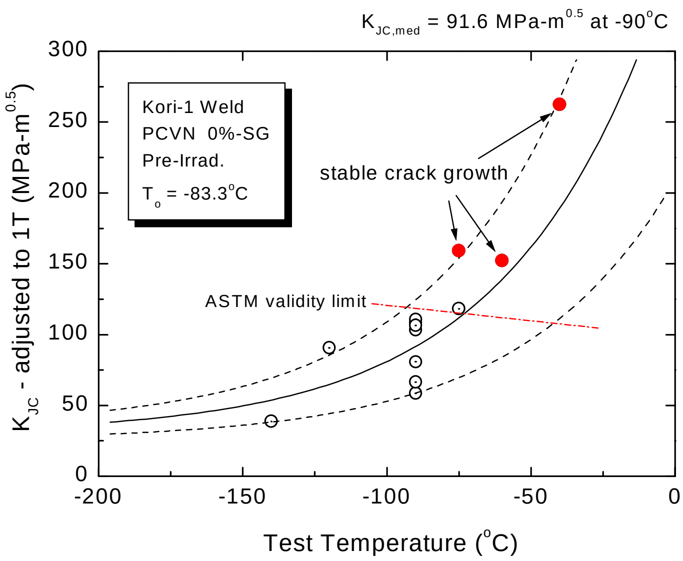


Figure 4. Fracture toughness test result of Kori-1 beltline weld, Linde 80 WF-233, measured by PCVN specimens.

measurements was 7 °C. The T_o value at 99% confidence level after applying 2.6-sigma was -65.1 °C. When 19.4 °C (35 °F) was added, the lower bound RT_{To} of WF233 weld was -45.7 °C(-50 °F).

In figure 5, the fracture toughness curves from the master curve methods and current ASME Code are compared. As shown in the figure, the fracture toughness test data of WF233 and 95% confidence curve were bounded by the reference fracture toughness curve with RT_{To}, verifying that RT_{To} can replace RT_{NDT}.

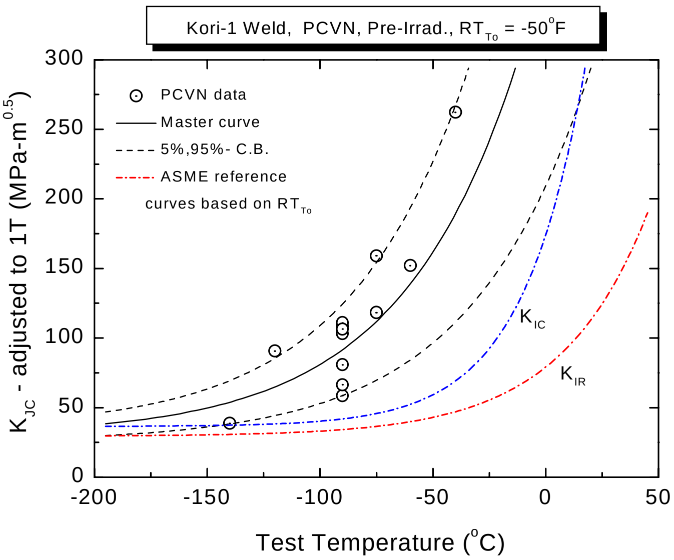


Figure 5. ASME fracture toughness reference curves, K_{IC} and K_{IR}, based on the measured RT_{To} with PCVN test data of unirradiated Kori-1 weld.

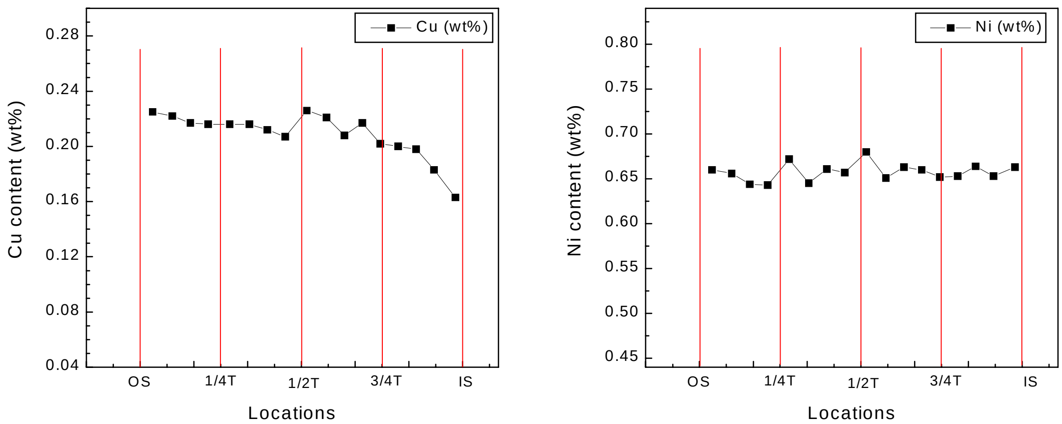
3.2 Weld Chemistry Analysis

Figure 6 shows the variation of copper and nickel contents along the weld centerline. The copper contents varied from 0.16wt% at the bottom to 0.23wt% at the top location. The nickel content does not show a noticeable variation, ranging from 0.64 to 0.68wt%. The reason for copper and nickel variation along weld centerline is postulated that in the lower part of the weld the base metal with low copper content is melted into the molten pool of the weld due to the U-shaped weld groove. The average values of copper and nickel are 0.210 and 0.657wt%, respectively. The copper content corresponds perfectly to the weld metal qualification test report and WCAP-8586 report, while the nickel content is somewhat higher than the results from those reports, and is rather close to the re-analyzed results[9].

The measured chemistry was used to determine the chemistry factor in accordance with Reg. Guide 1.99, Rev. 2. The chemistry factors for the average and maximum values of copper and nickel contents are 174 and 184^{o}F, respectively. The values from the chemistry are smaller than 196^{o}F from the surveillance data and 204^{o}F from the best-estimate chemistry of 0.29wt% Cu and 0.68wt% Ni[9]. With respect to conservatism, 0.29wt% Cu is reasonable, but the actual chemistry data in this study does not match well with a large Charpy index temperature shift at the energy of 41J after irradiation. This discrepancy might come from an inaccuracy in determining the initial Charpy T_{41J} value. If other Charpy test data was added to those in the surveillance program, the T_{41J} value become higher by about 8^{o}C. If this value is used as the baseline data, the chemistry factor from the surveillance data is about 178^{o}F, which corresponds with the values from the measured data in this study. Though, it is uncertain which chemistry values represent the radiation embrittlement of WF-233, it is clear that the best-estimate chemistry seems somewhat conservative.

3.3 Initial RT_{NDT} of WF233

In the previous section, the lower bound initial RT_{To} of the WF233 weld was calculated as -45.7℃ from the PCVN(pre-cracked Charpy V-notch) specimens. However, it was based on the test results of the limited number of specimens, and comparison with available database would be necessary to determine the fracture toughness characteristics of the WF233 weld. Test results on some of the Linde



a) Copper b) Nickel

Figure 6. Variation of copper and nickel content along the thickness of WF233 weld

80 welds[15] are summarized in Table 3. As shown in the table, the T_o values measured from the PCVN specimens were about 20℃ lower than those from the 1T-CT specimens. From PCVN test results in table 3, it can said that the fracture characteristics of WF-233 would be at least 6℃ better compared to WF-70 and 72W welds.

Table 3. Comparison of fracture toughness test results of some of Linde 80 welds

Weld	T_o (ºC)	Test Temp. (ºC)	Number of Specimens	Specimen Type	Source
WF-233	-83	-90	7	PCVN	KAERI
WF-70	-77	-84	7	PCVN	B&W
WF-70	-58	-	56	1T-CT	ORNL
72W	-74	-	24	PCVN	KAERI
72W	-54	-	74	1T-CT	ORNL

Before the ASME Code Cases were issued, the initial RT_{NDT} of the WF-70 weld of the RPV in the Zion NPP was conservatively redefined as -32.2℃(-26˚F) based on the results of the drop weight test, or NDTT[16]. This value was verifies by comparing with the available fracture toughness test database of the materials. If the methodology of Code Case N-631 had been applied, the initial RT_{NDT} of that materials would have been -38℃ for 1T-CT specimens. Though the quantitative relationship between the test results of PCVN and 1T-CT specimens are not clearly defined, there would be some conservatism if the initial RT_{NDT} of the WF-233 welds is determined as -32.2℃, or that of WF-70 weld.

3.4 Comparison with USNRC Method

Recently, USNRC approved the Master Curve application of Kewaunee NPP in determining adjusted RT_{NDT} on irradiated Linde1091 weld[17]. In the SER on the matter, USNRC proposed a method to incorporate T_o value into adjusted RT_{NDT} calculation with appropriate margin and PCVN bias factor. The method used to determine the initial RT_{NDT} for Kori Unit 1 in this study was compared with that of USNRC applied to Kewaunee in table 4.

Table 4. Comparison of the method to determine the RT_{NDT} from T_o

Item	Kori Unit 1 Method	USNRC Method	Remark
Average To	-83.3℃	-83.3℃	
Lower bound To	-65.1℃		K-1 considered 99% confidence value at –2.6sigma, sigma =7.2℃
RT_{To}	To+19.4℃= -45.7℃	To+18.3℃= -65.0℃	USNRC considered 1.1℃ as an implicit margin
Margin for IRT_{To}	0	2*7.8℃=15.6℃	Margin was already incorporated in K-1 method
PCVN bias	Not decided	4.7℃	
Additional margin	13.5℃		
Lower bound RT_{To}	-32.2℃	-44.7℃	Equivalent to Lower bound RT_{NDT}

As shown in the table, if USNRC's procedure had been applied to the test result of the WF-233 weld of Kori Unit 1, RT_{To} would have been much lower. This in return imply that the newly defined initial RT_{NDT} of WF-233, -32.2℃(-26˚F) would be still conservative with extra margin.

IV. IMPACT ON THE INTEGRITY ASSESSMENT

Figure 5 shows the inter-relationship of the various aspects of the RPV integrity assessment. With newly defined parameters, such as initial RT_{NDT}, Cu and Ni contents, and fluence values, some aspects of the RPV integrity have to be revised. In case of Kori Unit 1, PTS and P-T limit curves will be affected by recent development.

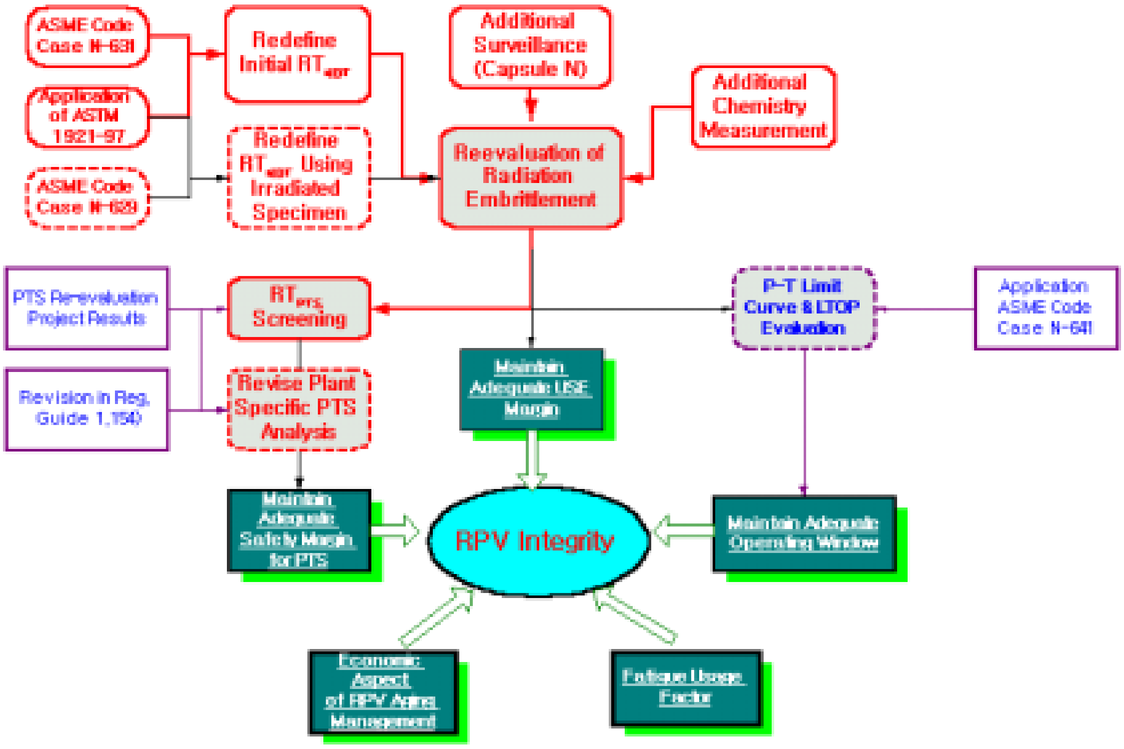


Figure 5. The Various Aspects of the RPV Integrity Assessment for Life Extension
(Boxes with the dotted line are the work to be done)

4.1 Pressurized Thermal Shock

As shown in figure 5, RT_{PTS} of the RPV materials is affected by the change in the initial RT_{NDT}. The revised RT_{PTS} projection incorporating the latest surveillance test result[18] is shown in figure 6. With redefined initial RT_{NDT}, the operating year when the RT_{PTS} exceed the PTS screening criteria of 300˚F is increased from 37 to 54. Though with the new initial RT_{NDT}, RT_{PTS} is expected to exceed the screening criteria before the end of the extended operation period. However, it would give enough time to implement the corrective and mitigative actions to reduce the risk associated PTS events. Also, the potential revision of the PTS rule with increased screening criteria will remove the PTS issue from the integrity assessment of the Kori Unit 1 RPV.

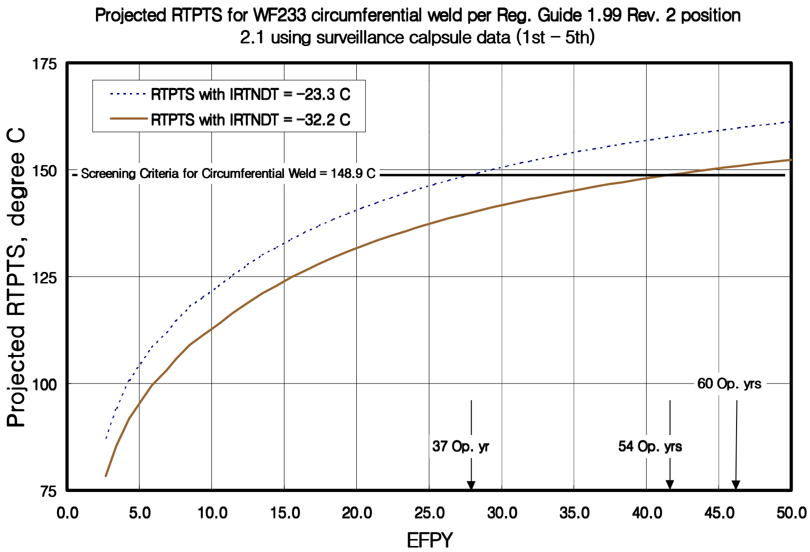


Figure 6. Comparison of the RT_{PTS} projection with old and new initial RT_{NDT} of WF233.

4.2 P-T Limit Curve

Heatup and cooldown limit curves are calculated using the most limiting value of RT_{NDT} (reference temperature-nil ductility transition) corresponding to the limiting material in the beltline region of the RPV. Using the adjusted reference temperature values, pressure-temperature limit curves are determined in accordance with the requirements of Appendix G, 10 CFR Part 50, as augmented by Appendix G, Section XI, of the ASME Boiler and Pressure Vessel Code[19].

Based on the projected adjusted RT_{NDT}(ART) at 1/4T, the cooldown curve at the end of the extended operation (60 Op. Yrs, or 46.4 EFPY) was constructed following the App. G method and is plotted with the pump cavitation curve in the figure 7. The area between the P-T limit curve and the pump cavitation curve is the allowed operating window during the cooldown process. As shown in the

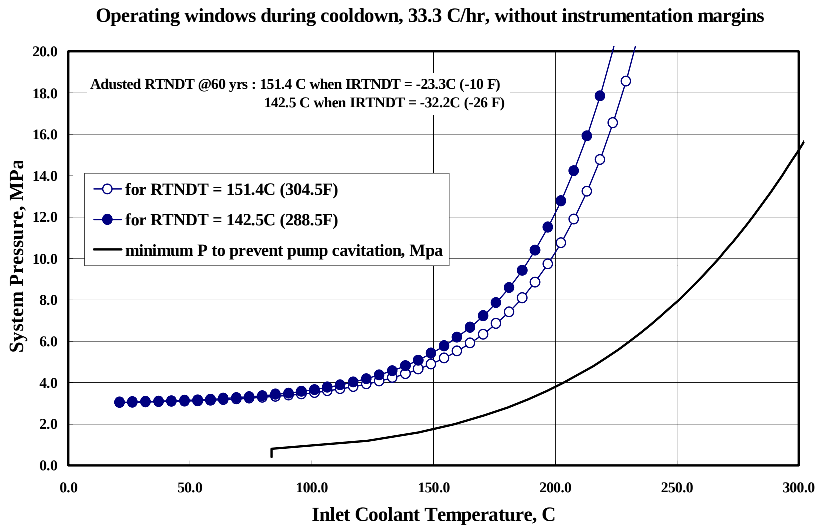


Figure 7. Comparison of the Cooldown part of the P-T limit curve at the end of life extension

figure, with newly defined initial RT_{NDT}, the allowable operating window would be widened somewhat. However, the net benefit of newly defined initial RT_{NDT} is not that significant.

V. FUTURE WORK

It has been shown that the shifts of RT_{NDT} and associated margins in Charpy test and Master Curve techniques are comparable[20]. Once the initial RT_{NDT} of the RPV material has been determined using the Master Curve technique, it can replace the Charpy test based initial RT_{NDT} in Reg. Guide 1.99 Rev. 2 framework. Still, the direct measurement on the irradiated specimens can be used to confirm the above methodology and provide more reliable RT_{NDT} value for the irradiated specimen rather than using the projected value. Several utilities are actively pursuing the application of the Master Curve method to the irradiated specimens to revise the adjusted RT_{NDT} and RT_{PTS} at the end of the extended operation[17]. For WF233 weld of Kori Unit 1, the application of the Master Curve Method on the irradiated specimens should be considered as an potential option to reduce the uncertainties in the initial RT_{NDT} determination and accurately estimating the adjusted RT_{NDT} and RT_{PTS} at the end of the extended operation.

After the completion of the plant-specific PTS analysis for Kori Unit 1 in 1999[11], several key parameters has been changed, such as the initial RT_{NDT}, best-estimate weld chemistry, and projected fluence(though not much). If these changes were incorporated, it is expected that the integrated PTS risk will be further lowered than those estimated in the previous evaluation.

VI. SUMMARY

As a part of the activities to attain the integrity of the RPV for the period of the extended operation beyond the design life, the initial RT_{NDT} of the WF233 weld was reevaluated by applying the Master Curve technique to the archive weld material. By removing the some of the excess conservatism, the initial RT_{NDT} was redefined as -32.2℃ instead of -23.3℃ that is currently used. With the newly defined initial RT_{NDT}, the year that the RT_{PTS} exceeds the screening criteria increased by 17 years. Also, the allowable operating window would be widened somewhat, however, the net benefit of newly defined initial RT_{NDT} is not that significant. Still, the direct measurement of RT_{NDT} of WF233 weld on the irradiated specimens is considered as a potential option to reduce the uncertainties in the initial RT_{NDT} determination and estimation of the adjusted RT_{NDT} and RT_{PTS} at the end of the extended operation. It is expected that with lower initial RT_{NDT} and Cu and Ni contents, the integrated PTS risk will be maintained considerably lower than the limit specified in Reg. Guide 1.154.

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