

THE EFFECT OF ADJUSTED REFERENCE TEMPERATURE ON THE PROBABILITY OF FAILURE IN BOILING WATER REACTOR VESSEL WELDS

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ABSTRACT

One of the critical parameters in the probability of failure (POF) in Boiling Water Reactor (BWR) vessels' axial and circumferential welds is the material's adjusted reference temperature (ART). This ART depends on the material's chemistry, initial RT_{NDT} , and neutron fluence. A probabilistic fracture mechanics (PFM) evaluation, based on Monte Carlo Method, was performed to correlate the probability of failure in the BWR vessel welds with the material ART for a fleet of domestic BWR (36 vessels). The evaluation is for a BWR limiting low temperature over pressure (LTOP) event with Marshall flaw size distribution and typical weld material chemistry in individual vessel. The benefit of inservice inspection was not considered. The effect of weld residual stresses, stress corrosion initiation and crack growth was considered as part of the statistical input parameters. The evaluation was performed for both axial and circumferential welds in the reactor vessel beltline region. The probability of failure was estimated for the 40 years design life. The results quantify the increase of probability of failure versus material ART due to the LTOP event.

NOMENCLATURE

ART	Adjusted Reference Temperature ($^{\circ}$ F)
a	crack size (in)
CF	Chemistry Factor ($^{\circ}$ F)
da/dt	Crack Growth Rate (in/hr)
f	Fluence (10^{19} n/cm ² , E>1 MeV)
f _{surf}	Fluence at the Inner Vessel Surface (10^{19} n/cm ² , E>1 MeV)
K	Stress Intensity Factor (Ksi \sqrt in)
M	Margin ($^{\circ}$ F)

P(a)	Flaw size density distribution
S	Applied Stress (ksi)
t	Stress Corrosion Initiation Time (hr)
x	Distance from Inner Vessel Surface (in)
μ	Statistical Mean
σ	Statistical Standard Deviation
σ_I	Standard Deviation for Initial RT_{ndt} ($^{\circ}$ F)
σ_{Δ}	Standard Deviation for ΔRT_{ndt} ($^{\circ}$ F)

INTRODUCTION

Boiling Water Reactor vessel welds in the beltline region are subjected to neutron radiation embrittlement. This neutron radiation embrittlement has significant effect on the integrity of the vessel welds in the pressure boundary due to the decrease of fracture toughness of the weld material. The decrease of fracture toughness in the weld material is a function of copper and nickel content, and the level of neutron fluence in the beltline region, (Regulatory Guide 1.99, 1988). It is likely that as the BWR vessels are near the end of the design life, the increase in the ART would be significant that the fracture toughness of the material is much lower than the upper shelf energy.

Coupled with the observation from the operational data showing that stress corrosion cracking (SCC) of BWR vessels is more probable, study (Tang, 1996) was performed to evaluate the POF of the beltline vessels weld and the effect of inservice inspection on vessel reliabilities. In this paper, the quantification of the effect of ART on the probabilities of failure for vessel beltline axial and circumferential weld is presented.

RADIATION EMBRITTLEMENT OF REACTOR VESSEL MATERIALS

The Code of Federal Regulations requires that the reactor coolant pressure boundary be designed with enough margin to minimize fracture. This requires the evaluation of changes in fracture toughness due to neutron radiation throughout the design life. The changes in material fracture toughness can be estimated using the ART of the materials. The ART for the material in the beltline region can be calculated with the following equation (Regulatory Guide 1.99).

$$ART = \text{Initial } RT_{ndt} + \Delta RT_{ndt} + M \quad (1)$$

The initial RT_{ndt} is the reference temperature for the unirradiated material as defined in Boiler and Pressure Vessel Code (ASME, 1995). The ΔRT_{ndt} is the mean adjustment in reference temperature caused by irradiation calculated as (Regulatory Guide 1.99, 1988):

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

CF is the chemistry factor as a function of weight percent copper and weight percent nickel content for welds and base metal (Regulatory Guide 1.99, 1988). The neutron fluence, f , at any depth in the vessel wall is determined as:

$$f = f_{surf} e^{-0.24x} \quad (3)$$

M is the margin term calculated as (Regulatory Guide 1.99, 1988)

$$M = 2\sqrt{(\sigma_t^2 + \sigma_\Delta^2)} \quad (4)$$

After the calculation of material ART due to neutron embrittlement, the material fracture toughness, K_{Ic} can be calculated as (Dirks, 1982):

$$K_{Ic} = \begin{cases} 36.2 + 49.4e^{0.0104(T - ART)} & T - ART \leq 50 \\ 55.1 + 28.0e^{0.0214(T - ART)} & T - ART > 50 \end{cases} \quad (5)$$

FLEET WELD CHEMISTRY AND NEUTRON FLUENCE DATA

The weld chemistry and neutron fluence data for the fleet of domestic BWR are presented in Table 1 for both axial and circumferential welds in the beltline region. The weld chemistry in the weld material depends highly on the material heat and flux used in the welding process. The material chemistry data in Table 1 represent a typical value for the axial and circumferential vessel welds in the beltline region for each vessel. In four domestic BWR vessels, there are no circumferential welds in the beltline region. For copper weight percent, it ranges from 0.03 to 0.37 for the axial welds and from 0.02 to 0.35 for the circumferential welds. For nickel weight percent, it is from 0.2 to 1.2 for the axial welds and from 0.03 to 1.1 for the circumferential welds.

Typical peak neutron fluence is also presented in Table 1 for individual vessel. The actual fluence in each vessel weld depends on the azimuth angle of the weld relative to the fuel bundle configuration and the elevation of a particular location in the weld from the bottom of the active fuel (BAF). Therefore, the actual

fluence in each weld could be very well below the peak neutron fluence level. In the present analyses, these typical peak neutron fluence data are used in order to simplify the number of analyses. These also provide an upper bound on the probability of failure results. The typical peak neutron fluence is from 0.23×10^{18} n/cm² to 6.9×10^{18} n/cm² for the axial welds and 0.23×10^{18} n/cm² to 5.1×10^{18} n/cm² for the circumferential welds.

The initial RT_{ndt} data are also presented in Table 1. For beltline axial welds, it is from a minimum of $-70^\circ\text{F}(57^\circ\text{C})$ to a maximum of $23^\circ\text{F}(-5^\circ\text{C})$. For beltline circumferential welds, the minimum is $-70^\circ\text{F}(57^\circ\text{C})$ and the maximum is $20^\circ\text{F}(-7^\circ\text{C})$.

EVALUATION METHODOLOGY

Flaw Distribution

The failure of reactor pressure vessel (RPV) is based on the assumption of a presence of postulated flaws. These flaws can be caused by poor quality control in manufacturing, welding or service induced such as by corrosion and pitting. Marshall (1982) did a study on the number of manufacturing flaws and flaw size distribution. The flaw size density distribution is in an exponential form, with an average flaw size of 0.14 inch (3.56 mm) as follow:

$$P(a) = 0.0346e^{-4.06a} + 6.88e^{-6.94a} \quad (6)$$

The flaw density (Marshall, 1982) is 1 flaw/35.31 ft³ (1 flaw/m³) assuming a Poisson distribution. Another study was done on a section of material removed from the Midland vessel, (Dimitrijevic, 1993). This study produces two flaws with significant depth in 11370 in³(0.186m³) of welds. In other studies, (Babcock, & Wilcox, 1989), (Selby, 1985), a flaw density of 45 flaw/35.31 ft³(45 flaws/m³) was used. These flaw number and flaw size data are used as basis for flaw size distribution used in the probabilistic fracture mechanics analyses. Using a typical BWR vessel weld geometry, it was estimated that there is about 0.044 flaw per inch of weld.

Stress Corrosion Crack Initiation And Crack Growth

Cladding stress corrosion initiation data for cast stainless steel in BWR is spare. A literature survey of the laboratory component test data produced only three data points (Tang, 1996) in terms of time to failure (assumed to be crack initiation in RPV). Nonetheless, some field cracking has been observed. These data were used to formulate a relationship between failure time, t , and applied stress, σ :

$$t = 8.42 \times 10^{18} \sigma^{-10.5} \quad (7)$$

Conversely, a great deal of data is available for wrought sensitized stainless steel in BWR environment, (Tang, 1996). Although for a different material, these allow a use of typical representation of the distribution for the stress corrosion initiation. The statistical distribution of the BWR case stainless steel is assumed to be similar to the sensitized 304 stainless steel. A rank order residual statistic of the sensitized stainless steel data was used to obtain the appropriate distribution type. The lognormal distribution was found to have a better fit of the data distribution.

Stress corrosion crack growth data for low alloy steel (i.e., A533B and A508) for both constant load and constant displacement tests at 200 ppb oxygenated water at 288°C, (Ford, 1992) are evaluated in Tang (1995) along with more recent data (Van Der Sluys, 1991). The recent data shows no crack growth in most of the tests. Some significant crack growth is observed in some tests at high oxygenated water. These recent crack growth data at high oxygenated water correspond very closely to the old test data at low oxygenated water.

The test hold time also affects the crack growth test results. Some old crack growth results are probably due to the transient effect of the test loading conditions since the hold time data are not available. Recent results show that the crack growth is contributed mainly at the early stage of the test, right after loading. Essentially no crack growth was measured at the latter part of the test when a long hold time was used in the test.

Based on the difference between the old high oxygenated and the old low oxygenated water test data, the recent test data of the high oxygenated test data are adjusted downward to obtain the crack growth data for the low oxygenated water as:

$$da/dt = 0.118 \times 10^{-12} (K)^4 \quad (8)$$

From the ordered residual statistics, the crack growth data were shown to have a Weibull distribution. The mean and the variance of the stress corrosion crack growth threshold were also established from the test data (Tang, 1996). It is assumed to have a normal distribution. In the evaluation, no crack growth occurs unless the applied stress intensity factor is equal to or greater than the threshold.

Stress Intensity Factors

The stress intensity factor is calculated using influence method (Raju, 1982), (Buchalet, 1975) as

$$K = \sqrt{\pi a} \sum_{i=0}^3 Q_i C_i a^i \quad (9)$$

where C_i , Q_i and a are stress coefficients of a polynomial through wall stress profile, influence function and crack depth respectively.

The stress intensity factor due to clad residual stress was expressed as a curve fitted equation from the J-Integral evaluation of a clad reactor pressure vessel, (Structural Integrity, 1992).

In this evaluation, an inside surface elliptical longitudinal crack with an aspect ratio of $l/a = 10$ was used for the axial weld. A full 360° inside surface circumferential crack model was used for the circumferential welds.

Probabilistic Fracture Mechanics Evaluation

The random variables for the probabilistic fracture mechanics evaluation are presented in Table 2. The mean values of weight percent for Cu and Ni for individual plants were used in the evaluation but the standard deviations were assumed to be the same among the vessel fleet. The standard deviations are 0.045% weight for copper and 0.0165% weight for nickel. The neutron fluence was conservatively assumed time invariant using the end of life fluence level. The fluence standard deviation was assumed

to be 20% of the end of life fluence. Post weld heat treatment was assumed for the reactor vessel cladding with a mean clad stress of 32 ksi (220.63 MPascal) and a standard deviation of 5 ksi (34.47 MPascal) (BWR Vessel and Internals Project, 1995).

The reactor vessel weld failure probability was evaluated for the most severe low temperature over pressurization (LTOP) event occurred in one of the foreign BWR power plant. It has a temperature of 88°F (31°C) and a pressure of 1050 psi (7.24 MPascal). The benefit of inservice inspection to detect any stress corrosion initiated cracks in the vessel welds was not considered in order to obtain an upper bound on the estimate of the failure probability of the vessel welds. The probability of failure was calculated for a design life of 40 years for the plants.

A Monte Carlo method was used to perform the evaluation on the reactor vessel beltline welds in a probabilistic fracture mechanics program, VIPER (Vessel Inspection Program Evaluation for Reliability, Version 1.2, 1998). For axial welds, the number of Monte Carlo iterations was set to 50000. For circumferential welds, one million Monte Carlo iterations were used due a lower probability of failure. For the beltline axial welds, the evaluation was performed for each vessel in the fleet. For the beltline circumferential welds, only those vessels (10 vessels) with the end of life ART larger than 100°F (37.78°C) were analyzed.

ANALYSIS RESULTS

The failure probabilities of the vessel welds for the BWR fleet are presented in Figure 1. The failure probabilities are based on the condition that the LTOP event occurs and for the failure mode of fracture in the vessels. The evaluation shows that, for axial welds, the probabilities could be from 1.0×10^{-5} at an ART of -50°F (-45.56°C) to 1.55×10^{-2} at an ART of 147°F (63.89°C). The ART was calculated for 32 effective full power years (EFPY). The plant with the highest probability of failure in the beltline axial weld has a Cu weight percent of 0.1, Ni weight percent of 1.08 and EOL neutron fluence of 6.9×10^{18} n/cm². The plant with the lowest probabilities in the beltline axial weld has a Cu weight percent of 0.04, Ni weight percent of 1 and EOL neutron fluence of 0.23×10^{18} n/cm².

For beltline circumferential welds, only two vessels have 1 failure each in 1 million Monte Carlo iterations. This corresponds to a probability of failure of 1.0×10^{-6} due to the LTOP event. All other vessels that were evaluated are represented as run-outs in Figure 1. The weld chemistry and fluence data for the first vessels are 0.31 weight percent of Cu, 0.59 weight-percent of Ni with an EOL neutron fluence of 0.945×10^{18} n/cm². The second vessel has a 0.1 weight percent of Cu, 0.99 weight percent of Ni, and an EOL neutron fluence of 5.1×10^{18} n/cm².

The probability results presented in Figure 1 are the conditional probability of failure assuming the LTOP event occurs, corresponding to a probability of the event at unity. The actual occurrence of this event probability is much smaller, in the order of 1×10^{-4} . Therefore the actual probability of failure due to the LTOP event is much smaller.

In addition, the evaluation shows that the probabilities of failure for the beltline circumferential welds are at least a few orders of magnitude less than that for the beltline axial welds. Even with a higher ART in the beltline circumferential welds than the beltline axial welds, the analyses show that the circumferential

weld still have a lower probability of failure due to the pressure stress in the axial weld is twice as high as the circumferential weld. Thus the applied stress intensity factor in the axial weld would be two times higher than the applied stress intensity factor in the circumferential weld.

CONCLUSION

An evaluation was performed to assess the POF for the fleet of BWR vessels. The evaluation was for the beltline shell welds subjected to the LTOP event. The evaluation shows that the POF increases as the ART temperature increases. It is shown that the POF of the vessel beltline axial welds is a few orders of magnitude higher than the POF of the vessel beltline circumferential welds.

There is conservatism in the results from the above evaluation. The neutron fluence was assumed to be time invariant during the design life of the vessel and the EOL peak neutron fluence in each of the vessels was used. The actual neutron fluence can be much smaller depending on the azimuth angle and elevation of the welds relative to the fuel bundle configuration and elevation.

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Table 1 Beltline Weld Material and Neutron Fluence Data For BWR Vessels

Plant ID	Axial Weld				Circumferential Weld			
	% Weight Cu	% Weight Ni	Initial RT _{ndt} (°F)	Fluence N/cm ² (x10 ¹⁸)	% Weight Cu	% Weight Ni	Initial RT _{ndt} (°F)	Fluence n/cm ² (x10 ¹⁸)
1	0.25	0.35	10	1.25	0.31	0.59	20	0.945
2	0.28	0.35	10	0.605	0.09	0.65	-40	0.605
3	0.25	0.35	10	1.06	0.09	0.67	-40	0.792
4	0.05	0.96	10	1.23	0.06	0.87	10	1.23
5	0.05	0.96	10	1.27	0.02	0.9	10	1.27
6	0.1	1.08	-30	6.9	No circumferential Weld in Beltline			
7	0.19	0.97	-50	1.6	0.2	0.69	-50	1.6
8	0.24	0.36	23	0.36	0.26	0.61	10	0.36
9	0.24	0.36	23	0.51	0.35	0.58	-5	0.51
10	0.03	0.91	-50	3.6	0.03	1.02	-50	2.5
11	0.26	0.87	-44	0.58	0.23	1	-50	0.58
12	0.22	1	-48	1.61	0.34	0.61	-50	1.81
13	0.06	1.08	-30	2.5	No circumferential Weld in Beltline			
14	0.28	0.76	-50	1.8	0.17	1	-10	1.1
15	0.23	0.5	-50	1.54	0.07	0.03	-50	1.54
16	0.08	0.59	-30	0.75	0.1	0.68	-40	0.494
17	0.37	0.75	-30	0.45	0.24	1	-50	0.45
18	0.03	0.9	-6	0.536	0.04	0.95	-34	0.536
19	0.04	1.08	-12	1.9	0.09	1	-60	1.9
20	0.04	1.08	-12	1.9	0.09	1	-60	1.9
21	0.26	1.2	-20	1.5	0.18	1.03	-50	1.5
22	0.1	0.99	-65	5.1	0.1	0.99	-65	5.1
23	0.22	0.2	-50	2.21	0.22	0.2	-50	2.21
24	0.07	0.71	-60	0.5	0.06	0.85	-50	0.5
25	0.35	0.2	-8	3.74	0.22	0.11	-50	3.74
26	0.21	0.21	-45	0.88	0.06	0.97	-32	0.88
27	0.21	0.21	-45	0.79	0.11	0.96	-50	0.79
28	0.06	1.08	-30	4.9	No circumferential Weld in Beltline			
29	0.13	1.06	0	2	0.13	0.71	0	2
30	0.24	0.36	23	0.35	0.31	0.59	-5	0.35
31	0.24	0.36	23	0.49	0.05	0.96	-32	0.49
32	0.09	0.93	-50	6.6	No circumferential Weld in Beltline			
33	0.04	1.1	-50	0.79	0.04	1.1	-50	0.76
34	0.06	0.89	-20	0.78	0.06	0.89	-20	0.78
35	0.04	1	-70	0.23	0.04	1	-70	0.23
36	0.1	0.92	-38	0.757	0.09	0.92	-50	.757

Table 2 Random Variables

Property	Input	Statistical Distribution
Initial RT _{ndt}	μ,σ	Normal
End of Life Fluence	μ,σ	Normal
Cu, Ni	μ,σ	Normal
ΔRT _{ndt}	σ	Per Reg. Guide 1.99 Rev. 2
Clad Stress	μ,σ	Normal
Stress Corrosion Crack Initiation	Mean Power Law	Lognormal
Stress Corrosion Crack Growth	Mean Power Law	Weibull
Stress Corrosion Crack Growth Threshold	μ,σ	Normal
Flaw Size	μ,σ	Exponential
Number of Flaws	μ,σ	Poisson

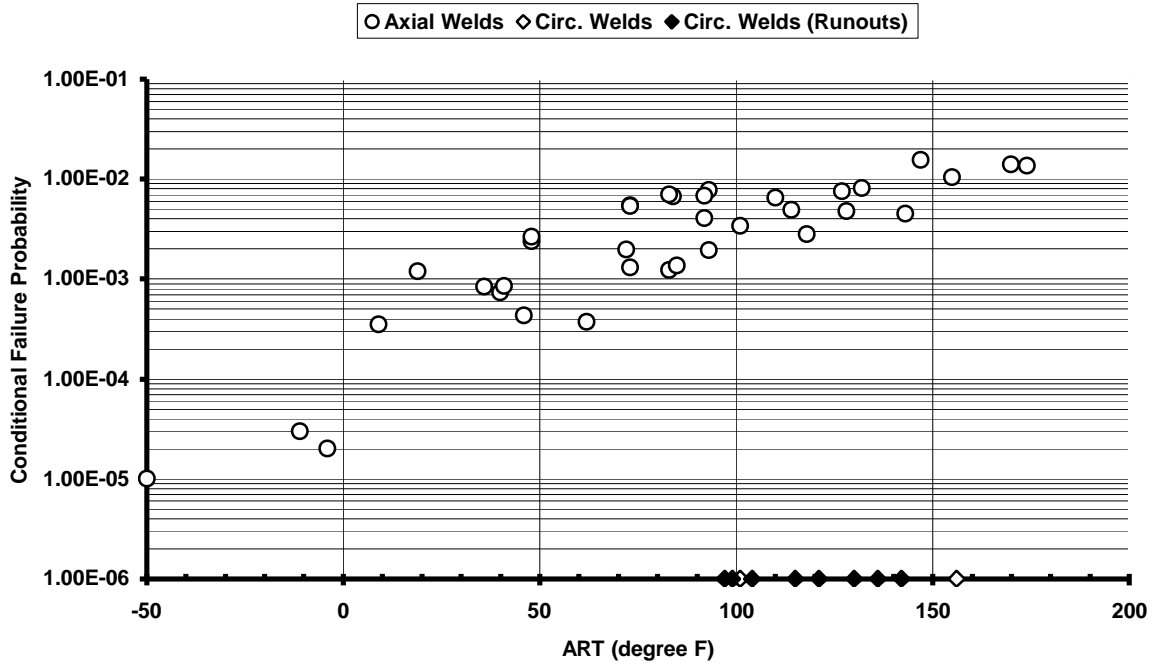


Figure 1. BWR Fleet Failure Probabilities Due to Low Temperature Over Pressurization Event