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U.S. Nuclear Regulatory Commission's Review of the Impact of Inservice Inspection of BWR Reactor Pressure Vessel Welds on Vessel Failure

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ABSTRACT:

The Boiling Water Reactor (BWR) Vessel and Internals Project (BWRVIP) proposed to eliminate inservice inspection of circumferential welds in BWR reactor pressure vessels (RPVs), except for small lengths of circumferential welds at the intersection of axial welds. The BWRVIP provided a risk informed assessment (BWRVIP-05) that included the frequency of events that could lead to BWR vessel failure and that estimated the probability of vessel failure from these events.

This paper discusses the U.S. Nuclear Regulatory Commission's (NRC) evaluation of the BWRVIP analyses and the results from its independent assessment. The BWRVIP and NRC evaluations of the probability of vessel failure were performed using probabilistic fracture mechanics. The results from these analyses are dependent upon a temperature-pressure transient, the amount of embrittlement projected for the RPV welds, the assumed flaw distribution and flaw density in the RPV welds, and the probability of detection of flaws by inservice inspection methods. These variables are assessed in the NRC evaluation and are the basis for determining whether inservice inspection of BWR RPV circumferential welds is necessary.

INTRODUCTION

In January 1991, the NRC published in the *Federal Register* a proposed Rule to amend Section 50.55a to Title 10 of the *Code of Federal Regulations* [10 CFR 50.55a], "Codes and Standards." One purpose of this amendment was to incorporate by reference a later edition and addenda to Section XI of the American Society of Mechanical Engineers (ASME) Code. This included the 1989 Edition of the ASME Section XI, Division 1, and Addenda through 1988. In addition, the Rule proposed to create Section 50.55a(g)(6)(ii)(A) to 10 CFR 50.55a "Augmented examination of reactor vessel," which required that all licensees perform volumetric examinations of "essentially 100 percent" of the reactor pressure vessels (RPVs) pressure-retaining shell welds during all inspection intervals in accordance with Section XI of the ASME Code on an "expedited" schedule, and revoked all previously granted reliefs for RPV weld examinations. "Expedited," in this context, effectively meant during the inspection interval when the Rule was approved or the first period of the next inspection interval. The final Rule was published in the *Federal Register* on August 6, 1992.

By letter dated September 28, 1995, as supplemented, the BWR Vessel and Internals Project (BWRVIP) submitted the Electric Power Research Institute (EPRI) proprietary report TR-105697, "BWR Vessel and Internals Project, BWR Reactor Pressure Vessel Shell Weld Inspection Recommendations (BWRVIP-05)" [Reference 1]. The BWRVIP-05 report evaluated the current inspection requirements for the RPV shell welds in BWRs, formulated recommendations for alternative inspection requirements, and provided a technical basis for these recommended requirements. As modified, it proposed to perform inservice inspections (ISI) on "essentially 100 percent" of the RPV axial shell welds, and eliminate the inspection of all but approximately 2 to 3 percent of the circumferential welds at the intersections of the axial and circumferential welds.

On August 14, 1997, the NRC staff forwarded to the BWRVIP its multi-disciplined, risk-informed independent safety assessment (ISA) [Reference 2] of the BWRVIP-05 document. The NRC staff's ISA identified a transient at a non-U.S. BWR (of U.S. design) in which the RPV was subjected to high pressure (7.9 MPa or 1150 psig) at a low temperature (26°C to 31°C or 79°F to 88°F). This low-temperature overpressure (LTOP) transient was not included as a design basis event for BWRs and was not considered in the BWRVIP-05 report, which was focused only on design basis events. However, the recognition of this transient led the NRC staff to determine that LTOP transients are of sufficient safety significance to be considered.

Further work was performed by both the NRC staff and the industry to more fully assess the risk associated with beyond-design-basis events for both the axial and circumferential welds at fluence levels projected to be reached later in life at some plants. This additional work included (1) studies of potential precursor events in order to better quantify the potential for LTOP events in BWRs, (2) additional probabilistic fracture mechanics analysis to both understand the sensitivities to various parameters and to support an uncertainty analysis, and (3) assessment of the proposed changes in inspection requirements relative to the probability of vessel failure. The NRC staff issued a Safety Evaluation (SE) of the BWRVIP-05 report, as supplemented, on July 28, 1998 [Reference 3]. Some of the results of that SE are presented below.

BACKGROUND

Conventional Vessel Analysis Codes

The conditional probability of vessel failure, P(F|E), or the probability of vessel failure assuming that the event occurred, can be calculated using conventional vessel analysis codes, such as VIPER (used by the BWRVIP) and FAVOR (developed by the Oak Ridge National Laboratory and used by the NRC staff). These codes are based on probabilistic fracture mechanics (PFM) methodologies that perform millions of deterministic vessel simulations using randomly selected values for the variables to determine the P(F|E) for a vessel subjected to a specific transient. The vessel P(F|E) is the ratio of the number of failed vessels to the number of simulations. For each simulation, the random variables (e.g., crack size, copper, nickel, and fluence) are assigned according to prescribed distributions with the form and parameters of the distributions specified by the user. Deterministic fracture mechanics analyses are then performed, and the vessel P(F|E) is determined.

RPV Embrittlement

Embrittlement is measured as an increase in the reference temperature resulting from neutron radiation, (ΔRT_{NDT}). The ΔRT_{NDT} is a function of copper and and nickel of the weld and the neutron fluence. The relationship between these parameters is described in Regulatory Guide (RG) 1.99, Revision 2 [Reference 4], which defines the RT_{NDT} of the embrittled vessel material as the sum of the unirradiated (initial) RT_{NDT}, the mean ΔRT_{NDT}, and a term to account for the uncertainty in the initial RT_{NDT}, copper and nickel contents, and calculation procedures. Although in theory the uncertainty in ΔRT_{NDT} has been partially accounted for by treating the initial RT_{NDT}, fluence, and copper and nickel contents as random variables, the VIPER and FAVOR codes conservatively specify the standard deviation for ΔRT_{NDT}. The square of the standard deviation for ΔRT_{NDT} is added to the square of the standard deviation for the initial RT_{NDT}. The margin term is calculated as the square root of this sum.

Limiting Transients

The initial BWRVIP-05 report was limited to design basis accident (DBA) events. In an effort to provide a broader risk-informed assessment, the NRC staff identified an actual LTOP event that occurred at a foreign plant, and performed considerable P(F|E) evaluations using this transient. The results of this effort were reported in Reference 2. The NRC staff also requested the BWRVIP to conduct its own identification of beyond-DBA events and to assess the P(F|E) due to the limiting beyond-DBA event. In responding to the NRC staff's request, the BWRVIP identified the loss of AC power during a post-outage primary system pressure test as the limiting LTOP event and reported the plant-specific P(F|E) for all participating plants under this transient. This LTOP transient has a constant pressure of 8.3 MPa (1200 psi) and a constant temperature of 37.8°C (100°F), which is somewhat less severe than the non-U.S. transient, which had a constant pressure and temperature of 7.9 MPa (1150 psi) and 31°C (88°F), respectively.

INPUT TO PROBABILISTIC FRACTURE MECHANIC ANALYSES

Pressure and Temperature of Transient

The NRC staff's probabilistic fracture analyses with and without consideration of inservice inspection (ISI) were performed using the pressure and temperature of the non-U.S. transient discussed above.

Material Properties and Neutron Fluence

Table 2-1 in Reference 2 indicates the weld processes used to fabricate the axial and circumferential beltline welds in BWR RPVs. Babcock and Wilcox (B&W) fabricated 9 BWR RPVs; Chicago Bridge and Iron (CBI) fabricated 16 BWR RPVs; Combustion Engineering (CE) fabricated 10 BWR RPVs; New York Shipbuilding fabricated 1 BWR RPV; and, Hitachi fabricated 1 BWR RPV. Based on the difference in materials used to fabricate the BWR RPVs, the NRC staff determined that three reference cases, corresponding to the B&W-, CBI-, and CE-fabricated BWR RPVs, were necessary to comprehensively evaluate all the BWR RPVs. The material property inputs to the FAVOR Code included mean and standard deviation values for the initial reference temperature, end of license neutron fluence, amount of copper, amount of nickel, the plain strain fracture toughness (K_{Ic}) and the fracture arrest toughness (K_{Ia}) as a function of temperature. The standard deviation of the ΔRT_{NDT} from embrittlement is also an input function. The NRC staff's input values for these parameters are listed in Table 7-1 of the Reference 2.

Flaw Size, Density and Distribution

Previous probabilistic fracture mechanics analyses of pressurized water reactors (PWR) reactor vessel welds were performed using the "Marshal" distribution. The NRC contracted with Pacific Northwest National Laboratories (PNNL) to determine the flaw distribution in reactor vessel welds from a canceled nuclear power plant. PNNL conducted a sequence of inspections using the Synthetic Aperature Focusing Technique for Ultrasonic Testing (SAFTUT) for the purpose of detecting and characterizing any fabrication (preservice) flaws in 20 linear meters of weldments. The results of these analyses are identified as the 'PVRUF" (Pressure Vessel Research Users Facility) data. The "PVRUF" data is the source for the flaw distributions developed by the NRC that are discussed in this paper. The PVRUF data is contained in NUREG/CR-6471,Vol.1 [Reference 5].

The BWRVIP's probabilistic fracture mechanics (PFM) evaluations used the "Marshall" distribution ("BWRVIP-Marshall" flaw distribution) with a flaw density of 30 flaws/m^3 to simulate original fabrication flaws. The number of flaws per vessel was sampled as a Poisson distribution with a mean value of 3.52. Growth of these assumed original fabrication defects was postulated to occur by stress corrosion cracking (SCC) in the low alloy steel weldment after initiation of SCC in the cladding.

The NRC staff used best-estimate and upper bound "PVRUF-Marshall" flaw distributions and "PVRUF-Exponential" flaw distributions (Section 2.6.2.4 of Reference 3). The NRC staff employed a flaw density of 995 flaws/m^3 (108 flaws/vessel) for the best-estimate and 1143 flaws/m^3 (124 flaws/vessel) for the upper bound flaw density.

The "PVRUF-Marshal" flaw distribution was based on the PVRUF data and on the assumption that, for flaws greater than 2 mm (0.0787 inches), the distribution follows a Marshall distribution with credit for preservice inspection.

To better characterize the PVRUF data the NRC staff developed another flaw size distribution based on an exponential fit without using the Marshall distribution. This revised distribution is referred to as "PVRUF-Exponential." This was in response to issues raised by the NRC's Advisory Committee on Reactor Safeguards (ACRS) which indicated that additional effort was needed to address uncertainties associated with the BWRVIP-05 analyses such as showing that flaw size distribution input models are justified and consistent with available data including those obtained in past inspections of welds. Keeping all other input variables the same, the PVRUF-Exponential distribution yields higher P(F|E) values than the PVRUF-Marshal distribution since this revised distribution has higher probability of containing larger flaws. The derivation of the PVRUF-Exponential distribution is detailed in Reference 3, Appendix A, and will not be discussed in this paper.

The NRC staff considers the PVRUF data to be the best source available for determining flaw size distributions and density in RPV welds because SAFTUT provides for better resolution of flaws than techniques used for inservice inspection of RPV welds in operating plants. The PVRUF-Exponential distribution is better than the PVRUF-Marshall distribution because the PVRUF-Exponential distribution provides a more accurate (better fit of the data) upper bound distribution. Hence, the NRC staff considered the PVRUF-Exponential flaw distribution and the flaw density derived from analysis of the PVRUF inspection data to be the appropriate distribution and density to be used in its evaluation [Reference 3].

Both the "PVRUF-Marshall" and the "PVRUF-Exponential" flaw distributions were modified to account for a single application of ISI. Table A-2 in Appendix A of Reference 3 provides the best-estimate and upper 95 percent confidence bound "PVRUF-Exponential" flaw size distributions with an assumption of inservice inspection (ISI) and that the crack propagates through the cladding to account for IGSCC. The "PVRUF-Marshall" flaw distribution with ISI is contained in Table 7-11 of Reference 2. The ISI adjusted flaw distributions were developed by Pacific Northwest Laboratories using the probability of detection from the PISC II study [Reference 6].

RESULTS OF STAFF ANALYSIS

The P(F|E) values using best-estimate and upper bound "PVRUF-Exponential" and "PVRUF Marshal" distributions are summarized in Table 2.6-1 of Reference 3 for the B&W, CE, and CB&I reference cases with ISI and without ISI and for axial and circumferential crack orientations corresponding to circumferential and axial welds, respectively. For each set of vessel conditions (i.e., chemistry, fluence, etc.), the NRC staff values of P(F|E) were determined through simulation of a maximum of 10^7 vessels, with a convergence criteria of 5 percent. This convergence criteria is met faster (i.e., with fewer vessel simulations) as the P(F|E) increases. In general, P(F|E) must be greater than about 1.5 x 10^{-4} for the convergence criteria to be met within the 10^7 simulations.

Analyses Using Circumferential Flaws

The highest calculated P(F|E) were for the B&W reference cases and the "PVRUF-Exponential" flaw distribution produced slightly higher P(F|E) than the "PVRUF-Marshal" flaw distributions. The P(F|E) for circumferential flaws for the B&W reference case without ISI was 1.0 x 10^{-6} using the best-estimate "PVRUF-Marshal" flaw distribution and was 2.0 x 10^{-6} using the best-estimate "PVRUF-Exponential" flaw distribution. The P(F|E) using the upper-bound "PVRUF-Exponential" flaw distribution for the B&W reference case without ISI was 1.13 x 10^{-5}. No failures were observed in 10^7 simulations using the upper-bound "PVRUF-Exponential" flaw distribution for the B&W reference case with ISI.

Analyses Using Axial Flaws

Table I summarizes the P(F|E) for axial flaws for the three reference cases. The columns entitled "Ratio" are the ratio of the P(F|E) for the case with ISI to the P(F|E) for the case without ISI. The evaluation of the impact of ISI is discussed in the next section of this paper.

As indicated in Table 2.6-2 of Reference 3, the P(F|E) resulting from use of the PVRUF-Exponential distribution is always higher than that for the PVRUF-Marshall distribution, for all vessel manufacturers (column entitled "Vessel Manuf."), and for both the best estimate (column entitled "Best Est.") and the upper bound distributions. For axial flaws, the increase in P(F|E) ranges from a factor of 1.3 to about 2.1. The lowest increases in P(F|E) (1.3 to 1.35) are for the cases of best estimate flaw distribution without inclusion of inservice inspection (ISI). The other cases (upper bound with and without ISI, and best estimate with ISI) have increases in P(F|E) that average 1.9.

TABLE I
Results of ISI Sensitivity Analyses for Axial Flaws

Vessel Manuf.		PVRUF-Marshall			PVRUF-Exponential		
		No ISI	With ISI	Ratio	No ISI	With ISI	Ratio
B&W	Best Est.	8.19×10^{-3}	3.12×10^{-3}	0.381	1.11×10^{-2}	6.54×10^{-3}	0.589
	Upper Bound	1.28×10^{-2}	4.65×10^{-3}	0.363	2.37×10^{-2}	8.56×10^{-3}	0.361
CE	Best Est.	1.52×10^{-3}	4.44×10^{-4}	0.292	1.97×10^{-3}	8.51×10^{-4}	0.432
	Upper Bound	2.62×10^{-3}	7.48×10^{-4}	0.285	5.31×10^{-3}	1.26×10^{-3}	0.237
CB&I	Best Est.	4.3×10^{-6}	5×10^{-7}	0.117	6.7×10^{-6}	6×10^{-7}	0.083
	Upper Bound	3.8×10^{-6}	NF (10^7) *	-----	1.65×10^{-5}	NF (10^7) *	-----

* No failures in the indicated number of vessel simulations.

Evaluation of ISI

The percent reduction in the P(F|E) resulting from ISI is one minus the ratio value in Table I. For both best estimate and upper bound PVRUF-Exponential distributions, ISI reduces the P(F|E) for axial flaws by at least 40 percent in all cases. Since no failures in 10^7 simulations were observed for circumferential flaws with inclusion of ISI the impact of ISI on circumferential flaws could not be determined analytically.

The reductions in P(F|E) for axial flaws with ISI is much greater for CB&I RPVs than for CE or B&W RPVs. This is principally due to the lower RT_{NDT} levels for CB&I RPVs, which results in lower P(F|E). For lower P(F|E), the vessel failures are dominated by larger flaw sizes, which are easier to detect during ISI. Therefore, the prevalence of large flaws, required to cause vessel failure for low RT_{NDT} levels, is significantly reduced and the P(F|E) is likewise significantly reduced. Conversely for CE and B&W welds, the critical flaw sizes are smaller, and ISI is not as likely to detect these flaws; therefore, the reductions in P(F|E) with ISI are not as great as for CB&I RPVs.

5.2 Evaluation of Flaw Size Distribution

Since the BWRVIP proposed in Reference 1 to perform inservice inspections on "essentially 100 percent" of the RPV axial shell welds and eliminate the inspection of all but approximately 2 to 3 percent of the circumferential welds at the weld intersections, the NRC staff's review also included an evaluation of the sensitivity to flaw size distribution.

The sensitivity is the ratio of the P(F|E) for the upper bound distribution to the P(F|E) for the best estimate distribution. The sensitivity to flaw size was determined using the PVRUF Exponential distribution. The sensitivity to flaw size for axial welds was determined from a flaw distribution with ISI. Using the P(F|E) with ISI in Table I, the sensitivity to flaw size for axial welds is 1.31 ($8.56 \times 10^{-3} \div 6.54 \times 10^{-3}$) for the B&W case and 1.48 ($1.26 \times 10^{-3} \div 8.51 \times 10^{-4}$) for the CE case. The sensitivity to flaw size for circumferential welds was determined from a flaw distribution without ISI. Using the P(F|E) without ISI in Table 2.6-1 of Reference 3, the sensitivity to flaw size for circumferential welds is 5.65 ($1.13 \times 10^{-5} \div 2.0 \times 10^{-6}$) for the B&W case. The values for the CB&I reference case for axial welds cannot be calculated because either one or both of the P(F|E) using best-estimate and upper-bound distributions create no failures in 10 million (10^7) simulations. It should be noted that the upper-bound distribution has a greater probability of containing large flaws (which result in a higher probability of failure) than the best-estimate distribution.

CONCLUSIONS

The NRC staff concluded that beyond design-basis events occurring during plant shutdown could lead to cold over-pressure events that could challenge vessel integrity. The industry's response concluded that condensate and control rod drive pumps could cause conditions that could lead to cold over-pressure events that could challenge vessel integrity. The BWRVIP's estimate of the frequency of over-pressurization events that could challenge the RPV is 9.5 x 10^{-4}/yr for BWR-4 facilities and 9 x 10^{-4}/yr for other than BWR-4 facilities. After accounting for actual injections which were not included in the BWRVIP analysis, the NRC staff conservatively estimates that the total frequency could be as high as 1 x 10^{-3}/yr (a point estimate).

The P(F|E) for the limiting reference case for circumferential flaws without ISI was 1.13 x 10^{-5}. Combining the frequency of cold over pressure events with the P(F|E) results in a failure frequency for the limiting reference case of 1.13 x 10^{-8}/yr [(1 x 10^{-3}/yr event frequency) x (1.13 x 10^{-5}/yr P(F|E))].

The industry and NRC staff performed probabilistic fracture mechanics analyses for the limiting plants. These analyses determined that the limiting plant specific P(F|E) for circumferential welds at 32 effective full power years (EFPY) were 1 x 10^{-6} from the BWRVIP's re-analysis and 8.2 x 10^{-5} from the NRC staff's analysis. Combining the frequency of cold over pressure events with the P(F|E), the failure frequency from the BWRVIP's analysis for the limiting circumferential welds was 9.0 x 10^{-10}/yr [(9 x 10^{-4}/yr event frequency for a BWR-3) x (1.0 x 10^{-6} conditional probability of failure)]. The limiting plant specific failure frequency for circumferential welds at 32 EFPY was determined by the NRC staff to be 8.2 x 10^{-8}/yr [(1 x 10^{-3}/yr event frequency) x (8.2 x 10^{-5} P(F|E))]. As depicted in NUREG 1560, Vol. I [Reference 7], core damage frequencies (CDF) for BWR plants were reported to be approximately 10^{-7}/yr to 10^{-4}/yr. In addition, Regulatory Guide (RG) 1.154 [Reference 8] indicates that PWR plants are acceptable for operation if the plant-specific analyses predict the mean frequency of through-wall crack penetration for pressurized thermal shock events is less than 5 x 10^{-6}/yr. The failure frequencies of circumferential welds in BWR vessels are significantly below the criteria specified in RG 1.154.

RG 1.174 [Reference 9] provides guidelines as to how defense-in-depth and safety margins are maintained, and states that a risk assessment should be used to address the principle that proposed increases in risk, and their cumulative effect, are small and do not cause the NRC Safety Goals to be exceeded. The estimated failure frequency of the BWR RPV circumferential welds is well below the acceptable core damage frequency (CDF) and large early release frequency (LERF) criteria discussed in RG 1.174. Although the frequency of RPV weld failure can not be directly compared to the frequencies of core damage or large early release, the NRC staff believes that the estimated frequency of RPV circumferential weld failure bounds the corresponding CDF and LERF that may result from a vessel weld failure. On the above bases, the NRC staff has concluded that the BWRVIP-05 [Reference 1] proposal, as modified, to eliminate BWR vessel circumferential weld examinations, is acceptable.

Although the failure frequencies for axial welds are relatively high, there are known conservatisms in these estimates. For example, these analyses were based on the assumption that the flaws in the axial weld with the limiting material properties and chemistry are all located at the inside surface of the BWR RPV and at the location of peak end-of-license (EOL) azimuthal fluence. Since flaws are distributed throughout the weld and the EOL neutron fluence will not occur for many years, the NRC staff has concluded that the present RPV failure frequency is substantially below that reported by the BWRVIP, and independently calculated by the NRC staff, and is not a near-term safety concern.

REFERENCES

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