August 22, 2007

Rick Libra, BWRVIP Chairman
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SUBJECT: STAFF EVALUATION OF BWRVIP RESPONSE TO NUCLEAR REGULATORY COMMISSION SAFETY EVALUATION OF "BWR VESSEL AND INTERNALS PROJECT, EVALUATION OF CRACK GROWTH IN BWR STAINLESS STEEL RPV INTERNALS (BWRVIP-14-A)" (TAC NO. MC2738)

Dear Mr. Libra:

The Nuclear Regulatory Commission (NRC) staff provided comments during a BWRVIP-NRC staff meeting at NRC headquarters on August 24-25, 2004, regarding the Electric Power Research Institute's (EPRI's) draft proprietary report, "BWR Vessel and Internals Project, Evaluation of Crack Growth in BWR Stainless Steel RPV Internals (BWRVIP-14-A)," dated November 2003. By letter dated September 12, 2005, the Boiling Water Reactor Vessel and Internals Project (BWRVIP) submitted their response to the NRC staff's comments by providing additional information addressing each of the issues identified by the NRC staff during the meeting on August 24-25, 2004.

There were three issues that the NRC staff requested that the BWRVIP address. The first issue was the need for confirmatory finite-element analysis (FEA) to determine the stress intensity (K)-distributions in the core shroud ring-to-shell welds since the BWRVIP-14-A report assumes that the generic through-wall K-distribution derived for the core shroud shell-to-shell (H4 and H5) weld geometry is also applicable to the core shroud ring-to-shell (H1, H2, H3, H6a and H6b) welds. By letter dated September 12, 2005, the BWRVIP provided additional evaluations to determine the K-distributions for the core shroud ring-to-shell welds using FEA techniques. The FEA techniques were benchmarked against the Cheng-Finnie analytical solutions for the core shroud shell-to-shell welds and show excellent agreement. Therefore, the additional finite element analyses provided in the BWRVIP response to the NRC comments on the draft BWRVIP-14-A report provide a necessary basis of comparing the BWRVIP generic K-distributions to the core shroud ring-to-shell weld K-distributions. These FEA results should be incorporated into the revised version of BWRVIP-14-A.

The second issue was in regards to requiring a more conservative bounding crack growth rate or the need to perform a more specific analysis for the core shroud ring-to-shell welds. For

some weld geometries and some material conditions the generic BWRVIP-14-A K-distributions are not conservative in all cases for the core shroud ring-to-shell welds. Similarly, the BWRVIP-14-A 95th percentile crack growth rate curve is expected to bound most of the crack growth rates. The K-distribution and the crack growth rates are uncorrelated variables. This suggests that the crack growth predicted by the BWRVIP-14-A guidelines will be non-conservative for a relatively small fraction of cases. If the total length of cracks in a given weld that could be addressed by these generic BWRVIP-14-A crack growth models were arbitrarily limited to a maximum of one-half of the total circumference, the consequences of underestimating the crack growth would be limited. With the low applied loads that are present on shrouds, crack opening areas will be small. The structural margins for gross failure of the core shrouds would still be large. For longer cracks, more specific analysis for core shroud ring-to-shell welds or a more conservative bounding crack growth rate of 5×10^{-5} in/h would be required.

Based on the combination of the K-distribution developed by the BWRVIP for H6a welds and the BWRVIP-14-A crack growth rate model (denoted as "H6a Avg OD to ID NWC" in Figure 1), an outside diameter (OD) to inside diameter (ID) crack in the H6a weld takes approximately [ ] months to grow from [ ] percent to [ ] percent through-wall. The combination of the BWRVIP-14-A generic K-distribution and the BWRVIP-14-A crack growth rate model (denoted as the "VIP-14A Total (NWC)" crack growth curve) predicts that it will take approximately [ ] months to grow from [ ] percent to [ ] percent through-wall under normal water chemistry. It should be noted that the generic K-distribution (used to calculate the "VIP-14A Total (NWC)" crack growth curve) includes operational loads and contributions intended to represent the effect of local stresses. The other projected crack growth curves shown in Figure 1 (i.e., "H6a Avg OD to ID NWC") based on other, specified K-distributions do not include any contribution from operating stresses. Including these operating stresses would further increase the difference between the growth predicted by the BWRVIP-14-A generic K-distribution and the H6a (core shroud ring-to-shell weld) K-distribution.

Figure 1. Predicted Crack Growth in Core Shroud Ring-to-Shell Welds

To date, no through-wall cracking has been found in core shroud welds despite the extensive cracking that has been observed. There are seven measurements on H2 and H3 welds. The "VIP-14A Total (NWC)" crack growth curve bounds the measured crack extension in all but one case. In that case the measured extension was [ ] inches, the predicted extension [ ] inches. The BWRVIP response states that the results for the H6a K-distribution contradicts this field experience, that such K-distributions are unlikely to actually occur, and that the generic BWRVIP-14-A K-distribution together with the BWRVIP-14-A crack growth rate correlation provides an adequate description of through-wall crack growth in ring-to-shell welds.

Although it is clear that field experience does show that K-distributions such as that postulated for the H6a weld are unlikely to occur in practice, it is difficult to quantify just how unlikely they are. A semi-quantitative argument to justify the low likelihood can be developed. According to information supplied by the BWRVIP,[*] cracking has occurred in at least 26 core shroud welds.

[*] Personal communication, Bob Carter (EPRI) to Meena Khanna (USNRC), May 16, 2006.

Let the probability that a crack in a weld has grown through-wall be F(t) where t is the time since the crack initiated. The probability that the crack has not grown through-wall is 1 – F(t). The probability, P, that no crack has grown through-wall in any of the 26 core shroud welds that have cracked is:

$$P = \prod_{i=1}^{26} \left(1 - F(t_i)\right)$$

where t_i is the time since initiation available for crack growth for each crack. This should include only time during which no mitigating measure such as hydrogen water chemistry (HWC) was applied. These times are not actually known. It is assumed that 10 years (120 months) is a conservative estimate of this time. This case simplifies to

$$P = (1 - F)^{26}$$

where F is the probability of through-wall growth after 120 months. The question is how large can F be before P is so low that it contradicts the field observation that no cracking has occurred. If we take P = 0.05, a typical statistical threshold for likeliness, then the field observations imply that F must less than 0.11.

To compute F, the distribution of stress intensity factors is assumed to be characterized in terms of the distribution of times required to grow a flaw from 0.1h to 0.8h (where h is the wall thickness) for a given crack growth rate, which is taken as the BWRVIP "95th percentile" growth rate. This distribution is assumed to be log-normal with the time corresponding to the BWRVIP-14-A generic K-distribution as the median, and the time corresponding to the H6a K-distribution as a high percentile. This percentile value is chosen to make the likelihood of through-wall growth consistent with field experience. The crack growth rate is also assumed to be distributed normally with a 95th percentile value similar to the BWRVIP-14-A crack growth rate model and the 5th percentile value an order of magnitude lower.

Monte Carlo calculations were performed by taking a sample from the failure time distribution and a sample from the crack growth rate distribution, and using the crack growth rate value to scale the time sample (which was computed using the BWRVIP crack growth rate 95th percentile correlation). The Monte Carlo samples can then be rank ordered to estimate the probability of failure, i.e., growth to 0.8h, by a given time. Calculations are shown in Figure 2 for cases where the time for growth to 0.8h corresponding to the H6a stress intensity distribution is taken as the 95th, 99th, and 99.9th percentile value of the distribution. For the 95th percentile case, the probability that the crack has grown to 0.8h through-wall is 0.17 and the probability that no cracking this deep would have occurred in any of the 26 cases is 0.007.

This is too low to be statistically plausible. For the 99th percentile case, the probability that the crack has grown to 0.8h through-wall is 0.11 and the probability that no cracking this deep has occurred is 0.05. While low, this is considered statistically possible and the conclusion is that the H6a K-distribution represents the 99th or higher percentile of the K-distributions observed in service. The value of [ ] months for the BWRVIP-14-A generic K-distribution and 95th percentile crack growth rate corresponds to the 25th percentile of the F99 distribution. Thus it would give conservative answers greater than 75 percent of the time. The crack depth would exceed 0.8h less than 11 percent of the time.

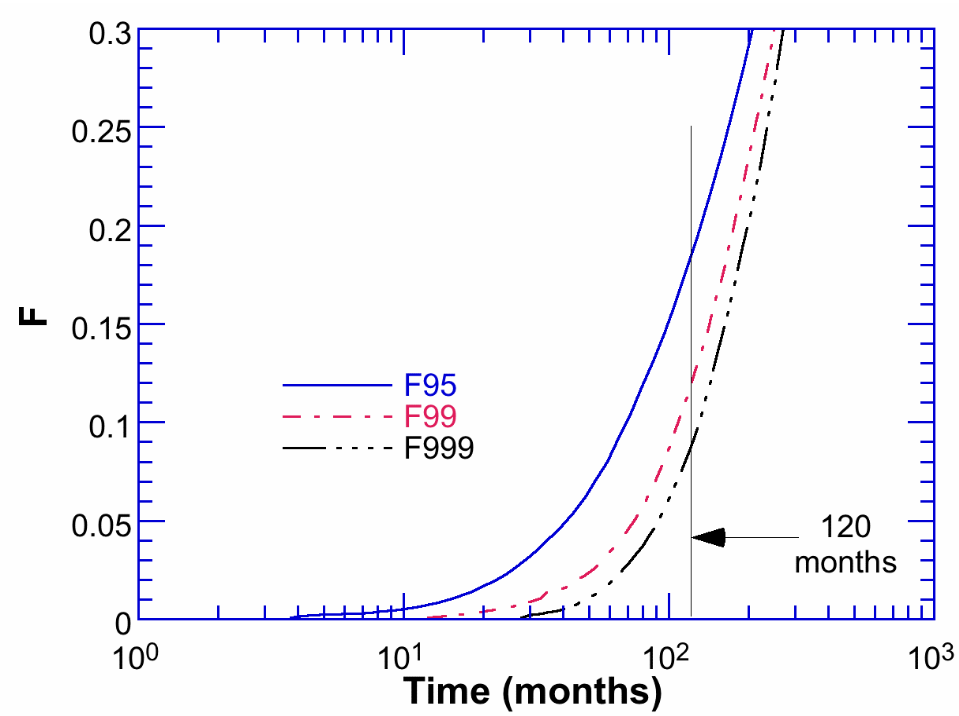

Figure 2. Times for Growth to 0.8h for Three Different Distributions of Stress Intensity Factor.

These results support the assertion in the BWRVIP letter dated September 12, 2005, that the combination of the BWRVIP-14-A generic K-distribution and the BWRVIP 95th percentile crack growth rate curve will provide reasonably conservative estimates of through-wall growth of cracks even though they may not be bounding in all cases.

The operating experience reported in BWRVIP-14-A should be updated to better reflect the number or instances of core shroud cracking that have occurred without through-wall growth. The extensive field experience on cracking is critical to the demonstration of the adequacy of the BWRVIP-14-A K-dependent approach for crack growth.

The third issue was in regards to the effects of neutron fluence on crack growth rates in the weld heat affected zones. For neutron fluence values up to 5 x 10^{20} n/cm^2 (E > 1 MeV), the BWRVIP-14-A 95th percentile crack growth rate curve may bound the crack growth rate only about 70 percent of the time. The NRC has observed a significant increase in crack growth rate in irradiated weld heat affected zone material at a neutron fluence value of approximately 5 x 10^{20} n/cm^2 (E > 1 MeV).

The BWRVIP proposes to use the BWRVIP-14-A "95th percentile" crack growth rate curve for unirradiated materials up to a neutron fluence value of 5 x 10^{20} n/cm^2 (E > 1 MeV) and to use a correlation presented in the BWRVIP-99 report, "Crack Growth Rates in Irradiated Stainless Steel in BWR Internal Components," for higher neutron fluence values. This results in a large jump in postulated crack growth rates at a neutron fluence value of 5 x 10^{20} n/cm^2 (E > 1 MeV). In reality, the transition is continuous, and the proposed crack growth rate correlation will be somewhat non-conservative for neutron fluence values less than but near 5 x 10^{20} n/cm^2 (E > 1 MeV) and quite conservative for the portions of the core shroud with neutron fluence values greater than 5 x 10^{20} n/cm^2 (E > 1 MeV). The potential non-conservatism is relatively small. The BWRVIP-14-A "95th percentile" crack growth rate curve may be expected to bound 70 percent of the crack growth rates for neutron fluence values somewhat below 5 x 10^{20} n/cm^2 (E > 1 MeV) instead of the 95 percent expected for unirradiated materials.

In its letter dated September 12, 2005, the BWRVIP provided additional information on the neutron fluence values associated with core shrouds. The neutron fluence varies significantly around the core shroud and through the thickness for the various ring-to-shell (horizontal) welds. In general the peak neutron fluence locations occur where the core is closest to the core shroud at the 45, 135, 225 and 315 degree locations (+/- 5 degrees). Thus only a limited region of the core shroud circumference and thickness will experience the peak neutron fluence.

This variability strongly mitigates the effect of any potential non-conservatism in the BWRVIP-14-A report at neutron fluence values just below the threshold value of 5 x 10^{20} n/cm^2 (E > 1 MeV). The portions of the core shroud for which the crack growth rate might be non-conservative is limited in extent both azimuthally and through-thickness.

Together with the conservatism inherent in the K-distribution in most cases, this level of conservatism in the crack growth rate model should assure conservative predictions of through-wall crack growth in almost all cases.

Therefore, the proposal to use the unirradiated crack growth rate curve for neutron fluence values less than 5 x 10^{20} n/cm^2 (E > 1 MeV) and the BWRVIP-99 crack growth rate correlation for neutron fluence values greater than 5 x 10^{20} n/cm^2 (E > 1 MeV) is considered acceptable.

The NRC staff has reviewed the BWRVIP's responses provided in your letter dated September 12, 2005, and finds that the BWRVIP has adequately addressed the issues raised during the August 24-25, 2004, meeting. The NRC staff requests that the BWRVIP incorporate the staff's recommendations, as stated above, as well as the responses to the NRC staff's issues in your letter dated September 12, 2005, into the -A version of the BWRVIP-14 report. The NRC staff also requests that the BWRVIP submit to the NRC the -A version of the BWRVIP-14 report within 180 days of receipt of this letter. Please contact John Honcharik of my staff at (301) 415-1157, if you have any further questions regarding this subject.

Sincerely,

/RA/

Matthew A. Mitchell, Chief
Vessels & Internals Integrity Branch
Division of Component Integrity
Office of Nuclear Reactor Regulation

Project No. 704

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The NRC staff has reviewed the BWRVIP's responses provided in your letter dated September 12, 2005, and finds that the BWRVIP has adequately addressed the issues raised during the August 24-25, 2004, meeting. The NRC staff requests that the BWRVIP incorporate the staff's recommendations, as stated above, as well as the responses to the NRC staff's issues in your letter dated September 12, 2005, into the -A version of the BWRVIP-14 report. The NRC staff also requests that the BWRVIP submit to the NRC the -A version of the BWRVIP-14 report within 180 days of receipt of this letter. Please contact John Honcharik of my staff at (301) 415-1157, if you have any further questions regarding this subject.

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