July 29, 2005

Bill Eaton, BWRVIP Chairman
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SUBJECT: SAFETY EVALUATION OF EPRI REPORT, "BWR VESSEL AND INTERNALS PROJECT, CRACK GROWTH RATES IN IRRADIATED STAINLESS STEEL IN BWR INTERNAL COMPONENTS (BWRVIP-99)" (TAC NO. MB3951)

Dear Mr. Eaton:

The NRC staff has completed its review of the Electric Power Research Institute (EPRI) proprietary report, "BWR Vessel and Internals Project, Crack Growth Rates in Irradiated Stainless Steel in BWR Internal Components (BWRVIP-99)," dated December 2001. This report was submitted by letter dated December 20, 2001, and supplemented by letters dated August 6, 2002, and September 21, 2004, for NRC staff review and approval. The BWRVIP-99 report addresses the crack growth correlation that can be applied under normal water chemistry or hydrogen water chemistry at fluences greater than $5x10^{20}$ n/cm^2 (E ≥ 1.0 MeV).

The NRC staff has reviewed your submittal and the staff's safety evaluation is attached. Please note that this safety evaluation is non-proprietary; the proprietary version of this SE was issued on July 15, 2005. The staff requests that the BWRVIP submit the proprietary and non-proprietary versions of the -A version of the BWRVIP-99 report within 180 days of receipt of this letter. Please contact Meena Khanna of my staff at 301-415-2150 if you have any further questions regarding this subject.

Sincerely,

/(RA by W. H. Bateman)/

William H. Bateman, Chief
Materials and Chemical Engineering Branch
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Office of Nuclear Reactor Regulation

Enclosure: As stated

cc: BWRVIP Service List

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Sincerely,

William H. Bateman, Chief
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SAFETY EVALUATION OF THE "BWR VESSELS AND INTERNALS PROJECT, "CRACK GROWTH RATES IN IRRADIATED STAINLESS STEEL IN BWR INTERNAL COMPONENTS (BWRVIP-99)"

1.0 INTRODUCTION

1.1 Background

By letter dated December 20, 2001, the Boiling Water Reactor Vessel and Internals Project (BWRVIP) submitted for staff review and approval the Electric Power Research Institute (EPRI) proprietary version of Report TR-1003018, "BWR Vessel and Internals Project, Crack Growth Rates in Irradiated Stainless Steels in BWR Internal Components (BWRVIP-99)," dated December 2001. This report was supplemented by letters dated August 6, 2002, and September 21, 2004, in response to the staff's request for additional information (RAI), dated January 8, 2003.

The BWRVIP-99 report provides new crack growth rates (CGRs) that can be used for irradiated stainless steels (SS) that have been exposed to fluences greater than $5 X10^{20}$ n/cm^2 ($E \geq 1.0$ MeV). The proposed CGRs were developed based on several inputs which are presented in the BWRVIP-99 report. First, the report provides an overview of the fundamental basis for the effects of irradiation on crack growth behavior. This is directly tied to the fundamental understanding of stress corrosion cracking (SCC) processes in austenitic structural materials. With this understanding, the report presents supporting data from crack growth measurements made on core shrouds through ultrasonic inspections. The report also summarizes the useful laboratory CGR data that have been measured in irradiated SS. In addition, the report provides a summary of other relevant data on unirradiated SS that have provided valuable insights into CGR behavior of SS following irradiation. The report also proposes disposition CGR curves for use with SS core components irradiated in the range of 5×10^{20} n/cm^2 ($E \geq 1.0$ MeV) to 3×10^{21} n/cm^2 ($E \geq 1.0$ MeV).

1.2 Purpose

The staff reviewed the BWRVIP-99 report and the supplemental information that was submitted to the staff to determine whether it will provide an acceptable CGR methodology that can be used for irradiated SS internal components for fluence levels ranging between 5×10^{20} n/cm^2 ($E \geq 1.0$ MeV) to $3 X 10^{21}$ n/cm^2 ($E \geq 1.0$ MeV).

1.3 Organization of this Report

Because the BWRVIP-99 report is proprietary, this safety evaluation (SE) was written not to repeat proprietary information contained in the report. The staff does not discuss, in any detail, the provisions of the guidelines nor the parts of the guidelines it finds acceptable. A brief summary of the contents of the subject report is given in Section 2 of this SE, with the evaluation presented in Section 3. The conclusions are summarized in Section 4.

2.0 SUMMARY OF BWRVIP-99 REPORT

The BWRVIP-99 report provides a crack growth methodology that can be used for irradiated SS internal components exposed to fluence levels in the range of 5×10^{20} n/cm^2 ($E \geq 1.0$ MeV) to $3 X 10^{21}$ n/cm^2 ($E \geq 1.0$ MeV). The CGR curves proposed in the BWRVIP-99 report for fluence levels greater than 5×10^{20} n/cm^2 ($E \geq 1.0$ MeV) are more than an order of magnitude higher than those presented in the BWRVIP-14 report,

ATTACHMENT

"BWR Vessel and Internals Project, Evaluation of Crack Growth in BWR Stainless Steel Reactor Pressure Vessel Internals," for the same environmental conditions but for fluence levels less than 5 x 10^{20} n/cm^2 (E ≥ 1.0 MeV).

The report provides an overview of the fundamental basis for the effects of radiation on crack growth behavior of austenitic SSs. It summarizes much of the relevant CGR data obtained from laboratory tests on irradiated SSs and from re-inspections of irradiated core shroud welds that have reached fluence levels greater than 5 x 10^{20} n/cm^2 (E ≥ 1.0 MeV), and presents disposition curves that can be used for the analysis of crack growth in irradiated materials for normal water chemistry (NWC) and hydrogen water chemistry (HWC). [ ].

The disposition curves are based on the data obtained from laboratory studies. Comparisons of the predictions of the integrated crack growth methodology (the disposition curves, the welding residual stresses, and the stress relaxation model) with field data on core shrouds are used to assess the overall adequacy of the proposed methodology.

The data available for irradiated materials are sparse. Unlike in the BWRVIP-14 report, the sources of the data used to develop the disposition curves are not clearly identified in the BWRVIP-99 report. However, more detailed information on the sources of the data and the conditions in the tests have been supplied in the response to the request for additional information (RAI) dated September 21, 2004. [ ]. In the current version of the BWRVIP-99 report, it is also argued that this dependence is consistent with the limited data available for irradiated materials. [ ]. The HWC curve bounds all of the limited data for HWC presented in the report and the responses to the RAI.

The BWRVIP-99 report uses the weld residual stress profiles proposed in the BWRVIP-14 report. However, credit is taken for stress relaxation due to irradiation creep. In order to evaluate this credit, stress relaxation due to irradiation is reviewed. [ ]. Based on the available data, this is a conservative choice in terms of the relaxation observed for uniaxial stress states. The predictions of the integrated crack growth model including the CGRs, the welding residual stresses, and the stress relaxation model are compared with field data on core shrouds. The comparisons in the current version of the BWRVIP-99 report are non-conservative because they compare results with the crack depth at the beginning of the inspection interval, but more appropriate comparisons are presented in the responses to the RAI as submitted by letter dated September 21, 2004. The comparisons in the RAI responses are given in terms of predicted CGRs, as a function of the average depth during the interval of observation, and the observed average CGR during the interval. Because the strong dependence of CGR on depth can make comparing predicted and observed CGRs difficult, comparisons were also made directly with the final predicted depths. Virtually all of the observations are bounded by the predicted results, which supports the overall conservatism of the integrated model.

3.0 STAFF EVALUATION

The staff evaluated the following issues: (1) adequacy of the NWC disposition curve over the proposed fluence range, (2) adequacy of the HWC disposition curve over the proposed fluence range, (3) appropriateness of the weld residual stresses, (4) stress relaxation of weld residual stresses, and (5) the adequacy of the overall methodology. Each of these issues are addressed below.

3.1 Disposition Curves for Normal Water Chemistry

The irradiated material database used for the development of the proposed disposition curves includes data from tests at the Halden reactor and data from a joint General Electric Nuclear Energy-Japan Power Engineer and Inspection Corporation (GENE-JAPEIC) program. In this evaluation, additional data[4] from an USNRC sponsored research program at Argonne National Laboratory (ANL) are also considered.

The database includes data on CGRs in Types 304, 316, 316NG, and 347 stainless steels at fluences ranging from 8 x 10^{20} n/cm^2 (E ≥ 1.0 MeV) to 3 x 10^{21} n/cm^2 (E ≥ 1.0 MeV). The dissolved oxygen levels in the NWC tests range from 0.2 to 8 ppm. Most of the conductivity levels are about 0.1 μS/cm, typical of modern BWR operating chemistries. Data are available for three GENE-JAPEIC specimens, four Halden specimens, and three ANL specimens. Except for one ANL specimen, only data that meet the American Society for Testing and Materials (ASTM) E 399, "Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials," screening criteria for allowable K values with irradiated yield stress values decreased by a factor of two have been used. This is consistent with the criteria used to screen data in the BWRVIP-99 report and the responses to the RAIs as provided in the BWRVIP's letter dated September 21, 2004. For one ANL specimen, the K values were about 25% higher than allowed, but the behavior seems typical in all respects and it was included in the analysis.

The assumption that is made in the BWRVIP-99 report is that the dependence of the CGR on the stress intensity factor K can be represented by a power law of the form:

$$\frac{da}{dt} = AK^n \qquad \text{Equation 1}$$

where A is a constant that depends on the material and water chemistry. The value of n is taken to be [ ]. This is reported to be consistent with GENE tests on cold-worked SSs, which have mechanical properties similar to those of irradiated SSs, and values similar to this are widely used to describe the stress corrosion cracking of unirradiated SSs. For example, the NUREG-0313, Revision 2, "Technical Report on Material Selection and Processing Guidelines for BWR Coolant Pressure Boundary Piping," the disposition curve uses n = 2.161.

In assessing the adequacy of the proposed disposition curve, it is important to address not only its relation to the available data, but also its relation to the overall population of materials to which it is presumed to be applicable (Types 304, 316, 347, 304L, 316L SSs with fluences of 5 x 10^{20} to 3 x 10^{21} n/cm^2 (E ≥ 1.0 MeV)). To assess this, Equation 1 was fit to each specimen for which data were available and a corresponding value of A was determined.

[ ] Figure 1 Halden CGR data for NWC with [ ]

The values of A for each specimen are summarized in Table 1. To be consistent with the BWRVIP-99 report, the values of A are for CGRs in units of in/h and K in units of ksi·in$^{1/2}$.

Table 1 Values of the crack growth rate parameter A, as expressed in Ln, for power law growth [ ] for CGRs in in/h and K in ksi·in$^{1/2}$

	Ln(A)	Specimen	Material	Fluence n/cm^2
[ ]	[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]	[ ]
ANL	-16.20	C3-B	304	0.9×10^{21}
	-16.82	C3-C	304	2.00×10^{21}
	-16.28	C16-B	316	2.00×10^{21}

These values of A can be considered as a sample of a population consisting of different heats and types of austenitic SSs irradiated to fluences between 8×10^{20} n/cm^2 (E ≥ 1.0 MeV) and 2.8×10^{21} n/cm^2 (E ≥ 1.0 MeV). The distribution of the values of A appears to be approximately log-normal, as shown in Figures 2 and 3.

[ ] Figure 2

[ ] Figure 3

[ ] Figure 4 (Same as Figure 1) Comparison of Halden data with fits of the form [ ]

A comparison of the fits of the form [ ] with the Halden data is shown in Figure 4. The models are consistent with the general trends in the data, although there is significant scatter in the data. One striking feature is the relative narrowness of the distribution. [ ]. In contrast, for primary water stress corrosion cracking (PWSCC) of Alloy 600, the 95th and 5th percentiles of a similar distribution differ by almost a factor of 30. The BWRVIP-99 disposition curve is compared with the 95th percentile and the mean curves for the population in Figure 5. [ ].

[ ]

Figure 5
Comparison of the BWRVIP-99 disposition curve with the population mean and 95th percentile curves

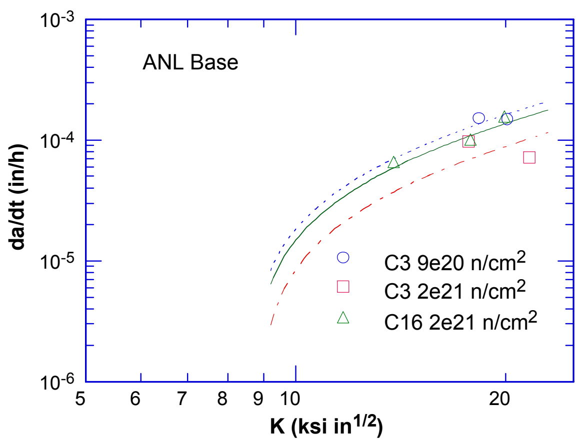
Because the available data are limited, the best way to describe the K dependence of the CGR is not clear. To assess the impact that a different assumption for the K dependence of the CGR would have on the population estimates, the data were refit using a form originally proposed by Scott[1] to describe stress corrosion CGRs in Alloy 600:

$$\frac{da}{dt} = B(K - K_o)^{1.1} \qquad \text{Equation 2}$$

Equation 2 can be fit to the data for each specimen as before. To get a single parameter representation, K_o was not chosen independently of B. Comparisons of the data with the curve fits are shown in Figure 6.

[ ] [ ]

(a) (b)



(c)

Figure 6
Comparison of data with $B(K-K_o)^{1.1}$ fits

The values of B and K_o for each of the data sets are given in Table 2.

Table 2 Values of the crack growth rate parameters B (as expressed in Ln) and K_o for a Scott model type growth $B(K-K_o)^{1.1}$ for CGRs in in/h and K in ksi·in$^{1/2}$

	Ln(B)	Ko	Specimen	Material	Fluence n/cm^2
GENE-JAPEIC	[ ]	[ ]	[ ]	[ ]	[ ]
Halden	[ ]	[ ]	[ ]	[ ]	[ ]
ANL base	-11.42	8.42	C3-B	304	0.90×10^{21}
	-11.58	8.49	C16-B	304	2.00×10^{21}
	-12.00	8.69	C3-C	316	2.00×10^{21}

The distribution of B is approximately log-normal, as shown in Figures 7 and 8.

[ ]

Figure 7
Probability plot for Ln(B) for power law crack growth $B(K-K_o)^{1.1}$

[ ]

Figure 8
Median ranks for observed values of ln(A) compared with a log-normal distribution with log mean -11.93 and standard deviation 0.47

In Figure 9, the BWRVIP-99 curve is compared with population curves based on the Scott model.

[ ]

Figure 9
Comparison of the BWRVIP-99 disposition curve with the population mean and 95th percentile curves

Because of the differences in the shape of the curves, it is not as easy to relate the BWRVIP-99 disposition curve to the population curves in this case. However, it is clear that the results are similar. For a substantial range of K, the disposition curve lies between the mean and 95th percentile curves. Also, despite the apparent differences in the forms of the equations, over the range of K of most interest, 12-20 ksi·in$^{1/2}$, the K dependence predicted by the Scott model form and BWRVIP models is similar.

Overall, the proposed disposition curve is expected, in most cases, to conservatively estimate the CGRs for austenitic SSs with fluences less than 3 x 10^{21} n/cm^2 (E ≥ 1.0 MeV). The database, although limited, contains a fairly wide variety of SSs. Although it does not contain many heats of each type of steel, the relatively modest variations seen for the much larger compositional variations associated with the different types of steels provides strong evidence that heat-to-heat variations will not affect the conclusion that the disposition will give conservative results in most cases. The curve does not bound the growth rates expected from every heat of austenitic SSs at these fluence levels, but the degree of conservatism is consistent with that found in other disposition curves, e.g., that for PWSCC of Alloy 600. It is less than the level proposed by the BWRVIP for unirradiated materials, in which case they used a 95th percentile curve. (In that case they chose a 95th percentile fit to all the data, rather than a fit to the population of materials. For a large database, the two approaches should give similar results). However, in the case of the unirradiated material, the distribution is much broader, and it can be argued that the potential consequences of exceeding the disposition curve are greater (the ratio of the 95th and, say, 75th percentiles are much larger).

3.2 Disposition Curves for HWC

The addition of hydrogen to the BWR coolant can result in a substantial decrease in the susceptibility of SSs to stress corrosion cracking and in a substantial reduction in CGRs of cracks that may have already formed prior to the initiation of HWC (as defined in BWRVIP-62). HWC can be achieved with or without the addition of noble metals. In either case, the result is a substantial reduction in the electrochemical potential of SSs in the reactor.

The effectiveness of HWC has been widely demonstrated in laboratory testing for unirradiated materials and been confirmed by a significant amount of operating experience. In practical terms, there are two issues: (1) how low electrochemical potentials can be achieved in-reactor, especially in high radiation regions, and (2) if low electrochemical potentials are achieved, what is the effect on the CGRs. The BWRVIP-99 report is concerned only with the second of these two issues.

It is known from slow strain rate testing and from CGR data at very high fluences* that the benefit of HWC is not observed at high fluence levels. However, the threshold fluence above which HWC is not effective is not well known and is probably dependent on a number of factors. The BWRVIP-99 report assumes that the threshold fluence is greater than 3 x 10^{21} n/cm^2 (E ≥ 1.0 MeV) for the materials and conditions of interest.

Reductions in the CGRs of actively growing cracks with HWC have been repeatedly demonstrated in tests at Halden, GENE, and ANL, at fluences less than 3 x 10^{21} n/cm^2. The fluence levels for the materials on which the tests were conducted and the factors of decrease in CGR when the switch to HWC was made (the reduction factor) are summarized in Table 3 and shown as a function of fluence in Figure 10. The measurement of the

* The Halden test results described in Section 4.2.2 of the BWRVIP-99 report show that for 304 SS irradiated to 9x10^{21} n/cm^2 (E ≥ 1.0 MeV), the loading conditions were well within the valid K based on conservative estimates, but the specimen showed an increase in CGR under HWC. See also Reference [2].

reduction factor is subject to some uncertainty, since it is difficult to make accurate measurements of the low CGRs that are typical of HWC.

Table 3 Reduction factor observed for CGRs for transition from NWC to HWC

	Material	Fluence	Reduction Factor
Halden	[ ]	[ ]	[ ]
GENE	[ ]	[ ]	[ ]
ANL Base	304	0.90×10^{21}	25.9
	316	2.00×10^{21}	24.3
		2.00×10^{21}	17.4
	Average Reduction Factor		38.2
Halden	[ ]	[ ]	[ ]
Studsvik	304L	8.00×10^{21}	1

[ ]

Figure 10
Reduction factors for CGR for transition from NWC to HWC

The BWRVIP-99 report assumes a reduction factor of [ ] to determine the HWC disposition curve. This seems conservative based on the data in Table 3. More controversial is the choice of the upper limit for the effectiveness of HWC as 3×10^{21} n/cm^2 (E ≥ 1.0 MeV). CGR tests at Halden[2] and Studsvik[3] show no benefit of HWC at fluences ≥ 8×10^{21} n/cm^2 (E ≥ 1.0 MeV). The data in Figure 10 also suggest that the reduction factor decreases with increasing fluence (the high fluence results from Halden and Studsvik are included in Figure 10. [ ]. Chopra[4] has reported the results of a test on a Type 304 SS irradiated to 2.0×10^{21} n/cm^2 (E ≥ 1.0 MeV), in which no reduction of CGR was observed in HWC. The K value in the test (as determined after post-test examination of the crack length) exceeded the generally accepted limits for such tests on irradiated materials by 15%. However, in another test on a Type 304 SS irradiated to 9×10^{20} n/cm^2 (E ≥ 1.0 MeV), a substantial benefit (reduction factor = 25.9) was observed even though the K value exceeded the acceptance limit by 28%.

Based on the available data, values for the cutoff ranging from 1.8×10^{21} to 5×10^{21} n/cm^2 (E ≥ 1.0 MeV) for the cutoff fluence for a reduction factor of [ ] could be defended. Therefore, the staff finds that the value of 3×10^{21} n/cm^2 (E ≥ 1.0 MeV), as indicated in the BWRVIP-99 report, appears to be reasonably conservative, but may not be bounding in all cases.

3.3 Appropriateness of the Weld Residual Stresses

In applications to core shrouds, it is likely in many cases, that the extent of cracking will be largely controlled by the residual stresses. Even the 50th percentile curve for irradiated materials shows CGRs that are high enough to grow through-wall fairly rapidly if high residual stresses are present. Conversely, if the residual stress distribution is such that the stress intensity becomes negative part-way through the wall, crack growth will be halted even for the 99.9 percentile CGR curve.

The appropriateness of these residual stresses was discussed extensively in a previous evaluation report on the BWRVIP-14[5] report. For completeness, a number of these issues are discussed here.

The K distributions determined from the computed residual stresses for shell-to-shell welds provided in the BWRVIP-14 report and the K distributions determined from the residual stresses computed independently by Battelle under work sponsored by the USNRC Office of Research are shown in Figure 11. The results provided in the BWRVIP-14 report are given for two values of the yield stress, 40 ksi and 67 ksi. Although the modeling assumptions and computation approaches used for the BWRVIP-14 calculations are significantly different than those used in the Battelle calculations, the K distributions are quite similar in character. The differences between the various solutions reflect, in some cases, a variation in a significant parameter (the yield stress), and in others, model uncertainty. Bounding K solutions were obtained by determining the maximum and minimum values for K at each depth from the six computed solutions.

Also shown in Figure 11 is the proposed BWRVIP generic K distribution. Compared to the actual K distributions for the shell-to-shell welds, it is non-conservative for shallow flaws, but more conservative for deeper flaws.

The distribution of K, as shown in Figure 11, includes only the contribution from the weld residual stresses. However, the K distributions in the BWRVIP-14 report include the effect of additional surface residual stresses, an applied load of 1.6 ksi, and an additional applied load of [ ] ksi. These are intended to represent additional stresses that may be present due weld repairs.

[ ]

Figure 11
Normalized K for shell-to-shell H4/H5 welds as a function of the normalized crack depth. The calculated residual stresses for yield stresses of 40 and 67 ksi from the BWRVIP-14 report are shown as H5 40, H4 40, etc. The residual stresses calculated by Battelle on the H3 side and on the H5 side of the H4 weld, respectively, are shown as Bat H4/H3 and Bat H4/H5.

The K distribution, corresponding to the bounding value of K, due to weld residual stresses is shown in Figure 11, and the added surface, applied, and weld repair loads along with the generic BWRVIP-14 K distribution for the total stress, is shown in Figure 12. In the critical region in the midsection of the wall, the BWRVIP distribution is more conservative than the total K based on the bounding K solution for residual stresses in the H4/H5 welds. The VIP solution does not bound the shell-to-shell K distributions at every depth. Thus, for very shallow cracks, the BWRVIP solution may underpredict the crack growth for some period of time. However, it is more conservative than these distributions in the sense that it predicts complete through-wall growth of an initial crack depth, a/t = 0.25, while the bounding solution for the shell-to-shell welds predicts arrest of a crack with an initial depth a/t = 0.25 in every case. The crack depths at arrest, based on a range of assumptions for the residual and applied stresses, are shown in Table 4. The results suggest that cracks in shell-to-shell welds would be expected to arrest at depths ranging from [ ]% to [ ]% of the wall thickness. Of the reported depths for the H4/H5 welds in the BWRVIP-14 report, only one exceeds [ ] of the wall thickness in depth, and that reported depth is only [ ] of the wall thickness, so within measurement errors it is also consistent with the results in Table 4.

Table 4 Non-dimensional arrest depth for H4/H5 welds for different assumptions about residual stresses, surface stresses, and added constant stresses

Residual Stress	Added Constant Stress	VIP Surface Stress	Arrest Depth (x/t)
[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]

[ ]

Figure 12
Distributions of total K for H4/H5 welds

The BWRVIP-14 report also describes residual stress calculations and measurements on the ring-to-shell welds. No K calculations are explicitly made for these stress distributions and weld geometries. However, in a previous evaluation,[5] estimates were made for these residual stress distributions. Based on these estimates, it was concluded that although the BWRVIP-14 generic solution is conservative (i.e., becomes negative at a deeper depth and has a shallower minimum) compared to most of the distributions, it is not always conservative for these welds. The residual stresses in these welds also show a fairly strong dependence on weld sequence and yield strength.

[ ]
(a)

[ ]
(b)

Figure 13 Estimated K distributions with R/t = 60 for (a) H6a and (b) H6b welds.

[ ]

Figure 14
Estimated K distributions with R/t = 60 for H2 and H3 welds

The results for the different welding residual stress profiles, applied loads, and surface stresses associated with the H2, H3, H6a, and H6b ring-to-shell welds are summarized in Table 5. In most cases, arrest is expected. However, in some cases, complete through-wall growth, that is not bounded by the BWRVIP solutions, is predicted. It should be noted that these results are based on estimates for the K distributions for ring-to-shell welds. Presently, there are no finite element solutions available for the K distributions for these geometries.

Table 5 Comparison of specific stress profiles for ring-to-welds with the BWRVIP generic profile including residual stresses, surface stresses, and either a [ ] ksi or [ ] ksi constant load.

	Applied Stress 3.2 ksi			Applied Stress 1.6 ksi		
Weld	Arrest	VIP bounds	25 ksi·in$^{1/2}$ bounds	Arrest	VIP bounds	25 ksi·in$^{1/2}$ bounds
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]

It should also be noted that in these calculations, no credit is assumed for any relaxation of these stresses by irradiation-induced creep.

3.4 Stress Relaxation of Weld Residual Stresses

Although the BWRVIP-99 report starts with the weld residual stress profiles proposed in the BWRVIP-14 report, the effective residual stresses are lower because of the credit taken for stress relaxation due to irradiation-induced creep. Stress relaxation due to irradiation is undoubtedly a real phenomenon, and for simple uniaxial stress states, the choice of the factor of [ ] seems conservative for fluences greater than 5 x 10^{20} n/cm^2 (E ≥ 1.0 MeV). A rigorous solution for the effect of radiation should start with the complex strain fields due to the welding process and then consider the relaxation of the principal strains due to creep and the subsequent redistribution of stresses. In the BWRVIP-99 report, the relaxation of the complex, multi-axial stress state near the weld is modeled simply by scaling the stresses by a relaxation factor determined from experiments on simple uniaxial stress states. Because of the conservatism in the original weld residual distribution (at least for the shell-to-shell welds in the core shroud), and the conservative estimate of the amount of relaxation that will occur, this approach is considered acceptable.

3.5 Adequacy of the Overall Methodology

Comparisons with the field data for average CGRs determined from the re-inspections are used to demonstrate the overall acceptability of the crack growth methodology developed in the BWRVIP-99 report. The comparisons in the original version of the BWRVIP-99 report are non-conservative because they compare crack depth at the beginning of the inspection interval, but more appropriate comparisons are presented in the RAI response letter dated September 21, 2004. The comparisons in the RAI responses are given in terms of predicted CGRs as a function of the average depth during the interval of observation and the observed average CGR during the interval. These comparisons show that the predicted results bound the field observations in nearly every case.

Because the strong dependence of CGR on depth can make comparing predicted and observed CGRs difficult, comparisons are also made directly with the final predicted depths. Again, virtually all the observations are bounded by the predicted results, which supports the overall conservatism of the integrated model.

The BWRVIP-14 report provides guidance for the analysis of cracks in core shrouds for fluence levels up to 5×10^{20} n/cm^2 ($E \geq 1.0$ MeV). The CGR curves proposed in the BWRVIP-99 report are more than an order of magnitude higher than those in the BWRVIP-14 report. The CGRs in the BWRVIP-14 report are for the same environmental conditions but less than 5×10^{20} n/cm^2 ($E \geq 1.0$ MeV) fluence. The response to RAI 99-3 focuses on the argument that the BWRVIP-99 report is conservative for fluences in the range of 5×10^{20} to 3×10^{21} n/cm^2 ($E \geq 1.0$ MeV). The staff agrees with the BWRVIP's response. The staff's concern was whether it was still appropriate to consider the methodology of BWRVIP-14 applicable to fluence levels as high as 5×10^{20} n/cm^2 ($E \geq 1.0$ MeV). This issue will be addressed under the staff's review of the BWRVIP-14A report.[5]

Based on its review of the report, the additional material provided by the BWRVIP, and the responses to the staff's RAI, the staff finds the guidelines provided by this subject report acceptable.

4.0 CONCLUSIONS

This report is an extension of the BWRVIP-14 report for irradiated BWR SS internal components exposed to fluence levels greater than 5×10^{20} n/cm^2 ($E \geq 1.0$ MeV). It presents a comprehensive review of the background and understanding of the effects of irradiation on SCC and crack growth behavior of austenitic SSs, including the information on measured CGRs of irradiated materials tested in the laboratory, and of actual core components of operating plants. Two CGR disposition curves are presented, one for NWC and the other for HWC. The report also recommends that significant credit be given for the relaxation of residual stresses by irradiation-induced creep.

The staff has completed its review and finds that the report includes a comprehensive discussion on the basis for data screening and the proposed disposition curves, but does not provide a detailed tabular summary of the data used to develop the disposition curves including material, stress intensity value, fluence level, conductivity, and the source of the data. Therefore, the staff requests that the BWRVIP revise the BWRVIP-99 report to include the more detailed description of the data, as provided in the RAI response that was submitted to the staff by letter dated September 21, 2004. The comparisons with field data, as provided in the RAI response, should also be included in the report, since the original approach provided a non-conservative comparison.

The staff's review of the proposed disposition curve for NWC and with fluences ranging from 5×10^{20} to 3×10^{21} n/cm^2 ($E \geq 1.0$ MeV) shows that the curve bounds most of the available data including the additional data from ANL, that was not used in the original development of the disposition curve. In addition to bounding most of the available data, analysis also shows that the disposition curve should provide conservative estimates of CGRs in the applicable fluence range for most [ ] SSs of the types commonly used for reactor applications. The staff, therefore, finds the proposed NWC disposition curve to be acceptable.

In addition, the staff's review of the available data on the effectiveness of HWC for the mitigation of CGRs in irradiated SSs shows that the factor of [ ] reduction in CGR should be conservative in most cases for fluences ranging from 5×10^{20} to 3×10^{21} n/cm^2 ($E \geq 1.0$ MeV). The proposed reduction factor seems quite conservative for fluences less than 1×10^{21} n/cm^2 ($E \geq 1.0$ MeV). There is more uncertainty over the upper limit of fluence for which HWC is effective. The choice of the fluence value of 3×10^{21} n/cm^2 ($E \geq 1.0$ MeV) as indicated in the BWRVIP-99 report, seems reasonably conservative, but it could be somewhat lower for some materials. However, for this application, the staff finds that the use of an upper limit of 3×10^{21} n/cm^2 ($E \geq 1.0$ MeV) to be acceptable.

The staff has reviewed the BWRVIP-99 report and the supplemental information that the BWRVIP has provided in its response to the staff's RAI. On the basis of the staff's evaluation above, the staff finds that the methodology proposed in the BWRVIP-99 report to credit the relaxation of residual stresses by irradiation-induced creep to be acceptable.

It should be noted that the scope of the conclusions drawn in this evaluation are specifically applicable to reactor pressure vessel internal components only. The staff requests that the BWRVIP incorporate the information that was provided in its response to the staff's RAI into the -A version of the BWRVIP-99 report.

5.0 REFERENCES

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