October 15, 2001

Mr. Roger A. Newton, Chairman
Westinghouse Owners Group
Wisconsin Electric Power Company
231 West Michigan
Milwaukee, Wisconsin 53201

SUBJECT:     SAFETY EVALUATION OF WCAP-15338, "A REVIEW OF CRACKING
             ASSOCIATED WITH WELD DEPOSITED CLADDING IN OPERATING
             PWR PLANTS"

Dear Mr. Newton:

By letters dated March 1, 2001, June 15, 2001, and July 31, 2001, the Westinghouse Owners Group (WOG) submitted topical report WCAP-15338, "A Review of Cracking with Weld Deposited Cladding in Operating PWR Plants," for staff review and approval. WCAP-15338 provides flaw evaluations based on Section XI of the American Society of Mechanical Engineers Code to justify that the Westinghouse reactor pressure vessels (RPVs) with underclad cracks are acceptable for operation for 60 years.

The staff of the US Nuclear Regulatory Commission has completed its review of the licensee's topical report. The staff has concluded that the topical report is acceptable for Westinghouse 3-loop RPVs because the underclad cracks satisfy the ASME Code flaw evaluation requirements for detected flaws. However, for renewal applicants for Westinghouse 2-loop and 4-loop RPVs who plan to reference this topical report, they need to address the plant-specific applicability of this topical report to their plants as described under Section 4.0, "Renewal Applicant Action Items," of the enclosed staff final safety evaluation report (FSER).

The staff does not intend to repeat its review of the matters described in the report, and found acceptable in the FSER when the report appears as a reference in license renewal applications, except to ensure that the material presented applies to the specified plant.

In accordance with the procedures established in NUREG-0390, "Topical Report Review Status," the staff requests that the WOG publish the accepted version of WCAP-15338 within 90-days after receiving this letter. In addition, the published version shall incorporate this letter and the FSER between the title page and the abstract.

R. Newton                                    -2-


To identify the version of the published topical report that was accepted by the staff, the staff requests the WOG include "-A" following the topical report number (e.g., WCAP-15338-A).

Sincerely,

/**RA**/


Christopher I. Grimes, Chief
License Renewal and Standardization Branch
Division of Regulatory Improvement Programs
Office of Nuclear Reactor Regulation

Project No. 686

Enclosure: Final Safety Evaluation Report

cc w/encl: See next page

R. Newton                                    -2-

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                                        Christopher I. Grimes, Chief
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cc w/encl: See next page

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SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION
TOPICAL REPORT WCAP-15338
A REVIEW OF CRACKING ASSOCIATED WITH WELD DEPOSITED CLADDING
IN OPERATING PRESSURIZED-WATER REACTOR (PWR) PLANTS
WESTINGHOUSE OWNERS GROUP


1.0  INTRODUCTION

By letter dated March 1, 2001, as supplemented by letters dated June 15 and July 31, 2001, the
Westinghouse Owners Group (WOG) submitted WCAP-15338, "A Review of Cracking
Associated with Weld Deposited Cladding in Operating PWR Plants," (Reference 1), for NRC
review.  WCAP-15338 evaluates the impact of cracks beneath austenitic stainless steel weld
cladding on reactor pressure vessel (RPV) integrity.

Underclad cracks were first discovered in October 1970 during examination of the Atucha
reactor vessel.  They have been reported to exist only in SA-508, Class 2 reactor vessel
forgings manufactured to a coarse grain practice and clad by high-heat-input submerged arc
processes.  The underclad cracks were detected from cutouts such as nozzle cutouts from a
reactor pressure vessel forging.  The regulatory position regarding this issue can be found in
Regulatory Guide (RG) 1.43, "Control of Stainless Steel Weld Cladding of Low-Alloy Steel
Components."  RG 1.43 states that detection of underclad cracks "normally requires
destructively removing the cladding to the weld fusion line and examining the exposed base
metal either by metallographic techniques or with liquid penetrant or magnetic particle testing
methods."  The maximum crack size reported by the industry was 0.5 inch in length and 0.165
inch in depth.  RG 1.43 concluded that the subsurface location and size of the underclad cracks
made them relatively insensitive to detection using nondestructive examination methods.
RG 1.43 did not discuss whether any of the underclad cracks were found by nondestructive
examination methods.

A detailed analysis on underclad cracks is provided in topical report WCAP-7733, dated July
1971, in which Westinghouse presented a fracture mechanics analysis to justify the continued
operation of Westinghouse units for 32 effective full power years (EFPY) with the underclad
cracks in the RPVs.  The staff accepted the topical report in 1972.  The destructive analyses
performed by Westinghouse after 1972 indicated that the dimensions of underclad cracks were
0.007 inch to 0.295 inch in depth and 0.078 inch to 2.0 inches in length.  Consequently, WCAP-
15338 used 0.295 inch as the bounding depth for the underclad cracks.  Since 1972, fracture
mechanics analysis has been improved significantly.  To reflect this improvement,
Westinghouse employed the latest fracture toughness information, applied stress intensity
factor solutions, fatigue crack growth correlations for SA-508 Class 2 material, and the IWB-
3611 and IWB-3612 acceptance criteria in Section XI of the ASME Code to evaluate the
acceptability of the RPVs with underclad cracks for the period of extended operation of 60 years
(approximately 48 EFPY).  It should be emphasized that underclad cracks are detected flaws,
not postulated flaws, and therefore require the ASME Section XI flaw evaluation.

Enclosure

## 2.0 SUMMARY OF WCAP-15338

As mentioned previously, Westinghouse used the bounding depth of 0.295 inch for the initial flaw depth of the underclad cracks. In the subsequent fatigue analysis, Westinghouse used the stresses due to the combined loading of pressure and thermal loading to calculate the maximum and minimum applied stress intensity factors (applied $K_I$) for the semi-elliptical inside diameter (ID) surface flaw for each transient cycle. The fatigue crack growth was then performed for each cycle using the ASME fatigue crack growth law for water environment. This process was repeated and the crack length was revised until the entire set of design transients, with cycles corresponding to the period of extended operation of 60 years, had been exhausted. Westinghouse's results indicated that based on the initial crack depth of 0.295 inch the maximum final crack depth at 60 years was 0.35 inch for the axial flaw with an aspect ratio (length to depth) of 6. Westinghouse also reported the final crack depths for an axial flaw with an aspect ratio of 2, a continuous axial flaw, and circumferential flaws of similar crack geometries. The stresses for the applied $K_I$ used in the above fatigue analysis were obtained using a generic Westinghouse 3-loop reactor vessel. For the applied $K_I$ formulas, the Raju-Newman solutions for cylindrical vessels (Reference 2) were used for cases with elliptic axial flaws, and the Buchalet and Bamford solution (Reference 3) was used for the case with a continuous part-through ID flaw. Based on the measured cladding residual stresses that were presented in the WCAP, Westinghouse concluded that the impact of the cladding on the flaw evaluation (allowable flaw size determination) is negligible and did not include the cladding effect in its analysis.

To demonstrate that a RPV with underclad cracks of depth corresponding to 60 years of operation could maintain its structural integrity, Westinghouse performed Section XI allowable flaw size evaluation for normal, upset, emergency, and faulted (Level A, B, C, and D) loading conditions. The irradiated fracture toughness ($K_{Ia}$ and $K_{Ic}$) was obtained using the $K_{Ia}$ and $K_{Ic}$ formulas in Section XI of the ASME Code, and an upper limit of 200 ksi $\sqrt{in}$ was set for $K_{Ia}$ and $K_{Ic}$. For the applied $K_I$ calculations, Westinghouse found the axial flaw to be limiting and calculated the allowable flaw sizes for the most governing transients of the normal and upset conditions for the axial flaw with an aspect ratio of 6. After applying the ASME acceptance criteria of IWB-3612, i.e., $K_I < K_{Ia}/\sqrt{10}$, Westinghouse found that the most critical allowable flaw depth was 1.34 inches. Similar calculations were conducted for the emergency and faulted transients for the same flaw geometries with the ASME acceptance criteria of IWB-3611, i.e., $a_f$ (allowable flaw size) $< a_i$ (critical flaw size based on $K_{Ic}$)/2, and the most critical allowable flaw depth was found to be 1.70 inches. Like the fatigue analysis, Westinghouse also reported the allowable crack depths for the axial flaw with aspect ratio of 2 and with the continuous axial flaw. Since the estimated final flaw depth is smaller than the allowable flaw size, Westinghouse concluded that the Westinghouse RPVs with underclad cracks are acceptable for operation for 60 years.

## 3.0 STAFF EVALUATION

10 CFR 54.21(c) requires applications to include an evaluation of time-limited aging analyses (TLAAs). WCAP-15338 contains a TLAA of the impact of 60 years of operation on the growth of underclad cracks and their impact on RPV integrity.

Westinghouse's flaw evaluation is consistent with the flaw evaluation procedure in Section XI of the ASME Code. It started with an assumed initial flaw depth of 0.295 inch, the maximum

detected flaw depth of underclad cracks for Westinghouse fabricated RPVs.  In the subsequent fatigue analysis, Westinghouse used the Code-specified crack growth rate of A-4300 for low alloy steel in water environment to predict the fatigue crack growth for the RPV material.  This is conservative because all underclad cracks detected, to date, were not through wall and therefore were not in contact with a water environment. Using a water environment is conservative because the growth rate is greater than the growth of underclad cracks not normally exposed to water. The licensee reported that for an initial flaw depth of 0.3 inch, the final flaw depth will be 0.3107 inch for an axial flaw with an aspect ratio of 6 after 60 years of operation.  This initial flaw depth did not consider the clad thickness, of 0.188 inch.  However, even if the underclad crack was conservatively assumed to be through the clad thickness and the flaw growth was conservatively assumed to be ten times the Westinghouse's flaw growth for 60 years (not considering the clad thickness), the staff estimated that the final flaw depth would not exceed 0.59 inch.  This value represents the sum of the clad thickness of 0.188 inch, the initial flaw depth of 0.295 inch, and the flaw growth of 0.107 inch.  The staff made this worst-case assumption to bound the issue and to determine the impact of cracks that penetrate through the cladding.

Applied $K_I$ calculations were needed in both the fatigue analysis and the allowable flaw depth estimation.  For the various crack geometries considered in the submittal, Westinghouse employed the Buchalet and Bamford $K_I$ solution for continuous surface flaws on cylindrical vessels subjected to a higher-order stress distribution and the Raju-Newman $K_I$ solutions for semi-elliptic surface flaws on vessels.  The Buchalet and Bamford solution is acceptable because this finite element method (FEM) based solution has been validated against Rice's solution using the line spring method and Labben's solution using Bueckner's weight functions.  The Raju-Newman FEM solutions for the semi-elliptic crack geometries are acceptable because the solutions have been validated against results using other methodologies as reported in the original published technical paper by Raju-Newman.

In the subsequent allowable flaw depth determination, Westinghouse used the acceptance criteria based on applied $K_I$ (IWB-3612) for the normal and upset conditions and the criteria based on flaw size (IWB-3611) for the emergency and faulted conditions.  The staff accepts this approach because using the mixed sets of criteria still provides similar margins specified in the Code, and, therefore, meets the intent of IWB-3600.  Further, using the Code specified formulas for $K_{Ia}$ and $K_{Ic}$ for the RPV material subjected to neutron embrittlement is a standard practice for Section XI flaw evaluations, and using an upper limit of 200 ksi√inch for toughness in the upper shelf temperature regime is conservative because many test data indicated higher values.

Section XI flaw evaluation requires applicants to consider residual and clad induced stresses.  However, the staff agrees with Westinghouse's conclusion that the impact of the cladding residual stresses on the flaw evaluation is negligible.  This is because for an allowable flaw depth of 1.34 inches, the net contribution to applied $K_I$ due to a self-balanced residual stress distribution in a narrow region of approximately 0.25 inch at the vessel base metal and cladding interface is very small.  Westinghouse did not consider the additional tensile stresses caused by different thermal expansion coefficients between the base metal and cladding (the cladding effect) either.  Based on the information from the  topical report submitted by the Babcock & Wilcox Owners Group on underclad cracks (Reference 4), the staff estimated that the applied $K_I$ due to this cladding effect is about 7 ksi√in for a typical normal and upset condition transient, which is less than 15% of the total applied $K_I$.  Judging from the generous margin between the

estimated final crack depth at 60 years (0.59 inch) and the allowable crack depth (1.34 inches), the staff determined that including the cladding effect in the allowable crack depth analysis would not change Westinghouse's conclusion, and hence, the Westinghouse 3-loop RPVs with underclad cracks are acceptable for operation for 60 years.

It should be noted that, in addition to the conservatism specified explicitly in terms of Code specified safety factors, there is conservatism inherent in the flaw evaluation process such as the use of the lower bound curves for $K_{Ia}$ and $K_{Ic}$ and the use of 200 ksi√inch as the upper limit for toughness for the RPV materials. Further, by using applied K equations for surface defects in the underclad crack (subsurface) fracture mechanics analysis, Westinghouse has built in additional conservatism in the evaluation process.

3.1 The Consideration of the PTS Transient

In the allowable flaw size determination for emergency and faulted conditions, Westinghouse studied a series of transients for a generic Westinghouse 3-loop reactor vessel. These transients included the large LOCA and large steamline break (LSB) and the dominating transients from the WOG pressurized thermal shock (PTS) studies. By including the most severe PTS transient in the allowable flaw size determination and showing that all ASME flaw evaluation requirements are satisfied, the licensee has demonstrated the structural integrity of the Westinghouse 3-loop reactor vessels under the PTS conditions. However, applicants who apply this topical report to their 2-loop or 4-loop vessel need to demonstrate that the transients for normal and upset conditions used in this report bound their plant-specific transients for these conditions and the transients for emergency, faulted, and PTS conditions for 3-loop reactor vessels used in this report bound their plant-specific transients for the corresponding conditions. Otherwise, they need to perform similar Section XI flaw evaluations using their plant-specific transients to demonstrate that their RPVs with underclad cracks are acceptable for operation for 60 years. This is applicant Action Item 4.1.

4. CONCLUSIONS

As stated previously, Westinghouse's methodology in performing the flaw evaluation is consistent with well-established flaw evaluation procedure and criteria in the ASME Code, and therefore, is adequate. Since the estimated final flaw depth revised by the staff (0.59 inch) is less than the allowable flaw size (1.34 inch for normal and upset conditions and 1.70 inch for emergency and faulted conditions), the staff determined that Westinghouse 3-loop RPVs with underclad cracks are acceptable for operation for 60 years. The additional conservatism associated with the Westinghouse methodology includes: (1) using the maximum crack depth of 0.295 inch as the initial crack depth, (2) considering all underclad cracks as surface cracks, and (3) using the fatigue crack growth rate for surface flaws in a water reactor environment. The staff also concludes that, upon completion of the renewal applicant action items, the WCAP-15338 report provides an acceptable evaluation of a TLAA for the RPV components with underclad cracks for Westinghouse Owners Group (WOG) plants.

Any WOG plant may reference this report in a license renewal application to satisfy the requirements of 10 CFR 54.21(c)(1) for demonstrating the appropriate findings regarding evaluation of TLAA for the RPV components for the period of extended operation. The staff also concludes that, upon completion of the renewal applicant action items set forth in Section 4.1 below, referencing the WCAP-15338 report in a license renewal application and

summarizing in an FSAR supplement the TLAA evaluations contained in this report, will provide the staff with sufficient information to make the necessary findings required by Section 54.29(a)(2) for components within the scope of this report.

4.1 Renewal Applicant Action Items

The following are license renewal applicant action items to be addressed in the plant-specific license renewal application when incorporating the WCAP-15338 report in a renewal application:

(1)    The license renewal applicant is to verify that its plant is bounded by the WCAP-15338 report.  Specifically, the renewal applicant with a 3-loop RPV is to indicate whether the number of design cycles and transients assumed in the WCAP-15338 analysis bounds the number of cycles for 60 years of operation of its RPV.  The renewal applicant with a 2-loop or 4-loop RPV needs to demonstrate that the transients for normal, upset, emergency, faulted, and PTS conditions used in WCAP-15338 report bound their plant-specific transients for these conditions.  Otherwise, they need to perform similar Section XI flaw evaluations using their plant-specific transients to demonstrate that their RPVs with underclad cracks are acceptable for 60 years of operation.

(2)    10 CFR 54.21(d) requires that an FSAR supplement for the facility contain a summary description of the programs and activities for managing the effects of aging and the evaluation of TLAA for the period of extended operation.  Those applicants for license renewal referencing the WCAP-15338 report for the RPV components shall ensure that the evaluation of the TLAA is summarily described in the FSAR supplement.

5.0  REFERENCES

1.    Westinghouse Electric Corporation, WCAP-15338, "A Review of Cracking Associated with Weld Deposited Cladding in Operating PWR Plants," Pittsburgh, Pennsylvania, March 2001.

2.    Newman, J. C. and Raju, I. S., "Stress Intensity Factors for Internal Surface Cracks in Cylindrical Pressure Vessels," ASME Trans., Journal of Pressure Vessel Technology, Vol 102, 1980, pp. 342-346.

3.    Buchalet C. B. and Bamford, W. H., "Stress Intensity Factor Solutions for Continuous Surface Flaws in Reactor Pressure Vessels," Mechanics of Crack Growth, ASTM STP 590, American Society for Testing and Materials, 1976, pp. 385-402.

4.    Framatome Technologies, BAW-2274P, "Fracture Mechanics Analysis of Postulated Underclad Cracks in B&W Designed Reactor Vessels for the Period of Extended Operation," Lynchburg, Virginia, December 1996.

WESTINGHOUSE OWNERS GROUP (WOG)

Project  No.  686


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