September 25, 2002

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

SUBJECT: REVISED SAFETY EVALUATION OF WCAP-15338, "A REVIEW OF CRACKING ASSOCIATED WITH WELD DEPOSITED CLADDING IN OPERATING PRESSURIZED WATER REACTOR (PWR) PLANTS"

Dear Mr. Newton:

By letters dated March 1, June 15, 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 (ASME) Code to justify that the Westinghouse reactor pressure vessels (RPVs) with underclad cracks are acceptable for operation for 60 years. The staff's safety evaluation report (SER) was issued on October 15, 2001. The WOG provided a written clarification to Renewal Action Item 4.1(1) in a letter dated June 19, 2002.

The staff has completed its review of the topical report and the WOG's clarification. The staff's revised SER is enclosed. The staff has concluded that the topical report is acceptable for all Westinghouse reactor pressure vessels (RPVs) because the underclad cracks satisfy the ASME Code flaw evaluation requirements for detected flaws, and the Westinghouse 3-loop results presented and discussed in WCAP-15338 are applicable for all the Westinghouse operating plants.

The staff does not intend to repeat its review of the matters described in the report and found acceptable in the SER when the report appears as a reference in a license renewal application.

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 three months after receiving this letter. In addition, the published version will incorporate this letter and the enclosed SER between the title page and the abstract.

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

Sincerely,

/***RA***/

Pao-Tsin Kuo, Program Director
License Renewal and Environmental Impacts Program
Division of Regulatory Improvement Programs
Office of Nuclear Reactor Regulation

Project No. 686

Enclosure: Safety Evaluation Report

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. The staff's safety evaluation report (SER) was issued on October 15, 2001. The WOG provided a written clarification to Renewal Action Item 4.1(1) in a letter dated June 19, 2002.

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 an RPV 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 American Society of Mechanical Engineers (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.

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 $\sqrt{\text{in}}$ 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

Section 54.21(c) of Title 10 of the *Code of Federal Regulations* (CFR) 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 a 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. To use 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 ASME Section XI flaw evaluations, and to use an upper limit of 200 ksi$\sqrt{\text{inch}}$ for toughness in the upper shelf temperature regime is conservative because many test data indicated higher values.

ASME 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 percent 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 additional conservatism into the evaluation process.

3.1 The Consideration of Fatigue Crack Growth and PTS Transient

In determining the amount of crack growth during 60 years of operation, the WOG utilized transients for a Westinghouse 3-loop plant. 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 loss-of-coolant accident (LOCA) and large steamline break (LSB) and the dominating transients from the WOG pressurized thermal shock (PTS) studies. The WOG PTS studies led to the conclusion that the steam generator tube rupture, the small LOCA, the large LOCA, and the large steam line break would be the dominating PTS transients. Thermal stress and fracture analyses were performed for the beltline region, using the characteristics for the four transients. The large steamline break was determined to be the governing transient for the beltline region. By including the most severe PTS transient in the allowable flaw size determination and showing that all ASME flaw evaluation requirements are satisfied, the WOG has demonstrated the structural integrity of the Westinghouse 3-loop reactor vessels under the PTS conditions. In their June 19, 2002, letter, the WOG indicates:

a) The results for PTS for all Westinghouse plant designs are very similar, but the governing plant type is the 3-loop plant, because it has the highest predicted end-of-life fluence in the core region. Therefore, the 3-loop plant type that is discussed in the WCAP will be conservative for all Westinghouse designs.

b) The operating transients are all very similar for all the Westinghouse designs, 2-, 3-, and 4-loop plants. Results have been obtained for all three plant types and show very little difference. Therefore, the 3-loop plant types that are discussed in the WCAP are typical for all Westinghouse operating plants.

Given the conservative application of the 3-loop fluence results and similar operating transients, the staff concurs that the results of WCAP-15338 may be applied to 2- and 4-loop plants.

4.0 CONCLUSIONS

As stated previously, Westinghouse's methodology in performing the flaw evaluation is consistent with the 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 2-, 3-, and 4-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 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 10 CFR 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 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.

(2) Section 54.21(d) of 10 CFR requires that an FSAR supplement for the facility contains 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.

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