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MEMORANDUM FOR: E. G. Case, Acting Director
Office of Nuclear Reactor Regulation

R. B. Minogue, Director
Office of Standards Development

FROM: S. Levine, Director
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER - #15 - CHARACTERIZATION OF BWR FEEDWATER NOZZLE CORNER CRACKS

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Introduction and Background

This Research Information Letter has been prepared to transmit current information on the fracture mechanics characterization of nozzle corner cracks in BWR feedwater nozzles. This information represents the first phase of RES-sponsored work dealing with the characterization of pressure loading on nozzle corner cracks. The complete study, which will also evaluate out-of-plane flaws and thermal loadings, identified as the second phase, will follow as soon as it is available.

Because nozzle corner cracks have been found in the feedwater nozzles of boiling water reactors (BWRs), it became necessary to characterize these cracks in fracture mechanics terms for safety analyses. This characterization is in the form of curves that provide the relationship for the normalized stress intensity factor K in terms of pressure as a function of crack depth and position on the crack front for the determination of crack growth and of critical crack size.

Results

A testing program was conducted by Professor C. W. Smith at Virginia Polytechnic Institute and State University (VPI&SU) in which three-dimensional frozen stress photoelasticity was used to characterize cracks in nozzle corners in fracture mechanics terms. The first model geometry used was that of the intermediate test vessel (ITV) in the Heavy Section Steel Technology (HSST) program at Oak Ridge National Laboratory (ORNL). Results of the VPI&SU photoelastic experiments agreed closely with the earlier ORNL results. The results of these experiments are included in Enclosure I.

After verifying the photoelastic approach, the program was expanded to include scale-models having the geometry of a BWR vessel but containing only two diametrically opposite, cracked, feedwater nozzles. The results of these experiments to date are included in Enclosure II.

Most analyses assume a quarter-circular or quarter-elliptical flaw shape. Cracks removed by grinding from BWR feedwater nozzle corners show this general shape, but they cannot be accurately characterized due to the high radiation levels in the work area. In separate work not funded by RES, Delft University formed (and grew) fatigue cracks in A508 steel nozzles, and Professor Smith formed and grew "natural" cracks on plastic models of the same geometry. This work is included in Enclosure III. A comparison of crack shapes in these two programs showed the shapes to be identical. Also, a "naturally" grown crack was allowed to propagate completely through the nozzle in a photoelastic model of an ITV, and the final configuration of the flaw and its region of penetration were the same as those observed in a steel intermediate test vessel (ITV) experiment conducted by the HSST staff at ORNL. Because of these comparisons with results on steel models, we feel that the crack shapes that were observed in the BWR feedwater nozzle photoelastic models closely represent the crack shapes in the reactor vessel nozzles.

The accuracy of the flaw shape is quite important in the analysis. With nozzle corner cracks that have grown beyond the nozzle corner radius, the shape closely follows a quarter ellipse to a wall depth of 30%. Beyond that crack depth, the center portion does not grow as much. The photoelastic results have shown that a 2% retardation in the center from a quarter elliptical shape results in a K-value decrease of from 10% to 15%. Therefore, it is quite important to recognize this effect when analyzing calculations that assume a quarter elliptical shape of the crack front for crack depths greater than 30%. The reverse is true for cracks that are contained within the nozzle corner radius. Although they are part circular or part elliptical in shape, the flaw area encompasses a greater angle than that of a quarter circle or ellipse; thus the simplified assumption of flaw shape would result in an unconservative evaluation of the K-values.

The enclosed information (Enclosures I-III) contains the relationship between the imposed stress intensity factor, crack depth, and position on the crack front as caused by internal pressure. The upper part of Figure 7 in Enclosure II shows the relationship between the normalized stress intensity factor and position on the crack front for cracks of varying depths in a BWR feedwater nozzle due to pressure loading.

Evaluation and Applicability

These Phase One results from VPI&SU have been presented at the Third International Conference on Pressure Vessel Technology in Tokyo, Japan, April 1977; the Fourth Structural Mechanics in Reactor Technology Conference in San Francisco, California, August 1977; and the NRC Vessel Integrity Research Review Group Meeting of July 20-21, 1977. In each case, the data were particularly well received and in the following discussion periods, it was clear to the RES staff that the knowledgeable audience was satisfied with the validity and accuracy of the results. Thus, the VPI&SU photoelastic results are believed by RES to accurately represent the effects of relative crack depth, natural crack front shape, and pressure in the crack on the stress intensity factor as a function of position around the crack front for a surface crack at the inside corner of a BWR feedwater nozzle for vessel internal pressure loading. These results can be used to check the calculations, based on internal pressure, related to safety analyses of BWR feedwater nozzle corner cracks.

Future Work

Phase Two of the research program will be directed toward the photoelastic characterization of out-of-plane cracks, and the verification of a computer code for pressure loadings that will have the capability to analyze all operational loadings, especially the transient thermal loadings. When the Phase Two work is completed and the code validated, the licensing staff should be able to evaluate nozzle corner cracks considering all operational loadings.

Saul Levine

Saul Levine, Director
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Enclosures: see next page

cc w/encls:
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Enclosures:

Enclosure I - C. W. Smith, M. Jolles and W. H. Peters, "Stress Intensities for Nozzle Cracks in Reactor Vessels," VPI-E-76-25, November 1976, ORNL/SUB/7015-1, Distribution Category NRC 5 (In Press), Journal of Experimental Mechanics

Enclosure II - C. W. Smith and W. H. Peters, "Stress Intensity Factors for Nozzle Cracks in Reactor Vessels," (Progress Report February 28, 1977 through May 21, 1977 for HSST Quarterly Report) to be presented at Fourth SMIRT Conference, San Francisco, California, August 1977

Enclosure III - C. W. Smith, M. Jolles and W. H. Peters, "An Experimental Study of the Plate-Nozzle Tensile Test for Cracked Reactor Vessel Nozzles," VPI-E-76-26, November 1976 (see also), Proceedings of Fifteenth Midwest Mechanics Conference, March 1977