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CONTRACT TITLE

Analysis of Crack Initiation and Growth in the High Level Vibration Test at Tadotsu*

PRINCIPAL INVESTIGATORS AND KEY STAFF

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1.0 BACKGROUND

A High Level Vibration Test (HLVT) Program was carried out recently on the seismic table at the Tadotsu Engineering Laboratory of Nuclear Power Engineering Center (NUPEC) in Japan (Kawakami et al., 1989 and Hofmayer et al. 1989). The test model was constructed by modifying the 1/2.5 scale model of one loop of a PWR primary coolant system which was previously tested by NUPEC as part of their seismic proving test program. The hot leg of the model was fabricated from Japanese stainless steel which is almost equivalent to ASME specification SA-351 CF8M. The input motion applied to the vibration table consisted of a modified earthquake excitation of a high level which was increased up to the limit of the table so as to induce inelastic response in the model. The peak of the response spectrum of the input motion occurred at a frequency close to, but less than, the natural frequency of the test model (6.4Hz). A total of 14 major test runs were performed, each consisting of four segments of random motion lasting about 40 seconds.** The amplitude of the applied loading varied from cycle to cycle in each run and the peak loading increased progressively throughout the initial test runs. During the early test runs (up through Run 4), the model's response was mainly elastic. For Runs 5-9 the input motion was increased and plasticity was observed in the test model. For Runs 10-14 the input motion was scaled up to the capacity of the vibration table. Run 14 was terminated after applying one segment of the motion which lasted about 10 seconds. During the vibration tests the piping was subjected to an internal pressure of 1.57 Kgf/mm^2 (2.23ksi) and maintained at that pressure throughout the test.

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** There actually were more than 14 test runs performed since test runs were repeated and there were a number of low level preliminary tests. For some tests only one segment of random motion was applied. A complete description of the test runs is contained in the paper by Kawakami (1989).

Post-test examinations of the HLVT model have shown that bulging due to fatigue rachetting occurred in the hot leg pipe at two locations, one near the "vessel" attachment point and one near the elbow that was attached to the "steam generator." The bulging near the elbow was more pronounced than that near the vessel attachment. However, neither of these bulges resulted in failure of the piping system. Rather, a circumferential fatigue crack initiated in a weld repair on the elbow side of the girth weld. The length of the crack along the surface of the pipe and its depth were measured after each load sequence. Clip gages were also used to record the time history of the crack opening. After completion of the vibration test, the cracked surface was exposed and a Scanning Election Microscope (SEM) examination of the fracture surface revealed a predominantly "dimple rupture" mode of crack advance with no evidence of striations beyond the very early growth region. The maximum crack depth penetrated up to 94% of the wall thickness and extended over approximately 31% of the pipe circumference.

2.0 OBJECTIVE AND SCOPE

The objective of the study being performed at Brookhaven National Laboratory is to use the HLVT data to assess the accuracy and usefulness of existing methods for predicting crack initiation and growth under complex, large amplitude loading. The work to be performed as part of this effort involves:

- analysis of the stress/strain distribution in the vicinity of the crack, including the potential for residual stresses due to the weld repair,
- analysis of the number of load cycles required for crack initiation, including estimates of the impact of the weld repair on the crack initiation behavior (different material, effects of residual stresses, etc.),
- analysis of crack advance as a function of applied loading (classic fatigue versus cyclic tearing) taking into account the variable amplitude loading and the possible influence of the repair weld, and
- material property testing to supplement the work performed as part of the HLVT, providing the materials data necessary to perform the analysis efforts.

3.0 SUMMARY OF RESEARCH PROGRESS FOR FY 1990

A review of available information has been performed to select appropriate methods to determine the crack growth for specific loading conditions of the HLVT. The methods being considered include: ΔK, cyclic J-R curve, net-section stress range, and crack tip displacement. Preliminary findings indicate that a reasonable correlation between the actual and predicted numbers of loading cycles required for crack growth can be obtained from a net-section stress range criterion. Furthermore, preliminary calculations indicate that the use of ΔK does not provide compatible results with the HLVT test cycles which propagated the crack because of the presence of significant plastic strain. Studies regarding the application of these methods, as well as the others mentioned above, are continuing and will be completed in FY 1991.

The time histories of the crack tip opening displacement (CTOD) have been obtained from the recorded time history of clip gage readings after the crack initiation (Runs 12, 13 and 14). Strain time histories of the cross-section near the crack location were digitized and a finite element analysis was performed to convert the strain values to the member forces (axial force and bending moment) of the hot leg pipe. A preliminary report was completed which summarizes the procedures and results associated with the calculation of the time histories of the CTOD and member forces at the crack plane in the elbow region. To further check the adequacy of the analysis model, the time history of axial force was also calculated at the reactor vessel end of the pipe using the strain gage data at that location and compared with the corresponding force calculated near the crack location in the elbow region. The peak values and time history were shown to be similar.

A plan for the material property testing has been completed. The plan includes, fatigue crack growth rate tests, monotonic and cyclic J-R curve tests and tension tests to establish the stress-stain relationship of a strain hardened specimen of the material. The test specimens will include compact tension specimens with cracks in both the through-thickness and circumferential orientations and standard round bar specimens for tension tests. The material available for this test program consists of two curved pieces cut from the elbow region in the vicinity of the cracked pipe obtained from the HLVT Program. The testing will be performed at the David Taylor Research Center (DTRC) and the U.S. Naval Academy. Preparation of the specimens has been completed and the testing has been initiated. The testing will be completed in early FY 1991.

NUPEC has also agreed to cooperate on the fatigue crack growth analysis of the HLVT specimen. With regard to these studies they will: (1) support information exchange meetings, (2) provide experts to review and comment on the U.S. studies, and (3) perform some confirmatory analyses of the U.S. results.

4.0 FUTURE PLANS

Efforts on this program as discussed in Sections 2 and 3 will be completed in FY 1991. The fatigue crack growth calculations using the net-section stress range criterion and ΔK will be completed. Calculations using the cyclic J-R curve and crack tip displacement will also be performed and comparisons of the results made with the HLVT data. The results of the material property testing performed at DTRC and the Naval Academy will be utilized to support these studies. Further analysis regarding the refinement of calculations of the member forces on the hot leg pipe will also be performed. Cooperative efforts with NUPEC on this study will continue.

5.0 REFERENCES

1. Hofmayer, C. et al. (1989), "High Level Vibration Test of Nuclear Power Piping - Overall Plan, Input Motion Development and Analysis," Transactions of the 10th SMiRT, Volume S, pp. 93-98.

2. Kawakami, S. et al. (1989), "High Level Vibration Test of Nuclear Power Piping - Test Procedures and Test Results," Transactions of the 10th SMiRT, Volume K2, pp. 745-750.