High Level Vibration Test of Nuclear Power Piping - Overall Plan, Input Motion Development and Analysis

C. H. Hofmayer, J. R. Curreri, Y. J. Park, W. Y. Kato
Brookhaven National Laboratory, Upton, NY USA
J. F. Costello
U.S. Nuclear Regulatory Commission, Washington, DC USA
H. T. Tang
Electric Power Research Institute, Palo Alto, CA USA
S. Kawakami
Nuclear Power Engineering Test Center, Tokyo, Japan

INTRODUCTION

As part of cooperative agreements between the United States and Japan, tests have been performed on the seismic vibration table at the Tadotsu Engineering Laboratory of Nuclear Power Engineering Test Center (NUPEC) in Japan. The tests involved increasing the excitation up to the limits of the vibration table in order to induce inelastic response in a reactor coolant system piping model. The model was subjected to a maximum acceleration well beyond what nuclear power plants are designed to withstand.

The High Level Vibration Test (HLVT) 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 upper and middle steam generator shell supports of the model, which simulated the actual plant condition, were removed and the steam generator shell was truncated. Furthermore, the four lower support columns for the steam generator were replaced by a pin-type support. A modified earthquake excitation was used to drive the structure to a condition of substantial strain. Since the piping was pressurized, and the high level input motion was repeated several times, it was possible to investigate the effects of ratchetting and fatigue as well. An isometric view of the test model and support frame is shown in Figure 1. Further details of the hot leg pipe are shown in Figure 2. The piping in the model is stainless steel, 14-15 inches in diameter and 1 to 1 1/4 inches thick.

This paper describes the overall plan, the input motion development and pre-test analysis results. A companion paper in Session S of this conference describes the test procedure and test results (Kawakami et al, 1989).

OVERALL PLAN

The purpose of the HLVT program is to compare the results of a test of a large complex structure, driven substantially into the inelastic range by an earthquake excitation, with state-of-the-art analyses of the problem. Preliminary studies indicated that this could be accomplished by modifying NUPEC's PWR primary coolant system model and performing tests near the capacity of their seismic vibration table. It was found that inelastic response could be achieved by removing the upper and middle steam generator shell supports. However, in order to maintain control of the shaking table, the steam generator had to be truncated at approximately its midheight. To provide further assurance of inelastic response of the piping and improve the dynamic characteristics of the model, the four support columns for the steam generator were replaced by a pin-type support.

In developing the program plan, test data were desired for comparison with analytical predictions at different response levels. It was planned to obtain data for elastic conditions, a moderate plastic condition and the maximum plastic condition that could be obtained within the limits of the shaking table. The goal was to achieve this maximum plastic condition with as few lower level test runs as possible to minimize the cumulative fatigue damage to the test model during preliminary runs. However, a number of intermediate test runs were required to assure proper control of the shaking table. Since the piping system was pressurized with water to 157kg/cm^2 (2230psi), it was planned to repeat the maximum plastic run at least five times to investigate the effects of ratchetting and fatigue. If a through-wall crack was detected during one of these runs, it was planned to stop the test. If no significant cracks developed, and time permitted, consideration would have been given to performing additional tests.

INPUT MOTION DEVELOPMENT

The selection of a time history to be used for the test was done with three guidelines in mind; namely, the time history:

a) was deduced from an actual earthquake or had similar characteristics,
b) was compatible with the characteristics of the vibration table at Tadotsu,
c) established a peak response early in the event so that only a short portion of the time history needed to be used for analysis.

Several earthquake time histories were examined. These included the N-S, E-W and an SRSS combination of El Centro, the Kern County earthquake and several locations of the San Fernando earthquake. Of these different earthquake time histories, only the N-S component of El Centro peaks before 5 seconds and has what might be characterized as an exponential like envelope on the build-up portion to the peak. This characteristic enhances the ability of an excitation to create a large response quickly and with the use of minimum energy. Accordingly, the El Centro time histories were selected to start the development of the test input motion.

The response spectra for the N-S and E-W components of El Centro produce essentially two separate peaks. On the other hand, the SRSS combination of the two components focuses the energy of the excitation to produce a predominant single central peak. Since the test model has a single mode that will be excited to a condition of substantial strain, and since it was desirable to reduce the overall load on the driving vibration machine, the combined time history was selected for further development. In addition it was found that, except for some minor lower level peaks, virtually the entire response spectrum for 30 seconds of the time history is obtained in the first 4 seconds. Thus, it was concluded that the first 4 seconds of the combined El Centro time history is enough to represent the action of an actual earthquake.

Time scaling was used to shift the peak of the response spectra of the combined El Centro time history to the natural frequency of the test model. Furthermore this acceleration time history was multiplied by a factor of 3.3 to produce a peak acceleration of 1.15g (1104 gal). This factor was determined from the velocity limit of the shaking table (75cm/sec). Based on a nonlinear dynamic finite element analysis, it was found that the resulting time history could result in plastic strains in the piping model. However, the desired strain levels could not be achieved.

As a result of these preliminary analyses, further modifications were made to the combined El Centro time history. The final time history that was selected is shown in Figure 3 and was designated the Maximum Plastic Run (MPR) time history. The corresponding response spectra are shown in Figure 4. This time history has a peak acceleration of 1.82g (1785 gal) and was within the acceleration, velocity and displacement limits of the shaking table. Once again the velocity limit controlled the multiplication factor for the time history. Time scaling was used to shift the peak of the response spectrum to approximately 85 percent of the natural frequency of the test model. This was done to take into account any possible detuning that may occur as large strains are developed. Pre-test analyses indicated that this time history could produce strains in the piping system in excess of 3 percent.

Once the MPR level was achieved in the test sequence, it was desired to repeat this level of excitation a number of times to study ratchetting and fatigue effects. Since this test time history was short, it was decided to repeat the time history four times during one run. A quiet period of approximately 6 seconds was left between each time history segment to eliminate any adverse interaction effects that may occur if they were linked one right after the other. Since it was uncertain as to the amount of detuning that might occur at this test level, the time scale of each segment was changed slightly. This resulted in shifting the peak of the response spectrum for each time history segment by about 10 percent. Thus, it broadened the response spectrum for the entire test time history and provided further assurance that the desired strains could be achieved. The complete MPR time history and corresponding response spectra are shown in Figures 5 and 6. The four segments were designated A-B-C-D as shown in Figure 5. Segment A corresponds to the time history shown in Figure 3. To establish the parameters for proper control of the shaking table, the four segment wave had to be run at the lower test levels as well. However, in order to minimize fatigue damage until the full MPR level was reached, some intermediate level test runs were performed using only the Segment A time history.

PRE-TEST ANALYSIS RESULTS

For test planning purposes elastic-plastic analyses were performed by using the MARC Code. The straight pipe segments of the test model were represented by pipe elements and the five elbows in the test model were represented by elbow elements. The node and element numbers for the hot leg portion of the model are shown in Figure 2.

The analytical predictions of the maximum displacement at the top of the steam generator for three different test run levels are shown in Figure 7. These results compare well with the test results which are also plotted in the same figure. Figure 8 compares the test and analysis results for the acceleration at the top of the steam generator. The analysis results match the test results for tests run prior to some modifications that were made to the steam generator support. After the modifications, the difference between the measured accelerations and the predicted accelerations increased.

A comparison of test and the MARC analysis results of strain along the hot leg pipe for three test levels is shown in Table 1. For all three run levels the axial strains measured at the reactor vessel end were much higher than the analytical predictions. At the tapered transition joint the measured axial strains were higher than the analysis results for the lower test level. However, the trend reversed for the higher test levels. For the hot-leg elbow the axial strains measured during all test levels were much lower than analytical predictions. The differences were even greater for the hoop strains.

Based on the pre-test analysis results, the maximum axial strain (3.6%) was predicted to occur at the top of the hot leg pipe in the vicinity of the tapered transition joint with the hot leg elbow. In addition, a hoop strain of approximately 3 percent was predicted to occur at the top of the hot leg elbow on its inside surface near the middle of its arc. The analysis also indicated the possibility of significant hoop strain ratchetting in the hot leg elbow.

A ratchet/fatigue life analysis was performed prior to the test using the above analysis results and the procedures outlined in NUREG/CR-5023 (Severud et al, 1988). The axial strain range in the hot leg pipe in the vicinity of the tapered transition joint was predicted to be between 5 to 7 percent with 3 cycles per segment at the MPR level. These strain ranges, coupled with estimates from earlier low level runs, resulted in a prediction that a ratchet/fatigue failure could occur as early as the first run with the full four segment MPR time history. If ratchetting did not occur, but the same strain levels were achieved, it was predicted that a fatigue failure might occur after 5 to 6 MPR runs or longer. Recognizing the uncertainties in the above predictions, a ratchet/fatigue failure between the first and fifth MPR runs was considered to be within the realm of possibility, if the predicted strains were achieved.

The above analytical predictions were made by Brookhaven National Laboratory (BNL). Pre-test predictions were also performed by Westinghouse Hanford Company (Severud and Weiner, 1987) and Rockwell International (Jacquay and Larson, 1988) which are briefly summarized below.

Westinghouse Hanford utilized simplified elastic and inelastic analyses and concluded that the maximum axial strain range could be up to 4 percent. This estimate was based on an earlier version of the input wave which had a peak acceleration of 1.54g (1509 gal). Based on this work and updated pre-test analysis information provided by BNL, they concluded that cracking and leaks in the piping were likely to occur during the first, second or third MPR run. Their best estimate was that cracking would occur during the second MPR run. These predictions were based on the assumption that the test would induce axial strain ranges in the 3 to 7 percent range.

Rockwell performed their pre-test predictions for EPRI based on analyses with the ABAQUS Code. They performed analyses up to the peak acceleration of the MPR time history. Based on these results, they estimated that each segment of loading at the MPR level would result in an accumulated hoop strain of 3 1/2 percent with axial strain ranges from 2 1/2 to 7 1/2 percent. Considering uncertainties of material properties, their time of failure prediction was between the fourth segment of the first MPR run to the second segment of the third MPR run. Their best estimate was that a ratchet/fatigue failure of the hot let elbow would occur on the top side near its attachment weld to the hot leg straight pipe during the third segment of the second MPR run.

The actual test run sequence used during the test differed somewhat from the sequence used for the pre-test predictions. However, a crack did occur in the test model during the second full four segment run at the MPR level. Based on a review of the strain gage data in the region of the crack, it appears that the crack developed during the first segment of this run. Furthermore, the crack developed at the exact location as predicted in the above analyses. On the other hand, the axial strain ranges measured during the test were not as high as the pre-test analysis predictions. In addition, the large hoop strain ratchetting that was included in the calculations to predict the ratchet/fatigue life did not occur. Prior to the initiation of the crack, some bulging of the hot leg pipe at approximately one half to one diameter from the attachment weld to the hot leg elbow did occur. The possibility of such bulging was noted by P. Ibanez of ANCO Engineers, Incorporated who participated in a review of the final test plan.

CONCLUSIONS

The HLVT program has enhanced understanding of the behavior of piping systems under severe earthquake loading. As in other tests to failure of piping components, it has demonstrated significant seismic margin in nuclear power plant piping. The test provided extensive data which are being used to evaluate elastic and inelastic dynamic analysis techniques. Furthermore, it provided unique test data to understand fatigue crack initiation and growth under seismic loading conditions. Efforts are continuing to evaluate the test results and to perform more refined post-test analyses. A blind post-test prediction program involving engineers not previously involved with the program is also being performed.

REFERENCES

Jacquay, K. and Larson, J. (1988). Best Bet Pre-Test Failure Prediction for HLVT Tests. Letter report to H.T. Tang of EPRI dated April 5, 1988.

Severud, L. and Weiner, E. (1987). Pre-Test Analysis of HLVT Pipe System for High Level Vibration Response and Failure. HEDL Report EA/BNL-1.

Severud, L. et al (1988). High Level Seismic Response and Failure Prediction Methods for Piping. NUREG/CR-5023, pp. 56-57.

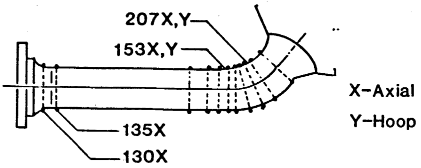
Kawakami, S. et al (1989). High Level Vibration Test of Nuclear Power Piping - Test Procedure and Test Results. Session S, 10th SMiRT.

ACKNOWLEDGEMENTS

This research program is being performed as part of a nuclear power technical cooperative agreement between the Agency of Natural Resources and Energy in Japan and the U.S. Nuclear Regulatory Commission. In the United States, the Electric Power Research Institute is also supporting this study. In Japan, this work is also supported as a cooperative study of Japanese electric utilities and manufacturers.

The authors wish to thank S. Shteyngart, Y.K Wang, J. Pires, and M. Reich of Brookhaven National Laboratory for their analytical support and advice during the course of this program. The authors also acknowledge L. Severud and E. Weiner of Westinghouse Hanford Company and K. Jacquay and J. Larson of Rockwell International for their pre-test prediction efforts and K. Merz and P. Ibanez of ANCO Engineers and T.Y. Chang of the University of Akron for their helpful advice during the test planning phase of this program.

Table 1
Maximum Strain (%) Along Hot Leg Pipe
(Pre-Test Analysis vs Test Results)



General Location	Gage No.	.4 MPR		.7 MPR		1.0 MPR	
		Test	Analysis	Test	Analysis	Test	Analysis
Rv Nozzle	130X	0.34	0.18	0.45	0.20	0.55	0.21
Hot-Leg Near RV Nozzle	135X	0.34	0.23	0.79	0.47	1.18	0.73
Tapered Trans-istion Joint	153X	0.83	0.52	1.29	2.31	2.28	3.56
	153Y	0.16	-	0.34	-	0.34	-
Hot-Leg Elbow	207X	0.39	0.46	0.57	1.12	0.83	1.54
	207Y	0.21	0.86	0.28	1.80	0.37	2.32

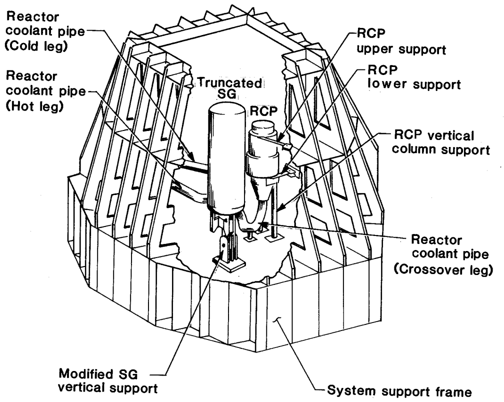


Fig. 1 HLVT Model

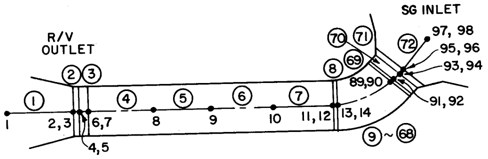


Fig. 2 Finite Element Model of Hot Leg Pipe

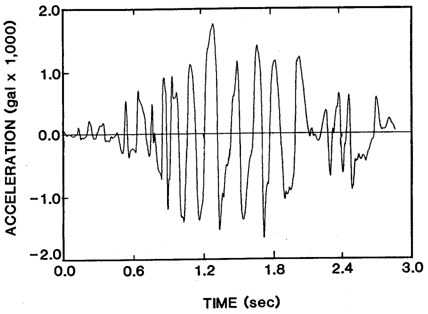


Fig. 3 MPR Time History - Segment A

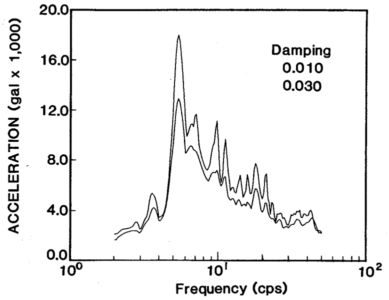


Fig. 4 Response Spectra for MPR Time History - Segment A

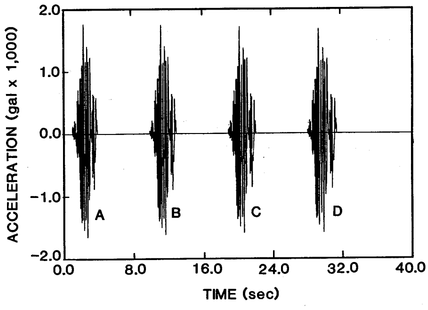


Fig. 5 Complete MPR Time History

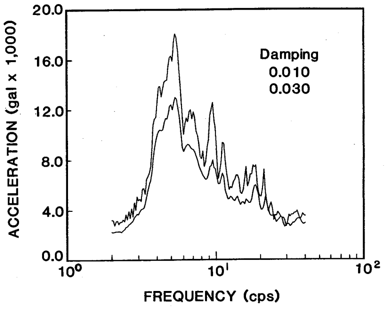


Fig. 6 Response Spectra for Complete MPR Time History

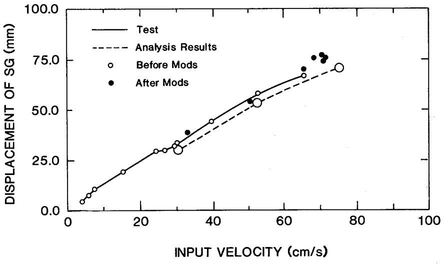


Fig. 7 Comparison of Displacement Response

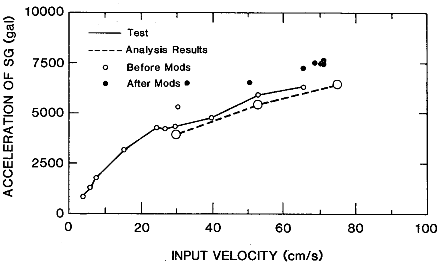


Fig 8 Comparison of Acceleration Response