Proving Test on the Seismic Reliability of the PWR Reactor Vessel

Hiroshi AKIYAMA, Heki SHIBATA
University of Tokyo, Tokyo, Japan

Muneaki KATO
Japan Atomic Power Company, Tokyo, Japan

Shoji KAWAKAMI, Tokue OHNO, Koji KOYAMA
Nuclear Power Engineering Center, Tokyo, Japan

Shun-ichi WADA
Mitsubishi Atomic Power Industries, Tokyo, Japan

Michihiro OHASHI, Katsuhisa FUJITA
Mitsubishi Heavy Industries, Ltd., Kobe, Japan

ABSTRACT

Since 1982, a series of Proving Tests on the Seismic Reliability for nuclear power plant has been carried out by Nuclear Power Engineering Center (NUPEC), using a large-scale, high performance vibration table at Tadotsu Engineering Laboratory, sponsored by Ministry of International Trade and Industry (MITI) of Japan. Seismic Proving Test of the PWR Reactor Vessel (RV) is the seventh among them, and was conducted in 1988 by a 1/1.5 scale model of an actual plant.

This paper presents the summary of results of the above test program as well as the seismic evaluation for the 1,100 MWe class PWR standard plant in Japan.

1 INTRODUCTION

The main objectives of the the PWR RV seismic proving test are as follows;

i) To confirm the integrity of the reactor coolant pressure boundary and support structure against earthquake, and;

ii) To analyze the vibrational characteristics of RV during earthquake and to confirm adequacy of the seismic design method.

In order to achieve these objectives, the test model, as similar as possible to the structure, scale and so on of actual plant RVs, was manufactured and tested under design earthquake conditions. The seismic integrity was proved directly by excitation of the model with the most severe seismic wave predicted in the current design, then the vibrational characteristics were examined and analyzed for the result of the seismic and sinusoidal wave tests to confirm the adequacy of the design method. Finally, the overall seismic safety and reliability of RV were proved for the actual plant. Fig. 1 shows the overall evaluation flow of this proving test program.

2 TEST MODEL

The modelling was performed based on the following policy to simulate as possible to actual RV and to obtain adequate test results:

1 The test model was designed to simulate a RV and its support structure for the 1,100 MWe class PWR standard plant.

2 The model was prepared with particular attention paid to the RV upper shell with coolant outlet and inlet nozzles as well as support structure which are important to prove the seismic reliability of the RV.

3 The model was made on a scale of 1/1.5 to the actual RV, considering excitation performance of the large-

scale high performance vibration table, and was designed so that the equivalent stress to that in the actual RV would appear.

Table 1 shows the law of similitude for the test model.

Fig. 2 shows an outline of the RV test model. The vessel model was supported on the support structure furnished at the top of the system support frame. Compensational masses are installed at the top, bottom, and inside of the vessel model to simulate the weight of the core internals, etc., so that the vibration characteristics of actual RV would be simulated. Tie rods were attached to the extensions of the nozzles to simulate the vertical downward reaction forces from reactor coolant pipe acting on the RV nozzle under operating condition of an actual RV.

3 EXCITATION

3.1 Input seismic waves

Among various kinds of waves, the waves which give the severest condition on RV were selected as the input waves of this test. The basic design earthquake ground motion S_1 and S_2, which had been improved and standardized by MITI for high seismic zone, were used as inputs to the reactor building analysis model of a standard PWR plant to obtain the floor response waves at the RV support level of the inner concrete. The selected waves were converted by the law of similitude to input waves for the test model. Table 2 shows conditions of the input waves. The model is basically excited horizontally and vertically simultaneously.

3.2 Outline of the test procedures and results

(1) Strength Proving test

The seismic excitations were performed with the S_1, $S_2(1)$, and $S_2(2)$ waves, which is considered to give the most severe design condition on RV, to verify seismic strength of the RV. Fig. 3 and Fig. 4 show the response wave form and distribution of the maximum acceleration of the model, respectively, for the $S_2(1)$ input wave, as some examples. And the maximum seismic response value at major points of the test model is shown in Table 3. The RV model was filled with water and pressurized to operating pressure of 157 kg/cm^2. The stress of test model due to seismic load and pressure was sufficiently lower than the allowable limit. In addition, since post-test inspection proved no abnormality, the integrity of the test model was verified.

(2) Design method confirmation test

Both sinusoidal wave sweep and seismic response wave vibration test were performed to obtain those data necessary to evaluate adequacy of the current seismic design method. Single excitation of horizontal and vertical direction, respectively, by the $S_2(1)$ seismic wave and El Centro seismic wave excitation were also performed to obtain response characteristics of the test model to natural seismic wave excitations.

The sinusoidal wave sweep excitation test results confirmed such vibration characteristics of test model that the natural frequency was 30.8 Hz, and that the vibration was of the rocking mode and damping ratio was 0.7 ~ 1.0%.

(3) Excessive vibration test

Excitation was carried out with the $S_2(2)$ seismic response wave for the strength proving test increasing its acceleration range to confirm the seismic design margin.

In addition to the excitation with normal supporting condition (step-I, 8-nozzle support), the step II test with 4-nozzle-support condition was carried out to increase load per nozzle by reduced number of support. Table 4 shows maximum seismic response at major parts of the test model at excessive vibration. As a result, maximum load at nozzle of the test model reached almost 2 times as high as the design value, but no abnormality was found in post-test inspection, and the RV integrity was confirmed with adequate seismic strength margins.

4 SIMULATION ANALYSIS AND DESIGN METHOD CONFIRMATION

Computational analysis for the test was performed to simulate vibrational response characteristics in the vibration test. Fig. 5 shows the analytical model for the test model. The modal time history analysis was performed as simulation analysis of the RV test model with the support rigidity calculated by the FEM structural analysis considering down forces, such as dead weight and reaction force of reactor coolant loop, and damping ratio (1%) obtained from the test result. Fig. 6 and Table 5 show the comparison of the vibration characteristics and seismic response, respectively. As a results, the vibration characteristics and seismic response which obtained in the test were revealed to agree closely with that obtained by the simulation analysis. These results confirm that seismic characteristics and responses of the model can be simulated by the computational analysis with lumped mass and spring model.

Furthermore, the design analysis, which uses response spectrum method with ±10% spectrum broadened, was performed and it was found that analytical response such as nozzle reaction force is higher than the test results. This confirmed that the current design analysis is on the conservative side.

5 EVALUATION FOR ACTUAL REACTOR VESSEL

The analysis for an actual plant was performed with the method used for design as described above. The analytical model of an actual RV is shown in Fig. 7 and the floor response spectrum curve used for the analysis is shown in Fig. 8. Table 6 shows the result of the analysis on the stress at an actual RV. The stress under seismic condition was lower than allowable limit, and this confirms the seismic safety and reliability of RV for an actual plant.

6 CONCLUSION

The seismic safety and reliability of an actual PWR RV were evaluated by this proving test. The result of this proving test is summarized as follows :

(1) The strength of PWR RV and its support structure was directly confirmed by the S_1 and S_2 seismic response wave excitation tests.

(2) The excessive excitation was carried out until a load twice as great as the design load acted on the nozzles, but no abnormality on the test model was found and the existence of adequate margins for seismic integrity was confirmed.

(3) The analysis of the test model was able to simulate the seismic response of the test.

(4) The adequacy of current design method was confirmed through comparison of the analytical result for the test model based on the current seismic design method with the test result, as well as the result from simulation analysis.

(5) The examination on the seismic stress of the test model confirmed that the seismic stress obtained by the current design method are on the conservative side, and stress due to seismic load has adequate margin to the allowable limit.

(6) Based on evaluation of the test, the seismic safety and reliability of an actual PWR RV were confirmed.

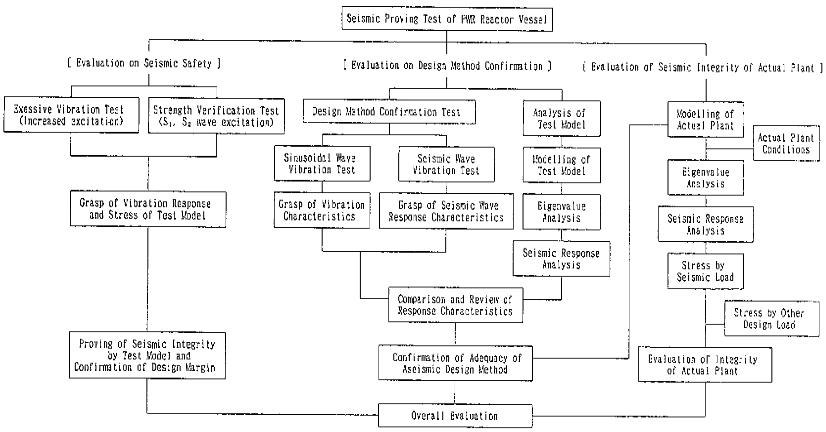

Fig. 1 Evaluation Flow of Seismic Proving Test of PWR Reactor Vessel

Table 1 Law of Similitude for the Test Model

Parameter	Symbol	Scaling Law	Scaling Ratio
Length	L	$L_m/L_p = 1/N$	1 / 1.5
Cross Section Area	A	$A_m/A_p = 1/N^2$	1 / 2.25
Strain	ε	$\varepsilon_m/\varepsilon_p = 1$	1.0
Stress	σ	$\sigma_m/\sigma_p = 1$	1.0
Displacement	x	$x_m/x_p = 1/N$	1 / 1.5
Force	p	$p_m/p_p = 1/N^2$	1 / 2.25
Frequency	f	$f_m/f_p = 1/X$	1 / 0.72
Acceleration	α	$\alpha_m/\alpha_p = 1/X^2N$	1 / 0.778
Weight	W	$W_m/W_p = X^2/N$	1 / 2.894
Spring Constant	k	$k_m/k_p = 1/N$	1 / 1.5
Density	ρ	$\rho_m/\rho_p = 1$	1.0
Young's Module	E	$E_m/E_p = 1$	1.0
Time	t	$t_m/t_p = X$	0.72

(note) N : scaling factor X : frequency ratio
subscript m : TEST MODEL
p : ACTUAL PLANT

Table 2 Input Waves for Proving Test of PWR RV

Seismic wave	Direction	Duration**	MAX. Acceleration **
S_1 floor response *	Horizontal and Vertical	18.0 sec	Horizontal: 480 gal
			Vertical: 155 gal
S_2(1) floor response *	Horizontal and Vertical	14.4 sec	Horizontal: 969 gal
			Vertical: 217 gal
S_2(2) floor response *	Horizontal and Vertical	28.8 sec	Horizontal: 918 gal
			Vertical: 526 gal

(NOTES)
* Floor response waves at the reactor vessel support floor level of the reactor building inner concrete based on the basic design earthquake ground motion S_1 and S_2.

S_1 (Simulated Seismic wave):
Improved and standardized plant for high seismic zone.
M = 7.0, Δ = 20 km.
Phase characteristics = El Centro NS (1940)
Ground V_s = 1500 m/s
S_2 (Simulated Seismic wave):
(1) Improved and standardized plant for high seismic zone.
M = 6.5, Δ = 7.2 km.
Phase characteristics = Cholame Shandon NO.8 N 40 W (1966)
Ground V_s = 1500 m/s
(2) Actual 4-loop PWR plant design wave
(high seismic zone, seismic wave enveloping distant and near earthquake)

** Based on the law of similitude for the reactor vessel test model, the table shows values multiplied by 1.286(1/0.778) for acceleration and by 0.72 for duration.

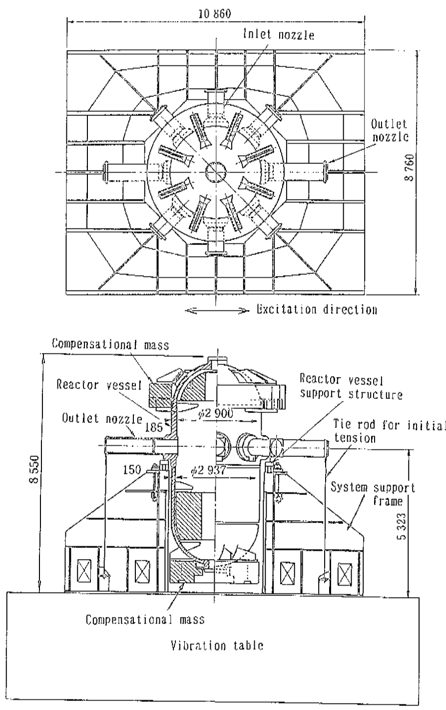

Fig. 2 PWR Reactor Vessel Test Model Outline Drawing

Table 3 Maximum Response Results in Strength Proving Test

Measuring Item / Measuring Point	S_1 vibration test	S_2(1) vibration test	S_2(2) vibration test
ACCELERATION			
RV top	467 gal	992 gal	960 gal
RV nozzle	477 gal	930 gal	889 gal
RV bottom	620 gal	1242 gal	1572 gal
NOZZLE LOAD			
horizontal	39 ton	75 ton	75 ton
vertical	25 ton	53 ton	68 ton
STRESS			
RV nozzle	1.0 kg/mm²	2.0 kg/mm²	2.5 kg/mm²
RV support	0.5 kg/mm²	1.1 kg/mm²	1.3 kg/mm²

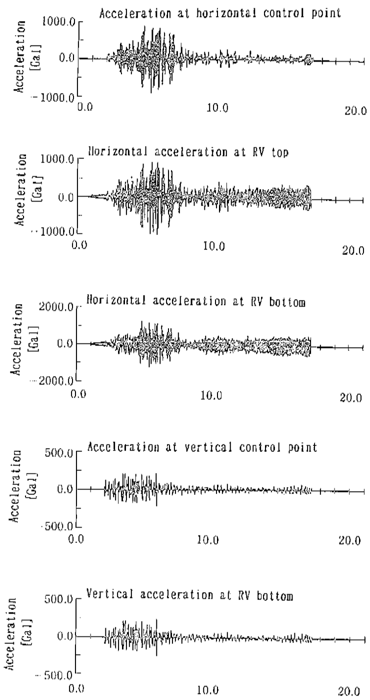

Fig. 3 Response Acceleration wave of RV for $S_2(1)$ excitation

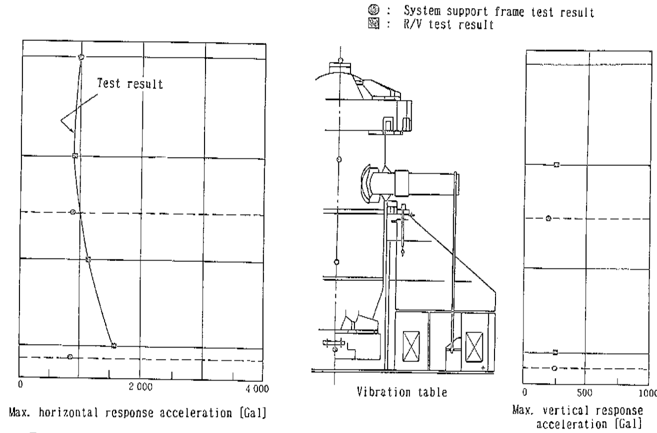

Fig. 4 Maximum Response Acceleration Distribution in $S_2(1)$ excitation

Table 4 Maximum Response Results in Excessive Vibration Test

Measureing item / Measureing point	EXCESSIVE VIBRATION TEST RESULTS				DESIGN ANALYSIS
	STEP I TEST		STEP II TEST		$S_2(2)$ with ±10% broadened
	$1.6S_2(2)$	$1.8S_2(2)'$	$1.7S_2(2)$	$2.0S_2(2)''$	
ACCELERATION					
RV top	1445 gal	2088 gal	2409 gal	3674 gal	1640 gal
RV nozzle	1299 gal	1614 gal	1417 gal	2559 gal	2150 gal
RV bottom	2241 gal	3254 gal	2630 gal	3955 gal	4540 gal
NOZZLE LOAD					
horizontal	119 ton	145 ton	235 ton	418 ton	242 ton
vertical	105 ton	142 ton	260 ton	492 ton	253 ton
STRESS					
RV nozzle	3.9 kg/mm²	5.0 kg/mm²	9.0 kg/mm²	15.2kg/mm²	2.9 kg/mm²
RV support	2.1 kg/mm²	3.1 kg/mm²	5.8 kg/mm²	12.3kg/mm²	4.0 kg/mm²

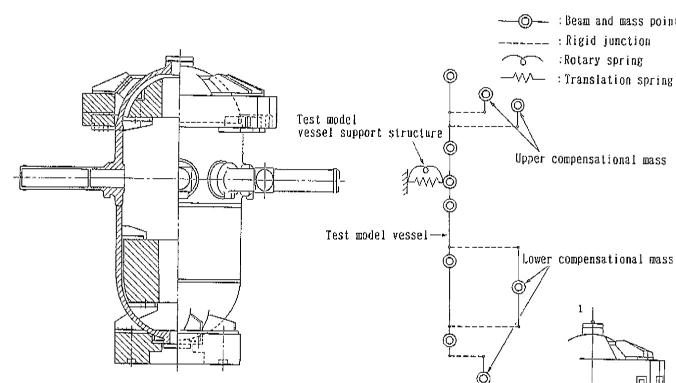

Fig. 5 Analysis Model for Test Model

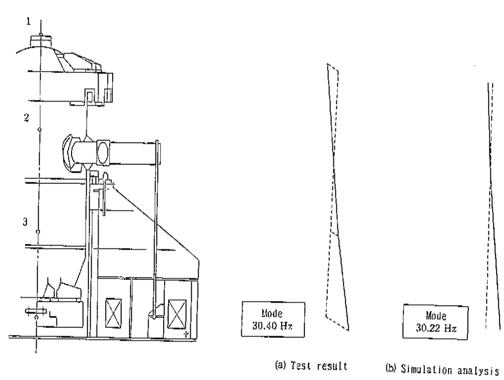

Fig. 6 Comparison of the Vibration Characteristic of Test Model

Table 5 Comparison of Maximum Response in Strength Proving Test

EXCITATION	Measuring Item / Measuring Points	TEST RESULTS	SIMULATION ANALYSIS	DESIGN ANALYSIS
S_1 excitation	ACCELERATION			
	RV top X	467 gal	490 gal	460 gal
	RV nozzle X	477 gal	494 gal	451 gal
	RV nozzle Z	154 gal	157 gal	155 gal
	RV bottom X	620 gal	629 gal	1076 gal
	DISPLACEMENT lower shell X	0.09 mm	0.11 mm	0.24 mm
	NOZZLE LOAD			
	horizontal	39 ton	47 ton	52 ton
	vertical	25 ton	26 ton	58 ton
$S_2(1)$ excitation	ACCELERATION			
	RV top X	992 gal	1049 gal	1022 gal
	RV nozzle X	930 gal	968 gal	1089 gal
	RV nozzle Z	238 gal	221 gal	217 gal
	RV bottom X	1242 gal	1242 gal	2641 gal
	DISPLACEMENT lower shell X	0.21 mm	0.24 mm	0.58 mm
	NOZZLE LOAD			
	horizontal	75 ton	95 ton	127 ton
	vertical	53 ton	63 ton	133 ton
$S_2(2)$ excitation	ACCELERATION			
	RV top X	960 gal	938 gal	1444 gal
	RV nozzle X	889 gal	929 gal	2008 gal
	RV nozzle Z	527 gal	534 gal	526 gal
	RV bottom X	1572 gal	1396 gal	5038 gal
	DISPLACEMENT lower shell X	0.23 mm	0.22 mm	1.12 mm
	NOZZLE LOAD			
	horizontal	75 ton	82 ton	242 ton
	vertical	68 ton	66 ton	253 ton

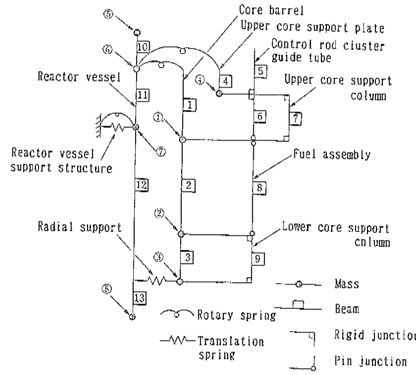

Fig. 7 Analysis Model for Actual Reactor Vessel

Table 6 Seismic Stress of Actual Reactor Vessel ($S_2(2)$ excitation)

	Analysis Results	Allowable Limit
REACTOR VESSEL		
primary membrane + bending stress	26.4 kg/mm²	48.0 kg/mm²
primary + secondary stress (range)	10.0 kg/mm²	56.4 kg/mm²
RV SUPPORT STRUCTURE bolt stress	19.0 kg/mm²	56.2 kg/mm²

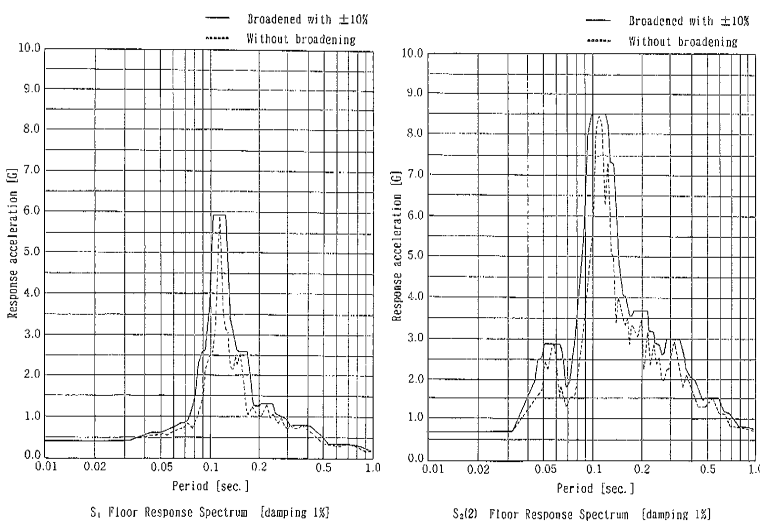

Fig. 8 Floor Response Spectrum for Actual Reactor Vessel