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Seismic proving tests for nuclear power plant, no. 3

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ABSTRACT: This paper presents a summary of the results of the BWR seismic proving tests carried out in Japan. Four large test models (primary containment vessel, reactor pressure vessel, core internals and primary loop recirculation system) were vibrated on a shaking table to verify their strength and ability to function during earthquakes. Test results indicated that BWR key components have an adequate margin of safety and that the current seismic design analysis method is appropriate.

1. INTRODUCTION

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 shaking table facility at Tadotsu Engineering Laboratory, under the sponsorship of the Ministry of International Trade and Industry(MITI) of Japan.

First series of the test has been carried out using test models [Primary Containment Vessel (PCV), Reactor Pressure Vessel (RPV), Core Internals (CI) and Primary Loop Recirculation System (PLR)] which were slected as key components in seismic reliability among the equipments of Japanese standardized 1100MWe BWR and PWR plant.

This paper presents a summary of the results of the BWR seismic proving test.

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

1) To confirm the structural integrity of the equipment against earthquake

2) To confirm the functional integrity during and after earthquake (for example, control rod drive scrammability or leak tightness of primary containment vessel)

3) To confirm the adequacy of the seismic design method

In order to achieve these objectives, the test model, being as similar as possible to the actual plant configuration, material, scale and so on, is tested under design earthquake conditions. The seismic safety and reliability of the model are directly confirmed by the test, and the adequacy of the seismic design method is also confirmed by the analysis of the test data.

2. TEST MODEL

The four key components (PCV, RPV, CI, PLR) were selected to be tested as the important ones from the standpoint of seismic safety.

Full scale or close to full scale models were selected and they were manufactured by the same method and under the same quality control as those of actual plants in order to obtain reliable estimations of actual BWR components.

PCV: 1/3.2 of 1100MWe class primary containment vessel

RPV: 1/2 of 1100MWe class reactor pressure vessel

CI : 1/1 of 1100MWe class core internals

PLR: 1/1 of 1100MWe class one primary loop recirculation system

Outline drawings of the test models are shown in Fig. 1~Fig. 4.

Table 1. Input wave for proving test

	PCV		RPV		CI		PLR	
	M, Δ	α_{max} (Gal)	M, Δ	α_{max} (Gal)	M, Δ	α_{max} (Gal)	M, Δ	α_{max} (Gal)
S_1 [1]	M=7.0 Δ=20 km	H : 1166 V : 561	M=7.0 Δ=20 km	H : 1034 V : 316	M=8.4 Δ=90 km	H : 970 V : 168	M=7.0 Δ=20 km	H : 1097 V : 197
S_2 [2]	M=8.5 Δ=68 km	H : 2456 V= 787	M=7.5 Δ=24 km	H : 1599 V= 511	M=7.5 Δ=24 km	H : 1362 V= 264	M=6.5 Δ=7.2 km	H : 2038 V= 358

1) S_1 : Simulated Seismic Wave - improved and standardized plant for high seismic zone

2) S_2 : Simulated Seismic Wave - Improved and standardized plant for high seismic zone

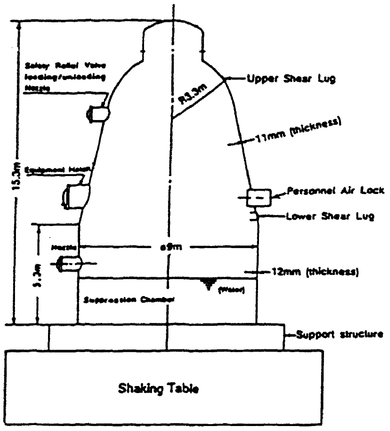


Fig. 1. Outline drawing of PVC test model.

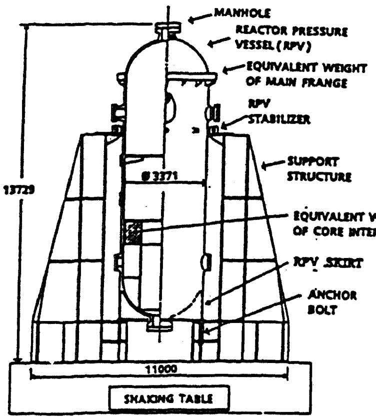


Fig. 2. Outline drawing of RPV test model.

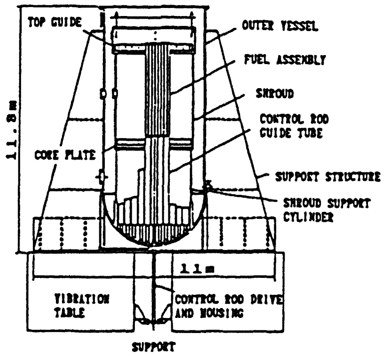


Fig. 3. Outline drawing of CI test model.

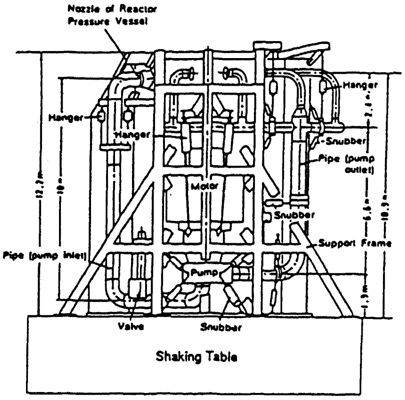


Fig. 4. Outline drawing of PLR test model.

3. TEST CONDITION

(1)Input seismic waves

Among various kinds of waves, the waves which give the severest condition on each components were selected as the input waves of this test.

The basic design earthquake 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 BWR plant to obtain the floor response waves at the component support level. The selected response waves were converted by the law of similitude to input waves for the test model. Table 1 shows conditions of the input waves. As a sample of input

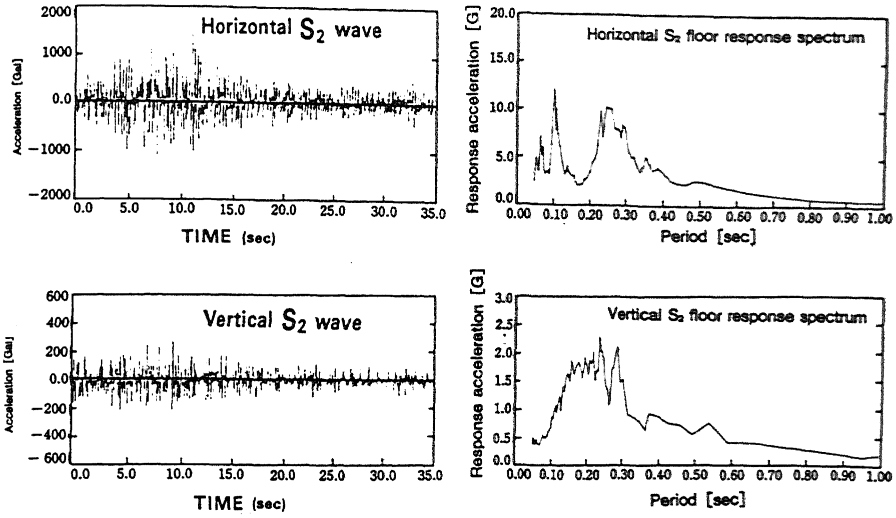


Fig. 5. Sample of input seismic waves (for proving test of Core Internals)

		Analysis	Test result
PCV base	(inner) (outer)	◑	● ○
Joint part of 2nd cylinder and 1st cone	(inner) (outer)	△	▲ △
Joint part of 1st cone and 2nd cone	(inner) (outer)	◧	■ □

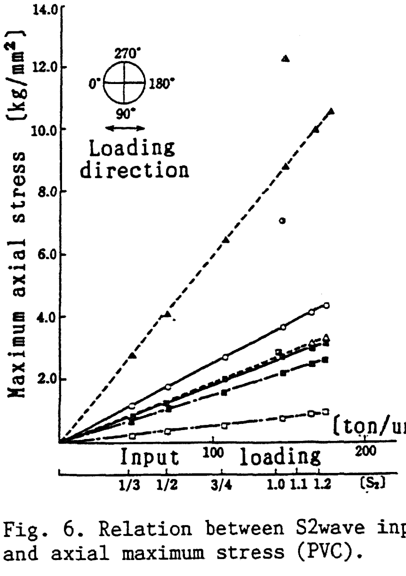
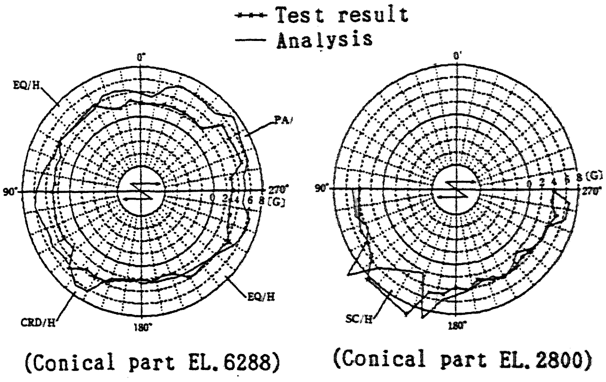


Fig. 6. Relation between S2wave input level and axial maximum stress (PVC).



(Conical part EL.6288) (Conical part EL.2800)

Fig. 7. Distribution of maximum response acceleration (PVC).

waves, Fig.5 shows acceleration time history and acceleration response spectrum of S_2 earthquake motions for CI test model. The models were basically excited to horizontal and vertical direction simultaneously.

(2)Enviromental condition

For each components, test conditions were as follows;

PCV : room temperature, atomospheric pressure
RPV : room temperature, atomospheric pressure, still water, and hydoro pressure; 6.9 MPa
CI : room temperature, atomospheric pressure, still water
PLR : room temperature, still water, pressure; 8.6 MPa

4. TEST RESULTS

4.1 Primary Containment Vessel

(1) Structural and functional integrity

1) Vibration table test

a)The integrity of structure and strength of hatch base of the PCV test model was confirmed directly.

Table 2. Measured stress (RPV).

Unit : kgf/mm^2

Test contents / Items / Component	Strength Proving Test			Marginal vibration test	S_2
	S_1		S_2	S_2	
	measured stress	allowable stress	measured stress	measured stress	allowable stress
Stabilizer(Yoke)	1.7	23.0	2.5	3.0	27.6
Stabilizer Bracket	7.9	52	10.3	12.1	56.0
Supporting Skirt	4.1	52.5	6.0	7.2	56.0
Anchor Bolt	30.0	52.5	30.1	30.3	52.5

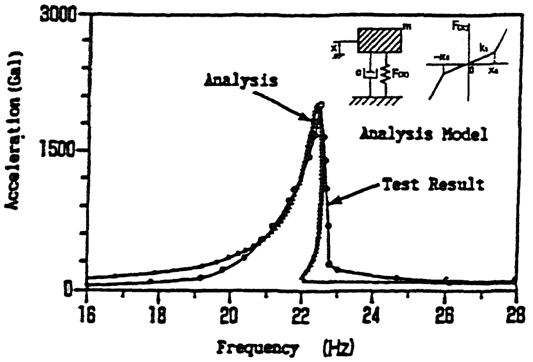


Fig. 8. Comparison of frequency response characteristics (RPV).

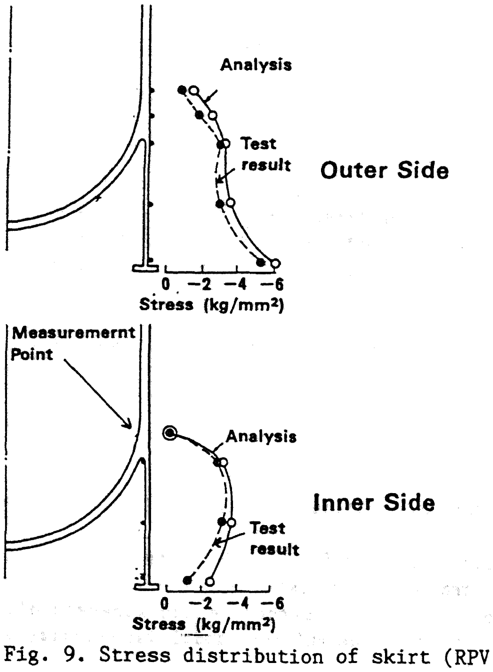


Fig. 9. Stress distribution of skirt (RPV).

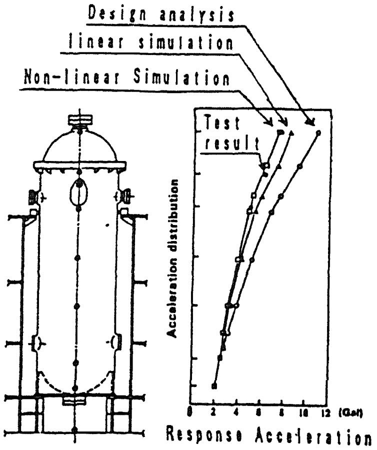


Fig. 10. Acceleration distribution (RPV).

b)The airtightness function was maintained after the vibration test.

c)The test model showed no abnormarity under the excitation intensity of 1.4 times S_2 motion and the linearity of response was kept. It was therefore confirmed that the hatch base had sufficient margin.

2)Static loading test

a)The integrity of general part such as PCV base was confirmed.

b)The airtightness function was maintained after the loading test.

c)The seismic margin of a general part such as PCV base was confirmed under the load equivalent to the level at a load intensity of 1.2 times S_2 motion.

(2) Adequacy of the seismic design method

a)It was confirmed that the present design analysis method based on the beam vibration model was adequate.

b)The comparision, examination and evaluation of the test results confirmed that beam vibration, oval vibration, slosing and seismic response could be simulated with reasonable analysis models.
(Fig.6, Fig.7)

4.2 Reactor Pressure Vessel

(1) Structural and functional integrity

1) The structural and functional integrity for the RPV test model was confirmed and also the sufficient margin in strength for S_1 and S_2 earthquake and for severer earthquake up to 1.7 S_2 was confirmed. (Table 1)

2) At the test of RPV free standing condition (by removing stabilizer), bending stress 254.8 Mpa was observed in RPV skirt. This stress value was up to 6 times of S_2 objective stress, and the

Table 3. Measured stress (CI).

Unit : kgf/mm^2

Test contents / Items / Component	Proving test			Marginal vibration test	
	S_1		S_2 A	S_2 B	S_2
	measured stress	allowable stress	measured stress	measured stress	allowable stress
Top Guide (Gride)	7.8	27.0	8.9	16.0	43.2
Fuel assembly (Channel Box)	6.5	30.5	7.9	13.3	40.7
Shroud	7.5	28.3	13.9	12.3	45.3

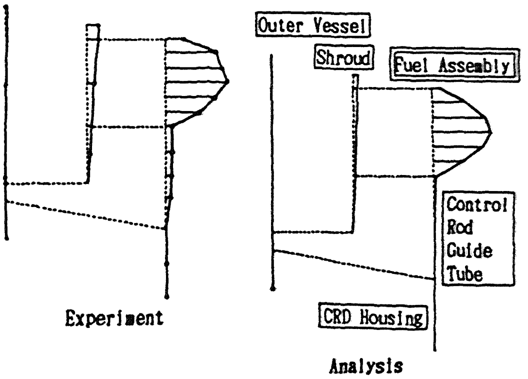


Fig. 11. Vibration mode shape of test model (CI).

sufficient margin was also confirmed.

3) Abnormalities were not found in the inspection. RPV pressure boundary function and supporting capability were maintained under the excitation.

(2) Adequacy of the seismic design method

1) The response of test model was able to be simulated by the current seismic design method.

The following vibrational behaviors of RPV were observed. That is, the slightly nonlinear vibration characteristics were occurred by the gap of the stabilizer. However, the relation between the earthquake response value and table output acceleration showed an approximate linearity.

This result indicates that current seismic design method based on linear analysis is reasonable. (Fig. 8～Fig. 10)

2)The estimated damping from the test data was larger than the current design value.

4.3 Core Internals

(1) Structural and functional integrity

1) The structural and functional integrity for CI test model was confirmed and also the sufficient margin in strength for S_1 and S_2 earthquake and for severer earthquakes up to 1.7 S_2 was confirmed. (Table 3)

The control rod scrammability was also confirmed in this test when the relative displacement at the center of fuel assemblies was about 34 mm during 1.7S_2 excitation.

2)Abnormalities were not found in the inspection. Core internals suppoting function capacity was maintained under the excitation.

(2) Adequacy of the seismic design method

1)The response of the test model was to be simulated by the current seismic design method.

The following behaviors of CI were observed. That is, (i)A group of fuel assemblies has only one predominant frequency and, at this frequency, fuel assemmblies move in the same phase. (ii)The lateral vibration mode for a fuel asemmbly coincides with the first mode of a simply supported beam at both ends. (iii)The displacement amplitude for fuel assemblies is uniform, ragardless of their location in the core.

These results indicate that the assumption on the seismic analysis of the BWR core is reasonable, i.e., a group of fuel assemblies can be replaced with a single elastic beam in consideration of the fluid interaction. (Fig. 11, Fig. 12)

2)The estimated damping from test data was larger than current design value.

4.4 Primary Loop Recirculation System

(1)Structural and functional integrity

The test model, which was manufactured according to the same seismic design analysis method as the

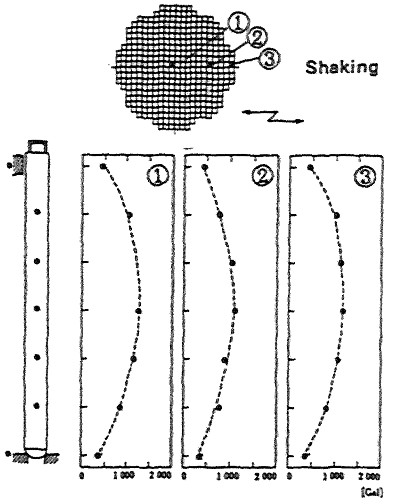


Fig. 12. Measured vibration mode of fluel assemblies (CI).

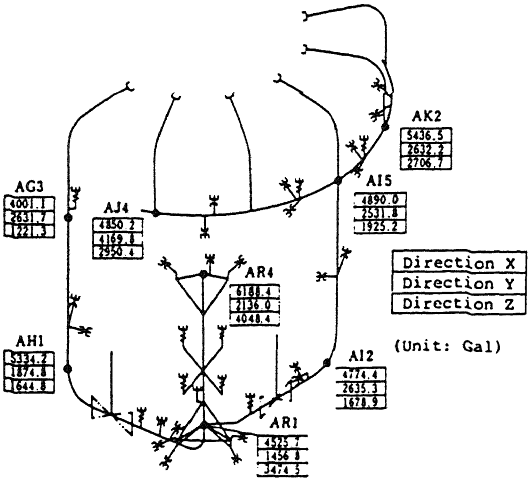


Fig. 13. Distribution of maximum acceleration in S2(H+V) seismic response wave vibration (PLR).

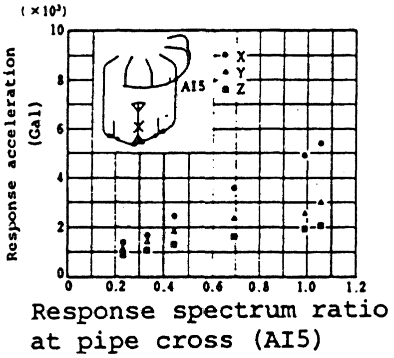


Fig. 14. Response acceleration/response spectrum ratio for S2wave (PLR).

actural system, showed sufficient margin in strength and the functional soundness was confirmed to be kept against the basic design earthquake ground motions (S_1 and S_2), which simulated the severest motion among the input conditions. Sufficient margins were also confirmed for severer earthquake than the designed earthquake motions.

(2)Adequacy of the seismic design method
The designed values (acceleration , support reaction force, pipe stress) based on the present design analysis method were compared with the measured values. It was confirmed that the designed values lay on the safety side of the measured values. The designed conditions were well examined to prove adequacy of the present design analysis method. It was also confirmed that the vibration behavior of the test model could be reproduced with the numerical analysis model. Thus, adequacyof the present analysis code was evalueted and data could be obtained to be used for future improvement of seismic technology for *PLR* system,e.g. the method of pipe support arrangement.
(Fig.13, Fig.14)

5. CONCLUSION

Seismic proving tests of four BWR test models were carried out using the large-scale high performance shaking table. The results of these proving tests are summarized as follows ;

(1)Primary containment vessel, reactor pressure vessel, core internals and primary loop recirculation system which are key component from the standpoint of safety against earthquakes, were confirmed to have an adequate strength and to maintain their function with *sufficient margin* against the severest seismic event which is postulated in the actual plant design.

(2)Based on the comparison of the test results and the simulation analysis, the appropriateness of the current seismic design method was confirmed.

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