



NUPEC project : seismic proving test on reactor shutdown cooling systems - (Summary of results)

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ABSTRACT

This test was conducted to verify the seismic safety and the reliability of the reactor shutdown cooling system of PWR and BWR. Mechanical and electrical components related to functions of this system during earthquakes, such as tanks, piping, heat exchanger, valves, pump, instrument, control panel and electrical power panel were selected and assembled as a test model. As the results of the tests, the functions of system and components maintained when subjected to severe earthquake accelerations.

1. Introduction

In order to verify the seismic safety and the reliability of the reactor shutdown cooling system, the following items were confirmed, analyzed, and evaluated.

- ① Integrity of system functions, during or after excitation, corresponding to functions required during earthquakes
- ② Integrity of electrical and instrumentation functions related to ①
- ③ Seismic margin of system facility functions
- ④ Validity of the design method for maintaining system functions during earthquakes

In this context, the reactor shutdown cooling system is the generic term for the following systems directly related to cooling functions for removing reactor core decay heat after reactor shutdown and shifting the plant to a cold state following earthquake-induced reactor shutdown, or normal plant shutdown.

[PWR]

- ① Auxiliary feed water system
- ② Boric acid injection system
- ③ Charging system
- ④ Residual heat removal system
- ⑤ Main steam relief valve system
- ⑥ Pressurizer relief valve system

[BWR]

- ① Reactor core isolation cooling system(RCIC)
- ② High-pressure core spray system(HPCS)
- ③ Residual heat removal system
- ④ Main steam relief safety valve system

2. Experiment

The verification test consists of the following:

- (i) Test to verify seismic reliability
- (ii) Test to confirm the validity of the current design analyzing method
- (iii) Test to confirm seismic design

In test(i), the system was vibrated using the severest seismic wave that could be

assumed in the seismic design of the reactor shutdown cooling system, and function integrity was verified. In test(ii), “sine wave vibration test” and “vibration test with seismic response wave” were conducted. The validity of the method for analyzing seismic response used to confirm and evaluate seismic function maintenance in the current design was confirmed. In the test(iii), the system was vibrated using a seismic wave more severe than the maximum seismic wave assumed in the design, and safety margin of the seismic design was confirmed.

Figure 1 shows the basic flow of the verification process.

2. 1 Operation scenario

The example of operation scenarios for PWR is illustrated in Figure 2. In relation to earthquakes, reactor shutdown cooling system operations can be broadly classified into the following stages: the cooling down operation following automatic reactor shutdown, the continuation of the cooling operation during the normal cooling operation, and the continuation of the cooling operation during long-term cooling following LOCA.

The systems included in each operating scenario and the functions to be maintained during earthquakes have been arranged as follows. Table 1 shows a comparison of operation modes of actual and simulated systems. P-1 to P-9 and B-1 to B-9 indicate the operation mode numbers in Table 1

2. 2 Test Model

The test model was planned to simulate the facilities and operation of reactor shutdown cooling system of typical nuclear power plants in Japan with power output of 1100Mwe.

2. 3 Specific functions to be verified

To verify the previously mentioned cooling operations required during and after earthquakes, the required detailed functions for each operation have been arranged as follows.

(System facilities)

- ① Pump startup function
- ② Water supply function
- ③ Motor-operated valve operation function circuits
- ④ Air-operated valve operation

(Electrical and instrumental facilities)

- ① Process quantity sensor measurement function
- ② Normal operation of signal processing circuits
- ③ Normal operation of logic sequence
- ④ Normal operation of switch gears

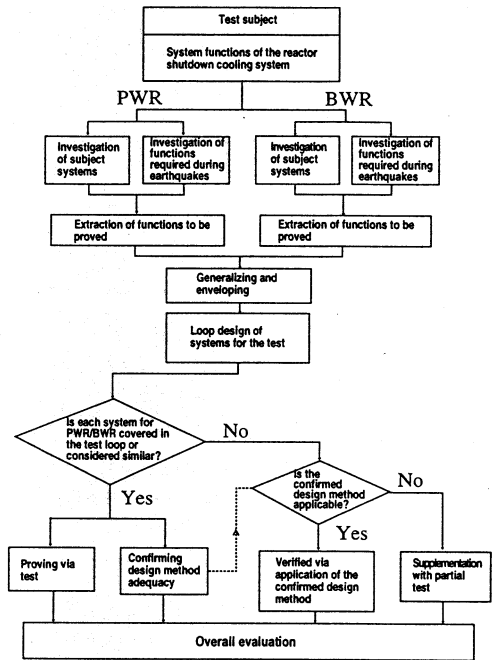


Figure 1 Basic flow diagram of seismic proving test

- ⑤ Signal system functions
- ⑥ Functions related to electric power systems
- ⑤ Normal operation of manual switches
- ⑥ Normal operation of indicators
- ⑦ ON-OFF function of electromagnetic valves
- ⑧ Signal transfer cables

2. 4 configuration and operation modes of test model system

To prove the function maintenance of reactor shutdown cooling system, test model configuration was examined, including the fluid system equipment and electrical and instrumental components.

For each piece of dynamic equipment, electrical component and instrumentation, the individual function during earthquakes was confirmed in the previous tests; thus, this test combines these components and focuses on verifying the total system function.

In the actual test, one set of system loops was generated from the appropriate representative equipment, based on test boundary and procedure, so that the operation modes of the reactor shutdown cooling systems of actual plant could be represented and simulated by switching valves.

Figure 3 shows the system diagram of the test model, Figure 4 shows the schematic drawing of the test model on the vibration table, and Figure 5 shows block diagram of electrical and instrumental components.

2. 5 Input seismic wave

In this test, many components installed on several floors of an actual plant are placed on one vibration table and vibrated simultaneously. The input wave for the verification test was generated to satisfy the acceleration response of each floor of the power plant on which the system facilities and the electrical and instrumentation components are installed. In the actual test, a spectrum was generated, which enveloped the floor response spectrum of standard earthquake ground motion for the high-seismic area plant design and for each actual plant design, and a simulated seismic wave conforming to these spectra was developed. Figure 6 shows the input wave form, and Figure 7 shows the spectrum.

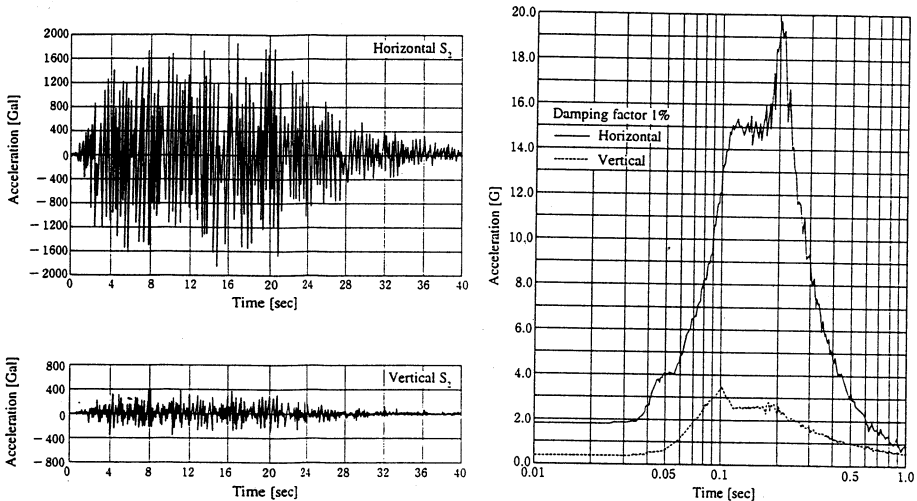


Figure 6 Input seismic wave(S₂) for verification test Figure 7 Acceleration response spectra(S₂)

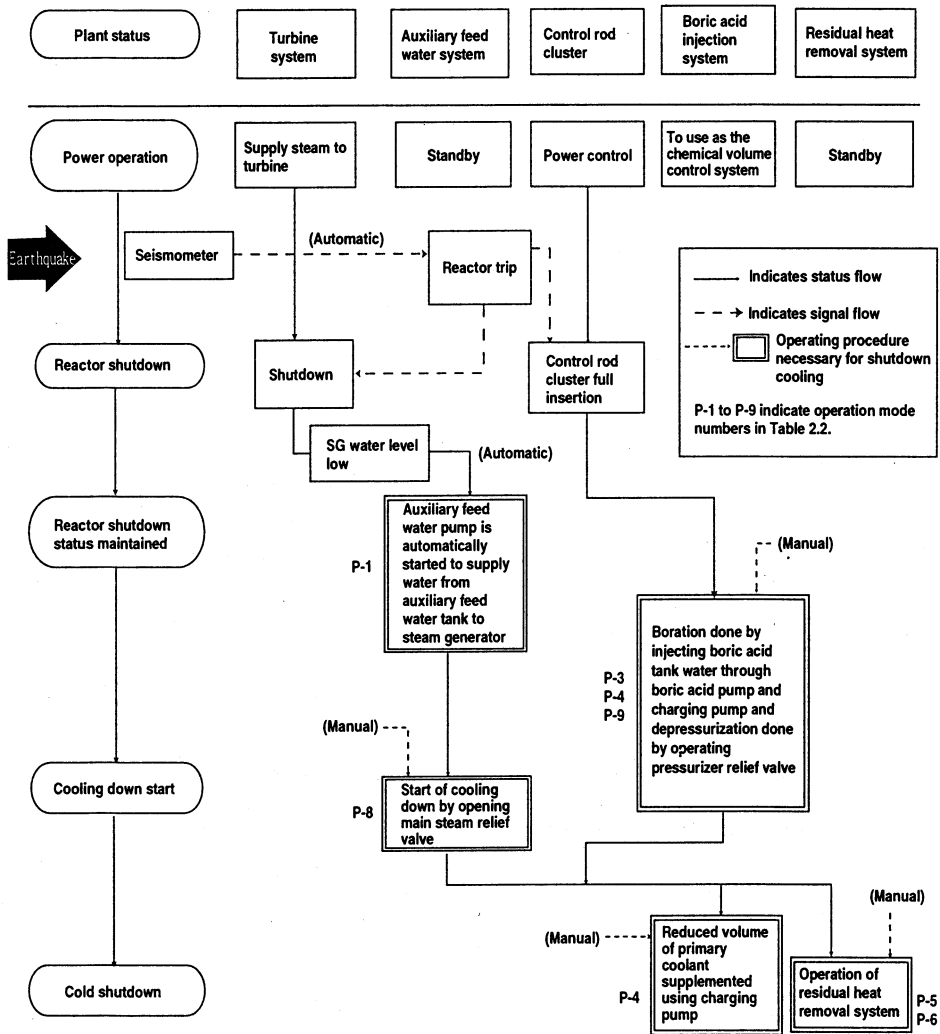


Figure 2 Example scenario of PWR plant operation during earthquake (seismometer-induced trip)

Table 1 Operation modes of the actual system and the test model

Operation mode of actual system				Operation mode of test model		Seismic motion to be considered
PWR		BWR				
P-1	Automatic start up of auxiliary feed water system during earthquake	B-1	Automatic start up of reactor core isolation cooling system during earthquake	E-1-2 (a) and E-1-2 (b)	Water supply from Tank A to Tank B [State of being open to atmosphere]	S ₂
		B-2	Automatic start up of high-pressure core spray system during earthquake		Automatic start up during vibration (a) Automatic start up via low water level signal (b) Automatic start up via black out sequence	
P-3	Manual start up of boric acid injection system after earthquake (up to the inlet header of the charging pump)		-	E-3	Water supply from Tank A to Tank B [State of being open to atmosphere] (Injection of boric acid is conducted via serial operation of the two systems described at left, but for operation of the test model, each system is separately represented by this mode.)	S ₂
P-4	Manual start up of charging system after earthquake (also working as the boric acid injection line)			E-4		
P-5	Manual start up of residual heat removal system after earthquake	B-5	Manual start up of residual heat removal system after earthquake	E-5	Supply of recirculation water via Tank A [pressurized state]	S ₂
					Manual start up after vibration	
P-6	Earthquake during operation of the residual heat removal system at time of normal shutdown	B-6	Earthquake during operation of the residual heat removal system at time of normal shutdown	E-6	Supply of recirculation water via Tank A [pressurized state]	S ₂
					Vibration during continued operation	
P-7	Earthquake during long-term operation of the residual heat removal system after LOCA	B-7	Earthquake during long-term operation of the residual heat removal system after LOCA	E-7	Supply of recirculation water via Tank A [state of being open to atmosphere]	S ₁
					Vibration during continued operation	
P-8	Depressurization and heat removal by main steam relief valve after earthquake (Corresponds to P-1 mode)	B-8	Depressurization by main steam safety relief valve after earthquake (Corresponds to B-1 mode)	E-8 . 9	Depressurization by relief valve and confirmation of check valve function (This mode is used to represent the checking function of each mode.) [Pressurized state]	S ₂
P-9	Depressurization by pressurizer relief valve after earthquake (Corresponds to P-4 mode)	B-9	Depressurization by main steam safety relief valve after earthquake (Corresponds to B-2 mode)		Manual open and close operations after vibration	

S₁ : the maximum design earthquake, S₂ : the extreme design earthquake

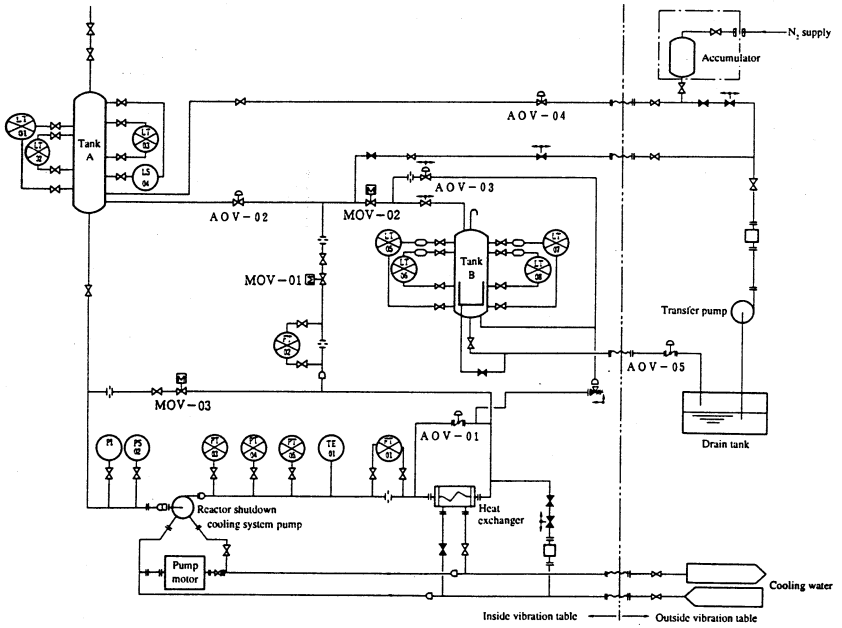


Figure 3 System diagram of test model

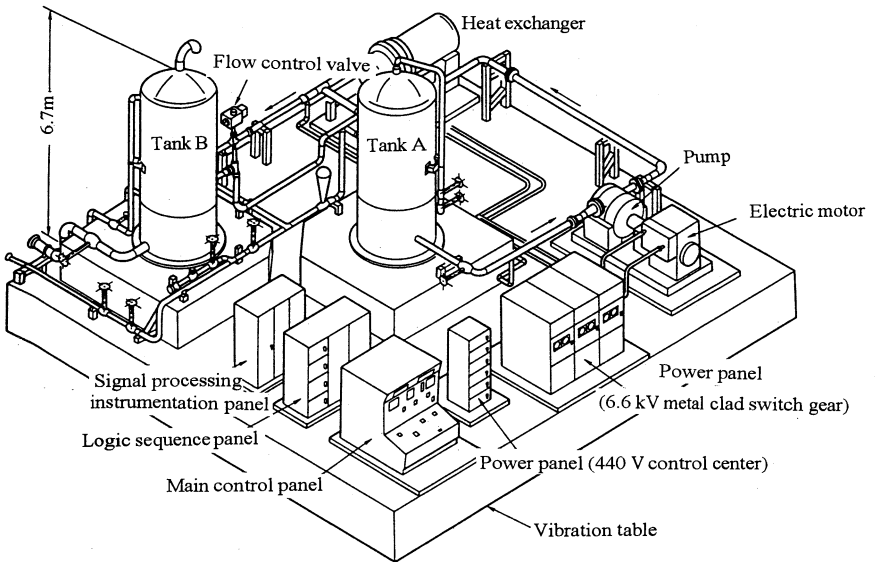


Figure 4 Schematic drawing of test model

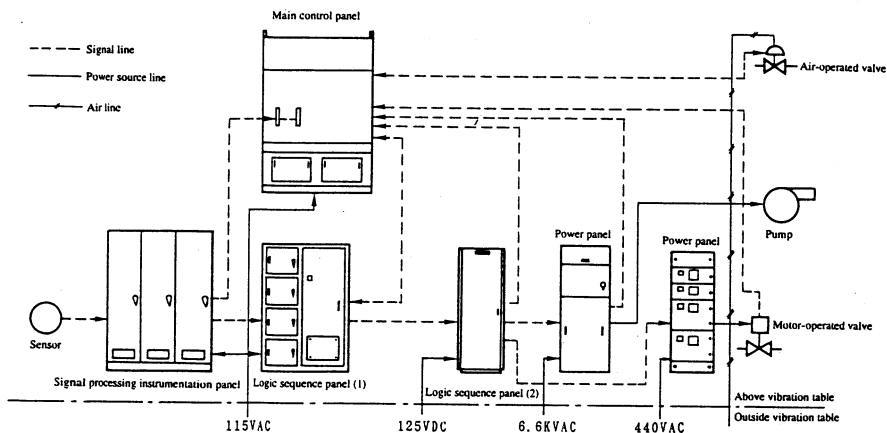


Figure 5 Block diagram of electrical and instrumental components

2. 6 Contents of Testing and Overview of Results

Testing consists of 7 items as follows.

- ① Partial test: investigation on the vibration characteristics of the pressure and differential pressure transmitter systems and power source facilities(not mentioned in this paper)
- ② Confirmation test of system characteristics without vibration: Comparison of system characteristics between with and without vibration
- ③ Preliminary test: Verification of the vibration characteristics and the response characteristics of the test model, and basic data on the generation and propagation characteristics of the pressure wave
- ④ Design method confirmation test: Confirmation of the validity of the seismic response analysis method used to confirm and evaluate the maintenance of seismic functions in the present design
- ⑤ Verification test: Verification of the seismic integrity of each function under input seismic wave (S2)
- ⑥ Marginal test: Clarification of the seismic margin of each function under seismic input conditions exceeding design earthquake motion(S2)

3. Evaluation

This seismic verification test is aimed to verify the maintenance of system functions of reactor shutdown cooling system during or after earthquake. Thus, test results were not evaluated using an analysis method as they had been before. Instead, test results were evaluated generally, according to the following principles.

3. 1 Evaluation of seismic safety

Data obtained from tests ① to ⑥ was analyzed and the following items were evaluated to conform that the test systems and facilities of the reactor shutdown cooling system had sufficient seismic integrity to the input seismic force.

(1) Evaluation of vibration characteristics

The observed natural frequencies of the equipment and electric items, that had been obtained by transfer function from the data during the sine wave sweep test and the design method confirmation test, indicated that all were equivalent to or more rigid than the design frequencies. So, the appropriateness of the natural frequency considered in the current seismic design based on the rigid support assumption was confirmed.

(2) Evaluation of pressure response characteristics

Although this test revealed the following phenomena resulting from the pressure response wave in pipes caused by vibration, there were no problems with maintaining the system functions. the detailed evaluation of pressure response characteristics is planning to be reported in another paper[1].

(3) Evaluation of the effects on each component

The effects of vibration on the functions of the pump, valve, and electrical and instrument were evaluated as follows.

(a) Pump water supply characteristics (see Figure 8)

No delay was observed in pump startup time during vibration (see Figure 9), and there was no significant different before and after vibration(2/3S2 to 1.5S2) in the number of pump rotations and the outlet pressure. Pump flow rate indicated increased fluctuation of about 1 % or less during 1.5S2 vibration. However, these fluctuations were considered to have caused no problems with cooling system functions, and values returned to normal after vibration.

(b) Valve operation time (see Figure 10)

Vibration had no perceived effect on the operation times of the motor- and air-operated valves.

(c) Transmitter and signal processing card input/output characteristics

Vibration had no significant effect on these characteristics.(see Figure 11)

(d) Electric panel functions

As mentioned above, vibration had no significant effect on characteristics of the signal processing loop card and on response time of signal processing circuit (see Figure 12). No abnormalities were found in the following tests on the logic sequence panel after vibration.

- Input relay test
- Confirmation test of overall notification alarm
- Semi-automatic test
- Logic test
- Output relay circuit test

(4) Evaluation of the effect on system functions

Detailed evaluations were made for each operating mode, and it was confirmed that all functions and signal transmissions were within the design tolerance from both the system level and the component (mechanical equipment, electrical and instrumental equipment) level. Table 2 shows the results of overall evaluation of system function maintenance at each vibration level and for all operating modes.

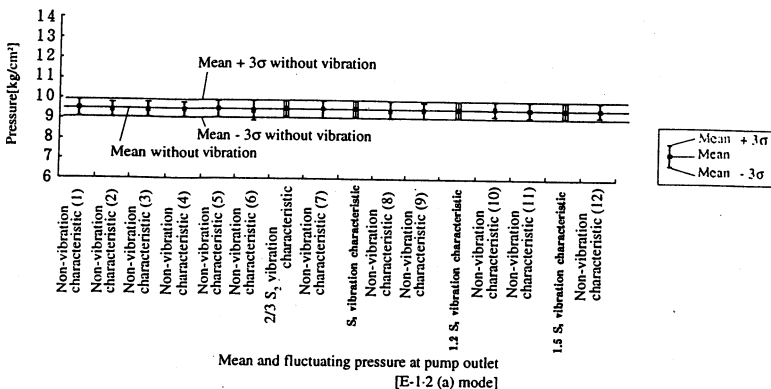
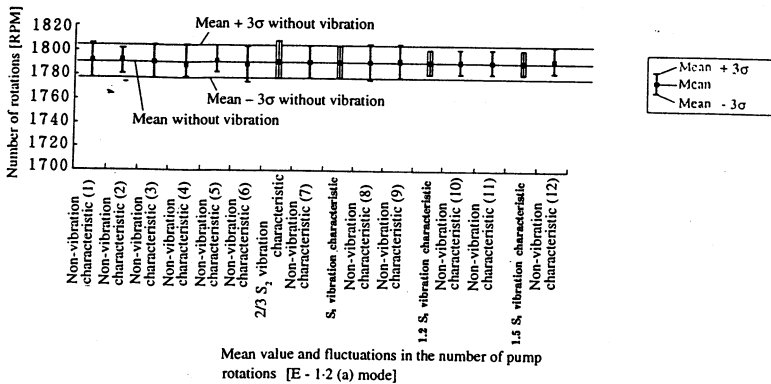


Figure 8 Effect of vibration on pump functions

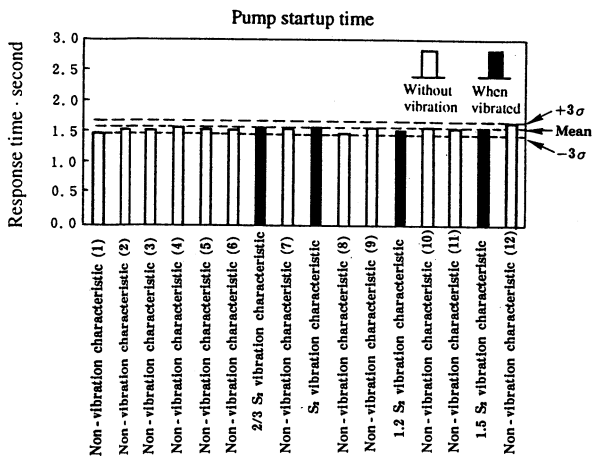


Figure 9 Pump start time

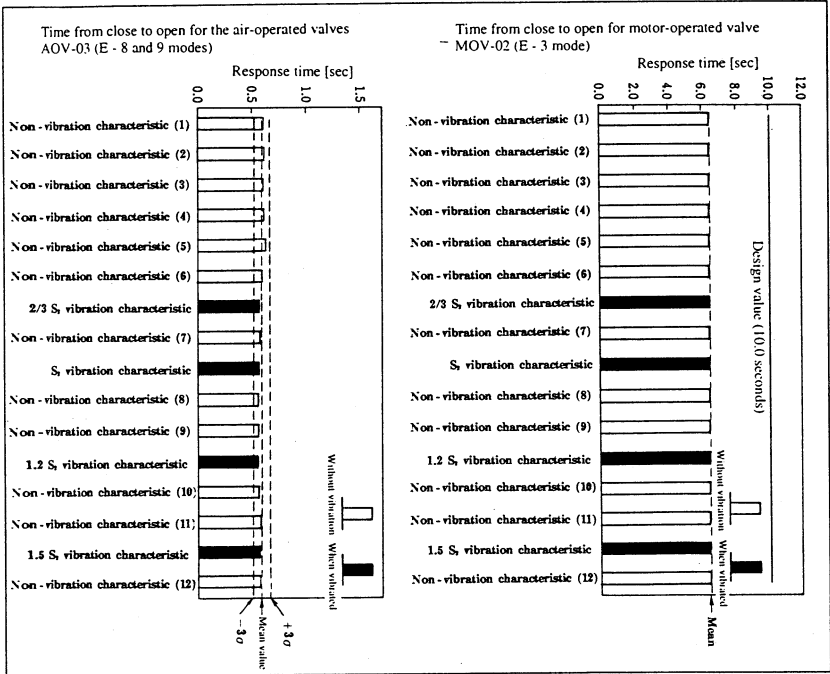


Figure 10 Effects of vibration on valve functions

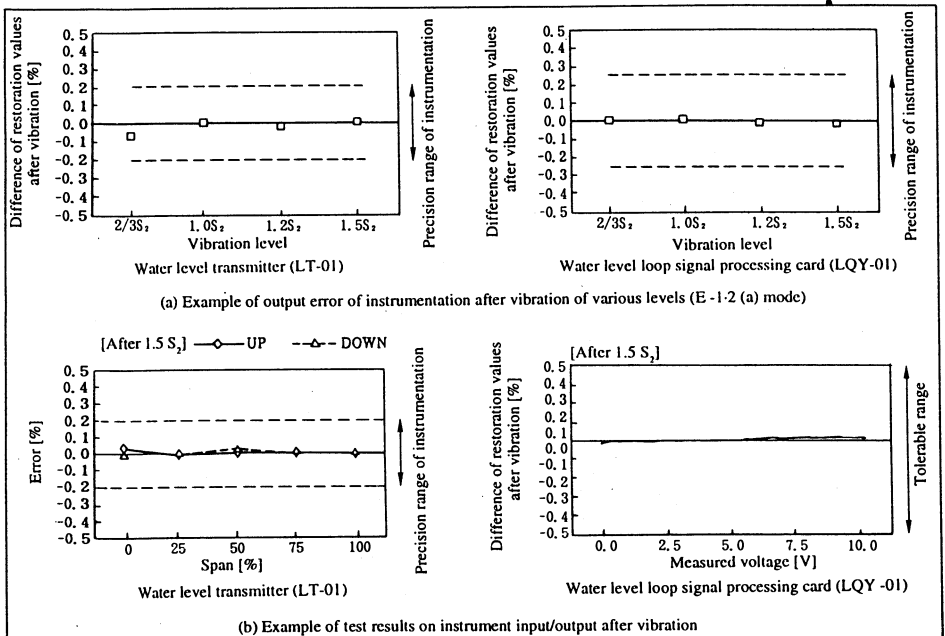


Figure 11 Effects of vibration on functions of electrical and instrumental equipment

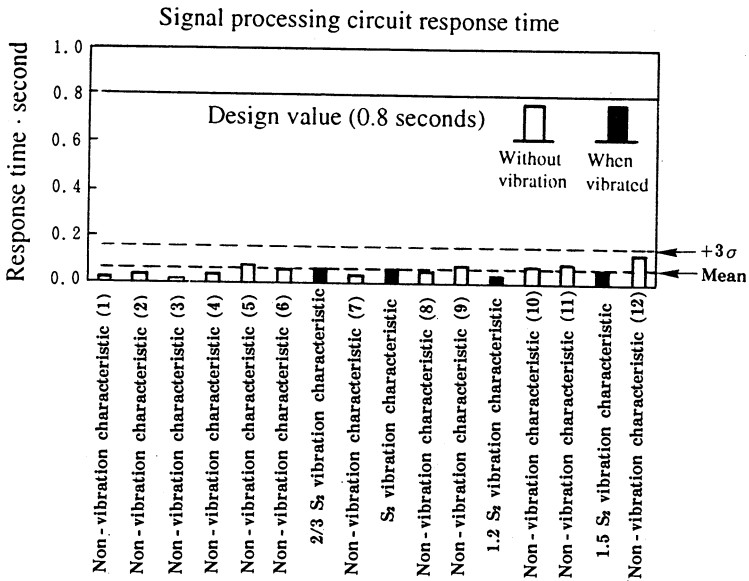


Figure 12 Response time of signal processing circuit

Table 2 Results of confirmation of all system functions for all operation modes

Test operation mode	Relationship between system operation and vibration	Line-up	System pressure	Results of integrated system functions			
				2/3 S _σ	S _σ	1.2 S _σ	1.5 S _σ
E-1-2 (a)	Automatic start of pump during vibration (low-water-level signal)	Water supply from Tank A to Tank B	Open to atmosphere	○	○	○	○
E-1-2 (b)	Automatic start of pump during vibration (external power source loss sequence)	Water supply from Tank A to Tank B	Open to atmosphere	○	○	○	○
E-3	Manual start of pump after vibration	Water supply from Tank A to Tank B	Open to atmosphere	○	○	○	○
E-4	Manual start of pump after vibration	Water supply from Tank A to Tank B	Open to atmosphere	○	○	○	○
E-5	Manual start of pump after vibration	Circulation via Tank A	Open to atmosphere → Pressurization	○	○	○	○
E-6	Vibration during continuation of pump operation	Circulation via Tank A	Pressurization	○	○	○	○
E-7	Vibration during continuation of pump operation	Circulation via Tank A	Open to atmosphere	○	○	○	○
E-8-9	Operation of relief valve after vibration	Circulation via Tank A	Pressurization	○	○	○	○
Vibration table acceleration (Gal)	Measured value	Status of system — (E-1-2 (a), (b), 3, 4, 7)	Horizontal	1338	1931	2347	2933
			Vertical	264	407	522	657
	Status of system — (E-5, 6, 8, 9)	Horizontal	1289	1906	2391	3170	
		Vertical	265	417	537	713	
	Target value of each level	Horizontal	1200	1800	2160	2700	
		Vertical	268	402	482	603	

○ : System functions established

These results confirmed that the test system maintained functions with sufficient seismic integrity when vibrated at 1.5 times the design acceleration for all operation modes.

3. 2 Evaluation of design method

(1) The test model system, in which function maintenance was examined by the current seismic design method, was vibrated under the seismic condition of the actual plant. The fact that the entire system and each facility functioned normally in accordance with the specified scenario confirmed the validity of the current concept for the design to maintain system functions during earthquake(the design method in a broad sense).

(2) In terms of the methods used to confirm the maintenance of facility functions in the present seismic design, the validity of the calculation method of the seismic response acceleration were confirmed from the results of the sine wave sweep test and the design method confirmation test. In addition the fact that each facility function was maintained normally indicated the validity of the evaluation method of determining function maintenance by comparing design response acceleration with the existing verified acceleration(the design method in a narrow sense).

3. 3 Evaluation of function maintenance in actual plant systems

Based on the results of verifying maintenance of the functions of the test system, which represented and simulated actual systems, and the test confirming the validity of the design method, investigation of the maintenance of the functions of each component and electrical and instrumental equipment comprising the reactor shutdown cooling system of actual plant was performed. As a result of this investigation, it was confirmed that both the PWR and BWR reactor shutdown cooling systems maintained functions for their seismic reliability during and after earthquakes.

Analytical examination conducted on the pressure response phenomena in pipes, which was new information obtained in this test, using piping system model of actual plant as an example, confirmed that the response value was lower than the value of the design pressure resistance of transmitters and was of a level that would not affect detection functions. In addition, analytical evaluation was made on the automatic start signal of the pump, confirming that the signal was on the safe side, being transmitted slightly earlier than normal.

4. Conclusion

- The test model designed to represent and simulate actual plant system maintained its functions during earthquake vibration.
- This fact proved the validity of current seismic design method, and then verified that reactor shutdown cooling system of actual plant should maintain its function during earthquakes.
- The pressure response wave in the piping during earthquake, a new finding through this test, did not affect the maintenance of the test model functions.(Detail evaluation is reported in another paper[1])

5. Reference

- [1] T. Fujita et. al., 1997, NUPEC Project : Seismic Proving Test on Reactor Shutdown Cooling Systems (Test and Analytical Method on Pressure Pulsation).,PVP(to be published)