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SEISMIC TEST RESULTS OF THE ESPECIAL VALVES AND VALVE ACTUATORS FOR NUCLEAR POWER PLANT

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Abstract

The functional requirements of several especial valves provided in the nuclear power plants during an earthquake has been previously evaluated via seismic test results and so forth; however, since the response acceleration has increased in line with a recent reassessment of standard earthquake ground motions, it is necessary to evaluate seismic operability with respect to high acceleration. In addition, from the viewpoint of equipment fragility in seismic PRA also, it is necessary to determine the practical seismic operability limits.

Here, we used a resonant shaking table in the Central Research Institute of the Electric Power Industry (CRIEPI), which is capable of seismic tests at acceleration levels that have been unachievable until now, and in seismic tests carried out on follows; (1) motor-operated valve actuators provided in nuclear power plants, (2) air-operated valve actuators provided in nuclear power plants, (3) the Main Steam Safety Relief Valve (SRV) provided in Boiling Water Reactor (BWR) nuclear power plants, (4) the Main Steam Isolation Valve (MSIV) provided in BWR nuclear power plants.

The seismic operability results obtained for these valves and actuators will be applied to a fragility analysis of seismic PRA.

This paper reports the details and results of the seismic tests for motor-operated valve actuator and the SRV, these results confirming that validated seismic operability was possible even at response accelerations as high as 20×9.8 m/s^2.

Keywords: valve, valve actuator, nuclear power plant, seismic test

1. Introduction

In general, the seismic design of valves is evaluated that the acceleration of valve actuator calculated by the piping analysis is within the acceleration which came from results of seismic tests to ensure the integrity of the valve in the nuclear power plants. The allowable acceleration of valves which is called operability of active components(A_T) and the limitation to the actuators called A_{T1} are applied to the seismic design is based on the past seismic test results. However, the response acceleration has been increased in line with a recent reassessment of standard earthquake ground motions. Regarding to the current operability of active components(A_T and A_{T1}), accelerations of past seismic tests were limited by the vibration capability of the test equipment, so that it was considered that the actual A_T and A_{T1} have higher. On the other hand, a high acceleration shaking table system using resonance vibration was developed by the Central Research Institute of the Electric Power Industry (CRIEPI) and was completed in 2015 (Ref. [1]). We carried out high-acceleration seismic tests using this shaking table for several type of valves as follows, with the aim of improving the validated accelerations as A_T and A_{T1}.

- Motor-operated valve actuators provided in nuclear power plants (Ref. [2,3,4])
- Air-operated valve actuators provided in nuclear power plants (Ref. [5,6,7,8,9])
- Main Steam Safety Relief Valve (SRV) provided in Boiling Water Reactor (BWR) nuclear power plants (Ref. [10])
- Main Steam Isolation Valve (MSIV) provided in BWR nuclear power plants (Ref. [11])

This paper reports the details and results of the seismic tests for motor-operated valve actuator and the SRV because the results of these two types of valves had already been finalized, these results confirming that validated seismic operability was possible even at response accelerations as high as 20×9.8 m/s^2.

2. Exprimental test program

2.1 Test facilities

The specifications of the test facilities are shown in Table 1 and Figure 1. These facilities used a Semi-Active Mass-Damper (SAMD) to reduce the acceleration transmitted to the outside. The seismic test conditions are shown in Table 2. In the seismic test, X direction and Y direction were performed separately. This seismic method did not have the influence in the Z direction.

Table 1 – Specifications of the test facilities

Items	Large vibration table	Resonance vibration table
Seismic table dimensions	5 m × 5 m	2 m × 2 m
Seismic direction	1 axis	1 axis
Maximum acceleration	2×9.8 m/s^2	20×9.8 m/s^2
Frequency range	0.5–40 Hz	10 Hz

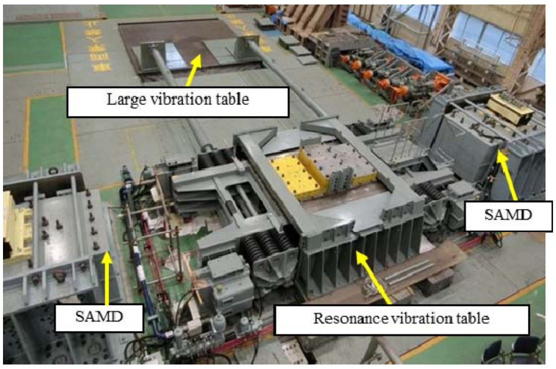


Fig. 1 – Seismic test facilities

Table 2 – Seismic test conditions

Acceptance criteria	Can be operated*1 (after seismic vibrations)
Seismic time	Over 15 seconds
Target Acceleration	20×9.8 m/s^2
Target frequency	About 10 Hz
Seismic wave	Consecutive sine waves

*1: Operating time can be measured, and it can be checked by checking that there is no significant difference.

2.2 Seismic wave

The seismic wave is a consecutive sine wave according to the characteristics of the seismic test facilities. Here, the test frequency was set in consideration of the target frequency of the test specimens, the characteristic frequency of the seismic wave input to the valves, and the specifications of the resonance table. The characteristic frequency of the piping systems which are included valves are about 10 Hz to 20 Hz, and these frequency components act on the actuator of valves. If the frequency of the excitation input wave is lower than the characteristic frequency of the test specimen, the inertia force will be applied to the whole system, and the effect of the inertia force on the failure mode is considered to be dominant. Therefore, the seismic test frequency of about 10Hz is appropriate.

2.3 Steps for selection of the test specimens

In general, the selections of the test specimens were practiced as following steps.

(1) Survey the functional requirements as the operability of active components

(2) Classify the candidate valves by functional demand and structures

(3) Classify the seismic critical parts and consider the failure modes

(4) Calculate the marginal acceleration (including different size (bore) of valve types)

In the above, after confirming the seismic marginal accelerations were the same for each structures, the test specimens were also taken into account testability (e.g. limitation of the loading mass of the resonant vibration table) and versatility of the actual nuclear power plants.

3. Results of seismic test

3.1 Motor-operated valve actuators

3.1.1 General description and selection of the test specimens for motor-operated valve actuators

Motor-operated valves for the nuclear power plants have functions as isolation valve to be secured the Reactor Pressure Vessel (RPV) boundaries in an emergency condition. During earthquakes, motor-operated valves must perform a mechanical motion in order to shut down the plant, maintain the plant in a safe shutdown condition, or mitigate the consequences of a postulated event. Also, following earthquakes, they have to perform mechanical motion to maintain the plant in a safe shutdown condition, or mitigate the consequences of a postulated event. Therefore, the operability of active components(A_{T1}) includes opening and shutting maintenance during an earthquake, and opening and shutting maintenance after an earthquake, depending on their functions in the system. In addition, since there are several manufactures of motor-operated valves various evaluations are individually required. The purpose of this paper is focus on the seismic performance of the motor-operated actuators which is one of the evaluation elements for the motor-operated valves.

There are two manufacturers of motor-operated valve actuators which are applied in Japanese nuclear power plants. The types of valves are chosen in accordance with the required torque. However, the basic structures of them is equivalent from the viewpoint of transmitting motor power to valve stem via gears. Motor-operated valves actuators comprise electrical components, including the motor, and transmission mechanisms, such as gears (Figure 2), and it is difficult to perform a detailed analysis and evaluation of each part.

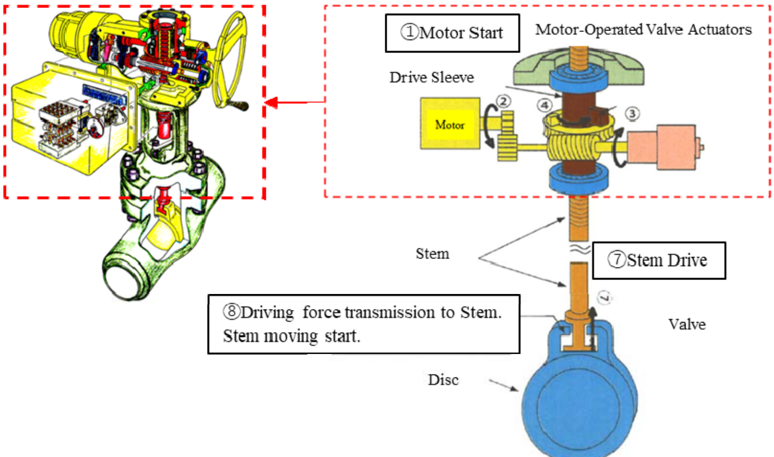
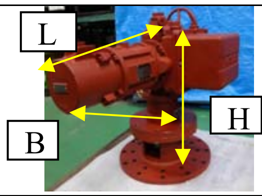


Fig. 2 – Structure of motor-operated valve

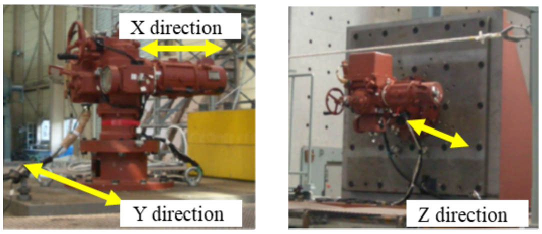
Therefore, we performed the calculations of marginal acceleration by simplified evaluation methods and the classifications of main parts by utilized IEEE382 to cover all types of motor-operated valve actuators. Through the above surveys, as shown in Table 3, six types of specimens were extracted.

Table 3 – Specifications of the test specimens

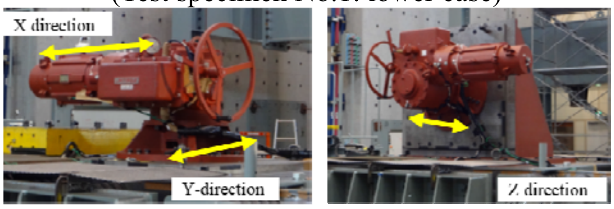
Test specimen No.	**Manufacturer**	**Items**	
1	A	Dimensions: B× L ×H =560×901×468 mm Total mass：477 kg	
2	A	Dimensions: B× L × H =308×1073×308 mm Total mass：512 kg	
3	A	Dimensions: B× L × H =460×1262×572 mm Total mass：677 kg	
4	A	Dimensions: B× L × H =610×1683×777 mm Total mass：1802 kg	
5	B	Dimensions: B× L × H =808×667×626 mm Total mass：430 kg	
6	B	Dimensions: B× L × H =806×1083×787 mm Total mass：660 kg	

3.1.2 Results of seismic tests for motor-operated valve actuators

Definitions of directions of seismic tests are shown in Figure 3. The results of seismic tests which were selected in 3.1.1, the performance of all of the specimens during and after the seismic tests were satisfied. Therefore, the operability of active components was confirmed at the target response accelerations of 20×9.8 m/s^2 or greater at the center of gravity of the valve actuators, in the horizontal directions (X and Y) and the vertical direction (Z).



(Test specimen No.1: lower case)



(Test specimen No.4: upper case)

Fig. 3 – Definitions of shaking directions

Figure 4 shows the summary of seismic test of test specimen No.2 for reference. Regarding to the other test specimens, we also confirmed the functional integrity of motor-operated valve actuator and there was no significant deference in operation time compared with test specimen No.2.

Summary of operating time (Open to Close)

Direction	Acceleration	Operating Time (sec)		
		Before	During	After
X	3×9.8m/s²	11.21	11.17	11.35
X	15×9.8m/s²	11.35	11.50	11.29
X	20×9.8m/s²	11.29	11.51	11.07
Y	3×9.8m/s²	11.28	11.35	11.21
Y	15×9.8m/s²	11.20	11.23	11.25
Y	20×9.8m/s²	11.25	11.16	11.17
Z	3×9.8m/s²	11.22	11.37	11.28
Z	15×9.8m/s²	11.07	11.64	11.38
Z	20×9.8m/s²	11.38	11.38	11.20

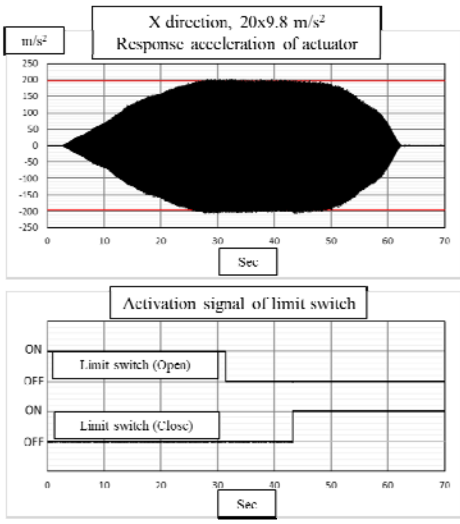


Fig. 4 – Summary of seismic test of test specimen No.2

In addition, such as butterfly valve, motor-operated valve actuator has a secondary reduction gear, so that we also performed seismic test. When the large acceleration was exerted, followings 2 events were occurred.

(1) Compressive deformation (protruding) of the gasket at a motor connecting part

Figure 5 shows the compressive deformation (protruding) of the gasket at a motor connecting part. Although the settling of the gasket was a main failure mode of this case, it was not affected the functional integrity of motor-operated valve actuator during the seismic test, so that it was determined that there was no problem.

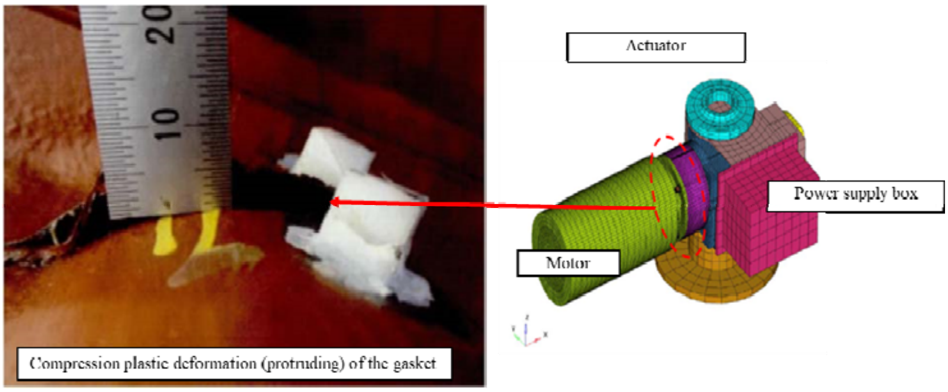


Fig. 5 – Compressive deformation (protruding) of the gasket

(2) Breakage of the secondary reduction gear

Figure 6 shows the breakage of the secondary reduction gear. As the result of survey, the critical part under the seismic condition is the flange of the mounting adapter at the connection between actuator and secondary reduction gear. Therefore, a seismic bracket that can withstand 20 × 9.8m/s^2 was designed based on the failure mode. Specifically, the thickness of the seismic bracket and the diameter of the mounting bolts have been revised and reinforced. In addition, a seismic test was performed to apply reinforced seismic bracket (Figure 7) to achieve 20 × 9.8 m/s^2 or more of a response acceleration of the center of gravity of the specimen in two horizontal directions and vertical direction. As the result, it was confirmed that the operability of active components.

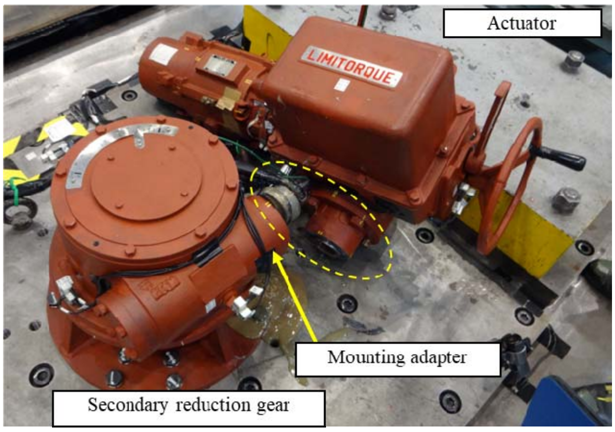


Fig. 6 – Breakage of the secondary reduction gear

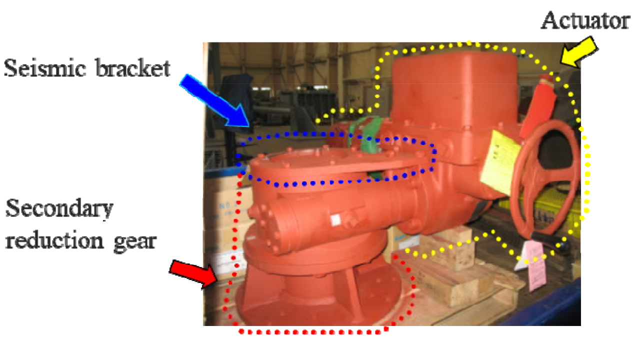


Fig. 7 – Motor-operated valve actuator with seismic bracket

3.1.3 Summary of seismic tests for motor-operated valve actuators

The operability of active components (A_{T1}) of the motor-operated valve actuators were 20×9.8 m/s^2.

3.2 Main Steam Safety Relief Valve (SRV)

3.2.1 General description and selection of the test specimens for Main Steam Safety Relief Valve (SRV)

SRVs are overpressure protection devices in the RPV boundary and are located on the main steam lines between the reactor vessel and the first isolation valve within the drywell. SRVs are typically structured as spring-loaded safety valves with pneumatic actuators as auxiliary actuating devices, and they provide the following protection functions.

(1) Safety function (spring-actuated mode)

The SRVs function as safety valves that are opened to prevent RPV boundary over pressurization. They are self-actuated by inlet steam pressure if not already signaled to open for the relief function. The SRVs are reclosed automatically when the inlet pressure reaches the reclosure pressure after blowdown. This function is used in RPV depressurization in the event of a design basis accident or a severe accident.

(2) Relief function (power-actuated mode)

The SRVs are opened using a pneumatic actuator upon receipt of an automatic or manually initiated signal to reduce pressure or to limit a pressure rise. The SRVs are reclosed automatically or in response to a manual signal after blowdown.

There is one manufacturer of SRV which is applied in BWR plants in Japan and this mamufacture has three types of SRV based on popping pressure. However, the basic structures which are related to functional requirement are equivalent. In addition, the seismic marginal accelerations calculated by simplified evaluation method are almost same as each types of SRVs, so that we selected the most popular type used in BWR plants in Japan as the test specimen (Figure 8). The specifications of the test specimen are shown in Table 4.

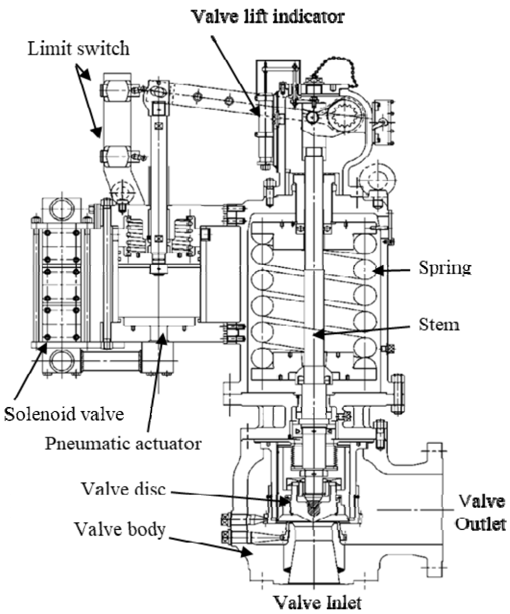


Fig. 8 – Structure of an SRV

Table 4 – Specifications of the test specimen

Dimensions	Approx. 1300 mm × 500 mm × 1800 mm
Total mass	1600 kg
Inlet size	6 in. (Nominal pipe size)
Outlet size	10 in. (Nominal pipe size)

3.2.2 Results of seismic tests for SRV

Definitions of directions of seismic tests are shown in Figure 9. The results of seismic tests which were selected in 3.1.1, the performance of all of the specimens during and after the seismic tests were satisfied. Therefore, the operability of active components was confirmed at the target response accelerations of 20×9.8 m/s^2 or greater at the center of gravity of the valve actuators, in the horizontal directions (X and Y) and the vertical direction (Z).

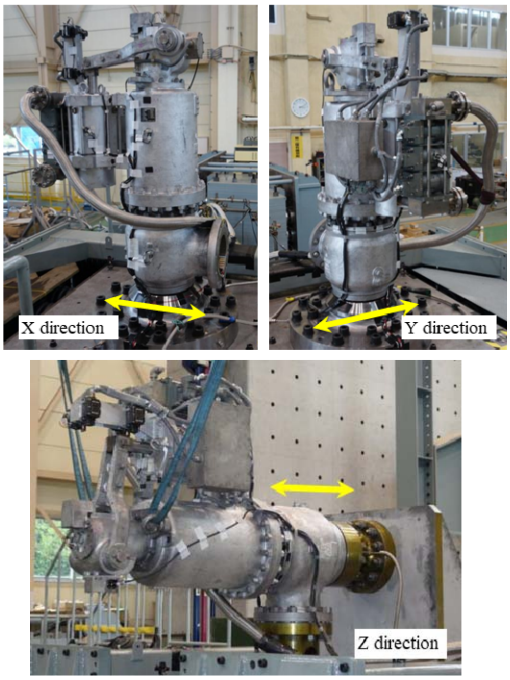


Fig. 9 – Definitions of shaking directions

The target response accelerations of the center of gravity of the pneumatic actuator were achieved. Figure 10 shows the response acceleration wave profile in the X direction, at a target acceleration of 20×9.8 m/s^2, for example. The test specimen showed no serious damage after all seismic tests, and the structural integrity of the test specimen was verified. Seat leakage was confirmed after high-acceleration tests over 10×9.8 m/s^2. Although the quantity of leakage could not be measured exactly using the prepared measuring cylinder, it was not so excessive as to prevent maintaining the inlet pressure. After the valve seat was wrapped, the next test was carried out. The conditions for evaluating the functional motion are described below.

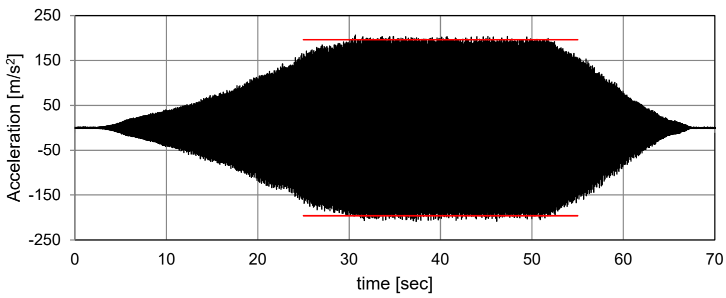


Fig. 10 – Response acceleration of the pneumatic actuator (X direction, 20×9.8 m/s^2 test)

(1) Testing for the safety function

The safety function motions during high-level acceleration over 10×9.8 m/s^2 were not achieved, but the motions were confirmed after the vibrations. The measured popping pressures shown in Table 5 were not excessively different from the baseline pressure of 8.56 MPa. Concerning the popping failure, the following events were confirmed from the valve inlet pressure profile. The inlet pressure was reduced at high acceleration without a gas supply. After the response acceleration reached the target level, gas started to be supplied. As the pressure increased, the rate of pressurization fell, and the pressure was stabilized below the popping pressure. As the acceleration decreased, the inlet pressure became stable. The inlet pressure profile in the X direction at 3×9.8 m/s^2 in Figure 11 shows that popping was achieved, and the inlet pressure profile in the X direction at 20×9.8 m/s^2 in Figure 12 shows that popping failed. The depressurization was caused by seat leakage especially under high-acceleration conditions.

Table 5 – Popping pressures of safety function

Direction, Acceleration level	Popping pressure during vibration (MPa)	Popping pressure following vibration *2 (MPa)
X, 3×9.8 m/s^2	8.45	8.62
X, 15×9.8 m/s^2	- *1	8.20
X, 20×9.8 m/s^2	- *1	8.52 *3
Y, 3×9.8 m/s^2	8.35	8.55
Y, 15×9.8 m/s^2	- *1	8.18
Y, 20×9.8 m/s^2	- *1	8.30
Z, 3×9.8 m/s^2	7.85	8.31
Z, 10×9.8 m/s^2	- *1	8.29
Z, 20×9.8 m/s^2	- *1	8.30

*1: Popping not achieved
*2: Average pressure for three pops
*3: Testing after seat was wrapped

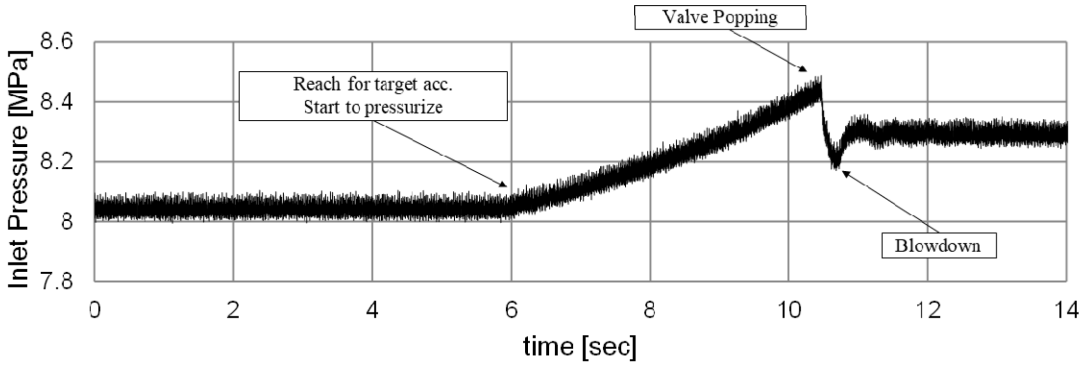


Fig. 11 – Inlet Pressure in X direction, 3×9.8 m/s^2 test

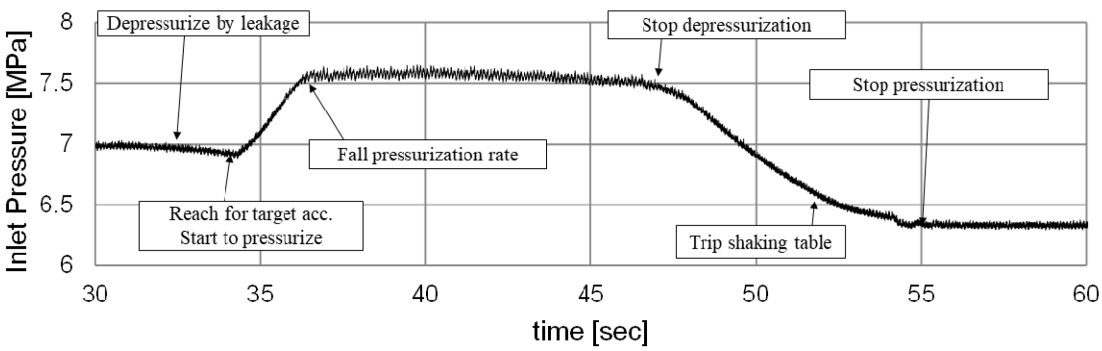


Fig. 12 – Inlet Pressure in X direction, 20×9.8 m/s^2 test

A) Discussion for safety function

The safety function during high-level shaking was not achieved. The reason is that the valve inlet pressure could not be increased to the popping pressure. The contact pressure of the valve seat decreased as the inlet pressure approached the popping pressure, which is a characteristic of spring-loaded safety valves. In such a state, the valve disc assembly is influenced by vibrations, and it is assumed that seat leakage also increases with high acceleration. In addition, seat leakage stops after the excitation is stopped.

The relief function during shaking exhibited no problems, and the safety function and the relief function after shaking exhibited no problems. The test valve suffered no serious damage. The reason why the safety function was not achievable during high-level shaking was the inability of the nitrogen gas supply system to supply nitrogen during a temporary valve seat leak. We assume that the safety function is achievable if there is sufficient gas supply, as in the steam in an actual plant. Thus, the safety function during shaking was evaluated as having no problem. Figure 13 shows the mechanism of set leakage.

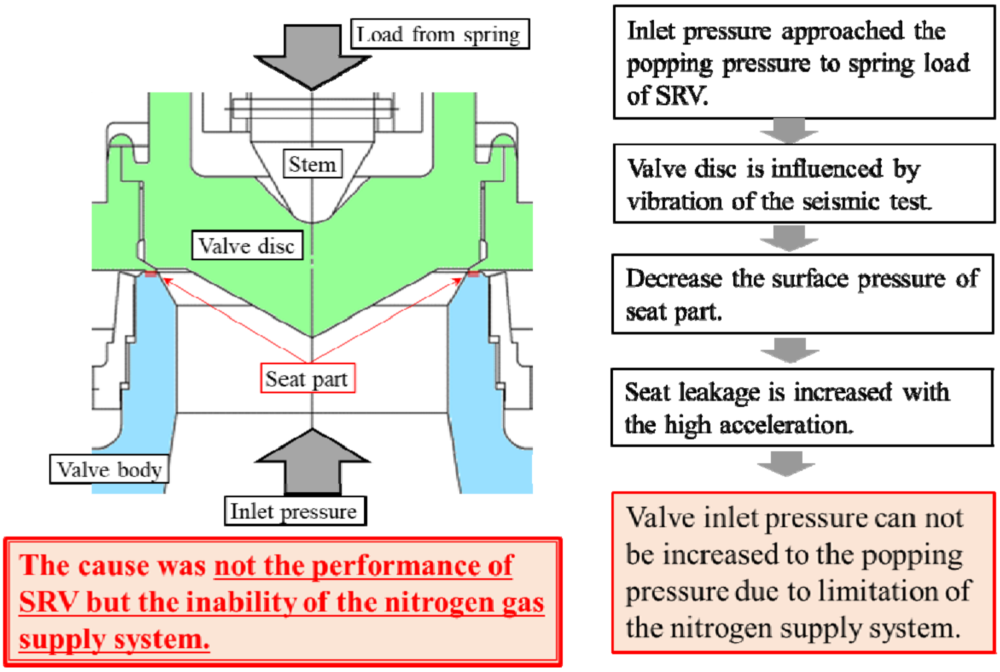


Fig. 13 – Mechanism of seat leakage of SRV during the seismic test

B) Discussion for seat leakage

Seat leakage was confirmed after high-acceleration tests over 10×9.8 m/s^2. The leakage was not so excessive as to prevent maintaining the inlet pressure. However, there are no quantitative and specific acceptable criteria for SRV seat leakage following an earthquake. Moreover, nuclear power plants mitigate damage by entering a shutdown mode following a large earthquake. A small amount of seat leakage is tolerable in depressurizing a reactor, and therefore does not cause a serious problem in safe shutdown of a plant. Thus, the small amount of seat leakage observed following shaking was evaluated causing no problem.

(2) Testing for the relief function

The relief function motions during vibration and after vibration were verified. All motions were confirmed successfully, and the measured opening times shown in Table 6 were not excessively different from the baseline opening time of 0.459 seconds. The opening time was defined as the time from energizing the solenoid valve (receiving function signal) to operating the upper limit switch (opening to full lift). Figure 14 shows the operating signals of the test specimen in the Y direction at a target acceleration of 20×9.8 m/s^2, for example. The limit switch signals and the power of the solenoid valve signal were normalized to values from

0 (OFF) to 1 (ON) by each contact voltage. The valve lift indicator signal shows the stem position, from closed (0%) to fully open (100%).

Table 6 – Opening times in relief function

Direction, Acceleration level	**Opening time during vibration(s)**	**Opening time following vibration (s)**
X, 3×9.8 m/s^2	0.457	0.453
X, 15×9.8 m/s^2	0.446	0.434
X, 20×9.8 m/s^2	0.424	0.436
Y, 3×9.8 m/s^2	0.468	0.456
Y, 15×9.8 m/s^2	0.450	0.402
Y, 20×9.8 m/s^2	0.410	0.400
Z, 3×9.8 m/s^2	0.468	0.447
Z, 10×9.8 m/s^2	0.418	0.430
Z, 20×9.8 m/s^2	0.302	0.472

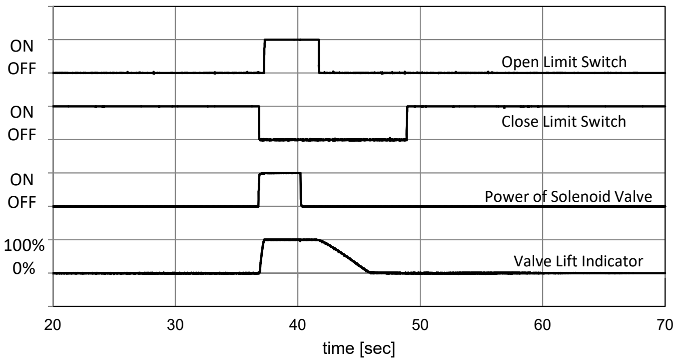


Figure 14 – Operating signals (Y direction, 20×9.8 m/s^2 test)

3.2.3 Summary of seismic tests for SRV

The relief function of the SRV was confirmed for response accelerations up to 20×9.8 m/s^2 for three directions. On the other hand, the safety function during high-level shaking was not achieved, but the reason for this was the limited capacity of the nitrogen supply system. The safety function of the SRV was assumed to be achievable if there is sufficient gas supply, like the steam in an actual plant. In addition, seat leakage was confirmed after high-acceleration tests. However, a small amount of seat leakage is a tolerable following a large earthquake, and therefore does not cause a serious problem in the safe shutdown of a plant.

4. Conclusions and future prospects

From the results of seismic tests, motor-operated valve actuators and SRV were judged to be capable of maintaining correct function for response accelerations up to 20×9.8 m/s^2 in all directions, that is, two horizontal directions and the vertical direction. The other type of valves (air-operated valve actuators and MSIV) are also organizing seismic tests data. We are planning to review and evaluate the functional maintenance confirmed acceleration based on the results of several seismic tests, to enhance the evaluation method and incorporate it into the Japanese seismic design code (JEAC4601(Ref. [12])).

5. Acknowledgements

This work was performed in a collaboration between Japanese Electric Power Companies and Nuclear plant manufacturers under a joint study titled "Study on improvement of validated seismic operability acceleration for the main steam safety relief valves" and "Study on improvement of validated seismic operability acceleration for the motor-operated valve actuators".

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