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A DEVELOPMENT OF THREE-DIMENSIONAL SEISMIC ISOLATION FOR ADVANCED REACTOR SYSTEMS IN JAPAN - PART 2

Kenji Takahashi*
The Japan Atomic Power Company （JAPC）, Ibaraki, Japan
Phone: +81-29-267-4141
takahashi.kenji@jnc.go.jp

Kazuhiko Inoue
JAPC, Ibaraki, Japan
inoue.kazuhiko@jnc.go.jp

Asao Kato
JAPC,Tokyo,Japan
asao-kato@japc.co.jp

Masaki Morishita
O-arai Engineering Center, Japan Nuclear Cycle Development Institute, Ibaraki, Japan
morisita@oec.jnc.go.jp

Takafumi Fujita
Institute of Industrial Science, The University of Tokyo, Tokyo, Japan
tfujita@iis.u-tokyo.ac.jp

ABSTRACT

Two types of three-dimensional seismic isolation systems were developed for the fast breeder reactor (FBR). One is the three-dimensional entire building base isolation system It was developed by collecting concepts Japanese companies from which a combination system with air springs and hydraulic rocking suppression devices was selected. The other is the vertically isolated system for main components with horizontally entire building base isolation, which was developed by adopting coned disk spring devices.

In the study, seismic condition was assumed based on a strict reference ground motion. Design data of the building and components are referred to FBR being developed as the “Commercialized Fast Reactor Cycle System”. Analysis based on these assumed conditions showed suitable combinations of natural frequencies and damping ratios for isolation. Devices were developed to satisfy the combinations.

In five years research and development, several verification tests were performed including shake table tests with scaled models. Finally it is found that the two types of seismic isolation systems are available for FBR. The result is reflected in the preliminary design guideline for the three-dimensional isolation system.

KEY WORDS: fast breeder reactor, seismic isolation system, air spring, hydraulic rocking suppression system

1. INTRODUCTION

The FBR design feature, compared with Light Water Reactor (LWR), is that the components are operated at high temperature and low pressure. High temperature generates large thermal strains in the components. Applying thinner component could reduce the stress intensity. Components with thin plate, however, do not resist intensive seismic loads. This is the reason the seismic isolation technology is suitable to FBR design. Seismic isolation technology enables not only mitigating the seismic design condition and realizing the thin plate components but also enhancing the structural integrity of the reactor building. The design guideline for the horizontal seismic isolation system was already published in Japan [1]. The next challenge is to mitigate the seismic load in the vertical direction. A project named ‘Three-Dimensional Seismic Isolation for Advanced Reactor System’ [3] was conducted from April 2000 to March 2005. This paper summarizes the whole project; mainly design condition, test results and practicability of the isolation systems.

2. SYSTEM CONCEPT

Two types of three-dimensional seismic isolation systems for FBR were selected in this R&D project through the viewpoints of realization and economic competency. One is the three-dimensional entire building seismic isolation system (3DeSIS), the other is the vertical isolation of main components with horizontal base isolation system (Vertical+2D SIS), which are schematically shown in Figure 1. In 3DeSIS, 3D seismic isolation devices support the entire reactor building. In the Vertical+2D SIS, horizontal seismic isolation devices support the building and the vertical seismic isolation devices support the 'common deck' that holds main components such as reactor vessel (RV), intermediate heat exchanger(IHX) and pumps.

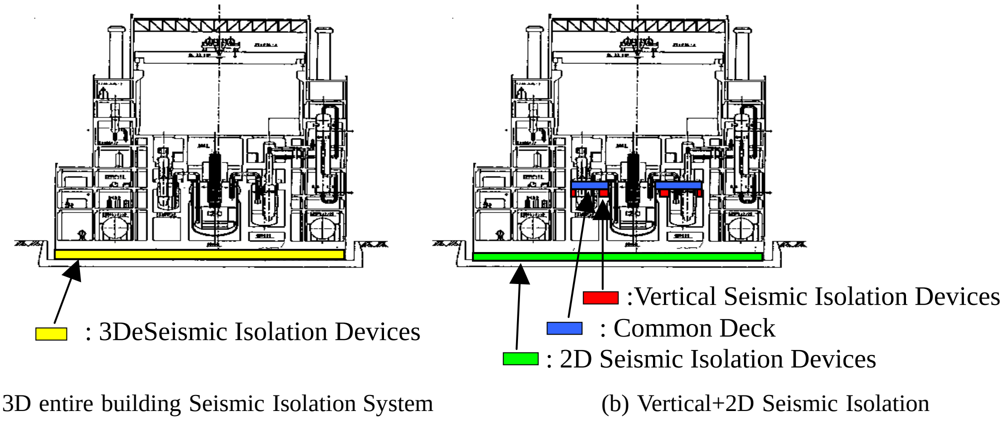


Figure 1 Three-Dimensional Seismic Isolation Systems

3. REQUIREMENTS

3.1 Seismic Condition

The seismic condition for the research was defined sufficiently large so not as to be required as a condition in the future. A horizontal ground motion spectrum once defined in a past study (Kato M. et al., 1995 [2]) is adopted (Figure 2). This spectrum envelopes all the S_2 design ground motions for the Japanese LWR in the short period acceleration range and the spectral velocity was extended up to 2.0 m/s in the period ranging from 0.62 s to 10.0 s since the long period range is important for the seismic isolation systems. The vertical ground motion spectrum is defined applying a spectral ratio of 0.6 through the entire period, resulting in the maximum spectral velocity of 1.2 m/s (also shown in Figure 2). A set of ground motion time histories was generated to be compatible to these spectra. Their maximum accelerations in the horizontal and vertical time histories are 8.31 m/s^2 and 5.56 m/s^2respectively.

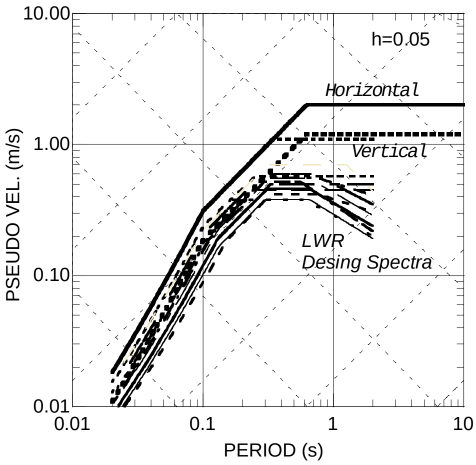
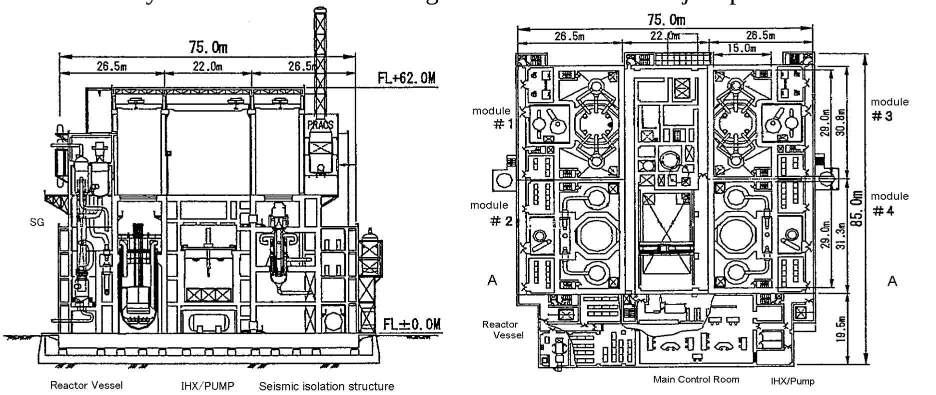


Figure 2 Design ground motion

3.2 Plant Condition

To obtain the requirements from the reactor building, middle-scaled sodium cooling type FBR plant was adopted for reference, which is one of the promising plants in the ongoing R&D project for commercialized FBR. Figure 3 shows the layout of the reactor building. Table 2 shows the major specifications of the plant [4].



(a) Cross-section of the plant (b) Floor layout plan of the plant

Figure 3 Layout of the reactor building

Table 2 Major specifications of the plant

Items	Specifications
Reactor type	Sodium-cooled loop type reactor
Electricity output	750MWe×4
Building size	82m×75m×62m
Weight of the reactor building	About 2650MN

3.3 Required Performance

In the beginning of the project, to define the appropriate range of isolation period, performances required of the seismic isolation devices were investigated from the response analysis of the components and the building structures.

(1) Component design aspect

-To sufficiently reduce vertical acceleration → Acceleration at the reactor support
$<14m/s^2$ (at 3Hz), $<9m/s^2$ (at 1Hz) and so on

-To avoid fuel assembly uplift → displacement of the reactor support plate< 6.5mm

-To avoid reactor vessel buckling. → Keep the theoretical formula with safety ratio 1.35

-To suppress relative displacement of piping → Displacement <0.7m for 3DeSIS, <0.12m for Vertical SIS

(2) Building structure design aspect

-To suppress amplification of vertical acceleration → Acceleration of the building $<9.8m/s^2$

-To avoid uplift of isolation devices → Acceleration of the device$<9.8m/s^2$

-To reduce horizontal acceleration (not to generate rocking motion)
→Acceleration of the building with rocking motion $<19.6m/s^2$

Suitable combinations of appropriate frequency and damping ratio both for 3DeSIS and Vertical SIS were mapped by analysis with simulation models (Table 3). The target combination s for the devices shown in Table 4 are included in the suitable region s .

Table 3 Target frequency and damping

(a) For 3D SIS

Frequency (Hz)	Damping (%) 2	10	20	40
20				
3.0				
1.5				
1.0				
0.67				
0.5				

(b) For Vertical+2D SIS

Frequency (Hz)	Damping (%) 2	10	20	40
20				
3.0				
1.5				
1.0				
0.67				
0.5				

Table 4 Targets for the seismic Isolation devices

Seismic isolation system type	Vertical Frequency (Hz)	Vertical Damping Ratio (%)
3DeSIS	Less than or equal to1.0	20～40
Vertical +2D SIS	Around 1.0	20～40

4. THREE-DIMENSIONAL ENTIRE BUILDING SEISIMIC ISOLATION SYSTEM

4.1 System Concept

At the beginning of this R&D, several conceptual ideas for a 3DeSIS were proposed. These ideas were evaluated with tests using some reduced scale models. Finally the 'rolling seal (U-shape rubber) type air spring' [7] was selected for further development. Criteria for the selection were isolation performance, system reliability, applicability to the real plant, maintainability and economic competency. The idea of the 'hydraulic type of rocking-suppression cylinder system' [6] was also selected to suppress the excessive rocking motion of the building, which occurs on the three-dimensionally isolated structure. Figure 4 shows the selected combined concept of 3DeSIS. At the bottom of the reactor building, 160 air springs are delivered at the inner area and 112 hydraulic supports function with rocking suppression systems at the outer area. The rocking suppression cylinder system is shown in Figure 5. Hydraulic pressure of the load support cylinder is connected to the rocking suppression cylinder and further to the accumulator unit which mitigates the shock of the vertical load by gas inside. All piston rods of the rocking suppression cylinder are connected to each other so that pistons at both ends of the building compensate the vertical counter force and suppress the rocking motion.

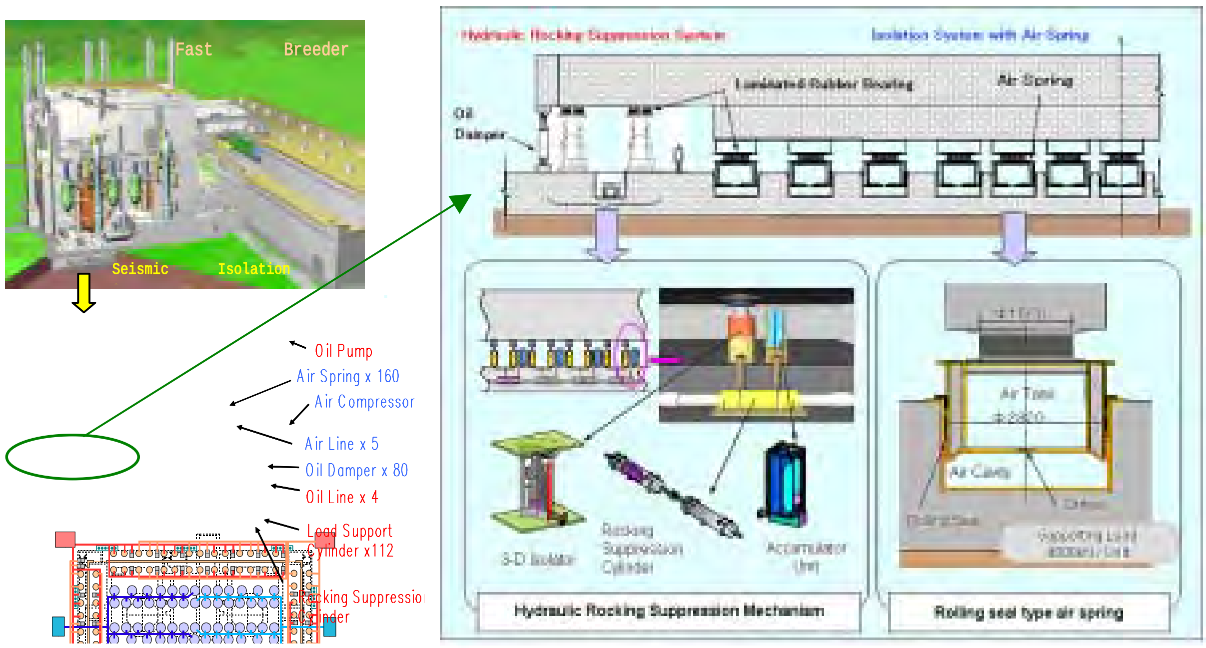


Figure 4 Concept of three-dimensional entire building seismic isolation system

Table 5 Main specifications of the candidates

	Hydraulic rocking suppression sys.	Rolling seal type air spring
Load Capacity	9.8 MN	9.8 MN
Inner Pressure	25 MPa	1.6 MPa
Vertical Period	2sec	
Horizontal Period	2.8sec	

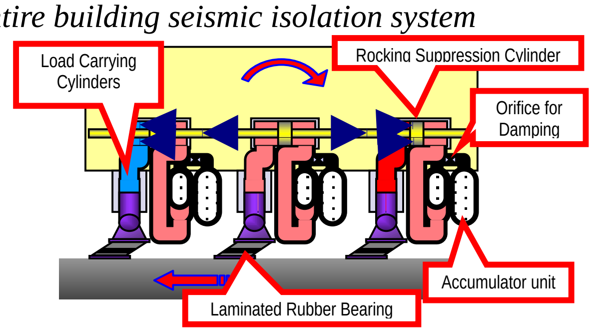


Figure 5 Rocking suppression system function

4.3 Verification Tests

(1) Air spring test

The Rolling seal type air spring was tested on the shake table with a 1/7 scaled model. The model consists of four air springs and four oil dampers. From the test result, natural frequency and damping ratio of the air spring and the oil damper were measured. The data were used for the combined system test on the shake table.

(2) Hydraulic function test

To investigate the performance of each element of the hydraulic rocking suppression system, cyclic load test was conducted with a 1/7 scaled model which consists of load support cylinder, rocking suppression cylinder, accumulator and corner cylinder. Natural frequency of the hydraulic rocking suppression system in the vertical direction and damping force were measured. Obtained data were used for the shake table test of the combined system.

(3) Combined system test

To investigate movement of the combined system of air spring and hydraulic rocking suppression system, shake table tests with a 1/7 scaled combined system were conducted (Figure 6). The scaled model consists of a building model, four air springs and four hydraulic support cylinders which are connected to four accumulators via four rocking suppression cylinders. The rods of the rocking suppression cylinders are connected to the corner cylinders installed at the corner of the shake table.

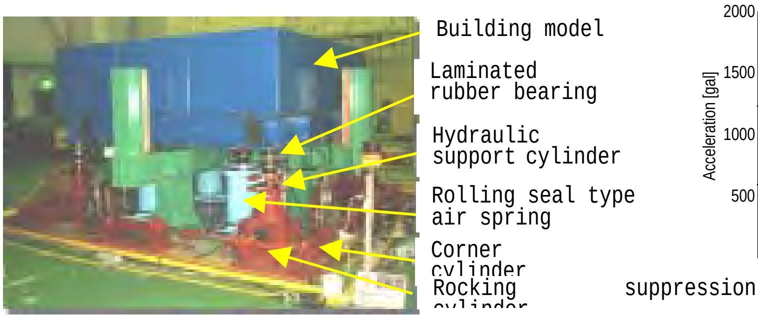


Figure 6 Picture of Combined System

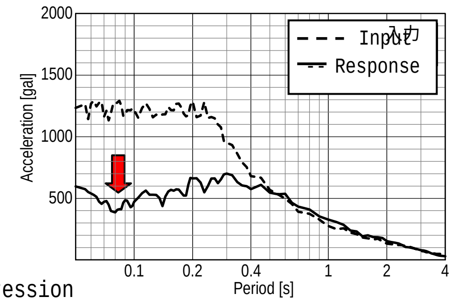


Figure 7 Floor Response Spectra (Vertical direction, model scale)

(4) Test results

- Support and isolation ability (Figure 7) were confirmed. Vertically, natural period and damping ratio (respectively 2.0sec, 40% in transformed real scale) satisfy the requirement.
- Devices move soundly. Especially, vertical movement of the sliding devices functions as expected.
- Damping by orifice shows good approximation to the analyzed value. Friction force accounts for a large part of the damping ratio. Applied to the real plant, friction is expected to become smaller.
- Damping ratio in the horizontal direction depends on the laminated rubber bearing with lead damper. This device functions as expected.
- Rocking motion was suppressed well by the rocking suppression device (inclination: less than 1/ 1000).
- Interference of vertical force and horizontal force are negligible. Analysis can be performed individually.

4.4 Applicability to the Plant

Based on the result of the verification test, applicability of the system was considered.

(1) Applicability of the Isolation Device

The test results show good approximation to the analyzed value in the simulation model. Designing factors were confirmed in the simulation. To design the real plant, a simplified practical model is applied to the simulation. The upper building elements are added to the practical model. Figure 8 shows the practical model. Vertical direction and horizontal direction are analyzed separately. The analyzed result with the practical model shows approximate value to the test result (Figure 9). The practical model is found to be applicable to the real plant.

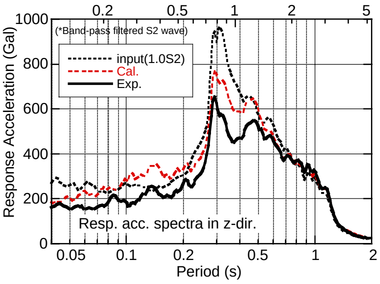


Figure 8
Floor Response Spectra
(Vertical direction)
-Comparison of experimental value and analysis of practical model without upper elements -

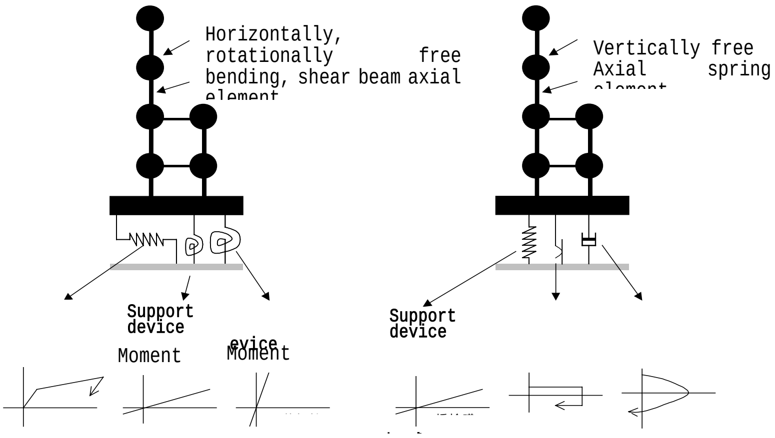


Figure 9 Practical model analysis
-With upper elements-

(2) Practicability evaluation

Practicability of 3DeSIS for the FBR is evaluated by confirming the specifications. Requirements and provided specifications are shown in Table 6. Values in Table 6 are shown on the real plant scale.

Table 6 Practicability Evaluation

	Required Items	Air spring	Hydraulic rocking suppression sys.
Performance	Variable range of natural period	1.0s〜3.0s	1.7s〜2.8s
		Whole system: 1.7s〜2.8s	
	Damping ratio	Air spring : 10% Oil damper : 10%	25%
		Total :more than 20%	
	Stroke margin	less than 1/2 of physical limitation	less than 1/2 of physical limitation
System reliability	Numbers of support device	160(5 lines)	112(4 lines)
	Protection from environmental condition	With protection cover (Applicable range -35C〜55C)	Dust seal
	Thermal condition	Air Conditioned	
	Exchange time of devices	Air spring : 0〜1time/60 years Oil damper :0 time/60 years	Oil seal: less than 1 time /20 years Bladder: less than 1 time/10 years Oil: less than 1 time/10 years
Applicability	Work space for maintenance	Space around the spring : 0.5m Width of the corridor : 3.5m Height of corridor : 2.2m (without adaptation of building)	Width of the corridor : 2.5m (without adaptation of building)
	Installation (With trial schedule)	Not causing bottleneck (Total 4.5 months)	Not causing bottleneck (Total 7.5 months)
	Allowable damaged device number*	27	8 (59)**
Maintainability	Required man-days for inspection	Patrol 1day by 2men ISI 4days by 6men	Patrol 4.5days by 4men ISI 18 days by 7men
	(Remarkable note)	- Sliding device is inspected intensively. - Sampling test device for durability affirmation is delivered.	

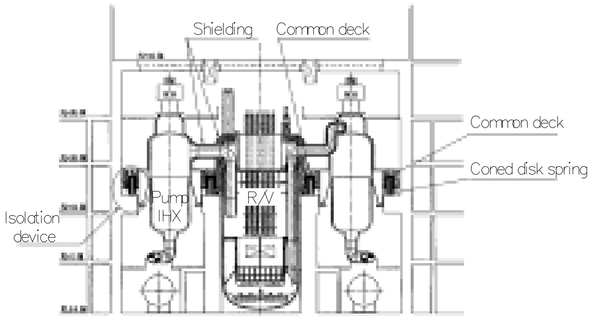
* In the condition of 1.0 S2 seismic force
** In the case that the damaged devices are not located at one side.

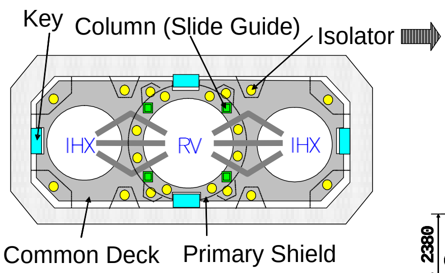
5. VERTICAL SEISMIC ISOLATION SYSTEM

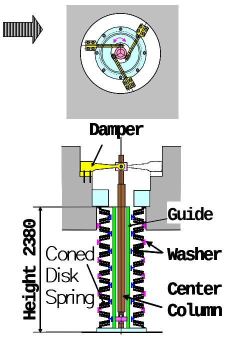
5.1 System Layout

Figure 10 shows the layout of vertical SIS based on the design of FBR. The common deck which supports main components (RV, IHX, Pump, piping) is vertically isolated from the reactor building by 20 seismic isolation device units. One unit consists of 70 coned disk springs. In the unit, five springs are stacked in the same direction and the next five springs are in the opposite direction. Washers are inserted between every 5 spring sets. Damping force is obtained from the three dampers attached at the top of the isolation unit. The damper is a type of cantilever made of steel.

Horizontally, the common deck is held by four key functions at every side and four sliding guides around the reactor. These functions keep the horizontal rigidity of the common deck. The temperature of the common deck is controlled and thermal expansion in the operation does not affect the support function.







Coned Spring O.D.	Φ1m
Coned Spring Thickness	27mm
Coned Spring / unit	5x14
Supporting Load	275tonf

Figure 10 Layout of vertical seismic isolation system

5.2 Verification Test

(1) Coned disk spring test

Test of the coned disk spring was conducted with several scale test pieces [5]. Properties were investigated with real size test piece because the size is huge and beyond the Japanese industrial standards.

(2) Damper test

Damper's characteristics were investigated with real size test pieces. This damper was designed to obtain 150kN damping force. In order to confirm the stability of dynamic characteristics and fatigue strength of the damper, cyclic loading tests with constant displacement with the estimated response wave were conducted.

(3) System test

To confirm the feature of the system, shake table tests were conducted with a 1/8 scale model of the common deck. Figure 11 shows the model, which has four coned disk spring units, four key functions and slide guides. In the basic test, system characteristics (response, natural period, damping ratio) were measured. Obtained data are applied to the design of a real plant. To raise the credibility of the system, a mass balance test was performed. Rocking motion with imbalanced masses delivered on the common deck was measured.

(4) Horizontal force test

Affection of the horizontal force and displacement to the vertical movement was investigated. The test was performed with a 1/8 scale model (5stack x 14) and 1/2 scale model （5stack x 4）.

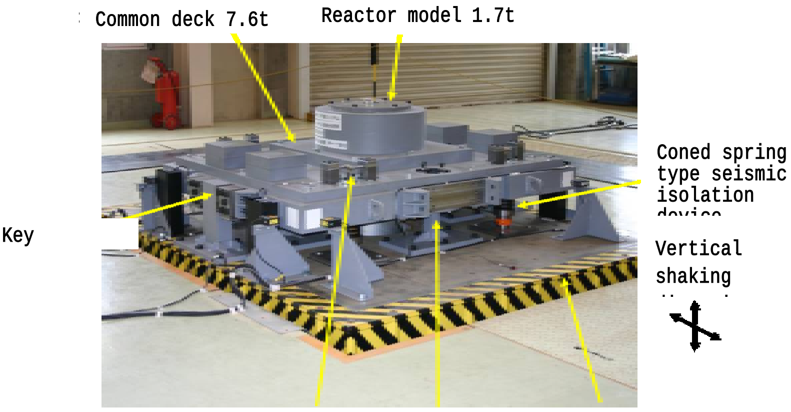


Figure 11 Picture of the vertical isolation system test

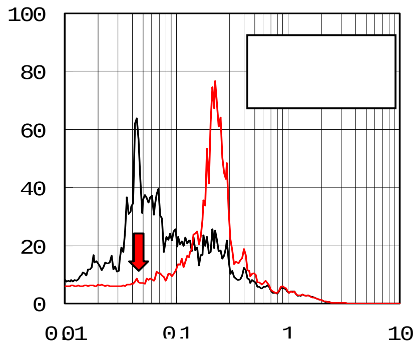


Figure 12 Floor response spectra (Vertical direction arranged to real plant scale)

(5) Test results
- The system moved soundly and performed the expected isolation ability (Figure 12).
- The large dimensional coned disk performed according to the theoretical rule.
- Friction coefficient between the coned disk springs (and washers) was about 0.1.
-The steel damper satisfied required damping ratio and durability.
- Rocking motion is negligible in the condition that the gravity center of the isolated staffs (components, piping and so on) is located inside the structure of the common deck.
- Affection of horizontal displacement is negligible for the vertical movement of the isolation device.
- Displacement of the isolation unit is not observed when washers with high rims are applied.

5.3 Applicability to the Plant

(1) Applicability of the isolation device

The test results show the system has the isolation ability in the real scale. Real size data of the coned disk spring were obtained. Analysis can be performed with the vertical and horizontal models. The gap between the common deck and supporting key is not generated in the normal operating temperature.

(2) Practicability evaluation

Practicability of the vertical SIS for FBR is evaluated by confirming the specification. Requirements and specifications are shown in Table 7. Values in Table 7 are shown on the real scale.

Table 7 Practicability evaluation

Items	Required Item	System
Performances	Variable range of natural period	0.6 ～ 0.8 s
	Damping ratio	20～40%
	Vertical stroke margin	±100mm （less than 1/ 2 of physical limitation）
System Reliability	Numbers of support device	20 coned disk spring isolation units /common deck
	Protection from environmental condition	Air conditioned （Temperature:20C～40C）
	Exchange time of devices	No exchange in life time (maintenance free)
Applicability	Work space for maintenance	Operation floor
	Install term (With trial schedule)	Not causing bottleneck 65days /common deck
	Allowable damaged device number	20 units (trifle damage)* The unit functions in the condition of slight damages
Maintainability	Required man days for inspection	Patrol: 16 man days In service inspection: 19 man days

* In the condition of 1.0 S2 seismic force

6. CONSIDERATION

6.1 Applicability

Noticeable points to adopt the isolation system are as follows.

(1) 3D entire building seismic isolation system

(a) Layout concept in the plant building is almost the same as the conventional plant. Isolation system is applied to the plant with little modification.

(b) The area where the isolation system is installed is not affected by radiation. In-service inspection can be done easily. Maintenance can be conducted any time when a failure is found in the daily patrol.

(c) Numbers of support device are 272. Function failure of 10% of total system devices does not lose isolation function. Device is able to be exchanged in the operation term.

(d) Oil, oil seal, bladder in hydraulic system and rubber in air spring are exchanged once in 10～30years. It can be detected in advance by investigating the sampling test device for durability affirmation.

(e) In order to keep the building floor level horizontal, pressure in the device and surrounding air temperature need to be controlled.

(2) Vertical + 2D seismic isolation system

(a) The coned dish spring is reliable and essentially maintenance free in its whole life.

(b) The common deck is installed at the area where components and piping are concentrated. A minimum number of isolation devices are installed.

(c) The common deck makes the reactor building a little larger.

(d) The system is installed at the area affected by radiation. Material and lubricant of the isolation equipment need to be radiation-proof. Access time needed for inspectors is limited and inspection is usually done with remote monitors.

(e) To exploit the function of horizontal isolation system under the reactor building, the common deck needs to be supported firmly in the horizontal direction. Temperature of the common deck needs to be controlled.

6.2 Further Research

To make the system more reliable, economical and practical, further research should be performed.

(1) Enhancement of reliability

(a) Verification test with real size model (3DeSIS)

-To obtain better designing properties

-To confirm behavior of the devices at near their performance limit

(b) Test with real building

-To obtain data in the real condition

(2) Cost reduction

(a) High pressurized air spring (3DeSIS)

-To make the air spring smaller and flexibly delivered

-To make the manufacturing cost lower

(b) Improvement of hydraulic seal (3DeSIS)

-To make the hydraulic seals stronger and durable

(c) Improvement of the layout (Vertical SIS)

-To avoid interference of equipment, i.e. horizontal support structure, cooling pipe

-To reduce the factors which make the reactor building large.

(3) Preparation of design guideline

-To stipulate combination way of force, margin, criteria, etc.

-To accumulate real and concrete data about the plant, i.e. inclination, temperature, water proof etc.

7. CONCLUSIONS

Three-dimensional seismic isolation systems for the nuclear plant were developed. From tests of the system element and analysis, both the ‘3D entire building seismic isolation system’ and the ‘Vertical+2D seismic isolation system’ were found to be applicable and their practicability should be developed further. Following are the basic items obtained in the study.

(1) Two types of isolation systems, a 3D entire building and a vertical +2D seismic isolation system were developed.

(2) For the 3DeSIS system, the ‘rolling seal type air spring with hydraulic rocking suppression system’ was finally selected from several kinds of concepts.
(3) For the vertical +2D system, the coned disk spring technology is applicable.
(4) Seismic condition for the analysis adopted a conventional ground motion used for the previous R&D. The ratio of the vertical to horizontal directions is settled to be 0.6.
(5) As the vertical frequency target, less than or equal to 1.0Hz in the case of 3DeSIS, around 1.0Hz in the case of vertical +2D SIS were settled. As the vertical damping ratio, 20 to 40% for both systems was settled.
(6) Verification tests of 3DeSIS were conducted. Isolation and rocking suppression were confirmed by shake table test with their combined 1/7 scale model furnishing four air springs and four hydraulic rocking suppression systems. Test results and analysis prove that the system is applicable to the real plant.
- Supporting load and isolation values (spring ratio, damping ratio) were reasonable and similar to the expected values.
- Rocking motion is suppressed by the hydraulic rocking suppression system.
- The practical simulation model for analysis is available to real plant design. Design data is prepared by adjusting the test result by scale factor.

(7) Verification test of vertical SIS was conducted and basic properties of the coned disk spring were measured.
- Each element of the isolation unit, coned disk spring, steel damper, and rimmed washer performed to the expected ability.
- Isolation systems including the common deck performed to vertical isolation ability.
- Horizontal force and displacement in the normal operation does not disturb vertical movement of the isolation devices.

(8) Practicability of the systems was evaluated with isolation performance, system reliability, applicability to the plant and maintainability.

AKNOWLEDGEMENTS

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