13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 3445

DEVELOPMENT OF THREE-DIMENSIONAL SEISMIC ISOLATION SYSTEM FOR NEXT GENERATION NUCLEAR POWER PLANT

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SUMMARY

Mitigation of seismic loads by seismic isolation technology is very promising for enhanced safety and economy of the next generation nuclear reactor, through rationalized and simplified design of structures, systems and components. The horizontal base isolation with laminated rubber bearings is a proven technology and its application has been widely spread including nuclear facilities. On the other hand, significantly increased benefit of mitigated seismic loads is expected with three-dimensional (3D) seismic isolation, since the seismic loads are inherently three-dimensional and the vertical component of the seismic load sometimes plays an important role in the structural design of reactor components. From these points of view, a large scaled research project has been undertaken for the development of 3D seismic isolation technologies, under the sponsorship of the Ministry of Economy, Trade and Industry of Japanese government.

Within this program, two types of 3D seismic isolation systems were selected appropriate for next nuclear power plant. One is the 3D entire building base isolation technology, and another is the vertical isolation device for main component with horizontally entire building base isolation technology. There were three promising ideas of the 3D entire building base isolation technology, i.e., “rolling seal type air spring”, “hydraulic 3D isolation system”, and “cable reinforced air spring”. Then one idea was chosen from these three ideas for next development. Also, “vertical component isolation system with coned disk springs” is under developing for vertical isolation for main plant components. This paper overviews the entire development program and the current status of these 3D isolation systems.

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INTRODUCTION

Fast Breeder Reactor (abbreviated FBR) is well known as a most promising nuclear power reactor in the next generation reactors. And FBR is also well known as a reactor that breeds the nuclear fuel. As Japan has little nuclear resources in its territory, the technologies those realize FBR have been developed for decades. In 1999, the R&D to realize the commercialized FBR has started as a Japanese national project. In the project, improving the economic competency of the commercialized FBR plant was set as one of the most important objectives as well as enhancing the safety.

The peculiar FBR design features compare with Light Water Reactor (abbreviated LWR) are high temperature and low pressure in components. Seismic design condition is common and it must be considered with temperature and pressure conditions. High temperature gives large thermal strain in components. Basically, thermal stress is in proportion to thermal strain, sectional rigidity of components and their boundary conditions. Therefore applying thinner component can reduce the stress intensity. In case of the design for thermal loads, thinner is the better.

On the other hand, in the design for pressure loads, the component thickness is based on pressure loads. Meanwhile, since the pressure loads are smaller in FBR than in LWR, relatively low stress would be induced and thinner components could be realized in FBR design. However, in the design for seismic loads, generally, thin component could not be realized, because such a thin component could not resist intensive seismic loads. At this point, the component design has a contradiction in choosing thickness for component. That is, the thickness must be thinner for thermal loads, must be thicker for seismic loads at the same time.

This very point was the reason for the seismic isolation technology was intended to introduce to FBR design, which enables not only to mitigate the seismic design condition and realize the thinner components, but also to enhance the structural integrity of the components and reactor building. In the R&D for the demonstration FBR, conducted from 1987 to 1997, horizontal seismic isolation technology was mainly developed. After the R&D was completed with the publication of the design guideline for the horizontal seismic isolation system [1], economical competency was strictly closed up than before. In such a situation, component design has challenged to realize thinner components. The only obstacle to the challenge was to mitigate the seismic load in vertical direction in the horizontal seismic isolation system, and the innovation and application of three-dimensional (abbreviated 3D) seismic isolation technology were required to solve the problem. On this background, ‘A large Scale R&D Project on 3D Seismic Isolation for FBR’ (abbreviated This R&D) started on April in 2000.

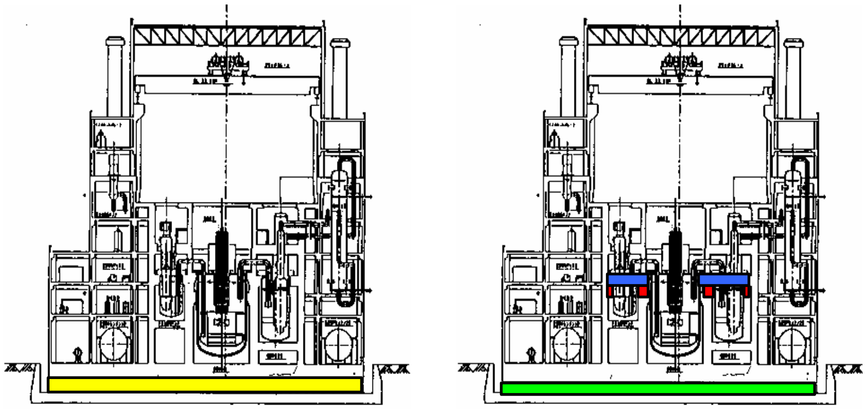
This paper shows the development policy of this R&D project, the performance requirements for 3D isolation system and devices, technical guideline for 3D isolation technology, and the selection result for next development step, which had been studied after the former conference.

DEVELOPMENT POLICY OF THIS R&D PROJECT

3D Seismic Isolation System Concept

A two-track approach was taken to promote this R&D by considering the realization and the development risk, so two types of 3D seismic isolation systems were selected appropriate to the FBR on this R&D project through the viewpoints of realization and economic competency. One is a 3D entire building seismic isolation system (abbreviated 3D SIS), the other is a vertically isolation for main components with horizontally entire building seismic isolation system (abbreviated V. +2D SIS).

Figure 1 shows both types of 3D seismic isolation systems. In the 3D SIS, 3D seismic isolation devices (abbreviated SID) support a reactor building as shown in Figure 1(a). In the V. +2D SIS, 2D SID support a building, furthermore, SID support a Common Deck that supports main components like the reactor vessel and the pumps etc. as shown in Figure 1(b).



(a) 3D Seismic Isolation System (b) V. +2D Seismic Isolation System

: 3D Seismic Isolation Devices
: Vertical Seismic Isolation Devices
: Common Deck
: 2D Seismic Isolation Devices

Figure 1. Three-Dimensional Seismic Isolation Systems

Development Plan of this R&D Project

Overall conceptual schedule of this project is shown in Table 1. As shown in the table, this project consists of three R&D items as Development Planning, 3D SIS development and V. +2D SIS development. These two types of 3D seismic isolation systems are developed respectively followed by the progress of the Development Planning. This project would be developed through the several experiments consisted of large-scale specimens. Outlines of each portion are shown below.

Table 1. Overall Conceptual Schedule of this R&D Project

Item	2000 2005
Development Planning	
3D Seismic Isolation System Development	Candidate concepts; Selection; Development; Design Guideline
V._+2D Seismic Isolation System Development	Development; Design Guideline
Feasibility study on the commercialized FBR	Phase II; Phase III

Development Planning

This item has a role of development navigation, which consists of setting initial conditions and development target. The initial conditions are seismic condition, building and component configurations, design feasibility evaluation criteria for component and building and so on. On the other hand, the development target is the property required to the 3D seismic isolation device like frequency and damping ratio. Both the initial conditions and development targets are required to update referring the relating commercialized FBR project in the early stage of this project.

3D Seismic Isolation System Development Method

In case of applying the 3D SIS to FBR, component layout has no need to change itself from that is appropriate to the horizontal seismic isolation system. This is a great advantage for plant design. However, it had the assignment to develop the 3D SID. While the device was required to exhibit 3D seismic isolation functions, there was no such a peculiar device when the project started. Consequently, this 3D SIS was developed by the method of collecting ideas from major private companies involved in the FBR development activities in Japan.

As the first step, nine ideas were proposed and then six of them were selected from the viewpoints of performance, reliability, applicability to FBR in design, construction, maintenance and economic competency. Then three ideas were selected through the development experiment activities using large-scale specimens. And then, an idea was selected for the next step development. And finally, this idea would be developed to the real 3D SIS through the experiments using large-scale test specimens.

V. +2D Seismic Isolation System Development Method

In case of applying the V. +2D SIS, the component layout has to be changed a little for installing the common deck in primary sodium circuit system. However, when this system was adopted, the assignment would be limited to realize the coned dish spring for the vertical isolation system supporting main components. The dish spring was selected as the vertical isolation device for its efficiency in design, layout, maintenance and economic competency. Since the coned dish spring technology was basically developed for smaller diameter spring, realization of larger size and confirmation of through plant life reliability on its performance could be major items of the assignment. So, the R&D on the applicability of the coned dish spring could be completed in a relatively short period.

As the development items, several experiments were planned to grasp the basic properties of the spring and to confirm the applicability of the current design formula to the larger size dish springs. Those experiments would be carried out using the large-size specimens to exclude the scale effect like a friction behavior from test results.

Target performances of 3D isolation devices

At the starting stage of the program, it was necessary to define the target performance, especially the vertical isolation frequency and damping, of the 3D seismic isolation systems to be developed. For this purpose, a design ground motion was defined, and an extensive series of parametric dynamic analyses was made with respect to the vertical frequency and damping.

Design Ground Motion

The basic idea in defining the design ground motion was that it should be sufficiently large so that no further increase is required in the future. With this in mind, the horizontal ground motion spectrum used in a past design study of a base isolated fast reactor design [1] was selected; see Figure 2. This spectrum was created so that it envelopes all the S2 design ground motions of the Japanese light water reactors 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 very important for the seismic isolation systems. The vertical ground motion spectrum was then defined applying a spectral ratio of 0.6 through the entire period, resulting in the maximum spectral velocity of 1.2 m/s, which is also shown in Figure 2.

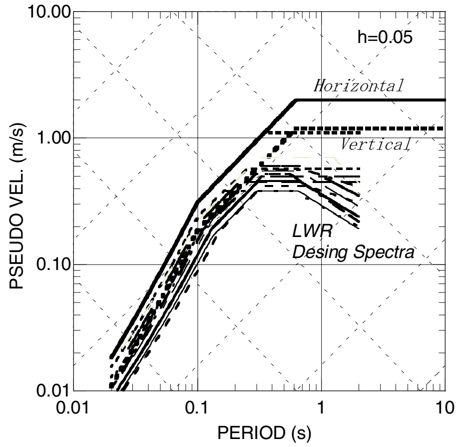
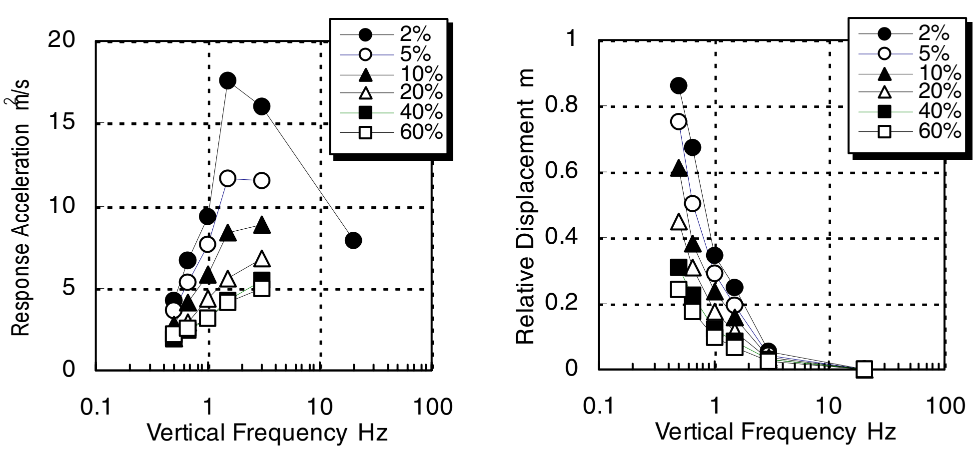


Figure 2. Design ground motion

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^2, respectively.

Isolation Frequency and Damping
In order to identify an appropriate range of vertical frequency and damping for seismic isolation purposes, an extensive series of dynamic analysis of a 3D isolated structure was made. Here, the vertical frequency and damping were the analysis parameters and ranged from 0.5 Hz to 20 Hz and 2% to 60%, respectively, while the horizontal isolation frequency and damping were fixed to be 1.0/0.5 Hz (1st/2nd stiffness) and 20%, respectively. The procedure and results of the analysis are described in detail in the reference [2]. In Figure 3 shown are some typical response results, in terms of (a) the maximum response acceleration at the reactor support level and (b) the maximum relative displacements of the 3D isolation devices. It can be noted that, as are noted in the horizontal base isolation, decreasing vertical frequency affects in decreased response acceleration and increased relative displacements. High damping can suppress excessive relative displacements especially in the low frequency range.



(a) Vertical response acceleration (b) Vertical relative displacement
Figure 3. Response results of a 3D isolated nuclear island

The target performance was then identified based on the above response results and the criteria in view of component design aspect and structure design aspect.
The component design aspect includes:

- To sufficiently reduce vertical acceleration so as to suppress reactivity insertion, to avoid fuel assembly uplift and to avoid reactor vessel buckling.
- To suppress relative displacement of piping

The structure design aspect includes:

- To suppress amplification of vertical acceleration
- To avoid uplift of isolation devices
- To sufficiently reduce horizontal acceleration

As a result, ranges of appropriate frequency and damping both for 3D base isolation and component vertical isolation systems were identified as shown by the shaded area in Table 2. Note that sufficiently low frequency and high damping are required especially in case of 3D seismic isolation.

Table 2. Identified target frequency and damping

(a) For 3D base isolation system

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

(b) For Component vertical isolation

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

In case of FBR, as the seismic load in vertical direction is not negligible, the vertical seismic isolation is especially effective to FBR by assuming a sufficiently large design ground motion.
Then both enhanced safety and economy could be expected by mitigation of the seismic vertical load.
The target performance of vertical isolation were set as 1.5 to 2 seconds for isolation period and 20% and up for damping to achieve a long isolation period in vertical direction to attain sufficient acceleration mitigation.

DEVICES FOR 3D BASE ISOLATION

At the starting time of the program, a number of conceptual ideas for a 3D base isolation device were proposed, among which some had been screened out for several shortcomings they had. At present three candidate concepts remain and development efforts are made on these concepts for final selection.

Rolling Seal type Air Spring

This concept uses a series connection of a laminated rubber bearing and an air spring with rolling seal type rubber [3], as is shown in Figure 4. A cylindrical cavity is prepared in the lower base-mat of the nuclear island and used as an air compartment. A steel/concrete cylinder is inserted to the cavity with a rolling seal type rubber to form an air spring. The cylinder is then connected to the rubber bearing which

is connected to the upper base-mat. A large stroke in the vertical direction is enabled by using the rolling seal. As a supporting system, air supply system and leveling devices are provided.
The diameter and the height of the compartment are 1.4 m and 3 m, respectively. The design air pressure is 1.6 MPa for normal condition and 2.0 MPa for design earthquake condition, resulting in the design vertical frequency is 0.5 Hz and the loading capacity of 9800 kN.
Critical issues for this device include:
- Ultimate rupture strength of the rolling seal rubber against internal pressure,
- Deterioration by aging of the rubber material,
- Smooth motion at the contact part of the cylinder and the air compartment, when a lateral load and a moment is applied.

Some experimental tests using small scale models of the device have been carried out to see whether these issues can be resolved, and some successful results are being obtained, see also the reference [3].

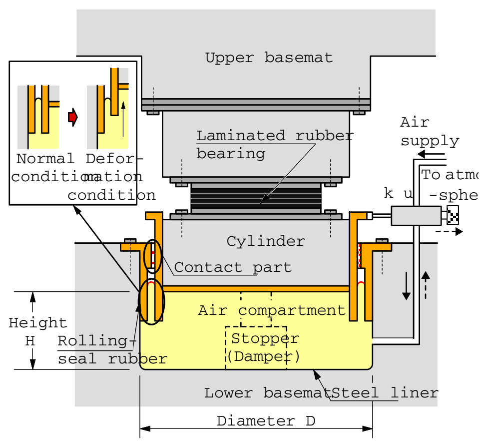
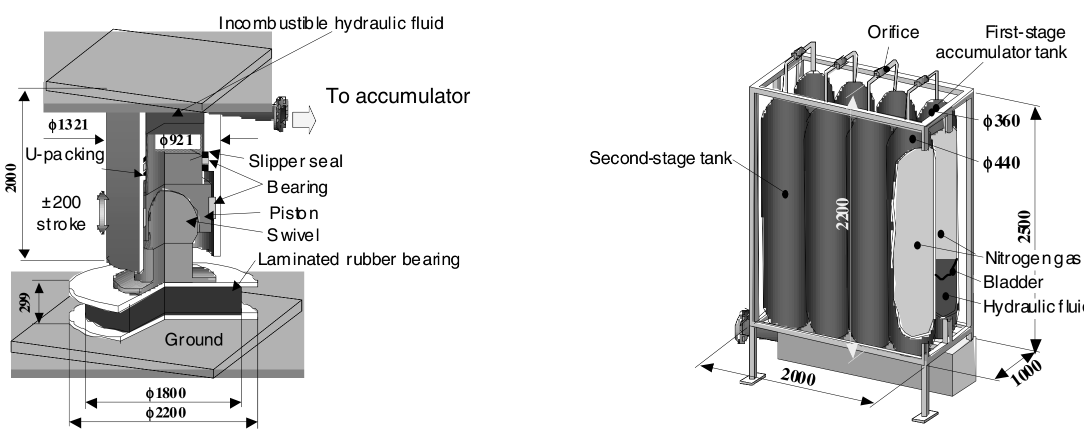


Figure 4. 3D base isolation device with air spring and rubber bearing

Hydraulic 3D Isolation System
In this system the isolator is consisted of a rubber bearing and a load carrying hydraulic cylinder which is connected to an accumulator unit [4], as shown in Figure 5.



(a) Schematic drawing of 3D isolator (b) Accumulator unit isolator

Figure 5. 3D base isolation device with hydraulic system and rubber bearing

In an event of seismic excitation, the vertical seismic force is converted by the load-carrying cylinders into pressure fluctuations of the hydraulic fluid, each cylinder being connected through piping to the first-stage tank of the accumulator unit. In this tank, the hydraulic fluid space is bounded by a flexible bladder containing nitrogen gas, to which the fluctuating pressure is transmitted. The vertical restoring force is generated by the bulk modulus of the gas contained in this first stage tank and in the second stage tank of constant volume. An orifice installed in the pipe connecting the first to the second stage tanks generates required vertical damping force.

The load carrying capacity of a unit is designed to be 9800 kN with fluid pressure being 15 MPa for normal condition and 20 MPa for design earthquake condition. The height and the outer diameter of the cylinder are 2 m and 1.3 m, respectively. For safety purposes, noninflammable hydraulic fluid is used.

Critical issues for this device include:

- Leak-tightness of the seal system between a piston and a cylinder,
- Friction characteristics of piston-cylinder system, especially with lateral loads,
- Verification of orifice damping capability,

Some experimental tests using small scale models of the device have been carried out to see whether these issues can be resolved, and some successful results are being obtained, see also the reference [4].

Cable Reinforced Air Spring

This concept is a 3D air spring to support and seismically isolate a structure by compressed air [5]. As is shown in Figure 6, it is composed of an inner and an outer cylinder, a rubber sheet between the two cylinders with reinforcing polyester fabric, and load carrying wire cables. The inner cylinder stands on the lower base-mat and the outer cylinder is connected to the upper base-mat. Since the movement in three dimensions is possible, 3D base isolation is realized with a single device, without using a laminated rubber bearing.

Here, the vertical restoring force is based on the bulk modulus of pressurized air. The horizontal restoring force is generated by the difference of effective pressurized area of the rubber sheet: the U-shaped rubber goes down in the side where the inner and outer cylinders come close and receives larger pressure force than the other side.

The diameters of the outer and inner cylinders are 8 m and 6 m, respectively, with the height of the inner cylinder being 3 m. The internal pressure is designed to be 1.4 MPa for normal condition. The load carrying capacity of a unit is 52 MN, and the natural frequencies are designed to be 0.27 Hz and 0.35 Hz, in the horizontal and vertical directions, respectively.

Critical issues for this device include:

- Ultimate strength of the wire reinforced system against internal pressure,
- Verification of vertical and horizontal restoring force (frequency),
- Verification of smooth motion in all three directions

Some experimental tests using small scale models of the device have been carried out to see whether these issues can be resolved, and some successful results are being obtained, see also the reference [5].

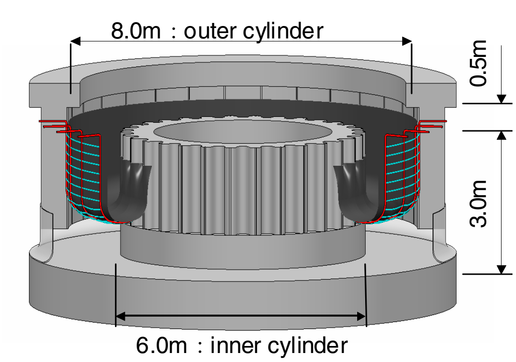


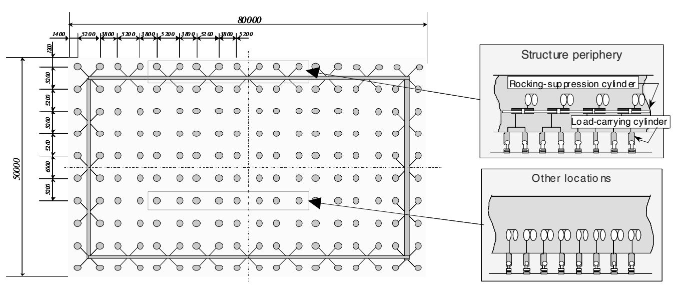
Figure 6. 3D base isolation with cable reinforced air spring

Rocking Suppression Device

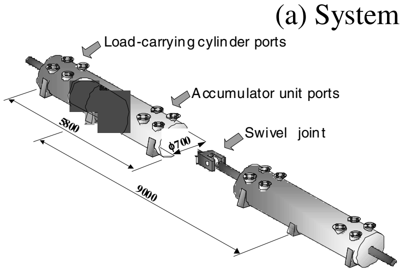
When a structure is 3D isolated, rocking motions are inevitably excited by horizontal inputs. Excessive rocking motions are undesired and should be suppressed, since they amplify the vertical displacements of the isolators that are placed on the periphery of the structure. In fact, the vertical displacements are in some cases doubled from the pure vertical translation motion.

As a promising solution to this problem, “rocking-suppression cylinder” is proposed in conjunction with the hydraulic system [5], which is schematically illustrated in Figure 7. The load carrying cylinders placed on the periphery of the structure are inter-connected by the rocking suppression cylinders. The rocking suppression cylinder has two hydraulic chambers and ports, one of which is connected to four load-carrying cylinders, and the other to one of the four accumulator units. Thus, out-of phase motion of the load carrying cylinders at the both sides of the structure is suppressed, while in-phase motion is freely allowed.

Basic functions of this rocking suppression system have been confirmed by a small-scale vibration test.



(a) System layout



(b) Rocking suppression cylinder

Figure 7. Rocking suppression system

Selection of an Idea for Future Development

At the starting point of this R&D, a number of conceptual ideas for a 3D base isolation device were proposed, and preliminary tests were done to study their fundamental feasibilities. Then some ideas had been screened out for several shortcomings they had. So, three candidate concepts, i.e., “rolling seal type air spring”, “hydraulic 3D base isolation system”, and “cable reinforced rolling-seal air spring”, remained. Table 3 shows main specifications of those concepts.

Table 3. Main specifications of the candidates

	(a) Rolling seal type air spring	(b) Hydraulic 3D isolation system	(c) Cable reinforced air spring
Load Capacity (MN)	9.8	10	70
Internal Pressure (MPa)	1.6	25	1.8
Vertical Period (second)	2	2	2.7
Horizontal Period (second)	2.8	2.8	3.6

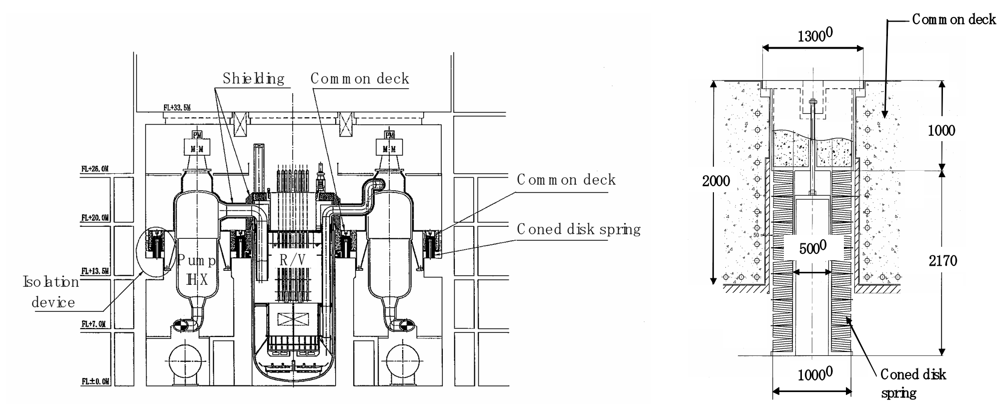
There were several proper subjects on each candidate to be studied. So development efforts, i.e. performance tests by using some reduced scale models and studies on design evaluations, etc., were made on these three concepts for final selection. Detailed figures, performances, test results, and study results of each candidate concepts will be showed in the presentation of the devices respectively. All candidates cleared the required evaluation items for selecting the 3D SID candidate. Then “rolling seal type air spring” was selected among above three ideas for further development, because it gained higher points than others in the evaluation items, especially in the performances, the applicability to the NPP, the maintenance ability and the economic competency, for selecting the 3D SID candidate.
At the same time, the idea of “hydraulic type of rocking-suppression cylinder system” (shown in Figure 7) was selected to suppress the excessive rocking motions of the building, which will occur when a structure is 3-dimensionally isolated.
As shown in Table 3, above selected idea, “the rolling seal type air spring with using the hydraulic 3D isolation system for the rocking suppression device” (abbreviated The Hybrid SID), would be developed in the next step. The design of 3D SIS, the performances, and the applicability to the practical power plant of the hybrid SID will be studied for several years.
Main points to study for the 3D SIS on the next step are as follows.

- To adjust the performance of the hybrid SID to the real NPP
- To raise the pressure of air spring for future
- To make the air spring larger
- To raise the economic competency of the hybrid SID

Vibration tests of the hybrid SID would be done in a few years.

VERTICAL ISOLATION SYSTEM FOR COMPONENTS

In parallel with the 3D base isolation development effort, a concept of vertical isolation system for components, which we call “common deck isolation system”, is also and pursued [6]. Here, the idea is that the reactor vessel and the major primary components are suspended from a flat slab structure (common deck) inside the reactor containment. This common deck is then supported by a couple of vertical isolation devices installed around each component (Figure 8(a)). Horizontal base isolation of the nuclear island is assumed.



(a) View of vertical isolation system (b) vertical isolator with coned dish springs

Figure 8. Common deck isolation system

The vertical isolation device adopted is a set of large bore coned dish springs; see Figure 8(b). They are piled up in parallel and/or in series to obtain required stiffness and stroke. In the present study, the vertical isolation frequency is designed to be 1.0 Hz, which is a bit higher than that of the 3D base isolation. This is due to a rather strict displacement limit of the secondary coolant piping systems.
The dimensions of a unit dish springs are: 1.0 m and 0.5 m for outer/inner diameters, and 27 mm for thickness. Seventy dishes (five in parallel and then 14 in series) are used to compose one unit isolator, with a stroke of ±100 mm and load capacity of 2.7 MN, to achieve 1.0 Hz. The total height of a unit is about 2.2 m. Twenty-eight units are used to support the common deck and the primary components. Necessary damping is provided by steel hysteretic dampers.
A key feature of this system is that the rocking motion is inherently not a concern, because it is possible to adjust the system so that the height of the center of gravity and the supporting level to be identical.
Some experimental tests on the mechanical and dynamic characteristics of the isolator are carried out [7].

CONCLUSIONS

A large-scale R&D project on 3D seismic isolation systems is underway for next generation nuclear reactor application. It is expected by 3D isolation application, a significantly enhanced safety and economy is achieved in the design of these plants.
In the project, a very large design ground motion is assumed and sufficiently low isolation frequency in the vertical direction, such as 2 s, is pursued to attain sufficient isolation benefit.
As for the 3D base isolation, three candidate devices, a rolling seal type air spring, a hydraulic system, and a cable reinforcing air spring, are developed. A rocking suppression device with hydraulic system is also proposed.
A concept of vertical component isolation in combination with horizontal base isolation is also pursued and developed. Here, coned dish springs are used as the isolator.

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