



A Development Program of Three-Dimensional Seismic Isolation for Advanced Reactor Systems in Japan

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ABSTRACT

Two types of three-dimensional seismic isolation systems were developed one by one. As for the 3 dimensional entire building base isolation system, development was conducted by collecting concepts. The vertically isolated for main components with horizontally entire building base isolation system was developed by referring the bored cone dish spring technology. In this R&D project, several tests would be conducted and some technical standards would be completed for about a decade.

KEY WORDS: FBR, development program, seismic isolation system, seismic design condition, damping ratio, response analysis, isolation system analysis, floor response spectra

INTRODUCTION

The peculiar FBR design features compare with Light Water Reactor (LWR) are high temperature and low pressure in components. High temperature of FBR gives large thermal strain in components. Therefore applying thinner component can reduce the stress intensity. 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 seismic isolation technology were required to solve the problem. On this background, 'A large Scale R&D Project on Three-Dimensional Seismic Isolation for FBR' (this R&D) started on April in 2000. This paper shows the development method of this R&D project, setting up the seismic condition, setting up the seismic design feasibility evaluation criteria for components and building, and the outline and results of the seismic response analyses of the component and building in order to get proper properties of the three-dimensional seismic isolation systems. Meanwhile, the analyses were conducted giving varieties in vertical properties under constant horizontal base isolation property, because the vertical seismic isolation properties were the key factors to be determined for the three-dimensional seismic isolation technology. The proper vertical seismic isolation properties are shown as the combinations of frequencies and damping ratios of the seismic isolation devices, and they are set as the target of this R&D.

R&D PROJECT OVERVIEW

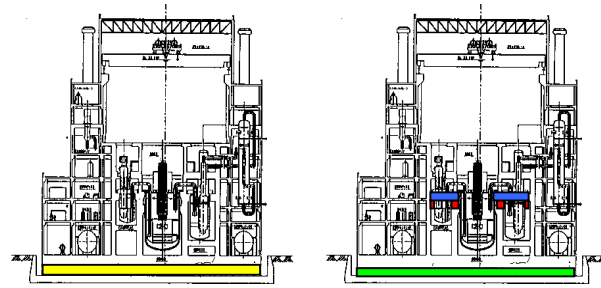
Three-Dimensional Seismic Isolation System Concept

Two types of three-dimensional seismic isolation systems were selected appropriate for FBR in this R&D project through the viewpoints of realization and economic competency. One is a three-dimensional Seismic Isolation System (3D SIS), the other is a vertical isolation of main components with horizontal base Isolation System (V. +2D SIS), which are schematically shown in Figure 1. In the 3D SIS, 3D Seismic Isolation Devices (SID) support the reactor building as shown in Figure 1(a). In the V. +2D SIS, 2D SID support a building, furthermore, vertical SID support a Common Deck that supports main components such as the reactor vessel (RV) and the pumps, as shown in Figure 1(b).

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 three-dimensional 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. Then six of them were chosen from the viewpoints of performance, reliability, applicability to FBR in design, construction, maintenance and economic competency. Then three of the six ideas were chosen again from the feasibility tests, last year. These three ideas consisted of concepts from devices of air spring, hydraulic with air accumulators. And then, they would be developed to the plural real 3D SIS through the experiments using large-scale test specimens to exclude the scale effect like a leak through the seal from test results.



(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

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 bored cone 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 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 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 SEISMIC CONDITION

At the first step of this R&D project, seismic design condition had to be settled. Meanwhile, as the condition could be applied to examine the ultimate behavior of the seismic isolation system, the seismic condition was set as 'S2' defined in Japan, which was the extreme design earthquake that was in a sense equivalent to SSE. Considering those factors, the horizontal seismic spectrum that was applied to the past R&D [2] for the horizontal seismic isolation system was quoted and settled as the seismic condition for this R&D. The spectrum had been made enveloping the design spectra in several Nuclear Power Plant (abbreviated NPP) sites in Japan and keeping the velocity spectrum constant in the longer period range.

The seismic condition was defined as 'Case Study S₂ for the 3D seismic isolation development', or abbreviated Case Study S₂ (further abbreviated CSS₂). On this project, the SID was to be developed adding some redundancy in its capacity.

CSS₂ for both in horizontal and vertical directions are shown in Figure 2. In the figure, horizontal velocity spectrum reaches 2.0 m/s in the period between 0.62 and 10.0 sec, vertical spectrum reaches 1.2m/s, damping ratio 0.05 is used. The ratio, vertical to horizontal, was to be 0.6, was settled considering the experience of the past.

CSS₂ was compared with a couple of response spectra of recent observed earthquake motions, Kobe Japan 1995[3], Kocaeli Turkey 1999[4] and Chi-Chi Republic of China 1999[5].

Observed motions were recorded at ground surface level and no correction was done. So, there was a difference in condition between CSS₂ and observed earthquake motions because CSS₂ was defined at the bedrock. Representative comparison results are shown in Figure 3 • 5. Data in Figure 5 were collected from the records on relatively hard rock. From these figures, the spectra of the observed earthquake motion records are almost enveloped by the CSS₂. In the comparison with Chi-Chi, it should be noted that the spectra exceeded CSS₂ in longer periods were based on the motions recorded in the vicinity or on the faults.

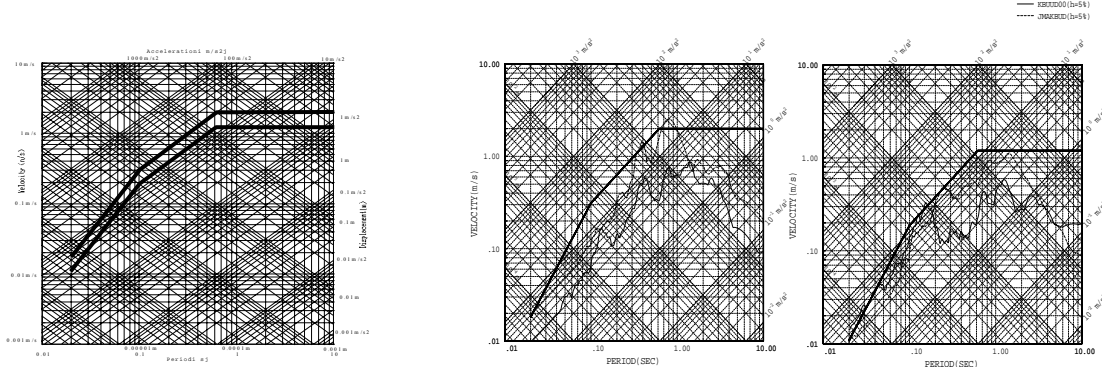


Figure2 Case Study S2 Spectra in Tripartite Coordinate

EW-Direction UD-Direction
 Figure 3 Comparisons with CCS₂ and Recent Observed Motions (Kobe Japan, 1995)

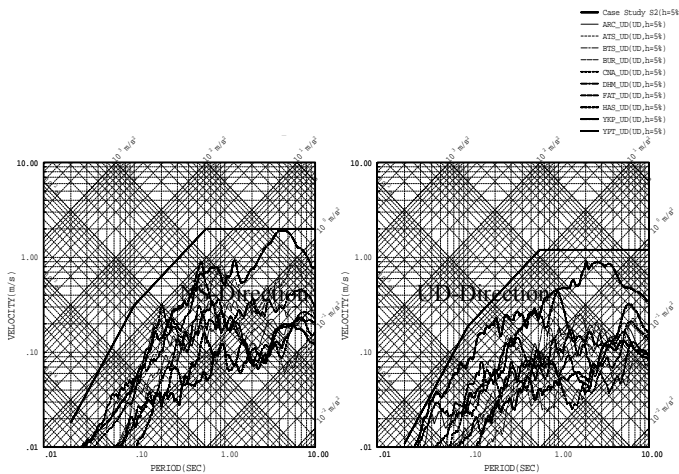


Figure 4 Comparisons with CCS₂ and Recent Observed Motions (Kocaeli Turkey, 1999)

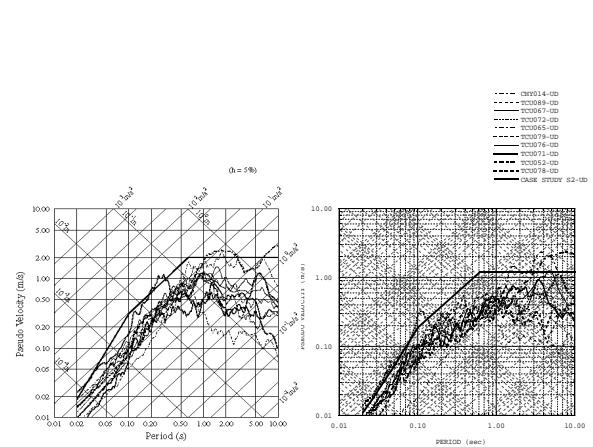
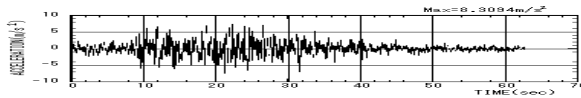
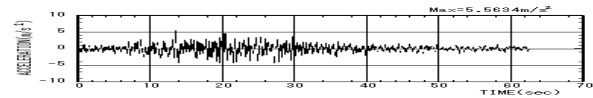


Figure 5 Comparisons with CCS₂ and Recent Observed Motions (Chi-chi Republic of China, 1999)

When the building and component response analyses were conducted, simulated ground motions were prepared based on CSS₂ spectra as input data. Horizontal and vertical simulated ground motions are shown in Figure 6. The maximum accelerations of input motions are 8.31m/s² in horizontal, 5.56m/s² in vertical respectively.



Horizontal Direction



Vertical Direction

Figure 6 Simulated Ground Motions

SEISMIC RESPONSE ANALYSIS

Analysis Method and Model

The main objective of conducting seismic response analyses is to identify the values of vertical frequencies and damping ratios fit for the three-dimensional seismic isolation devices. They are evaluated by comparing the analysis response values with the seismic design feasibility evaluation criteria.

The building seismic response analyses were conducted as a nonlinear response analysis both in horizontal and vertical directions by applying the simulated ground motions to the analysis model of the representative NPP building. Analysis model of the building in vertical and horizontal directions are shown in Figures 7,8 respectively. The SID are shown as an axial spring in Figure 7, as a combination of sway and rocking springs in Figure 8. Building structures were properly modeled as a lumped-mass model based on the experiences of the past. Total mass of the building model was estimated as about 170000t. Figure 9 shows the modeling concept of the building analysis model.

While the vertical soil spring is modeled in Figure 7 for its stiffness is comparable with that of the SID, horizontal soil spring is not modeled in Figure 8 for its horizontal stiffness is much larger than that of the SID. Meanwhile, the vertical soil spring stiffness was set as a constant value based on the axial soil stress, soil material properties and configuration of the building, and the damping coefficient of the soil spring was set depends on the fundamental natural frequency of the building-seismic isolation device-soil system. Meanwhile, the soil property was assumed as a secondary velocity equivalent to 1500m/s. In these figures, the reactor vessel support point is shown as the node number 33 in Figure 7, number 43 in Figure 8 respectively.

On the other hand, the component seismic analyses were conducted as a spectrum response analysis by applying the Floor Response Spectra (Abbreviated FRS) at the reactor vessel support point in the building analysis model to the reactor component analysis model. Reactor component analysis models in horizontal / rotational and vertical directions are shown in Figure 10. RV and inner structure were properly modeled as a lumped-mass model in horizontal / rotational directions or finite element model in vertical direction, based on the experiences of the past.

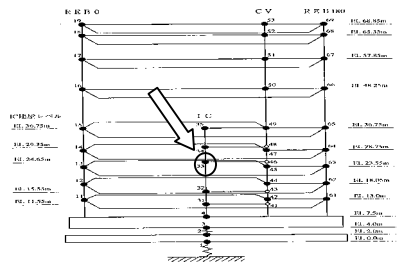


Figure 7 Building Analysis Model in Vertical Direction

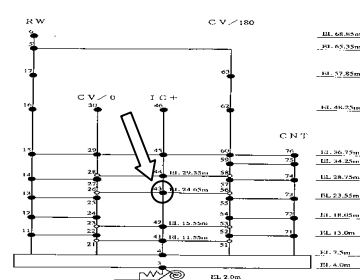
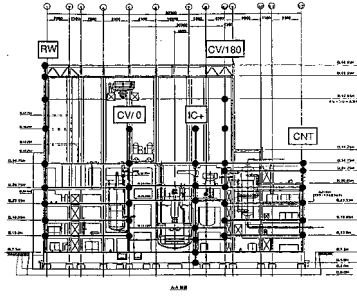
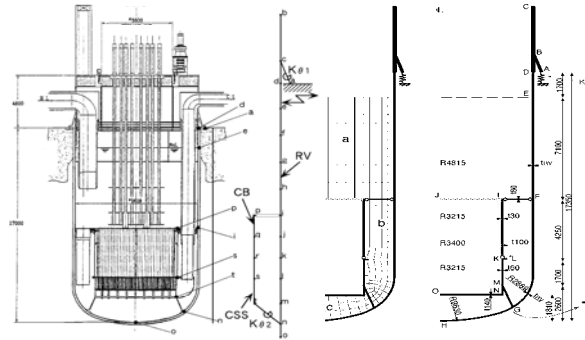


Figure 8 Building Analysis Model in Horizontal Direction



Horizontal/Rotational Direction

Figure 9 Modeling Concept of the Building Analysis Model
(Horizontal Direction)



Vertical Direction

Figure 10 Reactor Component Analysis Model

Analysis Parameters

Analysis parameters are shown in Table 1. As shown in the table, the vertical frequency is varied from 20.0 to 0.5Hz, vertical damping ratio is varied from 2 to 60%. In those values, 20Hz in vertical direction means no vertical seismic isolation device is installed, 0.5Hz is thought as the lowest seismic isolation device frequency that could be attained, 2% damping means no damper is installed. Parameters were specified having some margin. The damper possessing damping ratio greater than 40% is thought hard to realize. On the other hand, the 3D SID possessing vertical frequency less than 0.67Hz had been proposed in the ideas shown in '2.2.2 3D Seismic Isolation System Development Method' in this paper.

Table 1 Analysis Parameters

Vertical Frequency fv(Hz)	Damping ratio hv(%)					
	2	5	10	20	40	60
20.0	•	•	•	•	•	•
3.0	•	•	•	•	•	•
1.5	•	•	•	•	•	•
1.0	•	•	•	•	•	•
0.667	•	•	•	•	•	•
0.5	•	•	•	•	•	•

Parameters are applied to both analyses in horizontal and vertical directions.

Building Seismic Response Analysis Results

Eigen Value Analysis Results

Representative eigen value analysis results are shown as the participation functions in Figure 11 in horizontal direction, in Figure 12 in vertical direction, respectively. In Figure 11, fundamental participation function shows the sway mode and second participation function shows little deformation in the case of $f_v=20\text{Hz}$, which means this structure is seismically isolated only in horizontal direction. On the other hand, both fundamental and second participation functions show the rocking mode in the case of $f_v=0.667\text{Hz}$, which shows this structure reduces the vertical stiffness and rocking mode is induced as a result.

In Figure 12, in the case of $f_v=20\text{Hz}$, fundamental participation function shows the deformation mode like seismic resistance structure because the stiffness of seismic isolation system is equivalent to no vertical seismic isolation device is installed. And the fundamental natural frequency 9.37Hz is different from $f_v=20\text{Hz}$ because the soil spring stiffness governs this vibration system. On the other hand, in the case of $f_v=0.667\text{Hz}$, fundamental participation function shows the deformation mode like rigid body and the fundamental natural frequency 0.667Hz equals the seismic isolation device frequency 0.67Hz because this vibration system is not governed by the soil springs but governed by the vertical seismic isolation devices.

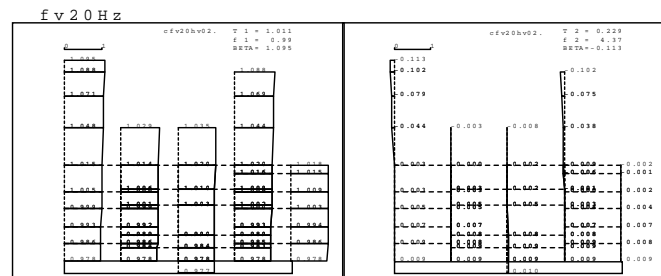


Figure 11(1/2) Representative Participation Functions
(Building Model: Horizontal Direction ($f_v=20\text{Hz}$))

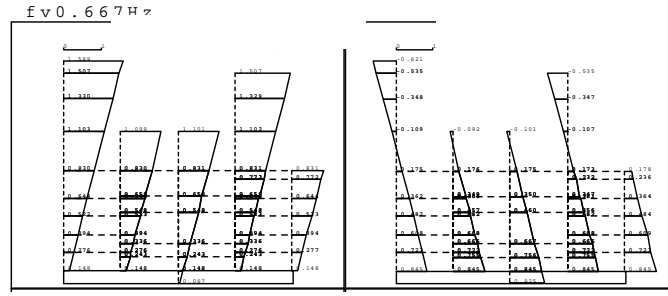


Figure 11(2/2) Representative Participation Functions
(Building Model: Horizontal Direction (fv=0.667Hz))

•1=0.107 (•1=9.37),BETA=1.700

•1=0.058 (•1=17.26),BETA=0.144

•1=1.502 (•1=0.67),BETA=1.

•1=0.058 (•1=17.24),BETA=0.001

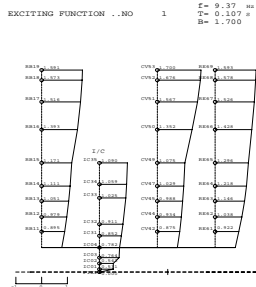


Figure 12 (1/2) Representative Participation Functions
(Building Model: Vertical Direction (fv=20Hz))

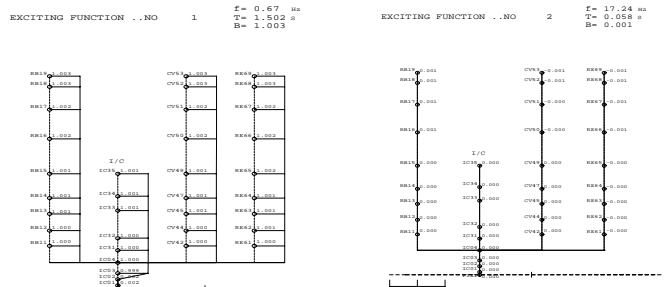
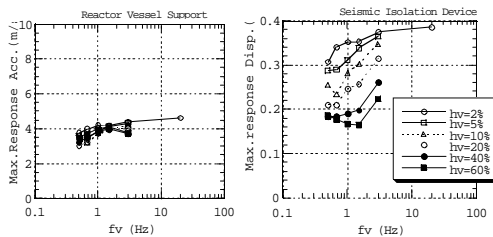


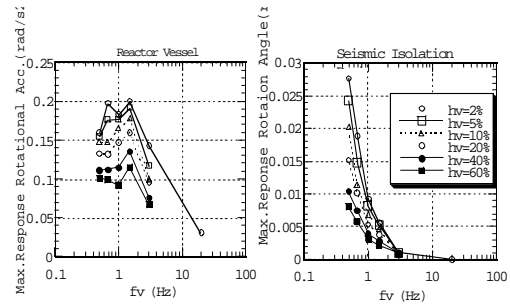
Figure 12 (2/2) Representative Participation Functions
(Building Model: Vertical Direction (fv=0.667Hz))

Maximum Responses

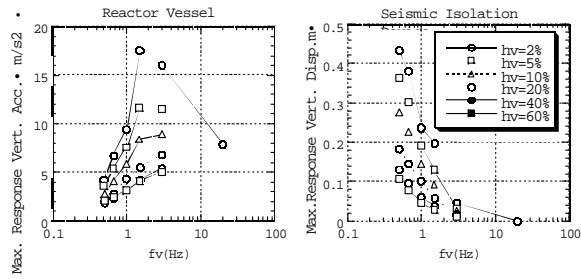
Maximum response acceleration at the RV support point and maximum response displacements at the layer in which the seismic isolation systems are installed, are shown in from Figure 13 to 15. In Figure13, the maximum horizontal response acceleration at RV support point is thought to be constant when the seismic isolation device stiffness is varied, on the other hand, in Figure 14, the maximum rotational acceleration increases when the vertical seismic isolation device stiffness decreases. In Figure 13, the maximum response displacement in horizontal direction decreases when the vertical seismic isolation device stiffness decreases, on the other hand, in Figure 14, the rotational response angle increases sharply when the stiffness decreases. The reason, the rotational acceleration and angle increases followed by the decrease of the stiffness, can be attributed to the change of the vibration modes. They change from sway to rocking. In Figure 15, maximum response acceleration in vertical direction decreases when the vertical seismic isolation device stiffness decreases in the region between 3.0 Hz and 0.5Hz, on the other hand, the maximum response displacement in vertical direction increases depending on the decrease of the vertical stiffness. These tendencies are in common with usual vibration systems; A system that has a longer period exhibits smaller accelerations and longer displacements than those of shorter period. From these outputs, the total horizontal and vertical maximum displacements were summed up by SRSS as shown in Figure 16, and compared with the design feasibility evaluation criteria relating to the piping system in the case of 3D SIS.



Max. Acceleration Max. Displacement
Figure 13 Maximum responses in Horizontal Direction



Max. Acceleration Max. Rotational Angle
Figure 14 Maximum responses in Rotational Direction



Max. Acceleration Max. Displacement
Figure 15 Maximum responses in Vertical Direction

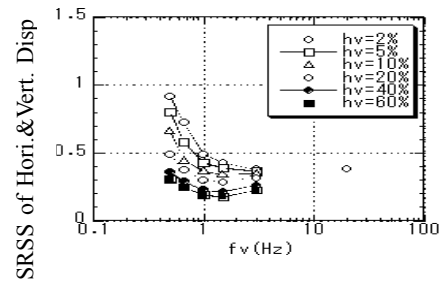


Figure 16 SRSS of Max. Hori.&Vert Displacements

Floor Response Spectra

The FRS at the RV support point are shown in Figure 17 and Figure 18 for horizontal and vertical directions, respectively. In Figure 17, little difference among the horizontal FRS is found, especially around 0.2sec, the fundamental natural frequency of the RV in horizontal direction. On the other hand, in Figure 18, remarkable differences in vertical FRS between fv20Hz and the others are found, in the region of the fundamental natural frequency of the RV in vertical direction of about 0.1sec. At the period of 0.1sec, FRS decreases by about 1/6, from that of 20Hz to those of others. This very point is why the seismic isolation system is applied to FBR. The spectra shown in Figure 17,18 in horizontal and vertical directions and in rotational direction were applied to the component analysis model to estimate the required responses.

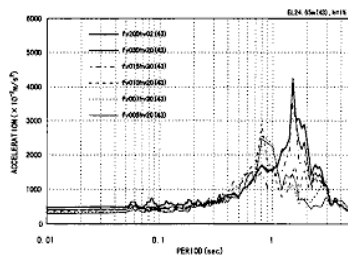


Figure 17 FRS at RV Support Point in Horizontal Direction

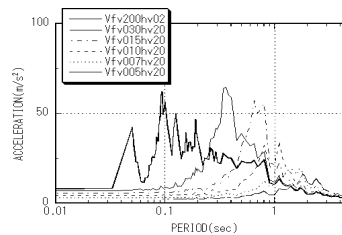


Figure 18 FRS at RV Support Point in Vertical Direction

TARGETS IN THE SEIMIC ISOLATION DEVICE DEVELOPMENT

Evaluation Results for Component Design

Seismic response analysis results were compared with the criteria for components to evaluate the applicability of the 3D SIS to FBR. Evaluation results are shown in Table 2,3. In these tables, the region of vertical frequency and damping that suit the component design criteria are shown for both types of the 3D SISs. In the tables, • means the redundancy over 1.0, • means 1.0 • 0.8, × means less than 0.8 respectively, where the redundancy is defined as the allowable value divided by the analysis response value. The shaded zones in the tables were provided to grasp quickly the proper combinations of the frequency and damping ratio. The dark shade means the corresponding combination of fv and hv that could realize the SIS. The light shade means the region that has only one item dissatisfying a component design evaluation criterion.

Table 2 Evaluation Results for Component Seismic Design
(For 3D Seismic Isolation System)

Vertical Frequency of the Device: fv(Hz)	3D Seismic Isolation System					
	Vertical Damping Ratio of the Device: hv(%)					
	2	5	10	20	40	60
20	×	•	•	•	•	•
	×	•	•	•	•	•
	×	•	•	•	•	•
	×	•	•	•	•	•
	•	•	•	•	•	•
3.0	×	×	•	•	•	•
	×	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•
1.5	×	•	•	•	•	•
	×	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•
1.0	•	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•
0.667	•	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•
0.5	•	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•

Note 1: Redundancy: Allowable Value/ Analysis Result

•: Redundancy over 1.0, •: Redundancy 1.0 •0.8,

×: Redundancy less than 0.8, •: No Evaluation

Note2: Evaluation Items From Top to Bottom in each Combination of fv and hv.

1st: Acceleration at core support plate in vertical direction

2nd: Relative displacement between core support plate and upper inner structure in vertical direction

3rd: Out of plane displacement of core support plate

4th: Combined stress in reactor vessel

5th: Relative displacement for the water/steam system in the case of the 3D Seismic Isolation System

Note3: •: Upper combination of 'fv' & 'hv'.

•: Just before the proper combination of the above

Table 3 Evaluation Results for Component Seismic Design
(For V.+2D Seismic Isolation System)

Vertical Frequency of the Device: fv(Hz)	V. +2D Seismic Isolation System					
	Vertical Damping Ratio of the Device: hv(•)					
	2	5	10	20	40	60
20	•	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•
3.0	×	×	×	×	×	×
	×	×	×	×	×	×
	×	•	•	•	×	×
	•	•	•	•	•	•
	•	•	•	•	•	•
1.5	×	×	•	•	•	×
	×	•	•	•	•	×
	•	•	•	•	•	•
	•	•	•	•	•	•
	×	×	•	•	•	•
1.0	•	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•
	×	×	×	•	•	•
0.667	•	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•
	×	×	×	×	•	•
0.5	•	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•
	×	×	×	×	×	•

Note : 5th Item: Relative displacement for the secondary sodium circuit system in the case of the V. +2D Seismic Isolation System.

Evaluation Results for Building Design

Building seismic response analysis results were compared with the criteria to evaluate the applicability of the SIC to FBR. Evaluation results for building design are shown in Table 4 only for 3D SIS.

From the table, the combinations of vertical frequencies less than 1.0Hz and vertical damping ratio between 20 and 40 • could be recommended for the 3D SIS.

Table 4 Evaluation Results for Building Design
(For 3D Seismic Isolation System)

Vertical Frequency of the Device: fv(Hz)	3D Seismic Isolation System					
	Vertical Damping Ratio of the Device: hv(%)					
	2	5	10	20	40	60
20	×	•	•	•	•	•
	×	•	•	•	•	•
	•	•	•	•	•	•
3.0	×	×	×	×	•	•
	×	×	×	×	×	×
	•	•	•	•	•	•
1.5	×	×	×	×	•	•
	×	×	×	×	•	•
	•	•	•	•	•	•
1.0	×	×	×	•	•	•
	×	×	•	•	•	•
	•	•	•	•	•	•
0.667	×	•	•	•	•	•
	×	•	•	•	•	•
	×	•	•	•	•	•
0.5	•	•	•	•	•	•
	•	•	•	•	•	•
	•	•	•	•	•	•

Note 1: •: Redundancy over 1.0, ×: Redundancy less than 1.0

Note2: Evaluation Items From Top to Bottom in each Combination of fv and hv.

1st: Vertical Acceleration in each point of the Building

2nd: Uplift displacement of each Seismic isolation device

3rd: Horizontal Acceleration in each point of the Building

Targets in the Seismic Isolation Device Development

Considering both of the evaluation results for the seismic isolation device properties for 3D and V. +2D SIS, the targets were set in Table 5. Development of the 3D SIS is going to progress for a while based on these targets. However, these targets should be updated referring to the relating commercialized FBR project progress, because these were settled based on the tentative conditions.

Table 5 Targets in the Seismic Isolation Device Development

Seismic Isolation System Type	Vertical Frequency (Hz)	Vertical Damping Ratio (•)
3D	Less than or equal to 1.0	20•40
V. +2D	Around 1.0	20•40

CONCLUSIONS

- (1) Development planning consisted of setting seismic conditions, design feasibility evaluation criteria and development target like frequency and damping ratio and so on. They were settled tentatively prior to the start of R&D.
- (2) Development methods for 3D and Vertical +2D Seismic Isolation System were settled. For the 3D system, the method of collecting ideas from major private companies was adopted. Three ideas were chosen from nine proposals, and they are under currently development. Another screening would be considered when necessary.
- (3) For the V. +2D system, the cone dish spring technology is applied to the vertical seismic isolation device. As the development items, several experiments are planned to grasp the basic properties of the spring and to confirm the applicability of the existing design formula to larger size dish springs.
- (4) The seismic conditions were settled as the seismic spectra 'Case Study S2' in horizontal and vertical directions. The ratio, vertical to horizontal, was to be 0.6, was settled considering the experience of the past.
- (5) The criteria for component and building seismic design feasibility evaluation were settled. The criteria for component design were settled for the design of core, reactor vessel and piping. On the other hand, the criteria for building design were settled for the design of seismic isolation device and building structural members like column, beam and so on.
- (6) Seismic response analyses for the building and reactor component were conducted to grasp the intensities of the responses at the reactor supporting point and seismic isolation layer in the building model, and at the core support plate and RV in the reactor component model. In the analyses, seismic isolation effects were remarkably recognized in the vertical FRS at the RV support point. The analysis results were compared with the design feasibility evaluation criteria to evaluate the applicability of the 3D SIS to FBR.
- (7) As the target in the 3D SIS development, vertical frequency: less than or equal to 1.0Hz in the case of 3D, around 1.0Hz in the case of V. +2D Seismic Isolation Systems, vertical damping ratio: from 20 to 40• for both 3D and V. +2D Seismic Isolation Systems, were settled.
- (8) The development conditions settled 'tentatively' would be updated referring to the progress of relating R&D activities.

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