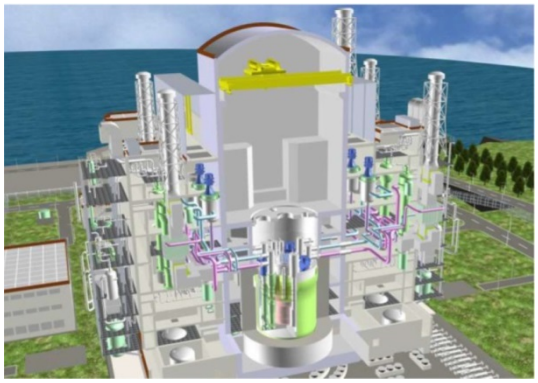
Mitsubishi Activities for Advanced Reactor Development - Sodium-cooled Fast Reactor -



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With the objectives of the effective use of resources, the reduction of the volume and harmfulness of high-level radioactive waste, etc., the basic policy of Japan is to promote a nuclear fuel cycle in which spent fuel is reprocessed and recovered plutonium, etc., are effectively used. As such, Japan has been developing fast reactors that utilize the fission reaction of plutonium using fast neutrons. After the Great East Japan Earthquake, the development environment for fast reactors changed drastically and in December 2016, it was decided to decommission the "Monju" prototype fast-breeder reactor. Although the situation has changed recently, the significance of developing fast reactors that enable the effective use of uranium resources and the reduction of the volume and harmfulness of radioactive waste remains unchanged. In December 2018, the Japanese government expressed in the "strategic roadmap" its expectations for the start of operations of a fast reactor around the middle of the 21st century. We are continuing to work on fast reactor development as a core company that is responsible for the development of fast reactors in Japan in order to achieve the "strategic roadmap" and realize the reduction of environmental load for a future that does not rely on fossil fuels.

1. Introduction

As energy consumption in emerging countries such as China and India is increasing rapidly, the depletion of resources such as fossil fuels is becoming a real problem. According to a recent survey, it is estimated that reserves of oil and natural gas will reach their limits in about 50 years and coal in about 130 years. Even in the case of nuclear power generation using uranium resources, if recycling by reprocessing spent fuel is not considered, its limit will be reached in about 100 years.

Under these circumstances, coupled with the issue of global warming, renewable energy utilizing solar power and wind power, which do not emit green-house gases (GHG) such as CO_2 during power generation, is attracting attention and is being developed to become the main source of power. However, renewable energy alone is unlikely to be a "stable and economical" source of energy that can sustain industry. Therefore, coexistence with nuclear power generation, which does not emit GHG and is an energy source that can handle the issue of resource depletion, is effective. Among such nuclear power plants, fast reactors enable breeding of fuel by using fast neutrons for fission without the use of moderators like light water reactors. These reactors can dramatically increase the usable life of uranium resources from 100 years to thousands of years by reusing plutonium extracted from the spent fuel of current nuclear power plants.

On the other hand, spent fuel contains a radioactive substance with a long life called minor actinide (MA) and its treatment and disposal are problematic. Since the fast reactor uses fast neutrons, it is possible to reload MA into fuel and convert it into radioactive waste with a short

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half-life, which contributes to the reduction in the volume of radioactive waste. In other words, fast reactors are epoch-making energy sources that can be a stable, ultra-long-term source of energy for thousands of years and can reduce the burden on the environment at the same time.

In Japan, based on this situation, research and development of fast reactors is being carried out mainly by the Japan Atomic Energy Agency (JAEA).

2. Activities of our company

Mitsubishi Heavy Industries, Ltd. (MHI) has actively participated in the development of fast reactors in national projects, such as the "Joyo" experimental reactor and the "Monju" prototype reactor. We have also played a leading role as a manufacturer through designing, manufacturing and installing major equipment. Then, in the "Study on Demonstration Reactor" conducted by electric power companies for the development of the reactor following Monju and the "Feasibility Study on Commercialization" conducted by JAEA and others, based on the MHI's loop type reactor we proposed, in consideration of the connection with the technology accumulated in Japan by the loop type Joyo and Monju, and the development of fast reactors has moved forward (**Figure 1**).

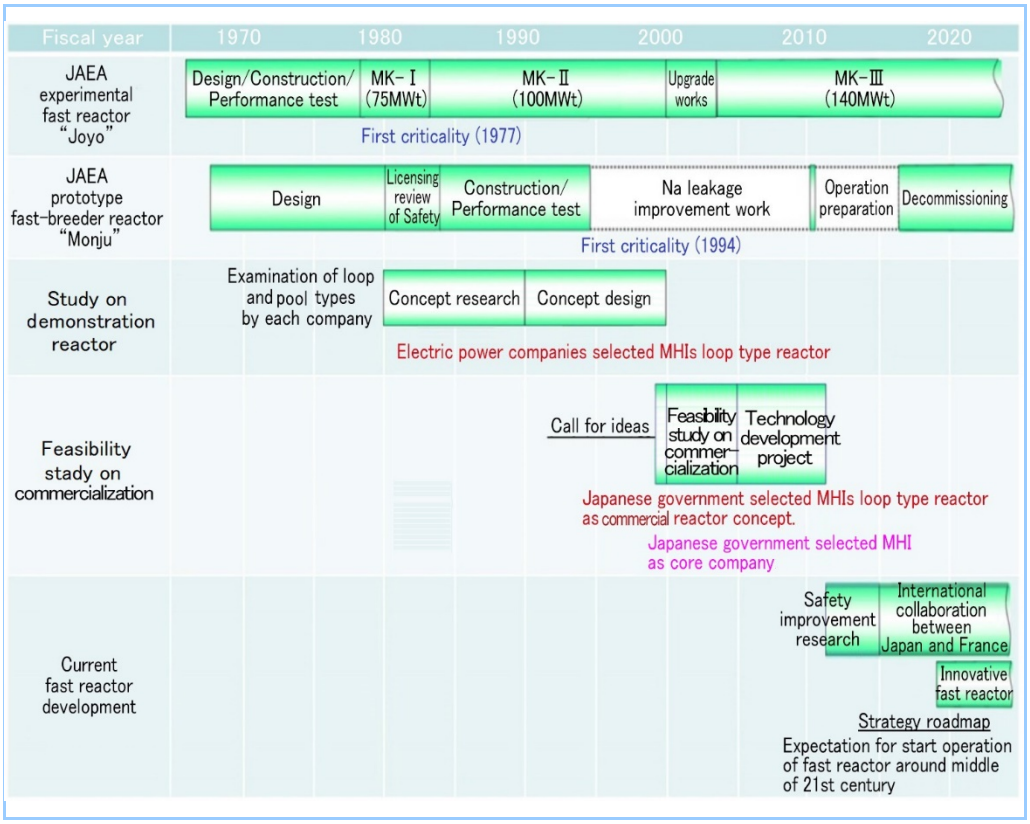


Figure 1 History of development on fast breeder reactor

After that, the Japanese government decided to concentrate the responsibility, authority and engineering function on a single core firm so that the development of fast reactors could be carried out efficiently under a clear system of responsibility. As a result of the public offering, we were selected as a core company and established Mitsubishi FBR Systems Inc. (MFBR), which concentrates on fast reactor development and engineering. MHI and MFBR have been working on the development of a pool type reactor until now as the core of fast reactor development in Japan through international collaboration between Japan and France, as well as the development of an innovative fast reactor for meeting the diversifying needs of the future flexibly.

3. Formulation of "strategic roadmap" for identification of future development work

The Japanese government established the "Fast Reactor Development Conference" consisting of the Minister of Economy, Trade and Industry, the Minister of Education, Culture, Sports, Science and Technology, the President of JAEA, the Chairman of the Federation of Electric

Power Companies of Japan and the President of our company in October 2016 to study how to proceed with fast reactor development in the future. The Fast Reactor Development Conference was held five times in total and in December 2016, the "Fast Reactor Development Policy" was decided at the Ministerial Conference on Nuclear Power. This policy includes statements of "we will continue to develop fast reactors with a sodium-cooled reactor using MOX fuel in mind", "we will formulate a strategic roadmap that identifies development work for the next 10 years or so" and "we will establish a strategic working group under the Fast Reactor Development Conference for the review thereof."

The strategic working group was held 16 times in total and the "strategic roadmap" was decided at the Ministerial Conference on Nuclear Power in December 2018. This roadmap includes statements of "the timing when the full-scale use of fast reactors is expected may be sometime in the latter half of the 21st century" and "for example, it is expected that a fast reactor on a realistic scale from the viewpoint of technology readiness level, financing and operational experience will be put into operation at the right time around the middle of the 21st century."

The strategic roadmap includes statements that the research and development will be proceeded with in a manner "for the next five years or so, (…) we will promote competition between various technologies" and that international collaboration will be utilized in a manner such that "in future development, through international collaboration utilizing bilateral and multilateral networks with France, the United States, etc., (…) we will work together in Japan and overseas to establish a technological foundation for commercialization and promote innovation."

We will steadily develop fast reactors in accordance with the fast reactor development policy and strategic roadmap.

4. Status of technological development

So far in Japan, loop type reactors of the "Joyo" experimental reactor and "Monju" prototype reactor have been developed, but pool type reactors are the mainstream overseas. The concept of the loop type reactor is that the intermediate heat exchanger and the primary pump are connected to the reactor vessel by piping. On the other hand, the concept of the pool type reactor is that the two are installed in the reactor vessel. Since the difference between the two reactor types is only the connection method of the primary system equipment, there is no significant difference in the required technology.

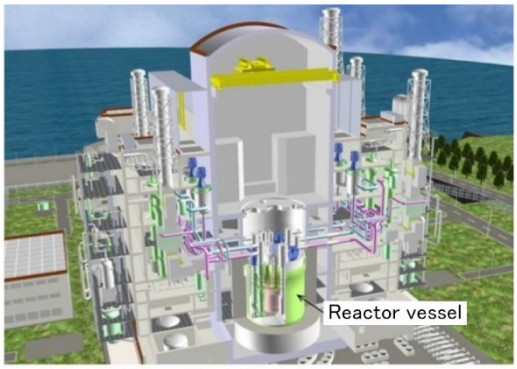
In accordance with the strategic roadmap shown in the previous chapter, MHI has been proceeding with development of pool type reactors leveraging the international collaboration between Japan and France in addition to the loop type reactors we have developed so far, aiming for efficient development through international collaboration. We are also developing the innovative fast reactor MCR (Mitsubishi Compact Reactor) to flexibly meet the diversifying needs of the future and have accumulated technologies that enable the provision of appropriate plants according to user requirements (required plant specifications). Among these developments, the development statuses of the pool type reactor and MCR are shown below.

4.1 Development of pool type reactor through international collaboration between Japan and France

Under the "Implementation Arrangement on French Next Generation Reactor Plan (ASTRID: Advanced Sodium Technological Reactor for Industrial Demonstration) and Collaboration of Sodium-cooled Fast Reactors" (2014-2019), MHI and MFBR, together with JAEA and French Alternative Energies and Atomic Energy Commission (CEA), jointly developed the main technologies for sodium-cooled fast reactors and acquired knowledge about pool type reactors. Furthermore, based on the knowledge acquired through this joint development, we are proceeding with the development of pool type reactors that can meet severe domestic seismic conditions.

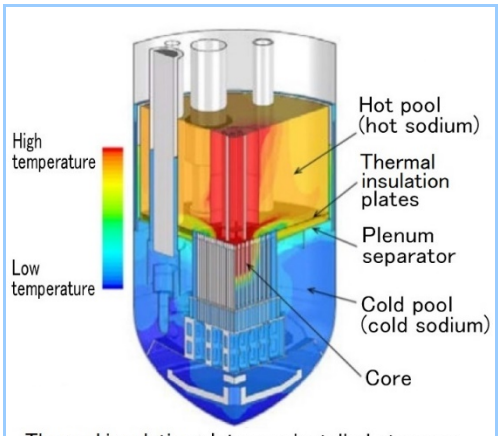
Pool type reactors have a larger reactor vessel diameter than loop type reactors, so it was considered to be severe in terms of earthquake resistance under domestic seismic conditions, but the prospect of establishing the pool reactor has been obtained by adopting structures with improved seismic resistance, seismic isolation systems, etc. **Figure 2** shows a bird's-eye view of the pool type reactor [(1)]. In particular, regarding the reactor structure of pool type reactors, we constructed a unique concept that ensures structural integrity based on seismic evaluation and thermal hydraulics evaluation. For example, the plenum separator that separates the high

temperature part and the low temperature part in the reactor vessel is provided with a reinforcing material to ensure the rigidity. Thermal insulation plates are also installed so that the temperature difference between the upper and lower parts of the structure is reduced. It has been confirmed by three-dimensional thermal hydraulics analysis that this structural concept reduces the temperature difference between the upper and lower parts of the plenum separator and ensures the structural integrity (**Figure 3**) [(2)].



Reactor vessel of pool type reactor is larger than that of loop type reactor.

Figure 2 Bird's-eye view of pool type reactor



Thermal insulation plates are installed at upper part of plenum separator to reduce temperature difference between upper and lower parts.

Figure 3 Results of evaluation of thermal hydraulics in pool type reactor

Furthermore, the research and development items shown in **Table 1** are currently underway for the commercialization of fast reactors. Among these, the development statuses of items No. 1 to No. 3, which are common issues for loop type and pool type reactors and particularly important for pool type reactors, are shown in Sections 4.2 to 4.4.

Table 1 Research and development underway for commercialization of fast reactors

	Development item	Purpose
1	Core seismic evaluation method	Development of a method that can evaluate the group vibration behavior of core elements that are displaced horizontally and vertically and collide with each other in the event of an earthquake.
2	Sloshing evaluation method	Development of a method that can evaluate the load generated when the sodium liquid surface in the reactor vessel collides with the reactor vessel ceiling due to sloshing in the event of an earthquake.
3	Three-dimensional seismic isolation system	Development of a seismic isolation system that can be placed in the same space as horizontal seismic isolation system and can reduce vertical seismic force in addition to horizontal seismic force.
4	Passive reactor shutdown system	Development of a passive reactor shutdown system that de-taches a control rod by its temperature dependency of a magnetism when the temperature of sodium rises excessively.
5	High-temperature neutron instrumentation	Development of equipment that can measure neutrons under high-temperature conditions inside the reactor vessel
6	Under sodium viewer	Development of inspection equipment that enables visual inspection in opaque sodium using ultrasonic waves
7	Buckling evaluation method	Development of a buckling evaluation method for thin-walled large-diameter vessels, which is a feature of fast reactor equipment
8	Acquisition of high-temperature structural material properties	Acquisition of high-temperature long-term material property data of structural materials used at high temperatures of 500°C or higher

As collaboration between Japan and France after the aforementioned arrangement, we concluded the "Implementation Arrangement on Sodium Cooled Fast Reactor Development Plan Collaboration" (2020-2024) in December 2019 with JAEA, CEA and MFBR for the purpose of efficiently proceeding with the future development of fast reactors. In the future, we will utilize the knowledge gained through research and development collaboration based on this arrangement and promote the development of pool type reactors that can be built in Japan with seismic conditions factored in.

4.2 Development of core seismic evaluation method to understand the behavior of core elements

The core of a fast reactor is composed of a large number of core elements, such as fuel

assemblies containing fuel pins, standing on the core support structure. Therefore, in the event of an earthquake, each core element is displaced in the horizontal direction while colliding with other core elements. In the case of strong earthquake motion, core elements rise and fall due to the vertical movement of the core support structure. In order to evaluate the complex and highly non-linear three-dimensional group vibration behavior caused by collision force and fluid force acting on these many core elements, we developed a core element group vibration analysis code, REVIAN-3D[3]. REVIAN-3D is a time history response analysis code that incorporates modal analysis methods and can evaluate group vibration behaviors including the rising of core elements even for a large core with more than 1000 elements.

We have verified evaluation methods using REVIAN-3D by vibration tests using a large excitation table owned by our company [4]. The development started from the test of a single full-scale core element. Then, the test system was expanded by gradually increasing the number of elements using a scale model, from a 37-element group system to a 32-element row system and then a 313-element multiple-element system. For each test, the validity of the analysis code was confirmed by comparing the test results and the analysis results, and the accuracy of the analysis code was improved by modifying the calculation model as appropriate (**Figure 4**).

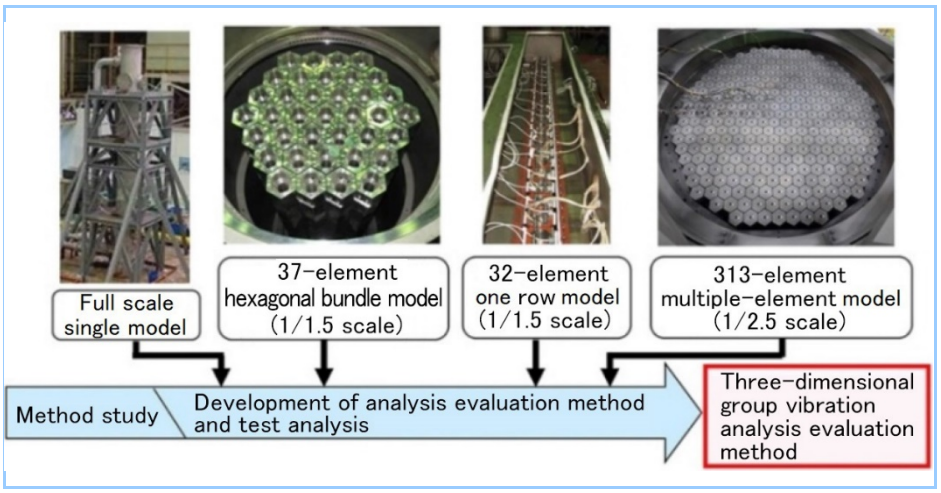


Figure 4 Gradual development of core group vibration analysis code

REVIAN-3D is an analysis code developed for next-generation fast reactors, but it is used for seismic evaluation of core elements during decommissioning for the approval examination of changes in the decommissioning plan of the “Monju” prototype reactor. In addition, in the development program collaboration between Japan and France described in Section 4.1, REVIAN-3D is used for benchmark analysis for comparative verification of Japanese and French analysis codes. In this way, we continue to accumulate verification data of REVIAN-3D for its application to approval and licensing analysis in future new regulations.

4.3 Development of sloshing evaluation method to determine load due to liquid surface collision

Fast reactors are systems that operate at higher temperatures and lower pressures than light-water reactors and have a sodium liquid surface in the reactor vessel, so in the event of an earthquake, sloshing of the liquid surface (liquid surface wave) occurs. Since the next-generation fast reactor adopts a seismic isolation system, the seismic load is reduced, but sloshing of the reactor vessel liquid surface is still likely to occur. Sloshing evaluation in conventional fast reactors was based on the criterion that the sodium liquid surface obtained by using the linear velocity potential theory does not collide with the ceiling of the reactor vessel. However, due to application of seismic isolation system and the stricter seismic conditions, it is necessary to introduce a non-linear sloshing evaluation method and estimate the impact load of the sodium liquid surface onto the ceiling. Therefore, the shaking table test (**Figure 5** (1), (2)) was conducted to understand the wave height and ceiling impact load caused by nonlinear sloshing, and a simple evaluation method that can evaluate the load in a short time and a detailed evaluation method using CFD analysis were examined[5]. As a result, the prospect of roughly evaluating the load at the load cell position using CFD analysis and a simple evaluation method was obtained (Figure 5 (3)). On the

other hand, the current simple evaluation method has low evaluation accuracy of the load applied to the entire ceiling (Figure 5 (4)), so we proposed an evaluation method for rationally obtaining the range and distribution of loads and verified it using CFD analysis[6]. In the future, we will incorporate these evaluation methods into the simple evaluation method to improve the evaluation accuracy and confirm the applicability to design evaluation.

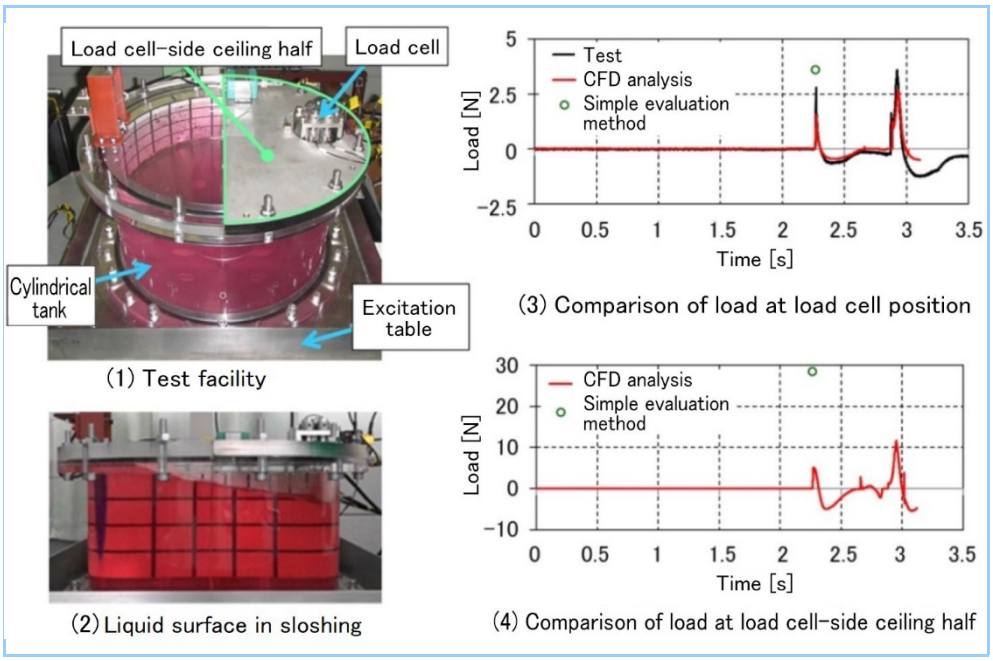


Figure 5 Sloshing test equipment and results of test, analysis and simple evaluation

4.4 Development of three-dimensional seismic isolation system that reduces horizontal and vertical seismic forces

Fast reactors that operate under conditions with higher temperatures than light-water reactors require equipment to have a thin-walled structure to reduce the stress generated by the temperature difference between the inside and outside of the vessel. Therefore, in order to reduce the seismic force acting on the thin-walled equipment, the introduction of horizontal seismic isolation technology was considered. However, to respond to the seismic conditions that have been increasing in recent years, it is important to reduce not only horizontal, but also vertical, seismic force. Aiming to achieve this, we are developing a new three-dimensional seismic isolation system (**Figure 6**) [7].

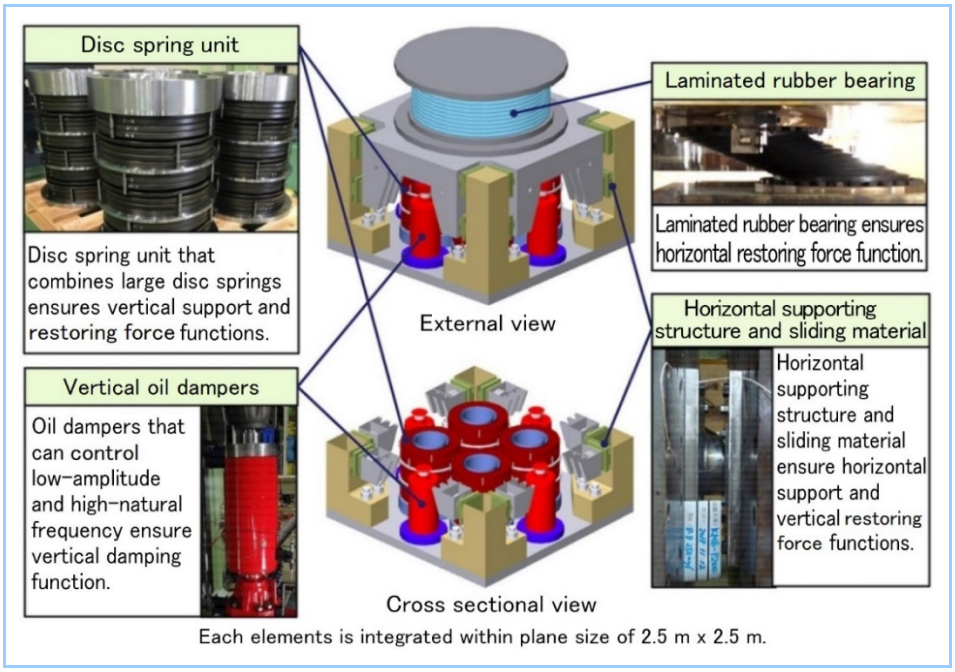


Figure 6 Concept of three-dimensional seismic isolation system

A three-dimensional seismic isolation system is required to have the function of reducing the vertical seismic force in addition to the horizontal seismic force in the same space as the conventional horizontal seismic isolation equipment. In order to realize this, it is necessary to achieve both support and recovery functions in a limited space. By using a disc spring unit that combines large disc springs, it was made possible to secure these functions in a small space.

Since it is unavoidable that the many disc springs used in the disc spring unit have individual differences in their spring characteristics, there were tasks in combining disc springs of (1) setting the combination of disc springs that can reduce the variation in the disc spring unit and (2) setting the analysis model used for seismic response analysis. Therefore, we boiled these tasks down to (1) the optimization problem of the combination of a huge number of disc springs and (2) the optimization problem of identifying the variables of the analysis model based on the test results and developed a method to which a metaheuristic algorithm, a type of AI, is applied in order to solve them[8]. By using this method, it is possible to efficiently acquire the combination of disc springs that can realize a stable load-displacement relationship and the variables of the analysis model that match the actual phenomenon. Seismic response analysis using these results indicated the horizontal and vertical seismic response reduction effects of this three-dimensional seismic isolation system.

In the future, we will conduct tests that actually combine various elements such as the disc spring and oil damper that make up the system to confirm the performance of the three-dimensional seismic isolation system, targeting its realization.

4.5 Development of small fast reactor MCR (Mitsubishi Compact Reactor)

In order to accept the various needs for fast reactors, we are aiming to improve safety, reliability and economy through innovative technologies. We are developing our own innovative small sodium-cooled fast reactor MCR, as the small reactor concept that enables a reduction of the development elements and development period and costs using the technology we have cultivated and has a low investment risk (**Figure 7**).

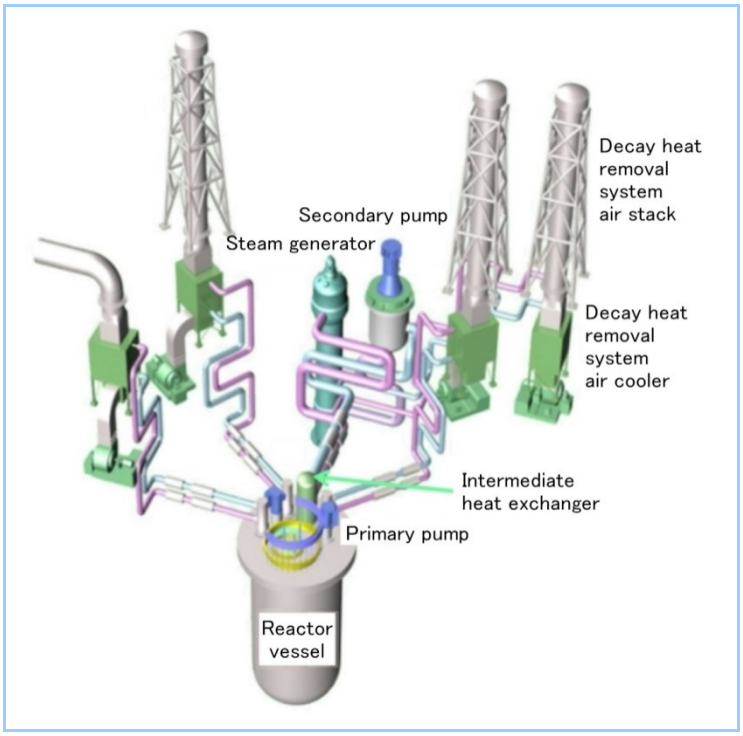


Figure 7 Bird's-eye view of MCR-200 plant

The MCR-200 is a technologically-matured small pool type sodium-cooled fast reactor with an electric output of about 200 MWe. MHI can make full use of the technology and knowledge that we have cultivated as a Japanese core company in the development of fast reactors in Japan. It was designed characteristically so that its output can be easily expanded to 1000 MWe electric output in order to flexibly accept the future needs of plant operators in Japan.

The main innovative technologies adopted for the MCR are the core using particle type metal

fuels and the nanofluid as secondary coolant in which nanoparticles are mixed in sodium coolant. The specific concept of the MCR safety enhancement is that prevention of power excursion only by the passive reactivity feedback can be achieved even in ATWS events of a reactor trip failure after an abnormal transient change. And the reactivity characteristics depends on the particle type metal-fueled core design. Accordingly, hypothetical core disruptive accident (HCDA) which has been regarded as the greatest threat since the initial development of fast reactors, can be prevented. In addition, the social peace of mind for using sodium as the coolant of fast reactor has been increased in order to dispel social concerns about the use of sodium by mitigating the chemical activity of sodium by using nanofluid. For example, sodium nanofluid can limit the influence of the sodium-water reaction in the steam generator. Furthermore, in order to realize future high economic efficiency comparable to other power sources, the MCR plant concept is developing as a plant that can increase output in response to social demands while controlling development costs. And the system configuration of this concept is simplified as much as possible from the stage of the small reactor.

5. Conclusion

The development environment of fast reactors changed significantly after the Great East Japan Earthquake. However, the Japanese government expressed expectations for the start of operations of fast reactors around the middle of the 21st century in its strategic roadmap. Recognizing the importance of the fast reactor cycle, which is a national project, we have been actively participating in the development of fast reactor from the initial stage, and we continue to work on the development of fast reactors for commercialization as a core company that plays a central role in the development of fast reactors in Japan. In the future, we will continue to develop fast reactors suitable for Japan in accordance with the national policy while leveraging international collaboration, and contribute to the reduction of environmental load and the realization of an energy supply that does not rely on fossil fuels.

The contents of this report include some of the results implemented as part of “Technology development for fast reactors” and “Technical development program on a fast reactor international cooperation, etc.” which are contracted projects from the Ministry of Economy, Trade and Industry.

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