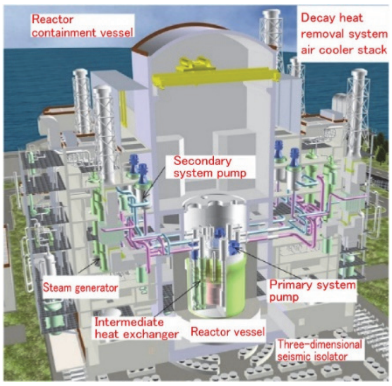
Activities for Constructing a Demonstration Fast Reactor as a Core Company



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The "strategic roadmap" (1), which was revised by the Ministerial Conference on Nuclear Power in December 2022, stipulates a plan to perform conceptual design and R&D of a demonstration sodium-cooled fast reactor between fiscal 2024 and fiscal 2028, and to make a decision to start the basic design work of the demonstration reactor and the licensing phase around fiscal 2028.

In July 2023, Mitsubishi Heavy Industries, Ltd. was selected as the core company to develop the demonstration reactor (2). Mitsubishi Heavy Industries, Ltd. has been working on the development of fast reactors to reduce radioactive waste and realize a future that does not depend on fossil fuels, as the core company to undertake the development of fast reactors in Japan.

1. Introduction

The useful life-span of nuclear energy is estimated to be up to about 100 years when recycling of spent fuel by reprocessing is not considered.

Among nuclear energy, fast reactors, which use fast neutrons for fission, can alleviate the environmental burden by reducing the volume of high-level radioactive waste and the potential hazard level, and can breed fuel and dramatically increase the number of years uranium resources can be used.

In addition, the strategic roadmap states that the status of accelerated development of innovative reactors, including fast reactors, in the world is such that the U.S. and Canada are in the process of launching projects to construct demonstration fast reactors around the 2030s based on the fact that China and Russia are promoting the development and demonstration of fast reactors ahead of the U.S., U.K., and France, and are planning to introduce commercial reactors in the 2030s.

In Japan, based on this situation of fast reactor development, the Advanced Reactor Working Group of the Ministry of Economy, Trade and Industry (METI) Nuclear Energy Subcommittee presented a technology roadmap for the development of advanced reactors in July 2022, in which the operation of a demonstration fast reactor is proposed to start in the mid-2040s and the development is planned to proceed accordingly (3).

2. Strategic roadmap for construction of demonstration reactor and Mitsubishi Heavy Industries, Ltd.'s approach

There are two types of fast reactors: loop type and pool type.

The loop type consists of a reactor vessel containing the core, primary sodium circulation pump, and intermediate heat exchanger, all connected by piping; the "Joyo" experimental reactor and the "Monju" prototype reactor are this type.

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On the other hand, the pool type consists of a core, primary sodium circulation pump, and intermediate heat exchanger, all in one large main vessel.

Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) has been engaged in the development of fast reactors since the 1970s, and took part in the design, manufacturing, and construction of “Joyo” and “Monju”. In 2007, MHI was selected as a core company and established Mitsubishi FBR Systems, Inc. (hereinafter referred to as MFBR), which specializes in fast reactor engineering, to accumulate and improve fast reactor technologies.

Since 2014, MHI and MFBR has also participated in international cooperation between Japan and France to acquire knowledge on pool-type reactors, and has accumulated technologies applicable to both types of fast reactors [(4)].

The strategic roadmap that was revised in December 2022 clearly states the significance of the development of fast reactors as follows: “By utilizing fast reactors, it is made possible to deal with the problem of radioactive waste, which is one of the most important issues in nuclear power, and to make nuclear power as a whole a recycling-oriented energy source.”

The roadmap also defines a plan for Japan to provide the conceptual design, research, and development of a demonstration reactor around fiscal 2024-2028 for a sodium-cooled fast reactor, and to make a decision on moving to the basic design and the licensing phase of the demonstration reactor around fiscal 2028 in response to the trend of accelerating the development of advanced reactors, including fast reactors, around the world.

In March 2023, the Agency for Natural Resources and Energy of the Ministry of Economy, Trade and Industry solicited conceptual specifications for the design of a demonstration reactor to be started in fiscal 2024, and core companies that would be responsible for its design, manufacture, and construction. MHI applied for this and was selected as the core company by the Fast Reactor Development Council and Strategy Working Group held in July 2023 [(2)].

3. Status of technological development

3.1 Selected domestic demonstration fast reactor design concept and future plan

The uranium-plutonium mixed oxide (MOX)-fueled medium-sized sodium-cooled pool-type fast reactor, which can be easily expanded to a large reactor with high economic potential, was selected as the main concept of the domestic demonstration fast reactor design (with metal fuel as a sub-concept).

This concept can realize a plant of high technological maturity by design, construction, technical accumulation of operational knowledge and past projects of domestic advanced reactors, and knowledge acquisition in international cooperation and this fact is one of the reasons because of selection this concept. Prior to the start of the conceptual design of the demonstration fast reactor, preliminary studies on the structure, safety design concept, and increase in the practical scale of the pool-type reactor are being conducted.

In addition, a high level of safety is ensured through a safety design in consideration of compliance with new regulatory standards reflecting international safety design standards (Safety Design Criteria and Safety Design Guidelines of GIF-SDC/SDG International Forum on Generation IV Reactors), and higher burnup fuel (large-diameter hollow pellets) is used to improve economy.

The feasibility of this fuel will be verified by irradiation tests in the “Joyo” experimental reactor, which is scheduled to be restarted in the future.

Table 1 compares the main specifications of this demonstration fast reactor with those of the “Monju” prototype reactor.

Figure 1 shows a conceptual diagram of the plant [(5)].

As examples of the conceptual studies of the main components conducted so far, **Figure 2** shows a conceptual diagram of the reactor structure, and **Table 2** the main specifications of the reactor structure.

The results of the study of the main design issues are described below.

First of all, as shown in **Figure 3**, one of the major flow-related design issues in a pool-type reactor is to prevent gas entrainment in the main vessel, which causes the intermediate heat exchanger (hereinafter referred to as IHX) located in the main vessel to suck in gas from the liquid surface, resulting in a decrease in heat transfer performance and an abnormal core reactivity; disturbance of the coolant sodium level in the hot pool in the main vessel causes bubbles to be generated by entrapped argon gas in the coolant, and these bubbles can affect the reactor power, so it is necessary to control the amount of this bubble generation to ensure safety.

As a result of the flow evaluation without excessive conservatism, which was performed only for vortices that could reach the IHX inlet window, it was confirmed that no vortices reaching the IHX inlet window would be generated and that gas entrainment was not expected to occur.

In the next, as for the seismic resistance, a computational fluid dynamics (CFD) analysis of the case where the liquid level of the coolant in the main vessel impacts the upper part of the reactor from the viewpoint of liquid level sloshing was conducted to confirm the structural integrity of the reactor by installation the seismic isolation system.

As for the impact resistance against mechanical energy (bubble expansion energy generated by rapid evaporation of coolant and other materials due to increased core temperature in a prompt criticality condition) generated in a hypothetical core damage accident (e.g., emergency reactor shutdown failure event at reduced core flow due to loss of external power), which is a severe accident unique to fast reactors, the strain of the main vessel and components, among other factors, are expected to be within the allowable range based on the impact response analysis.

Design evaluations for structural integrity, thermal hydraulics, and other complex technical issues, including the matters described above, have been conducted and the prospect of feasibility has been confirmed (6).

Table 1 Main specifications of demonstration fast reactor proposed by Mitsubishi

	Proposed sodium-cooled fast reactor	(Reference) Prototype reactor Monju
Output	650 MWe 150 MWe to 1,000 MWe is possible depending on needs	280 MWe
Reactor type	Pool (Knowledge gained through international cooperation)	Loop
Fuel (pellet)	MOX (large-diameter hollow pellet) : Metal fuel considered as sub-concept	MOX (solid pellet)
Core outlet temperature	550°C	529°C
Reactor vessel diameter	Up to approx. 16.5 m	Approx. 8 m
Main structural material	316FR steel (Stainless steel with high-temperature strength for fast reactors)	SUS304

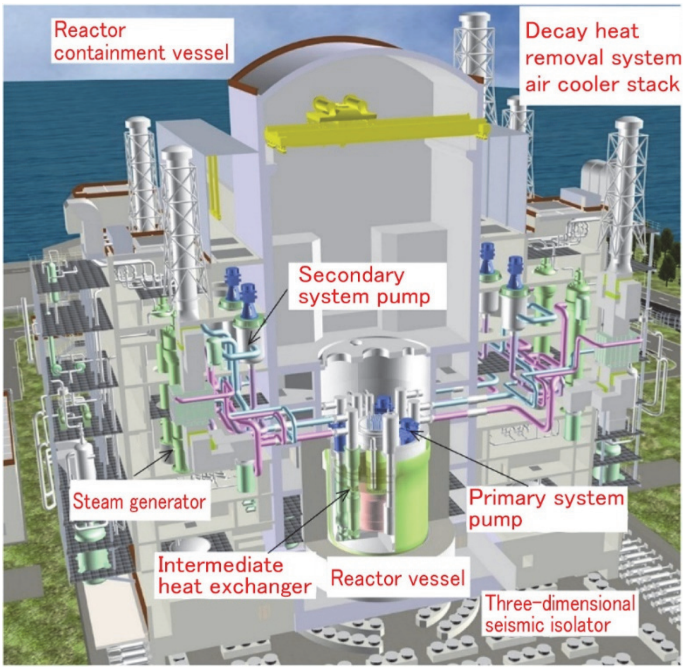

Figure 1 Bird's-eye view of demonstration fast reactor plant

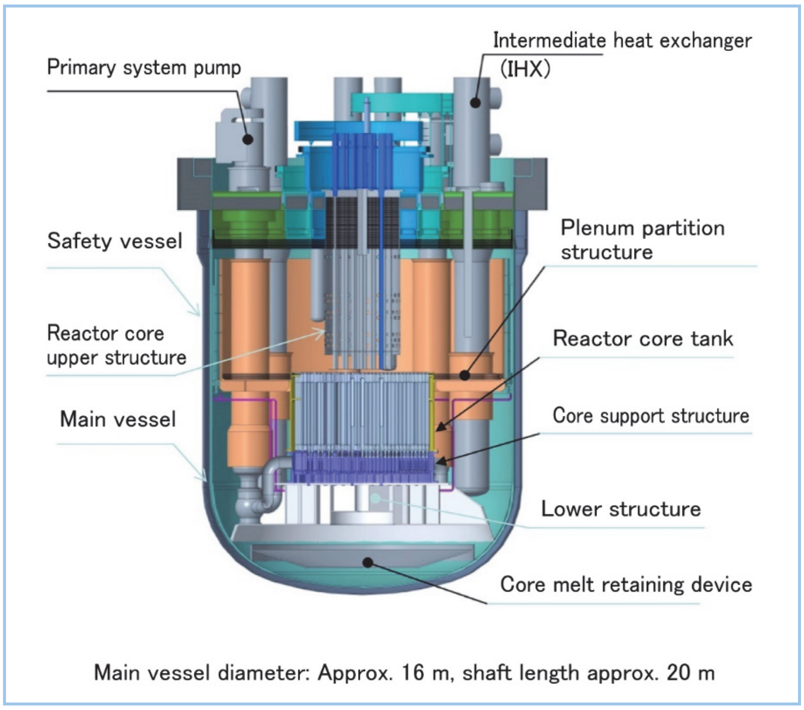

Figure 2　Conceptual diagram of reactor structure

Table 2　Reactor structure main specifications

Furnace wall protection type	Low-temperature sodium circulation
Main material	316FR steel
Operating temperature	High-temperature section: 550°C, Low-temperature section: 400°C
Seismic conditions	Seismic-isolated building
Severe accident preparedness	Assuming mechanical energy release in case of core damage
Number of intermediate heat exchangers	4
Number of primary pumps	3

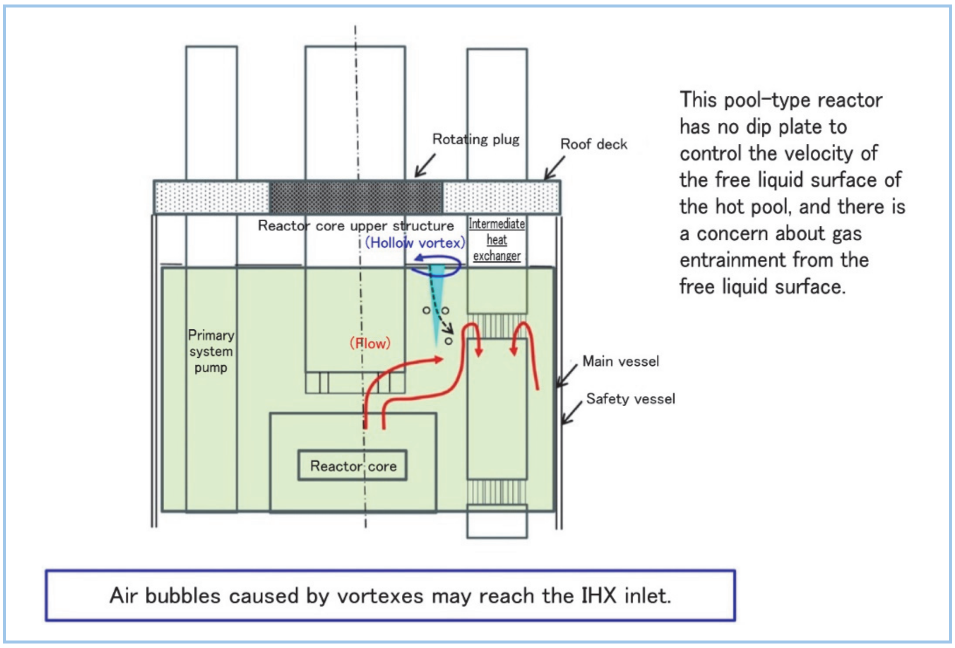

Figure 3　Gas entrainment behavior in pool-type reactor

Going forward, to start the conceptual design work based on the results of the previous studies, the main plant specifications and design conditions will be defined.

MHI will provide conceptual design to solidify the design of each facility such as core fuel, reactor structure, cooling system, reactor containment facility/building, and peripheral equipment according to the specifications and conditions defined. It will also construct a plant that is consistent and technically feasible as a whole system, and present evaluation results on the conformity to the development goals such as safety/reliability, economy, environmental load reduction, and effective use of resources.

In addition, MHI will promote research and development of newly introduced design and evaluation technologies, and improve the accuracy of the conceptual design and technical support by reflecting the results thereof.

Furthermore, MHI will formulate a development plan after the basic design in conjunction with the conceptual design, and continue to study the extrapolation of the design to a commercial-scale large reactor.

The results of these studies will be used as the basis for making a decision on the transition to the basic design at the end of the conceptual design phase, which is expected to be around fiscal 2028.

Figure 4 shows the overall plan for fast reactor development.

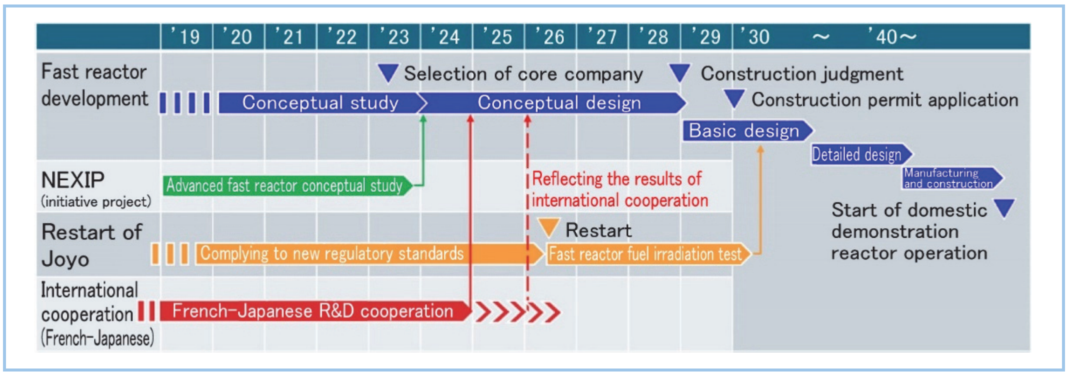

Figure 4　Fast reactor development plan

3.2　Addressing R&D issues related to demonstration fast reactor

In setting the R&D items to be implemented in the conceptual design phase, the Japan Atomic Energy Agency (hereinafter referred to as JAEA), MFBR, and MHI organized the functions that each facility within the plant should fulfill to meet the development goals, and identified the R&D issues that are required to be addressed to realize these functions. JAEA, MFBR, and MHI will address these R&D issues in a divided manner and reflect the R&D results in designing the demonstration reactor.

Figure 5 shows examples of the main identified R&D issues on the reactor structure to be studied by MHI [6].

The required safety functions include maintenance of the boundary function, prevention of core damage. Prevention of gas entrainment and development of self-actuated shutdown mechanism (hereinafter referred to as SASS) are identified as technical issues to achieve these functions.

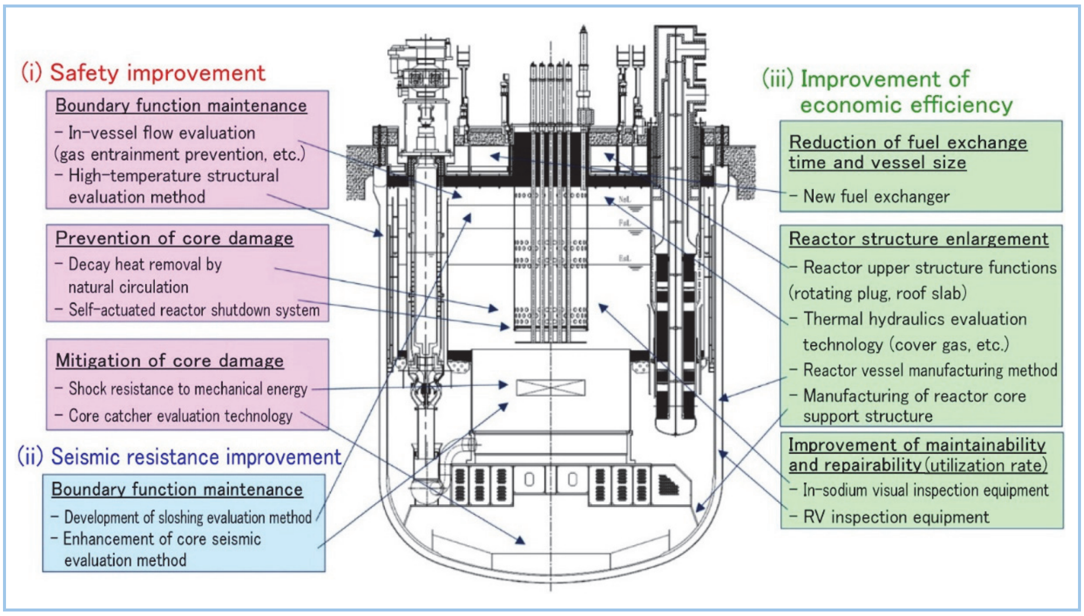

Figure 5　Organization and study of required functions and technical issues of reactor structure

As an example of R&D study, following paragraphs describes the feasibility evaluation of the SASS. The demonstration fast reactor is equipped with a SASS in the control rod disconnecting section of the reserved shutdown system, which can shut down the reactor by passively dropping the control rod when the temperature sensing alloy loses its magnetism due to an abnormal temperature rise of the coolant leaked from the fuel assembly to the upper part of the core.

In the pool-type reactor to be used as a demonstration reactor, the structure from the assembly outlet around the SASS to the vicinity of the temperature-sensing alloy has been changed from the loop-type reactor that was studied in the past.

Therefore, it is important to perceive the transportation delay time (**Figure 6**) required for the hot coolant from the fuel assembly to reach the SASS to evaluate the effectiveness of the SASS, and this delay time was again evaluated by CFD analysis. Using the delay time obtained from the CFD analysis, one-dimensional transient analysis of a typical anticipated transient without scram (ATWS) event, such as a loss of fluid (LOF)-type event, was performed using the plant dynamics analysis code (**Figure 7**).

When the coolant flow rate decreases due to an initiating event, such as a loss of external power supply, the power and coolant temperature will increase if the reactor trip of the active reactor shutdown system fails; however, when the SASS sensing alloy temperature reaches the disconnection temperature, the control rod drops. At this time, the maximum coolant temperature does not exceed the safety criterion (coolant boiling temperature). Then, the feasibility of SASS[6] has been confirmed.

As shown in the development plan in Figure 4, the development of individual components will move ahead to establish the plant concept in the conceptual design stage from fiscal 2024 to fiscal 2028, based on the assumption that the basic design will start in fiscal 2029 and the safety review will start in the 2030s. In the basic design phase, system performance, including operability, is planned to be demonstrated and confirmed to establish detailed specifications of the demonstration reactor for the regulatory body review.

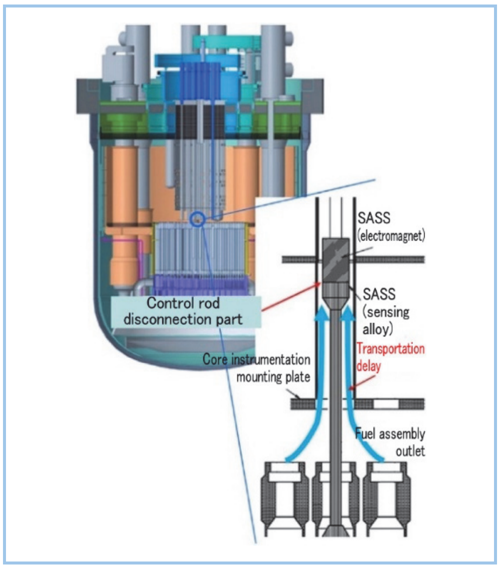

Figure 6 SASS peripheral structure

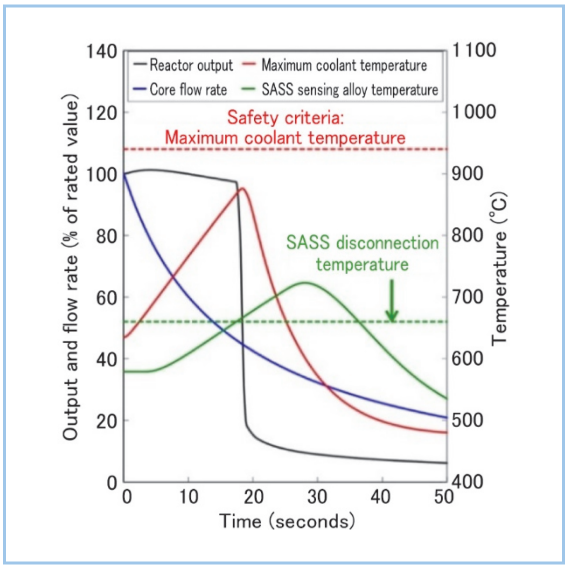

Figure 7 Transient analysis result of LOF-type ATWS event

3.3 French-Japanese and Japanese-U.S. international cooperation activities

The French-Japanese cooperation includes the joint development of key technologies for sodium-cooled fast reactors by MFBR and MHI, together with JAEA, Commissariat à l'énergie atomique et aux énergies alternatives (CEA) under the Arrangement for the Implementation on the French Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID) Project and Cooperation on Sodium Fast Reactors (2014-2019) and the Arrangement for Implementation on Cooperation on the Sodium-Cooled Fast Reactor Development Program (2020-2024), and others, in which expertise on pool-type reactors has been acquired.

Also, the Japanese-U.S. cooperation includes the conclusion in October 2023 of the Memorandum of Understanding on Sodium-Cooled Fast Reactor Technology (revised) by JAEA, MFBR and MHI with U.S. TerraPower, which is developing the sodium-cooled fast reactor "Natrium" as part of the Advanced Reactor Demonstration Program (ARDP), with the support of the U.S. Department of Energy (DOE), with the aim of establishing a cooperative relationship for fast reactor development and maintaining and improving technical capabilities related to fast reactor development.

As a result, studies are being carried out on the concept of each system, etc., in the case of a larger size than the currently planned specifications of Natrium and information exchange about the severe accidents in a metallic fuel core.

4. Conclusion

MHI has been actively promoting the development of a domestic demonstration fast reactor based on the sodium-cooled fast reactor technology that MHI have cultivated over many years. MHI will continue to study to develop fast reactors that simultaneously achieve high safety and economic efficiency while maintaining and developing a technology base of the world's highest level, thereby contributing to the practical use of fast reactors in the future.

This report presents the results of studies conducted as part of the projects entrusted by the Ministry of Economy, Trade and Industry (METI) of Japan: "Technical development program on a fast reactor international cooperation, etc." and "Technical development program on a common base for fast reactors".

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