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STUDY ON COMMERCIALIZATION OF FLOATING NUCLEAR POWER GENERATION FOR A NEXT GENERATION REACTOR DEVELOPMENT

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ABSTRACT

In the Green Growth Strategy, which considers climate change issues around the world and Japan's "2050 Carbon Neutral Declaration," the development of next-generation nuclear reactors with superior safety features has been identified as one of the key areas. Furthermore, Prime Minister Kishida put up the need for "development and construction of next-generation innovative reactors" at the Green Transformation Conference in August 2022. At the same time, based on the experience of the accident at TEPCO's Fukushima Daiichi NPS, nuclear power generation with improved safety is needed. One of the responses to these needs is offshore floating nuclear power generation plant (floating NPP) proposed by Professor Michael Golay and his colleagues at the Massachusetts Institute of Technology (MIT). This type of floating NPP combines a cylindrical floating structure with a nuclear reactor and floats several tens of kilometres offshore from the coast. A research group has been established in the Japanese industry and is working on the practical application and development of this technology.

The unique feature of this study is that the BWR (Boiling Water Reactor) is being worked on as a model plant, which differs significantly from MIT's existing research. Differences of operating procedure from existing onshore reactors were studied in 2021, and the main future development elements were as follows. The first is maintenance work, which is not a major issue, but the need to secure a dock for maintenance in Japan, and design and maintenance issues that take long-term operation into consideration are mentioned. Second, it is necessary to confirm the effects of shaking on reactor control, and evaluation and experimental methods have been studied to this end. In addition, we have been studying safety improvement measures based on the accident at the Fukushima Daiichi Nuclear Power Plant.

The estimated cost and construction period of the NPP are about the same as those of the current land-based NPPs. The detail of this is described in Sec.Ⅳ

This paper describes the research and development conducted in cooperation with Japanese industry and academia.

The safety advantages of floating NPP are as follows

(1) Less susceptibility to tsunamis
(2) A large amount of seawater in the vicinity can be used to remove decay heat from the reactor without the need for power.
(3) Offshore location away from land eliminates the need for an evacuation plan in the event of an accident.
(4) Quality can be improved by manufacturing at a centralized manufacturing site.

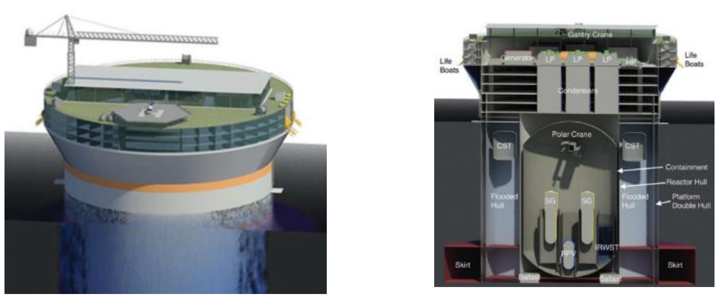

Fig.1 Conceptual diagram of floating NPP

OVERVIEW OF THIS RESEARCH AND THE TOPICS DESCRIBED IN THIS PAPER

In this study, the following 15 items were selected as major issues for research and development from among the "130 issues that need to be considered for realization"*1 identified in the preliminary survey.

*1: COCN 2021 report Appendix 1
http://www.cocn.jp/report/1a7c27e0ccd0f95876d2663e60b5dc3501c62b4d.pdf

1. Study of an outline schedule for realization
2. Rough estimation of construction cost of floating NPP
3. Safety equipment of floating NPP
4. Layout study of floating NPP (conceptual design level)
5. Counter measures against terrorism
6. Maintenance of floating NPP in offshore locations
7. Design and maintenance of floating structures considering long-term operation
8. Positioning technology suitable for floating NPP
9. Evaluation of BWR feasibility in floating oscillation
10. Efficient fuel exchange system and countermeasures against water oscillation of spent fuel pools
11. Diversification of reactor depressurization functions during severe accidents
12. Diversification of reactor water level measurement during severe accidents
13. Activities to establish a framework for international collaboration
14. Compliance with the London Convention and Protocol (handling of radioactive waste)
15. Collection of knowledge related to floating NPP

This year, the following seven points are selected from the above as those specific to floating NPP. (Rerated number to the 15 items is indicated in the brackets)

- Evaluation and experimental methods to confirm the effect on the reactor (change in the amount of heat removed from the nuclear fuel) due to the oscillation on the ocean in the case of BWR reactor type. (9.)
- Progress of the study on the layout of floating NPP, which is being conducted with reference to the study on the safety facilities that can be considered for floating NPP. (4.)
- The results of the study on counter measures against terrorism that are important from the viewpoint of nuclear material protection. (5.)
- Possible maintenance work of floating NPP facilities (nuclear power generation facilities and floating structures, etc.) on offshore, including whether or not maintenance work of floating NPP on offshore is feasible. (6.)
- The design and maintenance issues for floating structures, etc., taking into consideration long-term operation. (7.)
- Possible position-keeping technologies for floating NPP were examined. (8.)
- Measures against sloshing (a phenomenon in which the liquid level of the pool shakes violently) related to the efficiency of the fuel exchange system and the structure of the spent fuel pool where spent fuel is stored. (10.)

CURRENT PROGRESS IN SEVEN CONSIDERING POINTS

Influence of Oscillation on The Ocean in The Case of BWR Reactor

Generated steam in BWR plant to drive turbines by directly boiling the coolant (water) in the core with fuel rods. In the offshore case, there is concern that oscillations may cause fluctuations in the output of BWRs, resulting in emergency shutdowns during rated operation due to oscillations. In general, a transition phenomenon is known in which the heat transfer performance rapidly decreases due to a change in the boiling pattern when the heat load becomes excessive in the water boiling process. In previous studies on marine reactors, it has been reported that the critical heat flux (CHF) decreases due to the effect of oscillation. However, it is desirable to conduct thermal hydraulics experiments under high-temperature and high-pressure conditions assuming the actual reactor to quantitatively confirm whether the safety of the reactor is as good as or better than that of a land-based reactor.

In this study, we conducted a document review of similar experiments conducted in the past and estimated the in-core flow fluctuation in an oscillating field using the latest analysis code maintained by the U.S. National Regulatory Commission (NRC). In addition, items that should be considered in the review of licensing were extracted, and a methodology to incorporate the effects of the oscillation field into the analysis code used in licensing was studied. Based on these studies, the thermal-hydraulic parameters to be obtained in the experiments were narrowed down, and an experimental plan (experimental contents, equipment, and process) was developed to demonstrate the feasibility of BWR in the case of floating body oscillation. The oscillation conditions (period and amplitude) are very important factors in this experiment, but they have not been studied in this activity and will be an important issue in the future.

In the document review, we first conducted a broad overview survey, screened 14 references that clearly specified experimental conditions for oscillation and two-phase flow experiments, and then conducted a detailed survey to obtain the following results.

- There are no examples of experiments simulating oscillation under actual BWR conditions, and many of the specific thermo-hydraulic conditions (including nuclear thermal coupling) are not explicitly stated.
- Although not tests simulating oscillations, stability and critical power tests and performance evaluations using analytical codes have been conducted.
- It has been reported in several studies that feedback to CHF and neutron flux during "flow fluctuations" is predictable from the analysis (e.g., Isshiki prediction equation).

Next as an analytical method, in order to understand the effect of vertical oscillation of a floating BWR on the in-core flow, a sinusoidal vertical acceleration analysis was performed for a typical BWR with 1100 MW of electrical power. The TRACE code maintained by the U.S. Regulatory Commission was used as the system dynamics analysis code.

Figure 2 shows the effect of vertical acceleration oscillation on the core inlet flow velocity. The lower figure shows the vertical acceleration applied to the entire BWR plant. As gravity increases or decreases in the vertical direction for a BWR initially under rated operating conditions, the flow velocity increases or decreases due to the increase or decrease in the natural circulation driving force. The amplitude of the flow velocity response is generally proportional to the amplitude of the acceleration variation. Even when the acceleration amplitude is 0.8G, the change in inlet flow velocity is limited to ±4%.

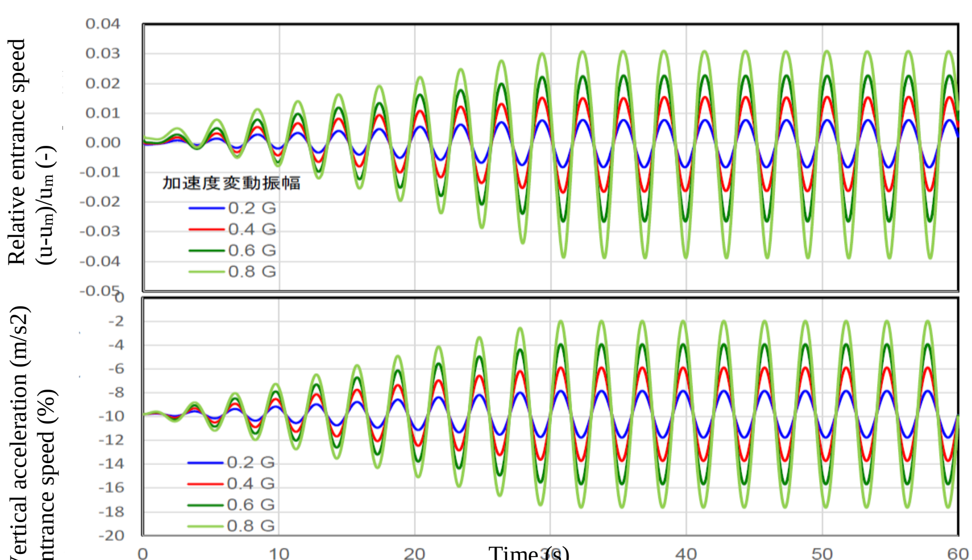

Fig.2 Vertical acceleration and reply of the core entrance flow quantity

Layout and Safety Equipment of Floating NPP

In the layout and design study of safety system facilities for floating NPPs, we use existing reactor models that have already been designed and have an operational record as the base case, and in particular, we have studied the latest type of existing onshore BWRs (ABWRs). In the layout of a floating NPP, the study was conducted to ensure the separation of categories as required by the safety review of an onshore BWR, and at the same time, the study includes to enhance diversity and multiplicity. Requirements to be considered in improving the safety of floating BWRs and constraints to accident countermeasures include the online maintenance, countermeasure for sever accident with static equipment, difficulty in connecting to a backup external power source, external risks specific to floating (flooding and sinking) , and poor accessibility.

Static systems have been installed in the in the ESBWR received by the U.S. Nuclear Regulatory Commission (U.S. NRC). For floating BWRs, we used the static system of ESBWRs developed for BWRs as the basis in order to improve the safety of floating BWRs over onshore BWRs, utilizing the unlimited seawater surrounding the floating BWR.

In addition, two static safety systems utilizing seawater will be installed, an ICS will be installed for the high-pressure water injection function and a GDCS for the low-pressure water injection function.

Counter Measures Against Terrorism

Floating NPP is located offshore and therefore have different physical protection system (PPS) characteristics than existing surface-based NPPs. It is important to reflect on these characteristics in the early stages of OFNP design.

Based on the previous OFNP research at the MIT in the US, the following three main points need to be considered in terms of anti-terrorism measures.

- Physical protection layer
- Organizing countermeasures against "vessel transfer" threats.
- Countermeasures against the threat of "torpedoes" and "aerial attacks.

Maintenance of Floating NPP Facilities at Offshore

For the floating structure, three inspection points were considered: the hull, ballast tanks, mooring, and thrusters were identified as inspection points for floating structures. We found it is necessary to improve the environment based on the premise that dry-docking may be required for large-scale repairs, etc.

For nuclear power generation facilities, we assumed that the inspection points and contents are the same as those for onshore NPP. As a result, it was evaluated that there was no particular impact on disassembling and opening inspections of components due to rocking, but the possibility of impact was considered for some of the operations, such as fuel transfer, handling of heavy materials, and bevel matching for welding operations. Design and maintenance issues for floating structures, etc., considering long-term operation

The design life of floating oil and gas production, storage, and offloading (FPSO) facilities, is about 25 years which is short compared to the typical 40-year service life of NPP. Therefore, design and maintenance of floating structures, etc. (excluding nuclear power generation facilities, but including mooring and Dynamic Positioning System (DPS)) considering long-term operation were studied.

As a result, the following areas were identified the major degradation events were corrosion and fatigue. In addition, when long-term operation is considered, each structure should be designed on the assumption that it will be replaced during the service period at the time of mooring.

Design and Maintenance of Floating Structures for Long-Term Operation

The design life of a floating production, storage, and offloading (FPSO) system is about 25 years (the maximum design life of a spar-type FPSO is 30 years according to a literature survey), which is shorter than the 40-year service life of a typical nuclear power generation system. Therefore, design and maintenance of floating structures (including mooring and DPS (Dynamic Positioning System), excluding nuclear power generation facilities) were studied in consideration of their long-term operation. The outline of the study is shown below.

- Extraction of parts of the structure to be maintained
  Extraction of the parts of a floating structure that are considered to be problematic when long-term operation is considered, based on literature survey and knowledge of the design life of the floating structure.
- Consideration from the viewpoint of design
  Design measures for the extracted parts will be studied when long-term operation is considered.
- Consideration from the viewpoint of maintenance
  Maintenance methods shall be organized for the sites extracted in (1) above.
  The following assumptions are made in the study.
    - The operation period is 40 years.
    - The shape of the floating structure shall be a nanocolumn type.
    - For position holding techniques, both mooring and DPS will be covered.

The results of the study on these three points are shown below. Basically, it can be concluded that the floating structure can be used to maintain the reactor for 40 years, which is the design life of the reactor.

Table3 Results of study of long-term operational measures for hull structure

Parts	Aging Phenomenon	Action from maintenance
Hull	Fatigue, corrosion	- Visual inspection*. - Thickness measurement*. - Repainting - Check condition of anodes (replace if anodes are worn out)
Hull (splash zone)	Corrosion	- thickness measurement - Maintenance free by using super stainless steel or titanium
Piping and vessels (ballast tanks, etc.)	- Corrosion - Loose bolts - Gasket damage - Fatigue from vibration from rotating equipment in small fittings - Decreased flow rate in the system due to blockage	- Measure thickness, inspect and clean inner surface periodically*2 - Check for loose bolts - Replace gaskets - Check for fatigue cracks due to PT at critical points - Piping replaced if necessary
Valves (ballast tank valves, etc.)	Poor sealing due to corrosion, marine organisms, etc.	- Inspect periodically (remove marine organisms, etc.) Replace if necessary
Mooring cables (entire mooring	Corrosion, wear, cracks (presumed fatigue)	- Visual inspection*. - Wear (wall thickness) measurement*2

Parts	Aging Phenomenon	Action from maintenance
system including shackles, etc.)		- Electrical potential measurement (confirmation of effectiveness of corrosion protection)* - Replacement in some cases
Other (specific locations are not specified)	Chloride stress corrosion cracking	- Periodic inspection - Replacement depending on the part

Position-keeping Technologies for Floating NPP

The ability to maintain the position of a floating structure is an extremely important technology for floating nuclear power plants, as it prevents the structure from capsizing or drifting away in the event of loss of external power. In the case of floating nuclear power generation, possible technologies to maintain the position of the floating structure can be divided into mooring and DPS, and mooring can be further divided into loose mooring (single point mooring and multi-point mooring) and tension mooring.

Based on the results of the study, it is considered that both mooring (excluding tension mooring) and DPS meet the three required functions for each of the position keeping technologies at this time. Either multi-point mooring or DPS could be adopted as a position-keeping technology for floating nuclear power plants (or both could be adopted). However, it is difficult to adopt a single-point mooring because the advantage of a single-point mooring, load-reducing effect, cannot be obtained for cylindrical structures, and the technology for transmitting power through a single-point mooring device has not been established. Tension moorings are also difficult to adopt because they capsize if the tendon (steel pipe) is damaged, and it is impractical to dry-dock them.

Efficient Fuel Exchange System and Countermeasures Against Water Surface Oscillation in Spent Fuel Pools

In designing a new floating nuclear power plant, we will study improvements related to the efficiency of fuel exchange operations and water surface oscillation of the spent fuel pool in order to realize efficient and safe operation of floating nuclear power plants.

Assuming a BWR fuel assembly, consider how to perform fuel replacement more safely and efficiently than existing methods, considering the oscillation of the floating structure, keeping the fuel subcritical, and avoiding contact and collision with falling fuel, racks, upper lattice plates, and so on.

- Plan to increase the moving speed of the fuel swapping machine.
- Plan for lifting and transferring multiple fuel bottles at once.
- Study of moving the fuel in a cover or installing a bulkhead between the reactor and the fuel pool like in PWR to increase accident resistance.

The following measures were considered for sloshing, assuming a pool of the same size as the existing reactor, and considering the following: (1) not to interfere with the fuel monitoring conducted by the government and the IAEA, (2) not to interfere with shaking, earthquake effects, and fuel replacement operations, and (3) to make the space for spent fuel storage as large as possible.

- Covering the spent fuel pool with a lid or plastic sheet to suppress the water surface oscillation.
- Put a lid or vinyl sheet on the spent fuel pool to prevent the water surface from oscillating.
- Install a wave return structure at the top of the pool.
- Ensure a sufficient height above the water surface to prevent water leakage from the pool, considering the sloshing wave height.

- The spent fuel pool itself is installed below the floating structure to reduce shaking caused by the floating structure.

Outline Schedule for Commercialization

Since the schedule to commercialization is an important issue for the feasibility of the project, an approximate schedule was also examined in this study for the purpose of practical application. As a result, it was evaluated that it would take 17 years to start operation if the design certification system in place in the U.S. is utilized, and 14.5 years under the current regulations in Japan.

The breakdown is as follows.

Siting Study Period

Based on the most recent environmental impact assessment period and the number of environmental impact assessment items considered for a floating NPP, we estimated the site investigation period to be 2.5 years. However, since this study can be conducted in parallel with the design and construction work shown in B., the impact on the overall length of the outline schedule was evaluated as 1 year for the period when the study cannot be conducted in parallel with the design work.

Design and Construction Period

As a result of the actual performance study of the nuclear-powered ship "Mutsu," it was confirmed that the period from the start of pre-startup tests to the acceptance of pre-operational inspection and receipt of ship inspection certificate is approximately 1.5 years, among others. Regulations for floating nuclear power generation need to be developed, and it is considered that they will be treated in the same way as the application of laws and regulations to offshore (floating) wind power generation facilities (Ship Safety Law and Electricity Business Law), and regulated by the Ship Safety Law and the Law Concerning Regulation of Nuclear Source Materials, Nuclear Fuel Materials and Reactors (Nuclear Reactor Regulation Law). The period of time prior to the start of construction is considered to be the design period.

For the period prior to the start of construction, the periods of design and regulatory review were evaluated. For the design period, the time required for basic and detailed design, as well as the time required for examination and discussion with regulatory agencies on issues unique to floating NPP (e.g., oscillation) were evaluated. For the design review period, we evaluated the time required for design certification, lump-sum construction and operation approval, installation permit, and construction plan approval.

Regarding the construction period, the Massachusetts Institute of Technology (MIT) has already studied the period for each of the three construction methods, referring to the actual construction of a monocolumn type floating production, storage, and offloading (FPSO) system. In this study, the period for the construction method most likely to be selected (approximately 2.5 years) was used. The construction start-up period was assumed to be after the lump-sum construction and operation approval or construction plan approval. The commissioning period was set at 1.5 years based on the experience of the nuclear-powered ship "Mutsu". Considering these factors, the following schedule for commercialization of the project was selected as a model case.

- Examination of issues unique to floating NPP and discussion with the regulatory authorities: 3 years
- Basic design: 2.5 years
- Detailed design: 3 years
- Detailed design for construction and operation approval: 1 year

- Construction: 2.5 years
- Commissioning: 1.5 years

The total time for A and B is 14.5 years. When design certification is used, the period of 2.5 years after detailed design is added to A and B as the period required for construction and operation approval, which is evaluated to be 17 years.

Cost Estimation

We evaluated and compared the construction costs of the different points of floating NPP and onshore NPP. The three comparison targets were the "floating structure" and "submarine transmission cable line" of floating NPP and the "civil and building parts" of onshore NPP, and their respective construction costs were evaluated.

The construction cost of the floating structure for floating NPP (electrical output of 1100 MW) was evaluated to be about 39-56 billion yen, the construction cost of the submarine transmission cable line was estimated to be about 30.4-47.5 billion yen, and the civil and building part was estimated to be about 82.5-137.5 billion yen. Based on these results, the construction cost of floating NPP is evaluated to be not roughly the same cost with that of onshore NPP (this evaluation is a rough estimate and does not evaluate a difference of about 10 billion yen).

Since the cost of constructing an onshore transmission cable line varies greatly depending on the location of the installation, the overall cost can be reduced if existing onshore power generation facilities can be diverted.

CONCLUSIONS

We would like to continue with the subjects under consideration and at the same time proceed with the design of the 15 items to be considered. In addition, we will continue to study regulations (especially those related to marine utilization), aiming to organize issues and make proposals for their realization.

The following four points are recommendations and measures for this project.

The industry should establish an organization to promote the concrete design and safety enhancement of floating NPP.

Universities and research institutes should activate research and development derived from floating NPP technology and foster human resources.

The Japanese government will establish an international cooperative framework. In addition, relevant laws such as the Ship Safety Law and environmental impact assessment methods for nuclear power generation should be developed for the realization of floating NPP.

The regulatory authorities should create a forum for the exchange of opinions on improving the safety of floating NPP.

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