Study on Safety analysis of floating nuclear power generation with PRA

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Abstract: In Japan's green growth strategy based on the "2050 Carbon Neutral Declaration," the development of next-generation nuclear reactors is positioned as one of the priority areas. One of the opportunities is floating (off-shore) nuclear power generation. Herein, a boiling water reactor (BWR) is used as one of the model plants, and this paper introduces research on characterizing the safety of nuclear reactors using Probabilistic Risk Assessment (PRA). In this research project, we have studied a BWR, with the goal of increasing the deployment options for BWRs, which are being developed in Japan as small modular reactors. No issue that cannot be solved by design innovations have been identified in the research, regarding the various issues that can be occurred from the installation of BWR types as an offshore reactor, the results of the PRA in this paper have not indicated any events that would cause the Core Damage Frequency (CDF) to exceed the international safety level.

Keywords: Off-shore Floating Reactor, PRA, Risk assessment, Advanced reactor

1. INTRODUCTION

The nuclear industry in Japan, which experienced the Fukushima Daiichi Nuclear Power Plant accident on March 11, 2011, is developing next-generation reactors with adequate safety learned from this accident. And it is the obligation of the nuclear industry in Japan to develop and deploy them in the next decade. As one of such efforts, this project is a joint project of major nuclear power companies, universities, manufacturers, it is the project of the Council on Competitiveness Nippon (COCN). This study is to confirm quantitively the extent of the risk in the case of installing nuclear reactors at sea by evaluating with PRA. Risk factors at sea are different from those on-shore, with the on-shore risks assumed to be higher. This project uses the frequency of core damage as the risk measure and uses it to characterize the difference in risk between on-shore and off-shore installations of BWRs.
The floating offshore reactor that is the subject of this study is that proposed by Professor Michael Golay and Professor Jacopo Buongiorno of the Massachusetts Institute of Technology (MIT) [1]. As shown in the Figure 1, a floating cylindrical structure containing a nuclear reactor is deployed tens of kilometers offshore. However, instead of the PWR they envisioned, we chose to deploy a BWR instead, that has no precedent in the world for practical use.

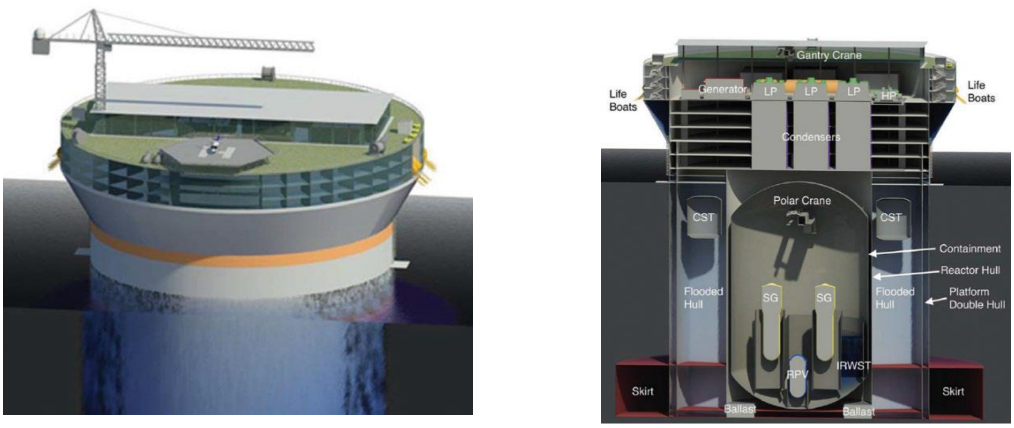

Figure 1. Floating nuclear power plant (OFNP) proposed by MIT [1]

2. CHARACTERISTICS OF THE OFFSHORE FLOATING NUCLEAR POWER PLANT

The offshore floating nuclear power plant studied herein is a combination of a floating structure, a BWR-type reactor, and a generator that is deployed tens of kilometers offshore, with the following advantages:
(1) The impact of tsunamis and earthquakes on nuclear power plants can be greatly reduced.
(2) The large amount of seawater in the surrounding area can be used to remove decay heat without the need for power.
(3) Being located offshore, far from land, would eliminate the need for evacuation of residents in the unlikely event of an accident.
(4) By manufacturing at a centralized facility and distributing it to mooring locations, high quality can be achieved and costs reduced, taking advantage of standardization.

One advantage of a BWR is that a steam generator is not needed, allowing the containment vessel to be smaller. One disadvantage of a BWR is the impact of wave motion on core coolability and void control, although a prior study [2] that examined the effects of rocking of a floating structure on the change in the void fraction inside a BWR and on critical hear flux concluded that the effect was small when the BWR is operating normally.

There are several projects underway around the world that are looking into offshore nuclear power plants using advanced reactors (e.g., molten salt). However, these types of reactors are still being developed and so we chose, at this stage, proven, already-deployed reactor technologies, with a focus on deployment in the short term. Longer term, we intend to expand the research program to consider the use of advanced reactors now being developed in the US, Japan, and elsewhere.

3. ISSUES WITH OFFSHORE FLOATING NUCLEAR POWER PLANTS

3.1. Overall Issues

Issues were listed by all organizations in the COCN review system. As a result, issues were raised regarding natural and man-made phenomena, abnormal events and accident response, nuclear material protection, rocking, floating structures, costs, maintenance, decommissioning measures, construction methods, and general regulations. These issues need to be resolved quickly. Prior work (e.g., [2]) has not identified any insurmountable problems. Other issues listed included probabilistic risk assessment, saltwater damage, location, off-site power supply, securing fresh water, and supply chains. These issues will be resolved through the actual operations of the start-up company to be established after COCN project.

3.2. Issues addressed in this study

Of the above issues, this study focuses on probabilistic safety assessment, which is likely to have a significant impact on system design. Probabilistic risk assessment (PRA) is used to assess the safety of nuclear power plants at conventional land-based nuclear power plants and is used here to characterize safety.

3.3. Previous studies on PRA of offshore nuclear power plants

There are few examples of risk assessments for offshore nuclear power plants, but the PRA results for a Russian floating nuclear power plant, which were introduced at an IAEA meeting, serve as a precedent, although they were not independently confirmed.

Russia has built and operated nuclear power plants on artificial floating islands to generate electricity in remote areas. The Pevek KLT-40S pressurized water reactor (PWR) offshore nuclear power plant in Eastern Siberia is equipped with two 150MWt reactors [3].

Regulator of Russia require to evaluate the safety by PRA before operation begins and that it be submitted as a safety analysis report [4]. According to documents from OKBM Afrikantov, the reactor's vendor [5], a Level 1 PRA was conducted for the KLT-40S, which derives the CDF for normal operation, low power, shutdown, internal hazards (fire and flooding), and external hazards. The results show that the CDF during normal operation is less than 10^{-7}/ reactor year, and during low power and shutdown is 3×10^{-9}/ reactor year. Although the details of the evaluation are not described, it is confirmed the reactor complies with the IAEA Level 1 PSA guide (i.e., complies with IAEA SSG-3), so it is roughly expected that offshore nuclear power plants can be designed and operated with sufficient risk reduction.

Table 1. Probabilistic safety assessment results for KLT-40S type light water reactor

Scope	Situation	Evaluation result (/reactor year)
Level 1 PSA	During operation	$< 10^{-7}$
Level 1 PSA	At stop or low power	3×10^{-9}

4. PROBABILISTIC SAFETY ASSESSMENT OF OFFSHORE FLOATING NUCLEAR POWER PLANTS

4.1. External events in offshore installations

From here on, the content is based on the COCN 2020 report [6].
When assessing the risks of offshore nuclear power plants, it is first necessary to select and evaluate the offshore hazards. Offshore plants are exposed to natural phenomena (submarine volcanoes, typhoons, etc.) and oceanographic conditions that are different from those on land. The effects of these (contribution to risk reduction/increase) are shown in Table 2.

Table 2. Comparison of offshore with onshore hazard events and risks

Initiating Event	Risk comparison with onshore	Reason of the comparison
earthquake	reduction	Earthquakes do not propagate underwater
tsunami	reduction	Tsunami height is inversely proportional to water depth
Wind (typhoon)	increase	Offshore wind speeds will increase
Volcano	reduction	Can be avoided by moving the floating object You can also choose the installation location.
fire	equivalent	The risks are equal
Giant Wave	increase	No waves on land
terrorism	reduction	Improved visibility due to poor terrorist access
Contact with other ships or submarines	increase	No ships or submarines on land
Contact with drift ice	increase	No drift ice on land
Slamming*	increase	No slamming on land

*: Phenomenon in which the surface of the hull impacts the surface of the water and is subjected to impact pressure

4.2. Risk assessment of offshore floating nuclear power plants

PRAs for domestic commercial reactors are: internal events PRA, internal fire PRA, internal flooding PRA, earthquake PRA, and tsunami PRA. Of these, internal fire PRA and internal flooding PRA are highly dependent on design and construction such as sectional separation and piping arrangement design, there are few effects specific to floating structures, so they are not addressed in this study. Therefore, a qualitative analysis of the risk for internal events, earthquakes, and tsunamis is implemented here based on the regulator’s review documents for Units 6 and 7 of the Kashiwazaki-Kariwa Nuclear Power Station [7][8] as the latest BWR plant. In addition, the risk of waves, which is assumed to be an inherent risk factor at offshore locations, is also conducted.
Here, only risks related to the nuclear system are considered, and events caused by damage to the hull or ship are not considered. Events caused by damage to the hull or ship can be new risk factors specific to floating nuclear power plants, such as the sinking or capsizing of the power plant itself, or damage to safety

equipment due to flooding. However, according to the Marine Accident Tribunal's "Marine Accident Report," many marine accidents are caused by human error [9], and it is confirmed that the contribution of operational aspects such as the movement of the power plant from land-based facilities and the monitoring of the surrounding area during installation is large, and they are considered to be separate from the characteristics of the site or system, so they are excluded from this review.

4.2.1 PRA of Internal Events

Internal events PRA covers events that occur due to accidental equipment failure or human error.
Then extracted in 4.1, damage to the hull and hull, an increase in the failure rate of equipment due to salt damage and constant rolling and tilting, the impact of marine organisms and drifting objects on water intake, spatial constraints on the installation of nuclear power systems, and a decrease in the reliability of off-site power sources can be considered. Here, at the stage where the design of the reactor and related equipment has not been finalized, it is assumed that the equipment reliability, facilities, materials, and functions will be equivalent to those of current nuclear power plants. On the other hand, considering the easy accessibility to the final heat sink, which is considered to be an advantage, it is assumed that in addition to the conventional safety systems, there will be an isolation condenser type system (IC) with seawater as the final heat sink. It is assumed that this system will function independently of the design basis accident response equipment when the primary system coolant boundary is sound.
The main accident sequences in the internal events PRA are shown in Table 3. Of these, it is expected that core damage can be avoided by IC in Event scenario a to c. The frequency of occurrence of these sequences is multiplied by the unreliability of the IC and other systems, and considering the reliability of the reactor facility design, the all CDF in internal events are expected to be reduced to the order of 10^{-7}/reactor year, which is lower than the safety target of $10^{-6.}$ /reactor year

Table 3. PRA of Internal Events evaluation results

number	**Event scenario**	**Evaluation result (/reactor year)**
a	Transient event + Decay heat removal failure	5.0×10^{-6}
b	Normal shutdown + Decay heat removal failure	2.7×10^{-6}
c	Loss of support system + Decay heat removal failure	5.5×10^{-7}
d	Transient event + failure to reclose SRV + failure to remove decay heat	2.1×10^{-7}

4.2.2 Earthquake PRA

Since a floating, rather than bottom-fixed, plant is being considered in this study, seismic motion does not propagate through the ground, but it does affect the plant through seawater. This makes it necessary to assess risk from ocean earthquakes. When assessing risk from ocean earthquakes, the Structures, Systems and. Components (SSC) will be damaged and lose function due to shaking, just like in an earthquake, so damage to the building must be interpreted as damage to the hull, but the anticipated initiating events and accident scenarios are considered to be similar to those for earthquakes. Therefore, the differences between earthquake PRA and ocean earthquake PRA are the frequency of hazard occurrence and the fragility of the SSC.
Seaquakes propagate as compressional waves, since the medium of seawater is compressible but has almost no shear stiffness. However, this does not mean that only P waves (compressional waves) caused by earthquakes in the ground propagate; there have been observational examples of S waves (shear waves), which carry most of the energy used by seismic motion to destroy structures, being converted into compressional waves by sedimentary layers under the seafloor and propagating underwater. In addition, it is not easy to compare the frequency of hazard occurrence with that of earthquakes, because the propagation characteristics in the sea and the wave patterns affecting floating structures vary depending on various factors and conditions, such as the thickness of the seawater layer, the structure beneath the seabed, the topography of the seabed, and the frequency band of interest.
In addition, it is not possible to confirm whether the spectral characteristics of the vibrations reaching the SSCs through the ground are equivalent to those through seawater, because the propagation characteristics of sea tremors vary depending on the conditions of various elements, the conditions of contact with the medium, and the arrangement of the SSCs. We have no knowledge of how the response of each SSC with various natural periods behaves in response to the input vibration, or of the fragility of each SSC.

Therefore, it is difficult to estimate the risk of sea quake events at present, not only in terms of the degree of impact on SSCs, but also in terms of what modes may act on power plants, because it is unclear. However, it is possible to estimate the comparative risk for specific conditions based on the following data.
Table 4 shows the results of the seismic PRA evaluation for the latest BWRs. The results show that the decay heat removal failure sequence accounts for 1/3 of the total CDF due to earthquakes, followed by damage to buildings, etc., and loss of all AC power events. The IC with seawater as the final heat sink is expected to reduce the frequency of sequences a, c, and e in Table 4, since they are expected to occur in decay heat removal failure sequences and total AC power loss events when the primary system boundary is healthy, and if the hazard fragility is equivalent to that of onshore installations, the risk due to earthquakes If the hazard fragility is equivalent to that of an onshore installation, the risk due to earthquakes is expected to decrease by about 1/2 to 1/3. This value is therefore almost the same level as the safety target of $10^{-6.}$ /reactor year

Table 4. Seismic PRA evaluation results

number	**scenario**	**Evaluation result (/reactor year)**
a	Transient event + Decay heat removal failure	5.3×10^{-6}
b	Reactor building damage	3.8×10^{-7}
c	Loss of all AC power (loss of external power + loss of DG)	3.5×10^{-7}
d	Damage to containment vessel and pressure vessel	8.9×10^{-7}
e	Loss of all AC power (loss of external power + loss of DG) + RCIC failure	3.7×10^{-7}

4.2.3 Tsunami PRA

The main impacts of the tsunami on the plant on land are assessed as follows:

- For water level drop, there is an isolation event due to loss of water intake function of the circulating water pump, and a loss of final heat sink due to loss of water intake function of the auxiliary cooling seawater system pump.
- In the event of a water level rise, seawater will flood outdoors and into buildings that have not been waterproofed, causing a loss of external power supply due to the submersion of the start-up transformer, and a loss of the final heat sink due to the submersion of seawater-based equipment such as auxiliary cooling seawater system pump motors. As the water level rises, water will flood into the reactor building from above the waterproofing measures, causing the submersion of power panels, etc., resulting in a loss of DC power supply and a loss of all AC power supplies.

According to Green's law, the height of a tsunami is proportional to the fourth root of the ratio of the water depths. Therefore, if the facility is installed offshore where the water is deep, the tsunami height observed there will be significantly lower than that observed at coastal locations. For example, when a 10m tsunami is observed over the entire surface of the power plant site, a 3m tsunami, roughly one-third the size, will be observed at a point 100m deep. For this reason, by installing the facility offshore, the tsunami hazard that reaches the facility is clearly smaller than when the facility is installed on land.
In addition, because the wavelength of a tsunami is several kilometers, which is longer than the length of the floating structure, the difference in water level between the front and rear of the floating structure during water level fluctuations is small. Therefore, it is considered that the inclination of the floating structure will be smaller than that of ocean waves.
Floating nuclear power plants move up and down in response to water level changes. Therefore, it is unlikely that the water intake function will be affected by a drop in the water level, and as for the nuclear power plant being flooded or submerged due to a rise in the water level, considering that sufficient measures against flooding and inundation are in place, damage to SSCs other than the submarine power cables is unlikely.
If the submarine power cable is damaged, loss of external power supply will occur, but under the assumption that other SSCs do not lose their functions due to tsunami, the result is the same level as the evaluation result of loss of external power supply for internal events.
Considering the magnitude of tsunamis acting on nuclear power plants, the fluctuation of floating structures themselves due to tsunamis, and the functions that floating nuclear power plants are supposed to have, there is almost no risk of tsunamis, and the CDF of 2.1×10^{-4}[/reactor year] due to tsunamis in the latest BWR is expected to be significantly reduced, and the safety It is sufficiently inferred that it will be lower than the safety target value10^{-6}/reactor year.

4.2.4 Waves

For land-based nuclear power plants, flooding is assumed as a mode of damage and loss of function to equipment, etc., when waves reach the plant, but PRA is not generally performed due to the possibility of waves reaching nuclear power plants. However, flooding is assumed as a mode of damage and loss of function to equipment, etc., when waves reach the plant.

In a floating nuclear power plant, the power plant itself is subject to flooding and inundation when covered with seawater, and the power plant itself also sways and tilts in response to changes in sea level. The former can be dealt with by taking measures to stop water from entering the water, and is considered a function that should be inherently provided when the plant is installed on the sea, so its impact will be excluded here. Therefore, from here on, we will consider oscillation and tilt.

The impact of the sway and tilt on the safety equipment, including the passive safety systems, in terms of thermal-hydraulic behavior has been studied by Zhang et al. [10] for the 300 MW floating nuclear power plant OFNP-300. In the bounding evaluation under a maximum swing angle of 20° or a tilt of 30°, it was concluded that although some passive safety systems may not function properly, there is little impact on safety. However, there is no knowledge regarding the impact on the maintenance of SSC functionality, i.e., the strength of SSCs exposed to tilt.

PRA that considers damage and loss of function due to inclination of SSC is considered in fault displacement PRA, and technological development and preparation of PRA standards are being promoted. The proposed standard states that "the design standards for ships, the Steel Ship Rules (Part D 1.3 General Requirements for Engines)" can be used as a reference for realistic strength evaluation of dynamic function maintenance, and it states that "the prime mover is required to be designed to operate under conditions of static inclination of 15° lateral and 5° longitudinal."

Here, we will consider the risk with reference to the maximum vibration amplitude and acceleration of OFNP-300 [10]. Since the horizontal and vertical orientation of a cylindrical offshore floating structure cannot be specified, assuming that the active equipment maintains its function even under conditions of a 15° inclination in either direction, it has been shown that there is a large margin of error compared to the 8.4° of the 10,000-year recurrence period in OFNP-300. In addition, the horizontal and vertical accelerations are $0.86m/s^2$ and $0.75m/s^2$ for a 10,000 -year recurrence period. The design response acceleration at the top of the foundation base of the latest BWR is 6.28 m/s2 (Ss-3) in the horizontal NS direction, 7.26 m/s2 (Ss-2) in the horizontal EW direction, and 7.74 m/s2 (Ss-1) in the vertical UD direction; the acceleration acting on the floating structure due to waves is very small compared to these values. Therefore, the effect of wave-induced acceleration on the power plant is not considered significant.

Based on currently available information, it is confirmed that the risk from waves does not negate the feasibility of floating structures from the perspective of safety. On the other hand, there is a lack of information on the damage conditions when the SSC tilts, and the impact of tilt on the plant cannot be generally ignored; it is something that has not been seen before, and may present a risk profile that differs from external hazards that have been considered up to now. This risk information is considered to provide important information for considering future specifications and operations, and it is hoped that a detailed risk assessment will be carried out in the future.

5. CONCLUSIONS

In this section, we have presented the concept of selecting hazards to be assumed in the risk assessment of floating nuclear power plants and of implementing PRA.

Furthermore, in considering the risks of onshore and offshore nuclear power generation, the characteristics of floating nuclear power plants that may affect the risks were summarized, and the design standards and operational considerations of floating nuclear power plants were considered, along with a qualitative analysis of the risks.

Floating nuclear power plants is expected to be reduced compared to land-based reactors, assuming that the floating nuclear power plant has a natural circulation emergency condenser system with seawater as the final heat sink.

Regarding earthquakes and ocean quakes, the extent of their impact on the SSC and the mode in which they act on the power plant are unclear, so it is not possible to estimate the risk at present and this is an issue to be addressed in the future.

Regarding tsunamis, considering the size of the tsunami that would attack a nuclear power plant, the fluctuations of the floating structure itself due to a tsunami, and the functions that a floating nuclear power plant should inherently have, it is expected that the risk of tsunamis will be almost eliminated and the frequency of core damage at sea will be significantly reduced.
- The risks associated with waves cannot be simply ignored, so a detailed risk assessment should be carried out in the future.
-Sinking should also be taken into consideration as an important issue in the design.

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