Safety Analysis of Flooding Accident in Shallow Water for Offshore Floating Nuclear Power Plant

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Abstract. The Offshore Floating Nuclear Plant (FNPP) integrates a nuclear reactor into a floating facility. A typical FNPP developed to supply desalinated water and electric power is analysed in this paper. Flooding accident is a postulated ship accident which should be considered in designing the FNPP in order to reduce harmful radiation impacts on the crew and environment. The integrity of the containment, the safety of spent fuel assemblies and the safety of the reactor core are the key factors to evaluate the accident consequences. Flooding accident in shallow water is investigated in this paper. For FNPP, the containment has sufficient strength to resist pressure from outside induced by seawater. Meanwhile, the seawater supplies enough heat sink for the cooling of the spent fuel assemblies. In order to investigate the safety of reactor core, a RELAP5 model with Passive residual heat removal system (PRHR) is used. The results suggest that the natural circulation in the primary system can be established and the residual heat can be carried out efficiently. The reactor core can keep safe during the flooding accident.

Keywords: FNPP, safety analysis, PRHR

1. Introduction

The Offshore Floating Nuclear Plant (FNPP) is a nuclear power plant which can be used to provide seawater desalination and electricity to islands and offshore oil drilling platform. A group of researchers throughout the world is doing project on this [1]. A typical FNPP project developed in China to supply reliable desalinated water and electricity is analysed in this paper. Design basis external event should be considered in designing the FNPP ensuring the ship has enough strength and capability to keep safe under harsh marine environment. Meanwhile, the safety of the FNPP will be ensured by reasonable ship route planning and safety protection, no matter in operating sea area or in the voyage, no flooding accident is expected to occur in the life period of the FNPP. However, in order to evaluate the safety of FNPP, flooding should still be taken as a hypothetical event and the accident consequences should be analysed and evaluated.

As shown in Fig. 1, after the ship sinks, the depth of water has a significant influence to the FNPP due to the difference of the water pressure. Thus, flooding accident is divided into flooding in shallow water and flooding in deep water [2], [3], [4]. Analysis and evaluation should be carried out respectively...
to consider different damage to the safety of reactor and containment from water pressure to the structure and equipment failure as a result of flooding.

![Diagram](image.png)

**Figure 1.** Different status of flooding accident.

For flooding in shallow water, when the accident happens, it is assumed that the ship will sink smoothly until the upper deck is submerged and the bottom lands on the seabed. The reactor containment and engine compartment will be submerged. As the reactor containment directly bears a certain capacity of design external pressure, the integrity of the containment will not be damaged in shallow water. While the rest of the non-watertight cabin should be considered to be flooded and the non-watertight equipment will fail to work.

The cause of flooding in deep water is the same as in shallow water, but the hull and the cabins of FNPP will be subjected to a larger external load after sinking as a result of deep water. In order to ensure that the structure will not be damaged in a short time, FNPP generally will adopt some measures such as the installation of containment accident submersion system to ensure that the containment is still able to resist external impact and biological invasion in a longer period of time. Sealing failure may occur in the reactor main coolant system under the external pressure and the seawater will enter the reactor and come into contact with the fuel assemblies. The core decay heat can be continuously exported. However, radioactive fission products may gradually enter the water inside the containment due to the corrosion of the fuel cladding and the main coolant equipment, and thus will be slowly released to the environment from the containment.

The FNPP is proposed to service in a shallow Sea region. The maximum water depth is about 30m, which is relatively shallow. Therefore, this paper mainly focus on the accidental result of flooding in shallow water.

2. **Analysis key points**

Fig. 2 illustrates the proposed analysis content and procedure of flooding in shallow water. As the containment has sufficient strength, the possibility of direct destruction of nuclear power plant by external events such as collision can be neglected.

As the ship begins to sink, the water gradually covers the entire vessel. In order to prevent the release of large amount of radioactive material, the FNPP should has reliable measures to continually carry out the decay heat of reactor core and the spent fuel assemblies. Meanwhile, the integrity of the containment should be kept.

The FNPP is equipped with a double-loop pressurized water reactor. The reactor is located in the containment. The containment is set to have the capability to withstand the external pressure of at least 0.6MPa(abs), which means the containment can withstand the pressure induced by 60m-depth water.
Therefore, when the FNPP submerges in shallow water, the containment will not fail in a short time under the pressure the external water.

The spent fuel pool is located in the spent fuel storage cabin. As the cabin is non-pressurized and non-watertight structure, its integrity will not be guaranteed under external water pressure. As a result, the entire spent fuel storage tank and spent fuel assemblies inside will be flooded with seawater. Although both conventional and emergency power will fail after the entire vessel is flooded, the seawater injected into the cabin and the spent fuel storage tank can replace the function of PTR system and keep the spent fuel assemblies safe in a long term.

![Analysis contents and procedure.](image)

In summary, passive residual heat removal system should be provided to ensure the decay heat in the reactor core can still be carried out even if all electric power is lost in order to specify acceptable fuel design limits and the design conditions of the reactor coolant pressure boundary are not exceeded. Thus, severe accident and early release of radioactive will not happen.

3. Accident mitigation strategy

After the ship sinks, the power supply cabin will be flooded by seawater. The conventional AC, emergency AC and UPS will fail at the same time. As a result, total loss of operability of all ship’s power sources shall be evaluated. The FNPP is equipped with a secondary passive residual heat removal system(PRHR) to alleviate the consequence of this accident. Fig. 3 illustrates the schematic diagram of PRHR. Each steam generator(SG) loop is equipped with a set of PRHR loop.

After the accident, the isolation valve in the SG steam pipeline and the isolation valve in the PRHR injection line will open, and the steam generated in the SG will enter the heat exchanger immersed in the cooling tank outside the containment. The heat energy will be transferred from the steam to the water in the pool. The cooled water will then be transferred back to SG. Both primary coolant system and SG loop will establish a natural cycle. The heat from the reactor core will be carried out passively.

It should be noted that heaving and rolling conditions have an nonnegligible influence to natural circulation [5]. After the ship sinks and gradually lands on the seabed, the whole vessel may keep in a relatively stable state and rest at angles determined by individual analysis approved by the administration [2]. In this paper, for a simple case, it is supposed that the ship rests at a small angle with no rolling and heaving condition. As for the effect of listing, since two SGs are arranged symmetrically, when the
height difference between heat source and sink on one side is reduced, the height difference on the other side will rise. Therefore, it should be designed and guaranteed that the decay heat can be effectively exported even if one cooling loop is lost.

In addition, cooling tank outside the containment has a limited capacity. But as the vessel submerges, seawater will continue to provide coolant to fill in the tank and to carry out the energy.

**Figure 3. Schematic diagram of PRHR in FNPP.**

4. Safety analysis

According to the analysis content and procedure shown in Fig. 2, after the accident of shallow water flooding happened, the safety of spent fuel, the integrity of containment and the consequences of reactor core need to be evaluated. Since the water will flood the spent fuel pool, the decay heat of the spent fuel will continue to be carried out. The spent fuel will keep safety in a long term. In addition, as a result of the shallow water, the containment will not be damaged by the external pressure of the water. Therefore, if the residual heat from the reactor core can be continuously derived after the occurrence of flooding accident, it can be ensured that the reactor core will not melt down in the short term and large-scale radioactive material release will not occur.

4.1. Model of the system

In this paper, the Relap5 program is utilized to establish a system analysis model to analyse and evaluate the safety of the reactor core under the submerged condition. The analysis model is shown in Fig. 4, where only one loop is shown and another loop is arranged symmetrically. This model integrates reactor, the primary system, the secondary system and the PRHR system. In the PRHR system, a C-type heat exchanger is utilized to enhance the heat transfer.

4.2. Analysis assumption

The following assumptions were used in this analysis.

A) At the moment of the ship begins to sink, the reactor is shut down manually.
B) For conservative consideration, all power is assumed to be lost after the occurrence of ship sinking and the mitigating effect of active equipment is not considered.

C) In a short term, the heat transfer pipe rupture caused by seawater corrosion is not considered.

D) After the ship reaches the seabed, the ship is assumed to stay in a steady state and rests at a small angle with no rolling and heaving condition.

E) For conservative consideration, only one loop of PRHR is considered in order to cover the effect of listing.

Figure 4. Nodalization of the PRHR system.

4.3. Results and discussion

In this paper, the transient results of 72h are analysed. Fig. 5 illustrates the results the thermal power of reactor core, SG and PRHR heat exchanger. After the reactor was shut down manually, the thermal power of reactor core dropped rapidly. With the shutdown of the steam turbine and the steam isolation valve, the steam generated in the SG enters the PRHR pipeline. After cooling in the PRHR heat exchanger, the steam will enter the SG through the water injection pipeline. Flow variation of SG inlet and outlet is shown in Fig. 6. With the application of PRHR, the heat removal capacity of the PRHR gradually matches the decay heat of the reactor core and reaches an equilibrium state.
As only one loop of PRHR is considered in this analysis, the flow rate of the two loops of primary system was slightly different which is shown in Fig. 7. In addition, this paper compares the differences of core temperature changes after applying different amounts of PRHR shown in Fig. 8.
Figure 7. Flow rate of primary system.

As the temperature difference of water in primary system, secondary system and PRHR decreases, the heat derived from PRHR also decreases gradually. Due to the large amount of water in the PRHR water tank, it still has enough water even after 72h since the flooding accident happened. In addition, the cooling of the water tank and the supplement of seawater were not considered in this analysis. Therefore, it can be concluded that after the FNPP sinking accident, relying on the PRHR, the decay heat of the reactor core can be continuously carried out and the safety of the reactor can be maintained without the need of the human intervention.

Figure 8. Temperature of the reactor core.

It should be noted that the analysis in this paper assumes that the ship will not capsize and after sinking the ship will rest with a small angle. But the actual situation is much more complex than this assumption with a great uncertainty. Therefore, when design the FNPP, it is necessary to set up a device to effectively control the reactivity in capsizing condition. Meanwhile, a certain emergency mechanism should be established to avoid large scale release of radioactive substances caused by the sinking of FNPP.
5. Conclusion
For a FNPP project, it is necessary to analyse the flooding accident as a hypothetical design accident. In this paper, the analysis content and method is proposed and the accidental result is analysed with Relap5 program.

In the case of flooding accident in shallow water, the reactor safety, the integrity of containment and the safety of spent fuel assemblies should be evaluated. Seawater injected into the vessel may provide an additional supplement to the spent fuel pool, making up the loss of coolant to carry out the decay heat. The containment is designed to be strong enough to withstand the external pressure induced by seawater. For the FNPP, the only method available to derive the decay heat of reactor core is PRHR and the analysis result shows that the safety can be maintained.

Acknowledgments
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