Safety Analysis of a 300-MW(electric) Offshore Floating Nuclear Power Plant in Marine Environment

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Abstract — The Offshore Floating Nuclear Plant (OFNP) integrates an advanced light water reactor into a cylindrical, double-hull, floating platform. It offers a series of potential benefits in economics and safety. The 300-MW(electric) version, named OFNP-300, uses an ocean-based direct reactor auxiliary cooling system (DRACS) to remove decay heat from the core passively and indefinitely during loss of feedwater or loss of off-site power events. In the ocean, the OFNP platform may roll during storms or even statically tilt following asymmetric flooding of underwater compartments. The effects of rolling motion and static tilt on the engineered safety systems are investigated in this paper using a RELAP5-3D (version 4.3.4) model of OFNP-300. The oscillations of the platform are described as the superposition of sinusoidal motions for the six degrees of freedom, i.e., heave, roll, pitch, yaw, sway, and surge. The plant’s thermal-hydraulic responses to two postulated accidents, i.e., loss-of-coolant accident (LOCA) and station blackout (SBO), are then studied in three scenarios: (a) a design-basis 100-yr storm, (b) a bounding scenario in which the platform is assumed to pitch and roll with an amplitude of 20 deg, and (c) a bounding scenario in which the platform experiences a static tilt of 30 deg. The results of the RELAP5 analysis show that the safety margins of OFNP-300 are not challenged in the aforementioned three postulated scenarios. From a thermal-hydraulic point of view, the pitch and roll motions affect the flow in the DRACS but have no negative effect on the temperatures in the core during LOCA and SBO. Static platform tilt is tolerable up to 45 deg, beyond which the emergency core cooling system can no longer function.

Keywords — Offshore floating nuclear plant, thermal hydraulics, marine environment.

Note — Some figures may be in color only in the electronic version.

I. INTRODUCTION

With 61 nuclear power plants under construction, nuclear power is currently experiencing moderate growth, especially in Asia. A more robust expansion is needed if nuclear is to play a significant role in combating climate change. However, nuclear power is still facing several challenges, the most important of which are capital cost, safety, siting, licensing costs, spent-fuel disposal, and proliferation. The three high-level challenges of achieving affordability, enhanced safety, and easy deployment can be met with the development of the Offshore Floating Nuclear Plant1 (OFNP).

The concept of OFNP, shown in Fig. 1, integrates a light water reactor (LWR) into a floating platform that is used in offshore oil/gas operations. Both technologies are mature and successful, with an established global supply chain.

OFNP is a plant that can be entirely built in a shipyard, transported to the site where it can be moored within a dozen miles off the coast within territorial waters, and connected to the grid via submarine transmission cables. OFNP can achieve its economic goals through plant simplification, modularity, shipyard construction, and efficient decommissioning.

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Massachusetts Institute of Technology is developing two OFNP designs in parallel that would find application in different markets: OFNP-300 and OFNP-1100, designated to achieve different electric power ratings. This paper addresses OFNP-300 only. The reactor in OFNP-300 is based on the Westinghouse Small Modular Reactor (WSMR), uprated to 300 MW(electric) (Refs. 2 through 5).

The floating structure chosen to house the nuclear plant is a cylindrical hull-type platform that shares many of its characteristics with the platforms used in the offshore oil and gas drilling industry. The cylindrical hull design offers substantial gains in dynamic stability at the scale for which OFNP is designed when compared to other offshore platform designs, such as semi-submersibles or floating barges. The cylindrical hull design also enables the reactor and containment to be located at an elevation below the waterline, which enhances physical protection from plane crashes and collisions with ships while also making it easier to access the ocean heat sink. The OFNP balance of plant includes a standard Rankine cycle and a step-up transformer, both located onboard the platform, as well as several submarine alternating-current (ac) cables to transmit the electric power to the grid on land. The platform characteristics of OFNP-300 are reported in Table I. More information on the OFNP design can be found in Refs. 6, 7, and 8.

Research work on the OFNP design, construction, siting, and security has been conducted and published.7-13 This paper focuses on the OFNP safety principles and their implementation in the OFNP design. The frequency and responses to design-basis events (DBEs) such as overcooling, overfilling, reactivity insertion, anticipated transients without scram, and spent-fuel accidents are the same as land-based reactors.

However, the OFNP responses to other DBEs like loss of flow and loss of coolant are based on passive safety systems relying on natural circulation, which is affected by platform motion in the ocean due to storms, waves, or even collision with ships. For example, platform motion can reduce the relative elevation of the thermal centers in a natural-circulation loop, thus reducing the flow rate, which in turn may reduce the heat transfer rate in the core and heat exchangers. Therefore, in this paper we investigate the effects of platform motion on the safety systems used to address such events, i.e., the direct reactor auxiliary cooling system (DRACS), the emergency core cooling system (ECCS), and the passive containment cooling system (PCCS).

### II. OFNP SAFETY OBJECTIVES

The OFNP safety philosophy is to eliminate (by design and siting) major accident initiators from extreme natural

![Isometric views of OFNP-300](image_url)

### TABLE I

| Parameter                  | OFNP-300   |
|----------------------------|------------|
| Hull/skirt diameter (m)    | 45/75      |
| Draft (m)                  | 48.5       |
| Total height (m)           | 73         |
| Main deck height (m)       | 12.5       |
| Displacement (ton)         | ~115 500   |
| Natural period for heave/pitch (s) | ~24.5/32.7 |
events, protect the plant with passive safety systems when an accident does occur, and drastically mitigate the radiological consequences of severe accidents. The OFNP’s top-tier objectives are directly inspired by the lessons learned from the Fukushima accident, as follows:

1. Eliminate earthquakes and tsunamis as accident initiators.
2. Eliminate the loss of ultimate heat sink (UHS) accident.
3. Ensure effective core and containment cooling during a station blackout (SBO) (loss of all ac power).
4. Reduce the possibility of containment overpressurization should a severe accident occur.
5. Eliminate the possibility of significant land contamination should a radioactivity release occur.

While a formal Probabilistic Risk Assessment study for the OFNP concept has not been performed yet, attainment of objectives 1, 2, and 3 is expected to result in a substantial reduction of the core damage frequency, even with respect to advanced passive LWRs built on land. Attainment of objectives 4 and 5 will reduce the large early release frequency and will make it possible to eliminate the need for near- and long-term evacuation of the local population. Table II shows how OFNP meets the safety requirements in comparison with other nuclear power plants.

III. DEFENSE IN DEPTH, EMERGENCY PLANNING ZONE, EXTERNAL EVENTS

Integration of the nuclear island within a floating platform increases the number of barriers to the release of radioactivity: In addition to the traditional four barriers (i.e., fuel pellet, cladding, pressure boundary, and containment), OFNP features a reactor hull and the external double-hull (see Fig. 2). While these additional barriers are not airtight in the same way that the containment shell is, they provide protection from external loads, and in an accident with containment bypass, they would reduce the magnitude and increase the delay of a radioactivity release into the environment.

Another unique feature of OFNP is the absence of any resident population in the 10-mile-radius emergency planning zone (EPZ) surrounding the plant. Compare that to the EPZ of terrestrial sites, which in the case of certain U.S. nuclear plants near major cities can host as many as several hundred thousand local residents; this has drawn undesirable media attention since it is challenging to demonstrate that a general evacuation can be executed successfully should a large radioactivity release from the plant occur. An additional benefit of the uninhabited EPZ is insulation from local population growth over the lifetime of the plant.

Since OFNP is a floating plant, seismic loads from the ocean floor do not transfer to the plant structures; consequently, earthquakes are completely eliminated as a safety concern. The importance of this feature, especially in highly seismic regions of the world such as the Pacific Rim, cannot be overstated.

As OFNP is sited in relatively deep water (≥100 m), tsunamis are also eliminated as accident initiators. The amplitude of tsunami waves changes with depth according to Green’s law,

$$A_1 = \sqrt{A_0},$$

where $A_0$ and $A_1$ are wave amplitudes at two different points and $b_0$ and $b_1$ are the water depths at those points. This equation shows that as a tsunami wave moves into more shallow waters closer to shore, its amplitude increases and can become quite destructive. The data from a Deep Ocean Assessment and Reporting of Tsunamis (DART®) sensor northeast of Japan from the March 2011 tsunami show that the water wave peaked at 1.78 m in 5660-m-deep water. Then, Green’s law predicts a corresponding wave amplitude of 4.9 m in 100-m-deep water. These are fairly large waves, but their period is very long, in the range of 10 min to 2 h (Ref. 15). Since the natural period of an OFNP platform (see Table I) is much less than the period of the tsunami wave, the plant will be able to float up and down quasi-statically without incurring damage or risk of submersion. The OFNP mooring system with chain-polyester omnidirectional lines and suction anchors is designed to have enough slack to accommodate the vertical motion.

The OFNP platform can also experience displacements and accelerations due to storm-induced waves and currents. The dynamic response of the OFNP-300 platform was studied by our partner Sevan Marine, using its codes with historical and extrapolated data for massive storms in the North Sea (Table III). Table IV shows the results: The displacements, rotations, and accelerations experienced by the platform during the design-basis, 100-yr return-time storm are quite benign and can be accommodated easily by the OFNP mooring system. The outstanding stability of OFNP is due to the cylindrical-hull design, the presence of a skirt, the mooring system itself, and the decoupling of the OFNP platform natural period from the period of the storm waves. The results in Table IV were used as input to the RELAP5 analyses, as explained in Sec. V.
### TABLE II
Safety Functional Requirements for Four Nuclear Power Plant Designs

| Safety Functional Requirement | OFNP-300                              | NuScale                                | AP1000                                 | APR1400                                 |
|------------------------------|---------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|
| Maintain nuclear reactor core integrity | Control rods, boron                   | Control rods, boron                    | Control rods, burable absorber rods, boron | Control rods, burable absorber rods, boron |
| Control core heat generation rate (reactivity control) |                                      |                                        |                                        |                                        |
| Provide process shutdown mechanism |                                      |                                        |                                        |                                        |
| Limit excess reactivity (excess power levels) |                                      |                                        |                                        |                                        |
| Control reactivity with inherent feedback |                                      |                                        |                                        |                                        |
| Remove core heat | Passive residual heat removal system, passive ECCS | Passive residual heat removal system, passive ECCS | Passive residual heat removal system, passive ECCS | Active residual heat removal system, active and passive injection systems |
| Maintain core coolant boundary integrity |                                      |                                        |                                        |                                        |
| Maintain core coolant makeup |                                      |                                        |                                        |                                        |
| Transport heat to UHS |                                      |                                        |                                        |                                        |
| Transport heat |                                      |                                        |                                        |                                        |
| Heat sink |                                      |                                        |                                        |                                        |
| Control oxidation of cladding | Advanced Zr alloy                    | Advanced Zr alloy                      | Advanced Zr alloy                      | Advanced Zr alloy                      |
| Control transport of radionuclides from primary circuit | Integral RPV with no primary system piping | Integral RPV with no primary system piping | Robust RPV and piping                  | Robust RPV and piping                  |
| Maintain pressure boundary integrity |                                      |                                        |                                        |                                        |
| Control primary circuit pressure | Safety and relief valves, pressurizer | Safety and relief valves, pressurizer | Safety and relief valves, pressurizer | Pilot-operated relief valve, safety valves, pressurizer |
| Isolate primary circuit from balance of plant | Steam generators                      | Steam generators                        | Steam generators                        | Steam generators                        |
| Control transport from containment |                                      |                                        |                                        |                                        |
| Maintain containment boundary integrity |                                      |                                        |                                        |                                        |
| Effect containment isolation |                                      |                                        |                                        |                                        |
| Containment structure |                                      |                                        |                                        |                                        |
| Containment isolation |                                      |                                        |                                        |                                        |
| Pressure control |                                      |                                        |                                        |                                        |
| Control energy in containment |                                      |                                        |                                        |                                        |
| Reduce energy sources |                                      |                                        |                                        |                                        |
| Heat removal |                                      |                                        |                                        |                                        |
| Immobilize releases | Containment immersed in seawater      | High-strength steel containment immersed in the cooling pool | Containment spray system                | Containment spray system                |
| Control transport from site | Filtered vent (possibly), EPZ at sea (possibly tow OFNP far from coast) | EPZ                                    | EPZ                                    | EPZ                                    |

*In case of release, the exposure of coastal population will depend strongly on the OFNP distance from shore. Order of magnitude estimates of radionuclide transport in the ocean are presented in Ref. 14.*
There are other conceivable external events that would need to be considered for a floating plant, the most important of which is collision with a ship, either accidental or the result of an intentional act of sabotage. The OFNP security plan is not discussed in this paper; however, several features of OFNP need to be considered to prevent and mitigate this event. Genzman et al. simulated ship collision using a finite element modeling software ABAQUS and proposed various potential damage mitigation options. First, OFNP will be sited well away from shipping lanes; second, the mooring system can be designed to rapidly move the platform out of the way of an incoming ship; third, all safety-critical components are in watertight underdeck compartments with azimuthal bulkheads, below the keel of the vast majority of large oil tankers available today; last, ballast tanks above the waterline can restore floatation in case of flooding of major compartments. Nonetheless, the RELAP5 analyses (described in Sec. V) also considered scenarios in which the platform is statically tilted due to asymmetric flooding of some compartments caused by ship collision.

### IV. ENGINEERED SAFETY SYSTEMS

Following U.S. Nuclear Regulatory Commission terminology, licensing-basis events can be categorized according to their expected frequency as abnormal operational events (AOEs) (frequency $>10^{-2}$/reactor year), DBEs (frequency $>10^{-4}$/reactor year), and beyond-design-basis events (frequency $>5 \times 10^{-7}$/reactor year).

For AOE, OFNP relies on the traditional systems that have been developed for LWRs, i.e., control rods and standby liquid boron control system (for redundant and diverse emergency shutdown), and shutdown cooling through the auxiliary or startup feedwater system. For DBEs, OFNP relies on passive safety systems developed for terrestrial plants but modified to take advantage of the underwater nuclear island design. Specifically, decay heat removal during a DBE at operational pressure is performed by DRACS, which is based on natural circulation from the reactor pressure vessel (RPV) to an intermediate closed water loop and ultimately to seawater (see Fig. 3). This system can function indefinitely without ac power or refilling of any tanks. All heat removal and cooling functions important to safety are to utilize the ocean as the heat sink. This includes safety-grade cooling for the containment vessel, spent-fuel pool, main control room, shutdown control station, vital electrical areas, and battery rooms. There is a small diesel generator, but it is not safety grade.

For a DBE that causes depressurization of the primary system, short-term core cooling is achieved by gravity-driven injection, from core-makeup tanks or accumulators. For long-term accident response, OFNP-300 adopts a PCCS similar to the WSMR, in which the normal design

| Storm (Return Frequency) | 1 yr | 10 yr | 100 yr | 10 000 yr |
|--------------------------|------|-------|--------|-----------|
| Surge (m)                | 3.92 | 5.22  | 6.55   | 9.25      |
| Heave (m)                | 1.02 | 1.91  | 3.78   | 10.14     |
| Pitch (deg)              | 2.64 | 3.21  | 3.82   | 8.40      |
| Vertical acceleration (m/s²) | 0.23 | 0.27  | 0.36   | 0.75      |
| Horizontal acceleration (m/s²) | 0.59 | 0.66  | 0.73   | 0.86      |

*Reference 13.*
of near-vacuum conditions results in very efficient condensation heat transfer at the inner surface of the containment shell, conduction through the steel shell, and then convective heat transfer in the gap between the containment shell and the hull, flooded with seawater upon detection of a major accident (see Fig. 4). The containment water inventory circulates back to the reactor core to keep it submerged under all postulated conditions. Note that no seawater is present within the containment or the RPV. This PCCS also operates indefinitely without ac power or refilling of tanks. As such, the OFNP-300 design has eliminated the loss of UHS accident altogether.

V. SAFETY ANALYSES IN MARINE ENVIRONMENT

In this section we describe the RELAP5 analyses of several postulated accident scenarios for OFNP-300, including loss-of-coolant accidents (LOCAs) and SBOs.

V.A. Methodology

The complex platform motions caused by external loads can be described as the superposition of several single sinusoidal motions with six degrees of freedom\(^ {18,19}\): heave, roll, pitch, yaw, sway, and surge (see Fig. 5). Taking the platform as the noninertial frame of reference for the analysis, the effect of the platform motion can be described as a series of inertial forces on the coolant flow. Heave, sway, and surge introduce additional translational acceleration of the noninertial origin of the platform:

\[
a_T = a_x + a_y + a_z = \frac{d^2 \ddot{R}}{dt^2},
\]

where

\[
a_x, a_y, a_z = \text{translational acceleration in the } x, y, \text{and } z \text{-axis in the inertial coordinates, respectively}
\]

\[
\ddot{R} = \text{position vector}
\]

\[
t = \text{time}.
\]

Specifically, heave motion results in a variable effective gravitational acceleration:

\[
a_z = g(t) = g_0 + g_a \sin(n \cdot t),
\]
where

\[ g_0 = 9.81 \text{ m/s}^2 = \text{gravitational acceleration in stationary state} \]
\[ g_a = \text{amplitude of the heave motion} \]
\[ n = \text{frequency of the heave motion} \]

In roll, pitch, and yaw, the coolant flow is affected by an inertial force per unit mass \( a_A \) caused by angular velocity \( \vec{\omega} \) of the noninertial coordinates, consisting of three parts, namely, normal force, tangential force, and Coriolis force, as follows:

\[ a_A = a_n + a_t + a_c = \vec{\beta} \times \vec{r} + \vec{\omega} \times (\vec{\omega} \times \vec{r}) + 2\vec{\omega} \times \vec{u}, \quad (3) \]

where

\[ a_n, a_t, a_c = \text{normal force, tangential force, and Coriolis force, respectively} \]
\[ \vec{\omega}, \vec{\beta} = \text{angular velocity and angular acceleration, respectively} \]
\[ \vec{r} = \text{position vector} \]
\[ \vec{u} = \text{co coolant velocity}. \]

\[ a = a_T + a_A. \quad (4) \]

The RELAP5-3D code is used here to study the OFNP safety performance under ocean conditions. The RELAP5-3D code is typically used to model stationary, land-based, thermal-hydraulic systems and contains specialized physics for the modeling of nuclear power plants. Mesina et al. developed a new version of RELAP5-3D (version 4.3.4) by modifying the field equations for a noninertial frame of reference such as occurs onboard moving craft or during earthquakes for a land-based system.\(^{20}\) Translational and rotational accelerations alter the magnitude and direction of the acceleration vector associated with the body force to form an effective gravity vector in the phasic momentum conservation equations coded into this RELAP5-3D version. The equations for calculating the acceleration are presented in Euler and yaw-pitch-roll angle systems. Of course, there is no guarantee that the closure relations in RELAP5-3D are accurate at very steep angles and/or accelerations. Therefore, the code was verified by the authors through comparison of the code-calculated accelerations and pressure change with analytic solutions for simple translational and rotational motion problems.\(^{20}\) We further verified the code by simulating the oscillations in pressure and flow in a flow loop with rolling motion at Tsinghua University\(^{21}\) and compared our data to the Tsinghua University experimental data.

**V.B. Model Description**

The RELAP5-3D nodalization for OFNP-300 is shown in Fig. 6. The primary system model includes the reactor core (subdivided into one hot channel and one average channel), one upper plenum, one central primary riser, one pressurizer, eight steam generator components, eight primary coolant pumps, one downcomer, and one lower plenum. The secondary system model is simplified to include the steam drum with steam and feed flows. The safety-related system of the model includes four core makeup tanks (CMTs) connecting to the primary system downcomer through direct vessel injection (DVI) lines, four automatic depressurization system (ADS) valves, two sump injection tanks, two in-containment pools (ICPs), one PCCS, and one volume representing the containment free space. Four separate DRACSs transfer heat from the CMTs to seawater as the UHS. The core and system geometry and operating conditions were adopted directly from the WSMR. The reactor model was first established and verified in Refs. 12 and 13. Some improvements of the model were made to study the effect of rolling motion and static tilt.
V.C. Platform Motion in Marine Environment

The displacements, rotations, and accelerations experienced by the platform in the design-basis 100-yr storm and implemented in the RELAP5 model are taken from Table IV. Because of the cylindrical symmetry of the system, it is assumed that the pitch and roll, and sway and surge motions of the platform are the same, respectively. The origin of rotation is the center of gravity of the OFNP-300 platform.

V.D. Accidents Analyzed

V.D.1. Station Blackout

In the unlikely event of a SBO where both on-site and off-site ac power is lost, the control rods drop as a result of the loss of power, shutting down the reactor. It is assumed that it takes 2 s for the control rods to drop to the bottom of the reactor core. The reactor coolant pumps (RCPs), the main feedwater pumps, and the cooling water pumps lose power and then coast down for a few seconds due to inertia. Natural circulation is established in the reactor coolant system (RCS). The steam drum will be drained since no feedwater is added. Prior to this, a protection system signal will actuate the valves below the CMTs, draining cold water into the RCS. Hot RCS water would enter the CMTs and in turn be cooled by the DRACS. The DRACS transfers heat to the seawater UHS, allowing heat removal indefinitely.

V.D.2. Loss-of-Coolant Accident

The postulated LOCA is caused by the rupture of one of the four DVI lines. A double-end rupture is assumed in this study. When water level and pressure continue to drop due to the loss of inventory, a protection system setpoint is reached when the control rods enter the reactor core. Shortly after reactor trip, isolation valves between the steam generator tubes and steam drum are closed, and the valves below the four CMTs are opened by a protection system signal. With the CMT valves open, the relatively cold, highly borated CMT water would enter the RCS. Hot RCS coolant would enter the CMT and be cooled as a result of heat transfer to the DRACS. The DRACS transfers heat to UHS via natural circulation. As the RCS water level reaches the elevation of the CMT balance lines, steam enters the lines and stops the natural circulation of liquid water. As the CMTs drain, the ADS valves on the CMT lines would open. Valves at the top of the ICP tanks and on the reactor vessel also open on the same signal. The opening of the ADS valves allows the RCS to equalize with the containment. As the pressures approach equilibrium, the
head in the ICP tanks is high enough to allow injection through check valves into the reactor vessel. With the ICP tanks drained, the condensate from the containment wall returns to the containment sump and flows back into the reactor vessel. This process continues indefinitely because seawater continues to remove heat from the containment wall and condenses water inside the containment flowing back into reactor core through the sump injection lines.

The safety system settings of OFNP-300 used in the RELAP5 model are shown in Table V. Table VI reports the limits for fuel, cladding, and RCS temperature and pressure, as well as the containment pressure and minimum departure from nucleate boiling ratio (MDNBR) used in this analysis.

V.E. Results

The OFNP-300 response to the extended SBO and LOCA events is discussed here. In both events the casualty occurs during normal, full-power operation. Three postulated scenarios are studied—design-basis scenario: platform motion caused by a 100-yr return frequency storm; bounding scenario 1: platform pitching and rolling with 20-deg amplitude; bounding scenario 2: platform tilting statically with a 30-deg angle. Both bounding scenarios are beyond the OFNP design basis and are postulated to occur for some unforeseen reason whose origin is immaterial for the purpose of this study.

V.F. Design-Basis Scenario: 100-Yr Storm

V.F.1. Station Blackout

At the beginning of the SBO, the mass flow rate in the primary system decreases sharply due to pump trip (see Fig. 7). Heat produced by the reactor core cannot be removed effectively by the primary coolant; hence, the RCS temperature and pressure rise. The control rods enter the reactor core in 2 s, significantly reducing the heat generated. As the pumps continue to coast down, the pressure and temperatures drop. When the CMT valves open about 50 s after the accident, cold borated water flows into the reactor core, which causes the mass flow rate in the reactor core to rise. The mass flow rate of the primary system then decreases gradually toward an oscillating value caused by natural circulation.

The primary system pressure variation is shown in Fig. 8. The pressure rises at the beginning of the accident, and then, the pressure drops rapidly because of the reactor

![Fig. 7. Mass flow rate in reactor core and primary coolant pump.](image_url)
trip. When the CMTs and DRACS start transferring heat to the UHS, the primary system pressure decreases gradually.

The inlet and outlet temperatures of the reactor core are shown in Fig. 9. The temperature rises before the reactor trips, and then it decreases. When the CMT valves open about 50 s after the initiation of the accident, cold water flows into the reactor core, which causes the temperature in the reactor core to drop to less than 450 K. When the coolant from the CMTs is heated, the temperature rises again. After the DRACS starts working at full power, the reactor core temperature varies slightly.

The mass flow rates in the CMTs and DRACS are shown in Fig. 10. The initial mass flow rate in the CMTs is large because the initial CMT coolant temperature is low and its density is high. The coolant in the CMTs is injected into the reactor core due to the large pressure head in the CMTs. When natural circulation is finally established, the mass flow rate in the CMTs is much lower than its initial value. Because of platform motion, oscillations in the DRACS flow are much more severe than those in the CMTs. The reason is that the DRACS is farther away from the rolling center of the OFNP-300 platform; therefore, the inertial forces are larger in the DRACS than in the CMTs.

Figure 11 shows the heat transfer rate in the DRACS hot leg and cold leg. At the beginning, because the temperature of the DRACS is quite low, the DRACS takes more energy from the primary system than it discharges to the seawater. After about 5000 s, a quasi steady state is reached, confirming that long-term stabilization of the RCS temperature and pressure is achieved with the ocean-based DRACS.

Figure 12 shows that the MDNBR can be maintained well above its typical limit in the early stages of the SBO. It can be seen in Figs. 9 and 11 that platform motion causes oscillations in the mass flow rates and DRACS heat removal rate due to the effect of the inertial forces on natural circulation. However, the oscillations have no negative effect on the safety performance of ONFP-300 during SBO.
V.F.2. Loss-of-Coolant Accident

When one of the four DVI lines breaks, the system pressure drops rapidly in the first few seconds. When ADS is actuated in about 250 s after the break and ICP starts injecting into the reactor vessel in about 500 s, abrupt changes in the primary system pressure result (see Fig. 13). When the water condensed on the inner surface of the containment flows back into the reactor core through the sump injection valve, long-term cooling is established, and the primary system pressure decreases gradually.

The peak cladding temperature (PCT) and coolant temperature variations are shown in Figs. 14 and 15, respectively. The temperatures decrease in general and do not exceed the safety limits with considerable margin. The mass flow rates in the CMTs and DRACS are shown in Fig. 16. The valves below the CMTs open after the low-pressure signal, and natural circulation is established. However, when the CMTs start draining at about 400 s, the mass flow rate of the CMTs becomes low. Although there is little water inside the CMTs after 500 s, the DRACS continues to remove some heat from the primary system by condensation in the CMTs. Natural circulation in the CMTs and DRACS works indefinitely and transfers about 1 MW of power from the RCS to the UHS (see Fig. 17).

The pressure variation inside the containment is shown in Fig. 18. The pressure peak is about 0.9 MPa, far less than the pressure limit of the containment. The containment wall is cooled by seawater, and the containment pressure drops in long-term cooling. It can be seen in Figs. 16 and 17 that platform motion causes oscillations in the mass flow rates and DRACS heat removal rate. However, the oscillations have no negative effect on the safety performance of ONFP-300 during a LOCA.

V.G. Bounding Scenario 1: 20-Deg Pitch and Roll Oscillations

V.G.1. Station Blackout

The OFNP-300 platform is assumed to pitch and roll much more severely in this bounding scenario than in the
design-basis scenario. As illustrated in Figs. 19 and 20, the primary system pressure and temperature behave almost the same in both scenarios. Figure 21 shows the mass flow rate in the CMTs and DRACS, while Fig. 22 shows the power transferred by the DRACS hot leg and cold leg. Although there is flow reversal in the DRACS (indicated by negative values of the flow rate), natural circulation still remains functional under the extreme 20-deg pitch and roll oscillations. The amplitude of the mass flow rate oscillations in bounding scenario 1 is almost seven times larger than in the design-basis scenario. However, the time average mass flow rate and power in
both scenarios are almost the same. As a result, all safety limits are still met with good margins.

**V.G.2. Loss-of-Coolant Accident**

The pressure variation in the primary system and containment in bounding scenario 1 is almost the same as in the design-basis scenario, as expected, since the blowdown phase is fast and not affected by the platform motion. However, the PCT has some peaks after 200 s (see Fig. 23) due to low water level in the primary loop. The top of the reactor core is sometimes covered with water and sometimes uncovered due to platform motion. When the ICP valves open at around 500 s, cold water enters the reactor core, and the peaks disappear due to the rise of water level until long-term cooling is established in 1000 s.

Figure 24 shows the reactor core inlet and outlet temperatures: The platform motion causes some oscillation of temperature, especially when the ICP valves open around 500 s. Figure 25 shows the mass flow rates in the CMTs and DRACS, while Fig. 26 shows the heat transfer power in the DRACS hot leg and cold leg. The oscillation is much more severe in bounding scenario 1 than in the design-basis scenario; however, the heat transferred from the reactor core to the UHS by natural circulation in the CMTs and DRACS is not needed to cope with the LOCA.

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**Fig. 22.** Heat transfer in the DRACS hot leg and cold leg.

**Fig. 23.** Peak cladding temperature.

**Fig. 24.** Reactor core temperature.

**Fig. 25.** Mass flow rate in the CMT and DRACS.

**Fig. 26.** Heat transfer in the DRACS hot leg and cold leg.
Therefore, all safety limits are once again met with good margins.

V.H. Bounding Scenario 2: 30-Deg Static Tilt

V.H.1. Station Blackout

It is assumed that the platform statically tilts to a 30-deg angle in the plane shown in Fig. 1. The tilt of the platform causes a very significant change in the relative elevation of the components in the passive safety systems, including CMTs, DRACS, and ICPs, because the safety systems are located on either side of the reactor vessel symmetrically.

As shown in Fig. 27, the mass flow rate in the higher CMT 2 is larger than in the lower CMT 1. As illustrated in Fig. 28, the mass flow rate in the higher DRACS 2 oscillates significantly due to a natural-circulation flow instability. The mass flow rate in the lower DRACS 1 also changes significantly at first; then, after 5000 s the pressure head in the lower DRACS 1 is no longer large enough to drive natural circulation, and the mass flow rate decreases to almost zero. Therefore, only half of the passive safety systems (the CMTs and DRACS) are ultimately functional when the platform is tilted 30 deg. The primary coolant temperature and pressure rise slightly after 5000 s (see Figs. 29 and 30), when only half of the passive safety systems work properly. However, after about 10 000 s, the temperature and pressure begin to drop gradually due to decrease of the decay heat.

Some sensitivity analyses were performed to study the influence of tilt angle. Results show that 30-deg tilt is the boundary for flow instability in the DRACS. When the tilt angle is less than 30 deg, the flow in the DRACS is actually stable. The reactor core is well cooled during SBO when the OFNP-300 platform is tilted 30 deg, and the safety limits are not violated.

V.H.2. Loss-of-Coolant Accident

The severe tilt causes different mass flow rates in the CMTs and DRACS, as illustrated in Figs. 31 and 32, respectively. The CMTs are drained in less than 400 s. After 600 s, there is some water flow inside the CMTs.
because of ICP injection and water condensation. The mass flow rate in the lower CMT 1 is larger than in the higher CMT 2. Figure 32 shows that the higher DRACS 2 has a positive mass flow rate while the lower DRACS 1 has a negative mass flow rate. The PCT decreases in the first 400 s. When a portion of the reactor core is uncovered with water because of platform tilt, the PCT sharply rises to nearly 750 K. But, when the ICP valves open, cold water enters the reactor core and covers it again, the PCT decreases (see Fig. 33). When the CMT drains, a protection system signal is generated to open the valves at the top of the ICP tanks to allow for ICP pressure equalization with the containment pressure. As the pressures approach equilibrium, the head in the ICP tanks is high enough to allow injection through check valves into the reactor vessel. Because the platform is tilted 30 deg, the head in the two ICPs is different. Therefore, the two ICP check valves open at different times, as illustrated in Fig. 34. The higher ICP 1 opens early but drains in about 1200 s, while the lower ICP 2 opens at around 1000 s and continues to inject into the reactor vessel while condensation water flows into the lower ICP 2, providing water for long-term cooling of the reactor core. The primary coolant pressure variation and containment pressure variation are almost the same in bounding scenario 2 as in the design-basis scenario.

Although the PCT rises during the LOCA, the reactor core is well cooled in the long term, and the safety limits are not violated when the OFNP-300 platform is tilted by 30 deg.

If the platform tilts to an angle larger than 30 deg, there might be some problems. First, if the DVI break position becomes lower than the top of the reactor core because of the tilt, water will flow out of the vessel before it can cover the top of the reactor core. Second, the lower ICP may fail to work properly because of insufficient pressure head. Therefore, the reactor could not be cooled in the long term. Our analysis shows that this situation materializes at around 45 deg, which is a very severe tilt that is not anticipated under any realistic scenario, even upon a major ship collision with asymmetric flooding of several compartments below the waterline.
VI. CONCLUSIONS

Station blackout and LOCA events were studied for OFNP (OFNP-300) under oscillating motion and static tilt of the platform. The thermal-hydraulic behavior of the OFNP-300 reactor was modeled with a recently developed version of RELAP5-3D (version 4.3.4) that is capable of modeling systems in a noninertial frame of reference. The impact of displacement, acceleration, and a combination of motions was investigated. Natural circulation was influenced significantly by the pitch and roll motions: The coolant mass flow rate oscillates due to the inertial forces; however, because of the outstanding dynamic stability of the OFNP-300 cylindrical-hull design, the oscillations are small during the design-basis scenario, and all thermal-hydraulic safety limits are met with large margin.

Even during a bounding scenario assuming the platform is pitching and rolling by 20 deg (beyond design basis), the platform motion still has a negligible effect on the safety performance of ONFP-300 during either a SBO or a LOCA.

When the platform is statically tilted, some passive safety systems may work improperly. Flow instability is observed in the DRACS. The reactor core is uncovered with water for a short period of time. However, the reactor core is covered again with water when the ICP valves open, and long-term cooling is established.

The results suggest that the safety limits of OFNP-300 are satisfied during postulated accidents with platform motion up to 20 deg or static tilt up to 30 deg.

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