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Citation	Buongiorno, J. et al. "The Offshore Floating Nuclear Plant Concept." Nuclear Technology 194.1 (2016): n. pag.
As Published	http://dx.doi.org/10.13182/NT15-49
Publisher	American Nuclear Society
Version	Author's final manuscript
Citable link	http://hdl.handle.net/1721.1/106334
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The Offshore Floating Nuclear Plant (OFNP) Concept

J. Buongiorno*, J. Jurewicz, M. Golay, N. Todreas

Nuclear Science and Engineering Department, MIT

77 Massachusetts Avenue, Cambridge 02139 MA, USA

Corresponding author: * jacopo@mit.edu ; 617-253-7316

Pages: 38

Tables: 3

Figures: 9

Abstract – A new Offshore Floating Nuclear Plant (OFNP) concept with high potential for attractive economics and an unprecedented level of safety is presented. OFNP creatively combines state-of-the-art Light Water Reactors (LWRs) and floating platforms similar to those used in offshore oil/gas operations. A reliable and cost-effective global supply chain exists for both technologies, therefore robust expansion in the use of nuclear energy becomes possible on a time scale consistent with combating climate change in the near future. OFNP is a plant that can be entirely built within a floating platform in a shipyard, transferred to the site, where it is anchored within 12 nautical miles (22 km) off the coast in relatively deep water (≥ 100 m), and connected to the grid via submarine transmission cables. OFNP eliminates earthquakes and tsunamis as accident precursors; its ocean-based passive safety systems eliminate the loss of ultimate heat sink accident by design. The OFNP crews operate in monthly or semi-monthly shifts with onboard living quarters, like on oil/gas platforms. OFNP is a reactor for the global market: it can be constructed in one country and exported internationally; it lends itself to a flexible and mobile electricity generation approach, which minimizes the need for indigenous nuclear infrastructure in the host country, and does not commit the customer to a 40 to 60 years-long project.

Keywords: offshore platforms, marine nuclear reactor, mobile plant

I. INTRODUCTION

With 73 reactors under construction worldwide, the nuclear industry is currently experiencing moderate growth. However, a more robust expansion is needed if nuclear is to play a significant role in combating climate change. The Electric Power Research Institute (EPRI) has estimated that 150-200 nuclear plants, each generating 1000 MW_e, would generate enough electricity to enable conversion of the whole fleet of passenger cars and light trucks in the U.S. to plug-in hybrids, thus effectively ridding the U.S. of its dependence on oil, and drastically reducing the emissions of greenhouse gases into the atmosphere. Nuclear heat can also be used to convert biomass to biofuel: if all liquid fuel used for transportation in the U.S. came from biomass (e.g., corn, potato waste), the energy required from nuclear plants (in the form of low temperature steam) would be about 260 GW_t¹. The above figures are ambitious but not unrealistic, since the current U.S. nuclear fleet comprises 99 reactors (~100 GW_e or ~300 GW_t) that were built in a period of only 20 years. However, several challenges exist, the most important of which are discussed next.

- The *capital cost* of nuclear plants is high, due to their many high-pressure components and heavy structures, which result in large amounts of concrete, steel and wiring used in the construction of the plant. Current Gen3+ plants require an upfront capital investment of 3-4 billion dollars per 1000 MW_e of installed capacity, and take 5-7 years to build. Such long lead times also result in high interest payments during construction, which adds 30-40% to the cost and increases the financial risk of new nuclear plant projects. The capital-cost reduction imperative should drive new nuclear projects towards simpler reactors, with maximum power

output, maximum modularity and factory construction, and minimum construction and decommissioning activities at the site. Construction time (from construction start to operation) must be limited to 3-4 years.

- In spite of the excellent safety record of the nuclear industry, especially the U.S. nuclear industry, there exists a negative perception about *safety* of nuclear plants in the public and governments of some countries. Prominent recent examples include Japan and Germany after the accident at Fukushima. Social acceptability of nuclear power today effectively means it must achieve a higher level of plant safety/robustness. In particular, risk of accidents from extreme natural events, such as massive earthquakes, tsunamis, tornadoes, wildfires and flooding, should be reduced, and land contamination following severe accidents should be made very unlikely.
- *Siting* of large industrial infrastructures near population centers is becoming increasingly difficult (NIMBY syndrome), and nuclear plants are no exception. Since almost 50% of Earth's population lives within 60 miles (100 km) of the ocean and sea coasts, nuclear power plants should be built near the coast, where customers are, without being on the coast, where residential, recreational or commercial uses of land are preferable.
- The current *licensing* process for new nuclear plants can be lengthy. For example, in the U.S. typically there are three steps before construction can begin: Early Site Permit, Design Certification, Combined Construction and Operating License. It takes at least a decade to complete a new nuclear project. Moreover, the regulations tend to be very prescriptive, which stifles innovation, and has made it difficult to license anything other than light water reactors.
- Concerns about disposal of nuclear spent fuel and proliferation are also important challenges for nuclear energy; however, their political dimension vastly outweighs their technical aspects.

Spent fuel disposal has proven intractable in the U.S. so far, whereas successful examples of political management of this issue exist in Finland and Sweden, which in principle could be duplicated elsewhere.

The challenges related to cost, safety and siting are amenable to being addressed by scientific/engineered solutions. Therefore, we have been focusing our efforts on those challenges. In summary, *new nuclear power plants must be more affordable, safer and easier to deploy.*

II. OFNP CONCEPT AND DESIGN

These three high-level requirements can be met with the development of the Offshore Floating Nuclear Plant (OFNP) concept, which is a combination of two mature and successful technologies, i.e., LWRs and floating platforms of the type used in offshore oil/gas operations, each with an established global supply chain. OFNP is a plant that can be entirely built within a floating platform 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. The OFNP can achieve its economic goals through plant simplification, modularity and shipyard construction and efficient decommissioning. The OFNP can also achieve an unprecedented level of intrinsic safety and physical protection by minimizing the hazards from extreme natural events (in particular earthquakes and tsunamis), ensuring long-term cooling through an indefinite availability of the ultimate heat sink, drastically reducing the magnitude of land contamination and public exposure from severe accidents, and reducing the

risk from terrorist threats, as will be discussed in the following sections. A comparison of the OFNP concept to other marine power reactors is presented in Section VIII.

MIT is developing two designs in parallel which would be used in different markets: the OFNP-300 and OFNP-1100, designated according to their electric power rating. Schematic drawings for these two designs are shown in Figures 1 and 2, respectively. The OFNP-1100 could be based on a class 1100-MW plant such as Westinghouse's AP1000², which is already NRC design certified and being built in the U.S. and China. The OFNP-300 could be based on a class 300-MW reactor, such as Westinghouse's Small Modular Reactor (WSMR)³. In both cases, the floating structure chosen to house the nuclear plant is a cylindrical hull-type platform that shares many of its characteristics with platforms used in the offshore oil and gas drilling industry. Cylindrical hull platforms offer substantial stability gains at the scale the OFNP is designed for.⁴

⁷ The hydrostatic and hydrodynamic behavior of a cylindrical hull can also be tuned with an added steel skirt as seen in Figures 1 and 2. The skirt shown is sized to enable the cylindrical hull to rise up and down vertically while maintaining hydrostatic stability, and lower its draft to better allow for transportation on a heavy lift ship. The cylindrical hull also offers the best protection to the reactor itself when compared to other offshore platform designs, such as semi-submersibles or floating barges. Locating the reactor in a center annulus offers it substantial protection on all sides via multiple hulls. Additionally, the cylindrical hull design 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. Overall, the cylindrical hull platform enables the entire plant to adopt a more vertical organization than alternative platform designs or existing terrestrial plants, which

makes the entire design more compact. Unlike terrestrial nuclear plants, the OFNP must be considered a single integrated system that incorporates considerations of reactor safety, access to vital systems, plant security, platform stability, effective operation, and crew comfort. Summary dimensions for the OFNP-300 and OFNP-1100 platforms are reported in Table I, and more information about the OFNP-300 design can be found in Ref. 8.

The OFNP platform is designed to be able to withstand significant damage while retaining flotation, in accordance with design practices from the U.S. Navy. Therefore, all levels at the waterline and below are water-tight with azimuthal bulkheads reaching up to the main deck (Fig. 3). The control room is located as close as possible to the three-dimensional center of the cylindrical hull to enhance its physical protection. Its steel walls are extra thick and hardened to better withstand impact and attack. There is a small (non-safety) diesel generator, located indoor on the main deck level, to provide power to non-essential loads, such as the living quarters or the balance of plant, in case of loss of offsite power. All safety-grade systems are passive, thus do not require any AC power, as explained in Section IV.

Refueling is performed in the same way of terrestrial plants, with production cycles of 12-24 months or longer, depending on economic optimization. There is a spent fuel pool aboard the platform which can store fuel for up to the lifetime of the plant, with a dedicated passive decay heat removal system, which rejects heat to the ocean.

Operations are organized in monthly or semi-monthly shifts with onboard living quarters, in a manner similar to oil/gas offshore platforms. The main deck accommodates a crane, a helipad,

and life boats. Access to the main deck can occur either via helicopter or boat through docking points and stairs at the waterline.

The OFNP balance of plant (BOP) is a standard Rankine cycle, with a somewhat higher thermal efficiency (estimated gain ~1-2%) than a terrestrial plant at comparable latitude, since the OFNP cooling water can be drawn from the deeper, cooler layers of the ocean⁹. The BOP layout is integrated into the floating platform, with the turbine island one level below the main deck for ease of access and maintenance. The BOP includes five small desalination units and two condensate storage tanks for water makeup to the steam cycle. The power transmission train comprises a step-up transformer (345 kV) located onboard the OFNP platform, and several submarine AC cables. AC transmission does not require a converter and is more economical than DC transmission for short distances from shore (<30 km)⁹.

III. CONSTRUCTION AND TRANSPORTATION

The OFNP design exploits the advances and experience in the construction of large floating structures in the oil/gas offshore industry and naval shipyards. The capabilities of modern shipyards in the U.S. and worldwide are astounding. For example, the Daewoo Shipbuilding and Marine Engineering shipyards build the World's largest oil/gas floating platforms (140,000-ton displacement, 136-m length, 30-m draft, Fig. 5a) and largest oil supertankers (500,000-ton displacement, 380-m length, 68-m beam, Fig. 5b) in just 24 months. The Technip shipyard in Finland routinely completes construction of spar-type platforms (>40m diameter, >100 m draft) within 20 months (Fig. 5c). Sevan Marine builds large cylindrical hull platforms (>100 m diameter, Fig. 5d), and has recently proposed this design for a 700-MW_e LNG-fired power plant.

Newport News Shipbuilding designs, builds and refuels the U.S. Navy's nuclear-powered aircraft carriers and submarines, such as the Gerald Ford, an aircraft carrier of 100,000-ton displacement, 340-m length, 41-m deck elevation, 12-m draft, with 2 nuclear reactors aboard, which was assembled in 36 months. Samsung Heavy Industries is completing construction of Prelude, a floating LNG plant which is also the largest offshore facility ever built (600,000 tons, 488 m long, 75 m wide): Prelude's hull was built in 11 months and is designed to withstand a Category 5 cyclone. These spectacular construction achievements for such large and complex structures result from the efficiencies available in today's shipyards. The OFNP is designed like a platform to take advantage of these modern capabilities.

We are currently studying three different methods for modular construction of the OFNP platform to give prospective shipyards maximum flexibility for utilizing their existing equipment and facilities. The first method is to build the entire platform vertically from bottom to top in a single large dry-dock out of small modules no larger than ~1,000 tonnes. This method consolidates work to a single shipyard and may consequently allow for more tolerance with schedule delays, but it severely limits potential construction locations and may present logistical challenges from site congestion. The second method of construction splits the OFNP into two halves: a bottom half with the containment and watertight hull and a top half with the balance of plant and living quarters. This method enables parallelization of construction and testing at two separate locations and reduces site congestion, but it requires the mating of the two halves at sea or in a bay with a giant sea crane. The third construction method splits the OFNP into several "mega-modules" that can be organized into one of four categories: hull, living quarters, balance of plant, and nuclear island. Each category has progressively more complexity and stricter

tolerances associated with it. This would allow simple modules to be fabricated at lower cost shipyards and specialized modules, such as the nuclear island, to be built at qualified shipyards. Ultimately, all of the modules would be brought to a central location for final assembly. In all cases, the final OFNP platform will be moved to a transportation ship and carried to the site. A rendering of the OFNP-300 transportation ship is shown in Fig. 5f.

A major advantage of the OFNP design is the drastic reduction of structural concrete. Many terrestrial nuclear plants have experienced substantial schedule delays and cost overruns, often related to trouble in pouring and curing the concrete to specifications. In 2012, the Royal Academy of Engineering published a report identifying several problems that are unique to the pouring of nuclear-grade concrete.¹⁰ Conventional reinforced concrete pouring relies on post-placement quality assurance; such as cube strength tests and cover meter surveys. If the concrete does not meet specifications, it is simply broken out and poured again. Nuclear concrete applications typically involve pours that are so large this practice becomes prohibitively expensive and time consuming. As an example the AP1000, a new plant designed to reduce concrete requirements, still requires a 5,400 m³, 41-hour continuous concrete pour for its basemat.^{11,12} Such operation must meet strict quality assurance standards beforehand and during the pour, to ensure no voids form and all specifications are met. This takes considerable personnel, equipment procurement, and preparation; not to mention the 28-56 day waiting period for strengthening required for such pours. Another unique aspect of nuclear-grade concrete is the procurement and testing of the entire supply chain leading to the main pour. Every aspect of nuclear grade concrete, from the materials going into it to the batch plants mixing it, to the trucks

carrying it must be certified and tested. The soil beneath any structure must be tested significantly more than standard construction sites to reduce the uncertainty in erosion and cracking from settling. Soil testing is an inherently uncertain procedure, and conducting tests that meet regulations and specifications can be exceedingly time consuming as well as a source of delays. While concrete is one of the most used construction materials, it is also one of the most demanding when used in nuclear power plant construction. The average terrestrial nuclear power plant requires approximately 200,000-350,000 m³ of concrete and every mistake adds significant cost and delay. The construction of the OFNP platform immediately benefits from a drastic reduction in the amount of structural concrete and the costs associated with it (Table II).

IV. SAFETY

Since OFNP is a floating plant, seismic loads from the ocean floor do not transfer to the plant structures; consequently, earthquakes are eliminated as a safety concern. Moreover, the plant is sited in relatively deep water, where tsunami waves are much smaller and their wavelength so long (i.e., order of tens of kilometers) that, upon passage of a tsunami wave, the plant simply rides the wave without danger of being submerged. Therefore, tsunamis are also eliminated as accident precursors. Of course severe storms are a concern. However, the platform can be designed to withstand extreme storms (e.g., Cat. 5 hurricanes) with acceptable pitch/roll rotation (<10°) and heave acceleration (<0.2 g), and will be sited preferentially in regions with low storm frequency and intensity. Furthermore, the reactor is well protected within multiple hulls, the main deck is well above the surface of the ocean, and the control room, the battery room, all safety-critical components as well as the radiological controlled area are in water-tight underdeck

compartments, so that flood hazards should be minimal. The OFNP adds to the level of defense in depth of terrestrial plants, as shown in Figure 6: there are two additional physical barriers (i.e., the platform double hull) and a large distance to shore.

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 offsite power events (Fig. 7). The Emergency Core Cooling System (ECCS) and ocean-based Passive Containment Cooling System (PCCS) maintain the fuel covered and the containment pressure low during Loss Of Coolant Accidents (LOCAs). For hypothetical severe accidents with core melting the In-Vessel Retention (IVR) approach is adopted; the containment is normally under vacuum, to prevent hydrogen explosions; the PCCS again ensures indefinite and passive heat removal through the containment shell. Note that no seawater is ever present within the containment or the pressure vessel. More information about the OFNP-300 safety systems can be found in Refs. 13 and 14. OFNP-1100 would use the same safety systems as AP1000, with the ocean as the ultimate heat sink, thus indefinite, passive core and containment cooling is achievable. No tanks have to be refilled, and again no seawater is ever present within the containment or the pressure vessel.

Through the use of the PCCS, containment over-pressurization is avoided for both OFNP-300 and OFNP-1100, thus there is no need to vent. However, should the containment pressure rise beyond its design limit for whatever unforeseen reason, venting can be done through a filter and underwater, which reduces land contamination to essentially zero. Therefore, evacuation of the

coastal population could be eliminated altogether. This is key to the social acceptability of nuclear energy. In summary, the OFNP concept builds on the excellent passive safety of Gen3+ and SMR designs, and provides additional levels of protection beyond it.

V. SECURITY

Offshore siting makes it easier to monitor the area surrounding the plant, and harder for prospective attackers to gather information about plant vulnerabilities. However, in addition to attacks from surface and air, an offshore plant is potentially exposed to subsurface attacks. In developing the OFNP security plan, it is important to identify all possible threats, and determine whether primary responsibility to protect against each threat lies with the plant owner/operator or the government, i.e., law enforcement or military personnel. Table III shows a preliminary categorization of security threats for the OFNP. For those threats that fall under the owner/operator responsibility, the security force at the plant must be able to fend off an attack until external intervention can occur. We have established this minimum coping time as 30 minutes. The nature of the postulated threats and the coping time requirement are guiding the development of the OFNP security plan, which is based on a combination of plant design, layered defenses and careful siting.

First, plant design: the access point to the plant is located on the main deck, high above the waterline, which impedes easy access by an attacking force. All vital nuclear components are located within multiple steel hulls below the waterline. The circular perimeter of the platform is easily defensible by the plant security force because of un-hindered line of sight.

Second, layered defenses: the area surrounding the plant is divided into four concentric zones, as shown in Fig. 8, which have the following designation and characteristics:

- **Monitored Area:** all traffic monitored by electronic detection measures within 8 nautical mile (nm) from the plant.
- **Large Ship Exclusion Area:** this zone is sized at 6 nm radius such that a large tanker heading towards the OFNP at 12 knots would take 30 minutes to reach the plant; trespassing of a large ship into this zone would trigger prompt intervention by the host nation coast guard or military forces.
- **Controlled Access Area:** no access permitted to any unauthorized boat or underwater vehicle within 1 nm of the plant. This area is also monitored with sonars.
- **Protected Area:** the boundary of this zone is equipped with physical barriers such as surface booms and underwater netting, to stop or delay surface or subsurface attackers, respectively. This zone is sized according to the blast radius from the explosion of an attacking boat laden with a large amount of explosive. The blast radius is currently being determined. The OFNP platform itself is located at the center of the protected area and is obviously a restricted access area.

Third, careful siting: the OFNP is sited within territorial waters, at distance from ports and major shipping lanes (Fig. 9); this minimizes the likelihood of accidental collision with ships, and maximizes the time available for intervention by the host nation coast guard or military in case of attack.

VI. ECONOMIC POTENTIAL

Within the nuclear community there are currently two camps regarding the economics of new reactors: those who support construction of large monolithic plants to take advantage of their good economy of scale (i.e., low cost per unit power installed), and those who support Small Modular Reactors (SMRs) built in high numbers in factories to take advantage of an economy of mass production. In reality, modularity is already being used in the construction of large plants such as AP1000, mostly to accelerate schedule, not reduce fabrication costs. On the other hand, cost reduction from factory fabrication of reactors will not materialize in the near term, before the massive initial investment for the dedicated factories that build the reactors is effectively paid-off. The OFNP concept introduces a new paradigm that combines good economy of scale, especially for the 1100 MWe version, and economy of mass production, as OFNP plants would be built in series and in *existing* shipyards. Since the cost of nuclear fuel is low, the levelized cost of electricity for a nuclear plant is roughly proportional to the ratio of the capital cost of the plant to its electric power output:

$$\text{LCOE}_{\text{Nuclear}} \propto \frac{C_{\text{plant}}}{\dot{W}} \quad (1)$$

where in turn C_{plant} scales approximately as $\dot{W}^{2/3}$. With OFNP the denominator of Eq. 1 is 300-1100 MWe, equal to or higher than the SMRs, while the numerator is lower than both SMRs and large terrestrial plants because of the cost savings in direct labor (no excavation and civil work), commodities (no concrete for containment, cooling towers and foundations), and at-site construction machines and temporary facilities (such as the module assembly building for AP1000). Therefore, a substantial reduction in the cost of electricity is expected for OFNP. A quantitative cost analysis is underway and will be reported in a separate publication.

VII. SITING

The ultimate success of the OFNP concept depends on selection of suitable sites that minimize the threats to the plant, and maximize its economic value. The two top-tier requirements that should guide site selection for the OFNP are as follows:

- There must be relatively deep water (at least ~100 m) within territorial waters (<12 nm), which ensures that tsunami waves will be small, since their amplitude decreases with water depth. For example, the Fukushima tsunami produced waves of only 2-m height in 100-m deep water. The water depth criterion can be relaxed for sites where tsunamis are not a concern, e.g., Persian Gulf.
- Other modes of electricity generation (e.g., natural gas, coal, renewables) must be either unavailable or not cost competitive. This obviously applies to any nuclear power plant, terrestrial or offshore. However, the OFNP has an advantage: if the economic climate for nuclear power deteriorates in a certain country or at a certain site, the OFNP can be moved to a more profitable site. With OFNP, the utility customer does not have to commit to a 40 to 60 years-long project, which reduces planning uncertainties. OFNP also minimizes the need for indigenous nuclear infrastructure in the host country, should the host country find that option attractive.

Desirable features for the OFNP sites also include (i) low frequency and intensity of storms, to minimize disruption of operation; (ii) distance from major shipping lanes, to reduce likelihood of collisions with ships; (iii) proximity to major load centres (e.g., cities, industrial installations), to minimize transmission losses; and (iv) unavailability or high cost of coastal land.

A global site-searching analysis informed by the above criteria was conducted¹⁵. The analysis identified suitable sites in three classes of countries:

- Countries rich in domestic oil and gas that would prefer to export their energy products rather than burning them for domestic electricity generation. Examples include Saudi Arabia, Qatar, U.A.E., Kuwait, Norway and Indonesia. The U.K. is an example of a country that may use nuclear to extend its declining hydrocarbon reserves.
- Countries with high seismicity, high coastal population density, and limited domestic energy resources. Examples include Japan, Vietnam, Philippines, China and Chile.
- Countries with small grids, high prices of electricity, and no incentives to develop a domestic nuclear infrastructure, so the OFNP plants could be supplied by and returned to the vendor country without the host country needing to organize the reactor construction and fabrication operations. Examples include the African continent, many South American countries, small island nations in the Pacific, but also, potentially, large mining operations in remote areas, and even U.S. DOD bases.

VIII. COMPARISON WITH OTHER MARINE REACTORS

Because of its offshore, floating, platform-based, passively-safe design, the OFNP concept differs from other marine-based reactor concepts such as the Russian floating reactor^{16,17}, which is an icebreaker reactor mounted on a barge and docked on the coast; the French FlexBlue concept^{18,19}, which is a small, remotely-operated, submarine reactor sitting on or near the seabed; the old Westinghouse Atlantic Generating Station²⁰, essentially a large terrestrial PWR built on a barge and moored in shallow waters with a huge breakwater; and the Korean offshore nuclear power plant concept²¹, a standard APR1400 plant built on a so-called gravity platform supported

by the ocean floor. The general concept of an offshore floating nuclear power plant integrated into a spar-type platform making use of naval reactors was introduced in a recent patent²². A summary of all civilian marine-based nuclear power plants proposed to date is reported in the Appendix. Limited experience exists also with civilian nuclear-powered merchant ships, such as the US NS Savannah in the 1950s and Japan's Mutsu in the 1970s, although the concept has attracted some new interest recently²⁵.

IX. CONCLUSIONS AND FUTURE WORK

The OFNP concept was presented, a nuclear plant for the global market with unique features that may make it more economically competitive and socially acceptable than traditional land-based nuclear plants:

- OFNP can be built in existing shipyards. This minimizes the upfront capital investment, enhances construction quality, reduces construction time and cost, and provides a reliable modularization approach;
- The OFNP site can be returned to “green field” conditions shortly after the plant is transported away from the site. Plant decommissioning can be done quickly and cost-effectively in a centralized shipyard;
- Coastal land usage for the OFNP is reduced substantially, thus increasing the number of potential sites;
- Safety concerns from earthquakes and tsunamis are eliminated, due to the relatively deep water the plant is moored in. Flood concerns are minimized through the use of a watertight, compartmentalized structure similar to naval ships;

- The ocean heat sink can be used to ensure decay heat removal indefinitely, without the need for external power or intervention. The likelihood of accidents with fuel damage and radionuclide release is drastically reduced^{*}; the need for land evacuation is eliminated. Both features are responsive to the new safety imperatives of a post-Fukushima world.

Ongoing work focuses on the plant's dynamic response to wave/wind loads from large storms; analysis of radioactive iodine and cesium retention and dispersion in the ocean following a beyond-design-basis accident with containment overpressurization; and assessment of platform damage from collision with a large ship.

ACKNOWLEDGMENTS

This project is funded by the MIT Research Support Committee. Matthew Strother of MIT produced the estimates for the OFNP platform natural period of oscillations. James O'Connell (CB&I) is gratefully recognized for his advice about construction costs of terrestrial nuclear power plants. Capt. Mark Thomas and LtCdr. Jarod Ketcham (U.S. Navy) provided valuable advice on naval ship architecture. Arthur Birch (ECSI International, Inc.), Thomas Isdanovich (ECSI International, Inc.), Harvey Stevens (Stevens Associates, Inc.) and Ron Thomas (ECSI International, Inc.) provided suggestions for and review of the OFNP security aspects.

NOMENCLATURE

AC: Alternate Current

BOP: Balance Of Plant

CB&I: Chicago Bridge & Iron

^{*} This statement will have to be qualified by a formal probabilistic risk assessment

DOD: Department Of Defense

DRACS: Direct Reactor Auxiliary Cooling System

EPRI: Electric Power Research Institute

IVR: In-Vessel Retention

LCOE: Levelized Cost Of Electricity

LNG: Liquefied Natural Gas

LOCA: Loss Of Coolant Accident

LWR: Light Water Reactor

NIMBY: Not In My Back Yard

NRC: Nuclear Regulatory Commission

OFNP: Offshore Floating Nuclear Plant

PCCS: Passive Containment Cooling System

SMR: Small Modular Reactor

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25. S.E. Hirdaris, Y.F. Cheng, P. Shallcross, J. Bonafoux, D. Carlson, B. Prince, G.A. Sarris, “Considerations on the potential use of Nuclear Small Modular Reactor (SMR) technology for merchant marine propulsion”, Ocean Engineering, Vol. 79, 15 March 2014, Pages 101–130.

Table I. OFNP platform characteristics

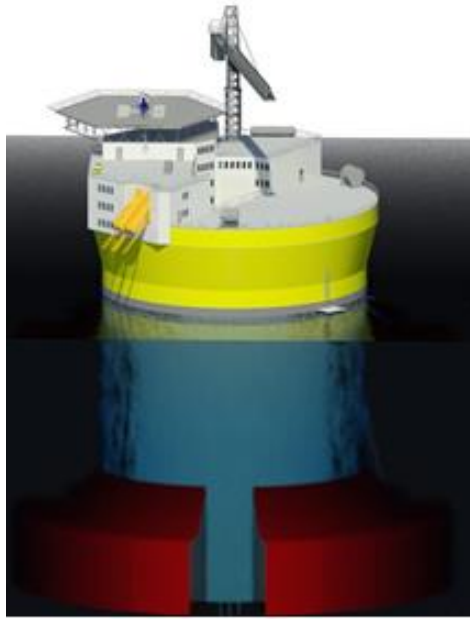
Parameter	OFNP-300	OFNP-1100
Hull /skirt diameter (m)	45/75	75/106
Draft (m)	48.5	68
Total height (m)	73	108
Main deck height (m)	12.5	34
Displacement (tonnes)	~115,500	~376,400
Natural period for heave/pitch (s)	~24.5/32.7	~25.9/51.3

Table II. Steel and concrete required for construction of OFNP and terrestrial AP1000

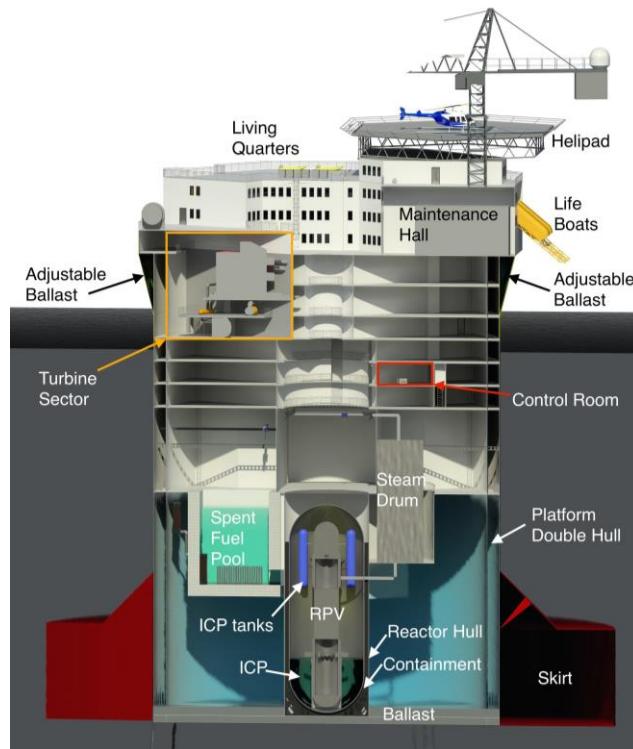
Plant	OFNP300	OFNP1100	AP1000
Steel (tonnes/MWe)	46.97	45.18	33
Concrete (m ³ /MWe)	2.39	4.50	69

Table III. Security threats postulated for the OFNP.

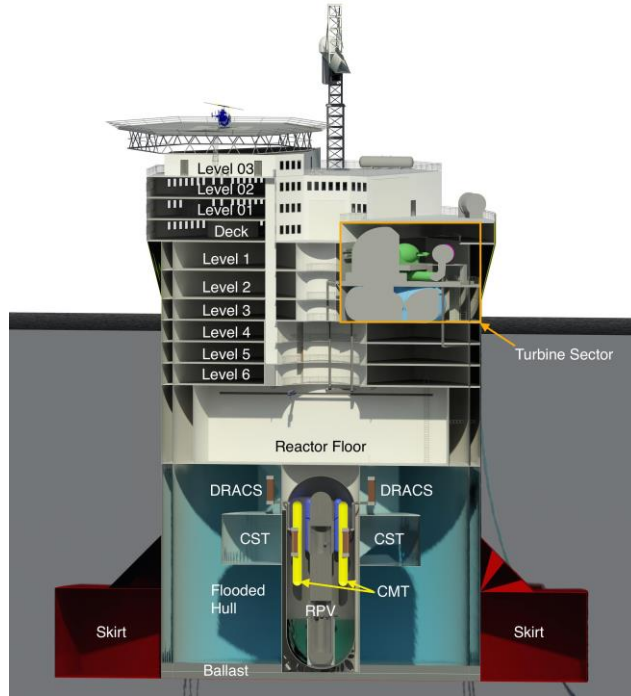
	Host Nation – National Military	OFNP – Security Team
Air	<ul style="list-style-type: none">• Military aircraft• Commercial aircraft• Missile	<ul style="list-style-type: none">• Drones• Light planes/Helicopters
Surface	<ul style="list-style-type: none">• Large tankers• Military surface vessels	<ul style="list-style-type: none">• Non-military boats
Subsurface	<ul style="list-style-type: none">• Large submarines	<ul style="list-style-type: none">• Mini subs (torpedoes)• Divers (explosives)



(a)

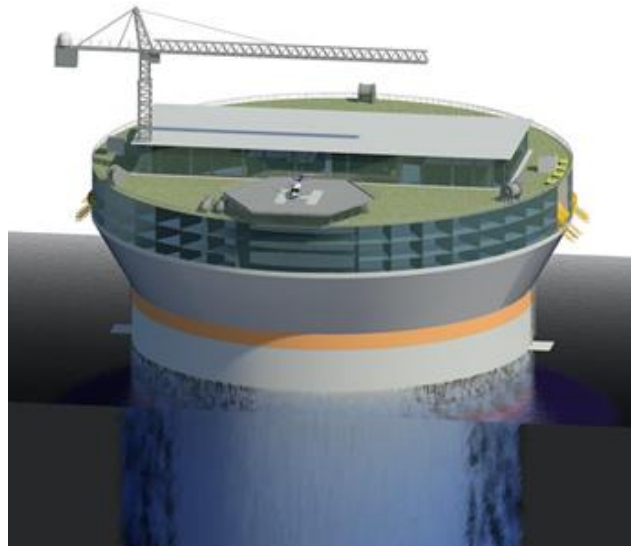


(b)

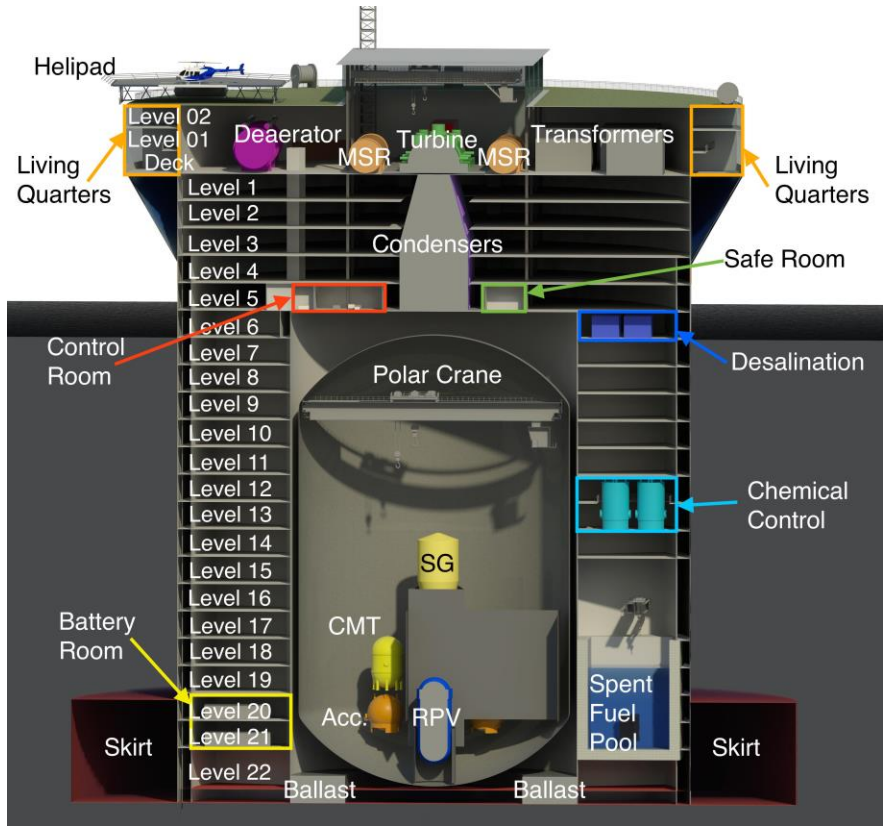


(c)

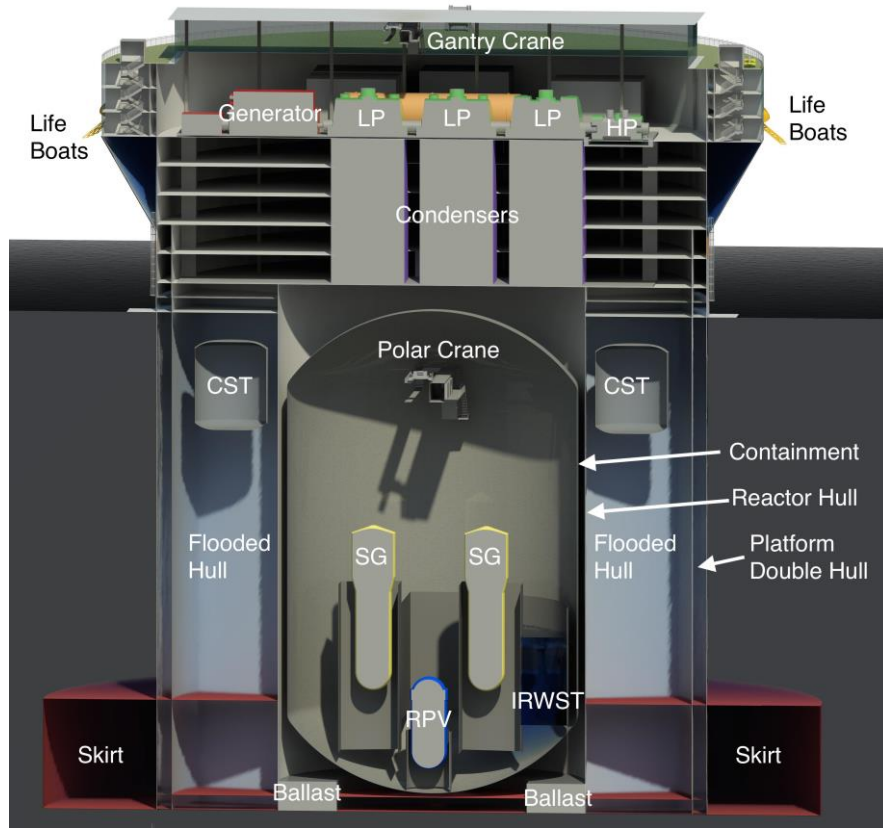
Figure 1. Isometric views of OFNP-300.



(a)

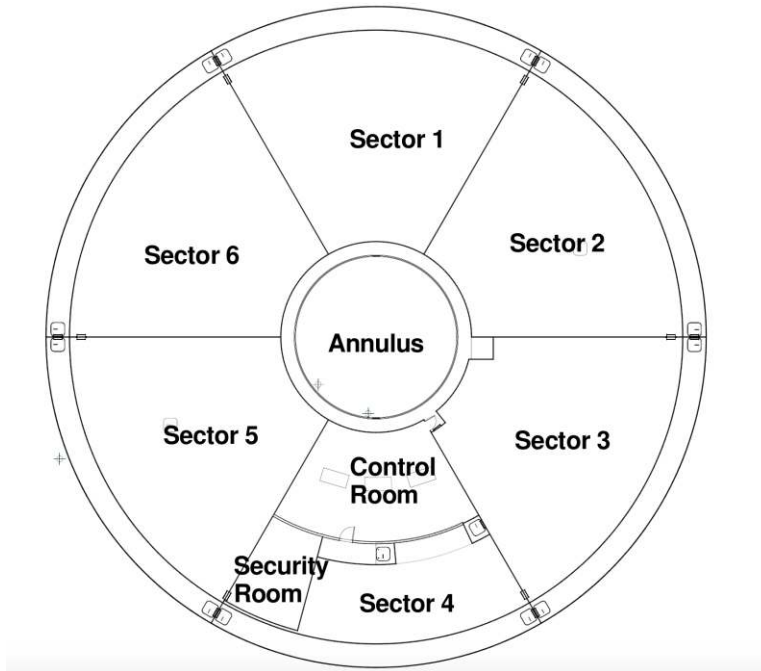


(b)

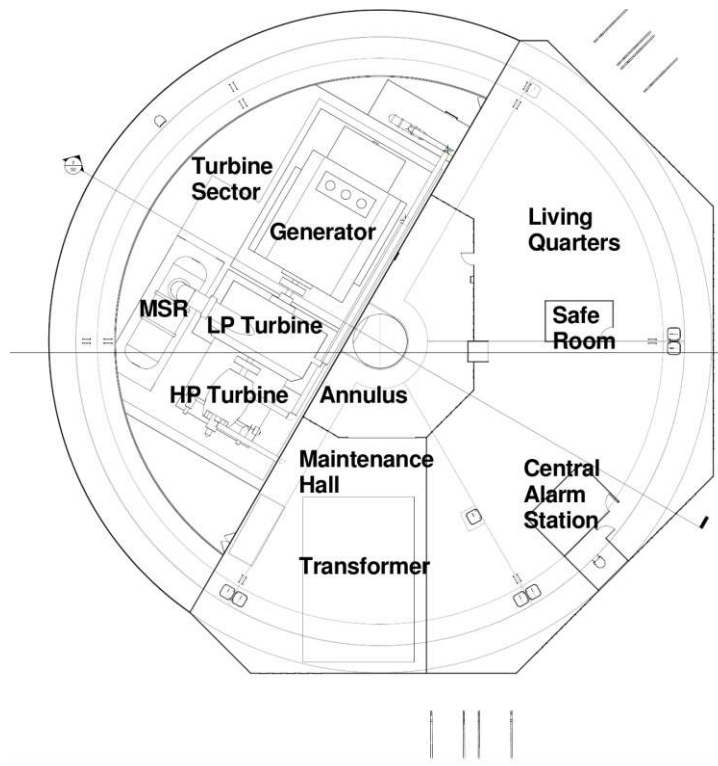


(c)

Figure 2. Isometric views of OFNP-1100.

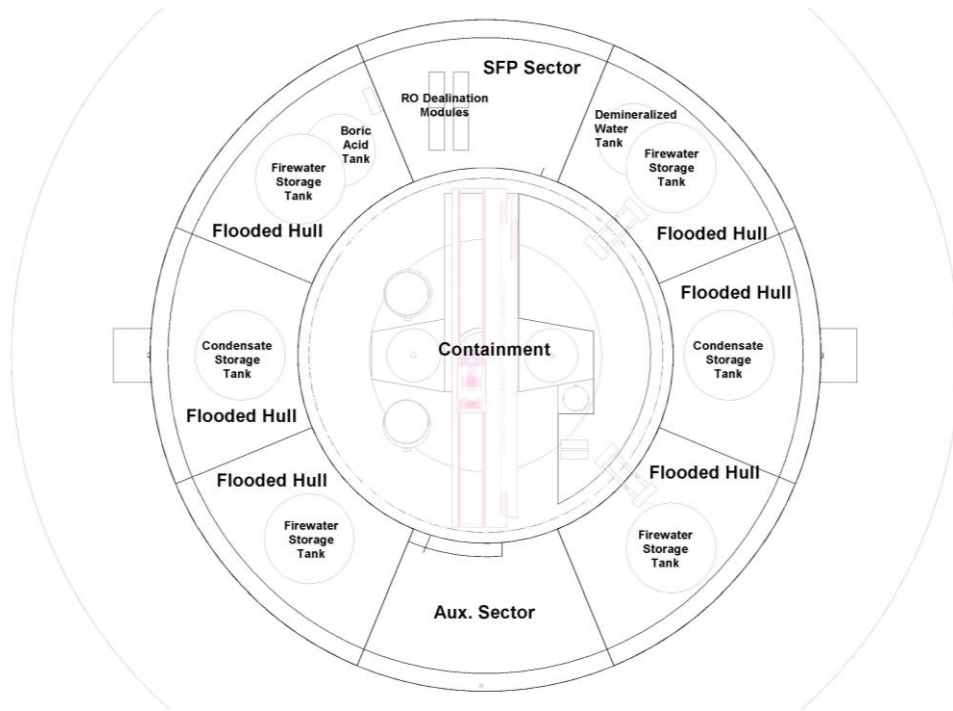


(a)

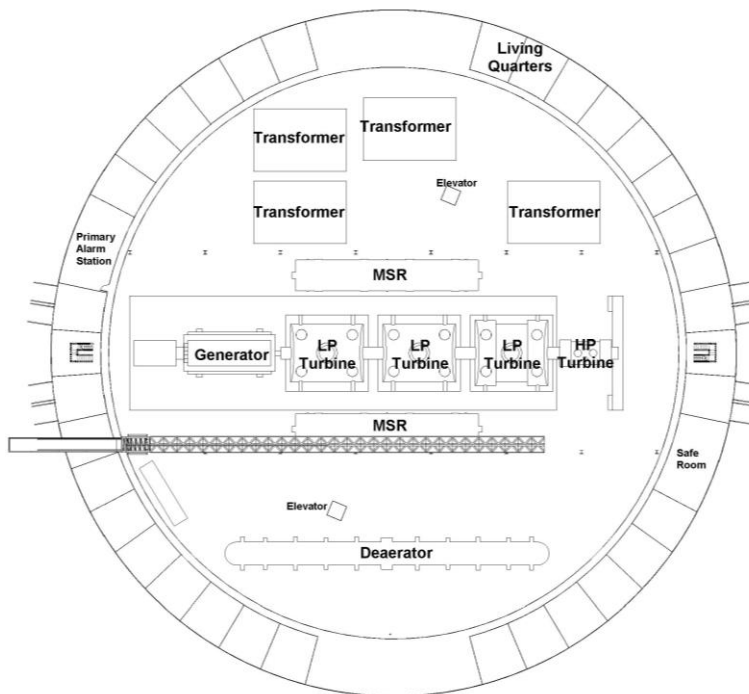


(b)

Figure 3. Floor plan for OFNP-300: (a) Level 5 and (b) the main deck.



(a)



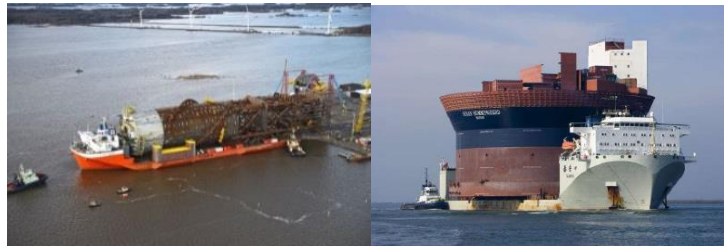
(b)

Figure 4. Floor plan for OFNP-1100: (a) Level 6 and (b) the main deck.



(a)

(b)



(c)

(d)



(e)

(f)

Figure 5. Large offshore structures and ships: (a) Thunderhorse platform; (b) T1 oil supertanker; (c) Technip spar; (d) Sevan Marine platform; (e) Prelude LNG facility; (f) rendering of the OFNP-300 transportation ship.

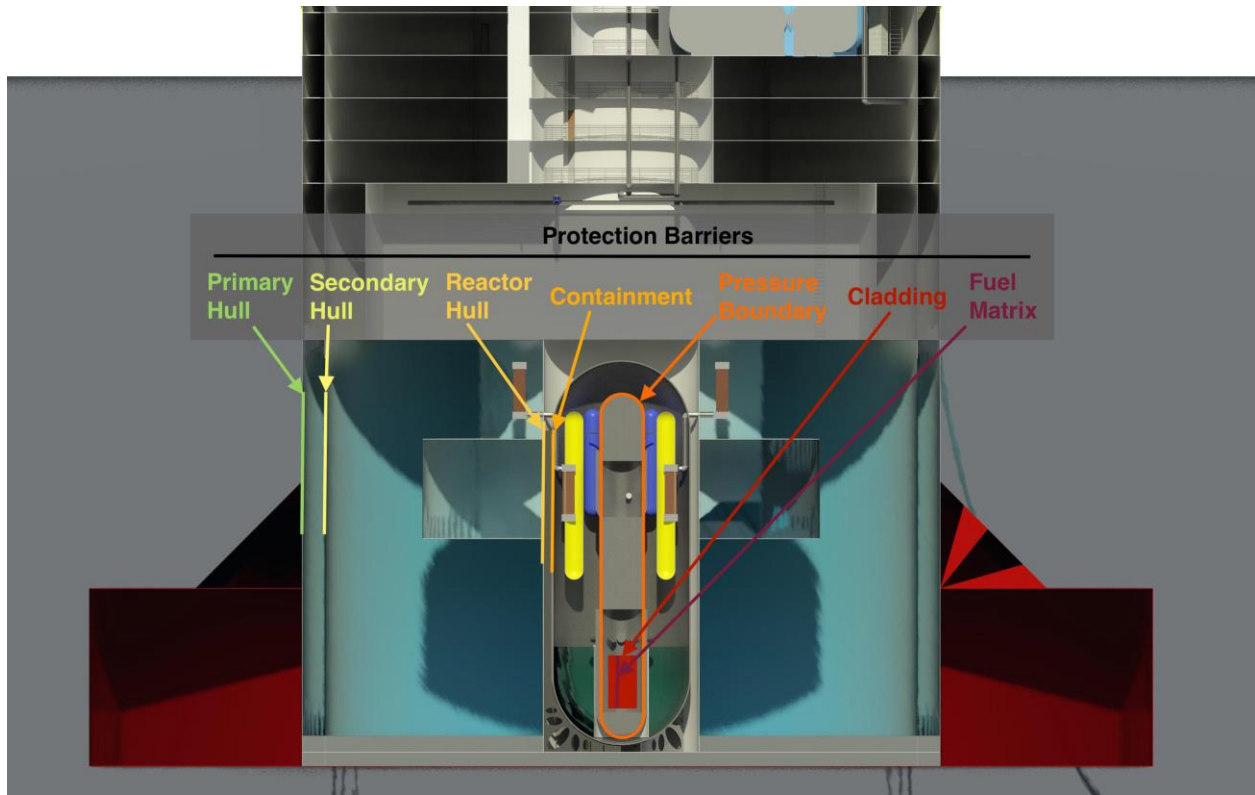
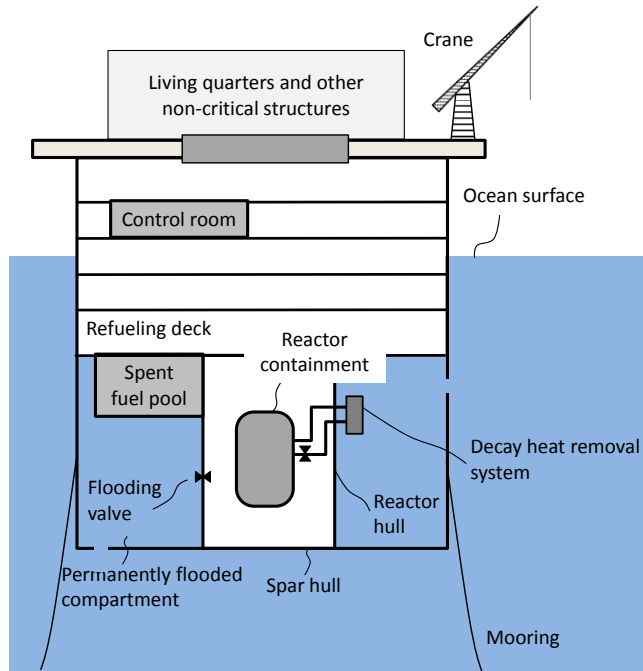
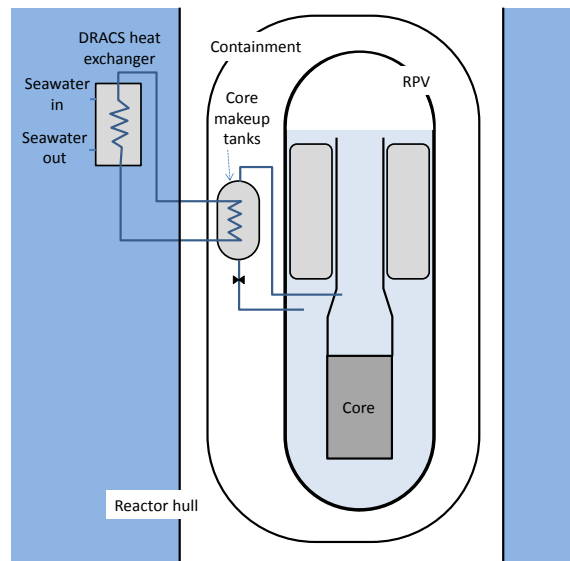


Figure 6. Defense-in-depth barriers for OFNP-1100.



(a)



(b)

Figure 7. Schematic drawings of the OFNP-300 (a) platform and (b) DRACS.

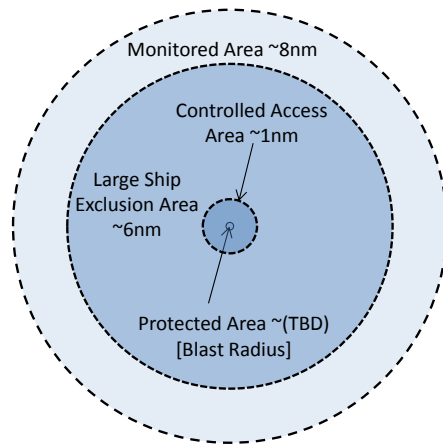


Figure 8. Security zones surrounding the OFNP. (1 nm=1.85 km)

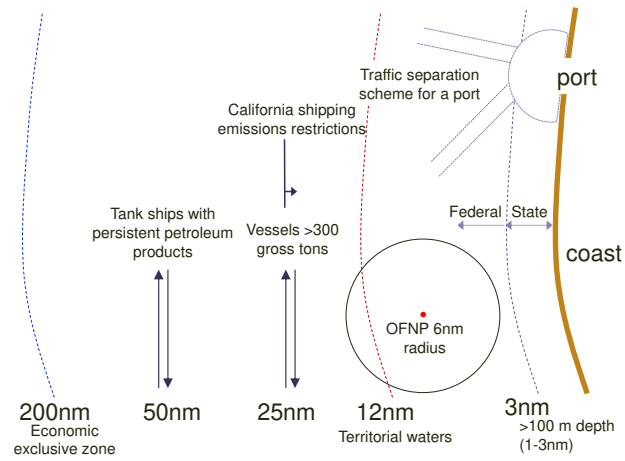


Figure 9. Generic OFNP siting with respect to the coast, ports and shipping lanes in the US. (1 nm=1.85 km)

APPENDIX - SUMMARY OF CIVILIAN OFFSHORE NUCLEAR POWER PLANTS BUILT OR DESIGNED

Name	Reactor Type and Power rating	Operating Conditions	Notes and References
ABV – 6M (RUSSIA)	VVER Thermal power - 38 MW Electric power - 8.6 MW	Design pressure, - 15.7 MPa Design temperature - 330°C Fuel material and enrichment – UO ₂ , 19.7% Superheated steam pressure /temp. - 3.14 MPa /290°C	Integral reactors with 100% natural circulation in the primary circuit; modular design for both land-based and floating nuclear power plants; Ref. 17
KLT – 40S (RUSSIA)	VVER Thermal power -150 MW Electric power -35 MW	Design pressure – 12.7 MPa Design temperature - 316°C Core coolant flow rate - 2,600 t/h Coolant temperature at core inlet/outlet – 280/317 °C Fuel material and enrichment – UO ₂ , < 20% Superheated steam pressure / temp. – 3.8 MPa / 290°C Steam generation capacity – 2 x 240 t/h	Serial modular reactors for nuclear icebreakers and sea vessels; floating nuclear power plant; Ref. 23
RITM – 200 (RUSSIA)	VVER Thermal power - 175 MW Electric power - 50 MW	Design pressure, - 15.7 MPa Steam generation capacity – 248 t/h Fuel material and enrichment – UO ₂ , < 20% Superheated steam pressure / temp. - 3.82 MPa / 295°C	Integral reactor with forced circulation in the primary circuit for nuclear icebreakers; Ref. 24
VK – 300 (RUSSIA)	BWR Thermal power - 750 MW Electric power - 250 MW	System pressure – 6.9 MPa System temperature - 285°C Fuel material and enrichment – UO ₂ , 4.0%	Natural circulation in primary circuit; Ref. 23
VBER – 300 (RUSSIA)	VVER Thermal power - 917 MW Electric power – 325 MW	System pressure / temp. – 12.7 MPa / 316°C Fuel material and enrichment – UO ₂ , 4.95%	Modular reactor based on marine propulsion reactor technologies for land-based and floating nuclear power plants; Ref. 17
Atlantic Generating Station – Offshore Nuclear Power Plant (USA)	PWR Electric power – 1150 MW Thermal output – 3425 MW	Operating pressure – 15.5 MPa Reactor inlet and outlet temp. – 292 / 325°C Fuel material and enrichment – UO ₂ , 3.2% No of coolant pumps – 4 Total reactor flow – 64500 t/hr	Ice condenser containment; large breakwater; twin units; Ref. 20
FlexBlue Underwater Power Plant (FRANCE)	PWR Electric power – 50 - 250 MW Thermal power – 150 - 750 MW	System pressure – 15.5 MPa System temperature - 310°C Fuel material and enrichment – UO ₂ , 3.1%	At conceptual design stage: autonomous operation, seabed, torpedo resistant; Refs. 18 and 19
Offshore Nuclear Power Plant (SOUTH KOREA)	PWR Electric power – 1400 MW x 2 units	Standard APR1400 PWR nuclear island with passive seawater-based containment and core cooling systems	Plant housed in concrete/steel structure resting on seabed, suitable only for shallow waters; Ref. 21
Semi-submersible Nuclear Power Plant and Multipurpose Platform (USA)	Naval PWR modules	Unspecified	Patent for a generic offshore nuclear reactor based on a spar-type or cell-spar-type floating platform; Ref. 22