Offshore co-generation of electricity and desalinated water: Trident

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ABSTRACT

The Trident Offshore Floating Nuclear Power Platform (OF-NPP) and Cogeneration and Desalinated Water (CDW) capstone is designed to synergistically combine three technologies - nuclear power, desalination, and modularized offshore platform efficiency and construction. A core aspect of Trident's design is its adaptable model, featuring the ability to utilize 1 to 8 Mark-1 Pebble-Bed Fluoride-Salt High Temperature Reactors (Mk1 PB-FHRs) for a capacity of 100 to 800 MW base-load electricity as well as the coupling of 1-2 25-Million Gallon per Day Salt Water Reverse Osmosis (SWRO) desalination plants. The structure parameters where defined as needing to accommodate multiple Mk1 PB-FHRs and SWRO plants. In this way, a modified Truss Spar platform was selected and designed to utilize these design parameters.

Identifying operational safety parameters is a major aspect to any nuclear power plant, given the additional aspect that Trident is a marine based and floating, the safety analysis has an even greater impact as public perception dictates much of the industries standards.

The reference site for the Trident prototype is 11 nautical miles off the coast, north of San Diego. Combining each individual technology into a hybrid product production (electricity and potable water) allows the system to economically capitalize on each industry's individual shortcomings and market susceptibilities.

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1.1. Introduction

In California, the average retail electricity price increased from 8.84 cents/kWh in 1990 to 14.29 cents/kWh in 2013[1]. Moreover, from the same source, the retail electricity price in California is consistently higher than national average retail electricity price from 1990 to 2013. Also, Jones[2] showed that the yearly precipitation accumulation of 2013 and 2014 is much lower than the historical average, the precipitation of 2014 is even lower than 2013. Therefore, developing the co-generation facility, which can alleviate the electricity price and drought, would benefit the community.

This project goal was to develop a technical design, regulatory strategy, and business plan for a floating co-generation facility, which is named Trident. Trident combines three technologies: Fluoride- Salt-Cooled High-Temperature Reactors (FHRs), Offshore Floating Nuclear Power Plant (OFNPP), and Salt Water Reverse Osmosis (SWRO) desalination. Thus, Trident was well prepared to address the energy and water challenges that California faces, and other regions where water scarcity exists. Trident will provide safe, zero-GHG, affordable electricity by placing the power plant offshore, away from the populated areas Moreover, Trident will also generate fresh, potable water; thus, alleviating drought pressures and ensuring a water supply in the future.

As shown in Figure 1, this project breaks into five stages. Our team then divided the project into three sections in stage 1: power plant, desalination, and offshore platform. Each team member in charge one section. This paper focused on the offshore platform, which included the offshore nuclear power plant design and the spent fuel transportation between platform and spent fuel transfer vessels.

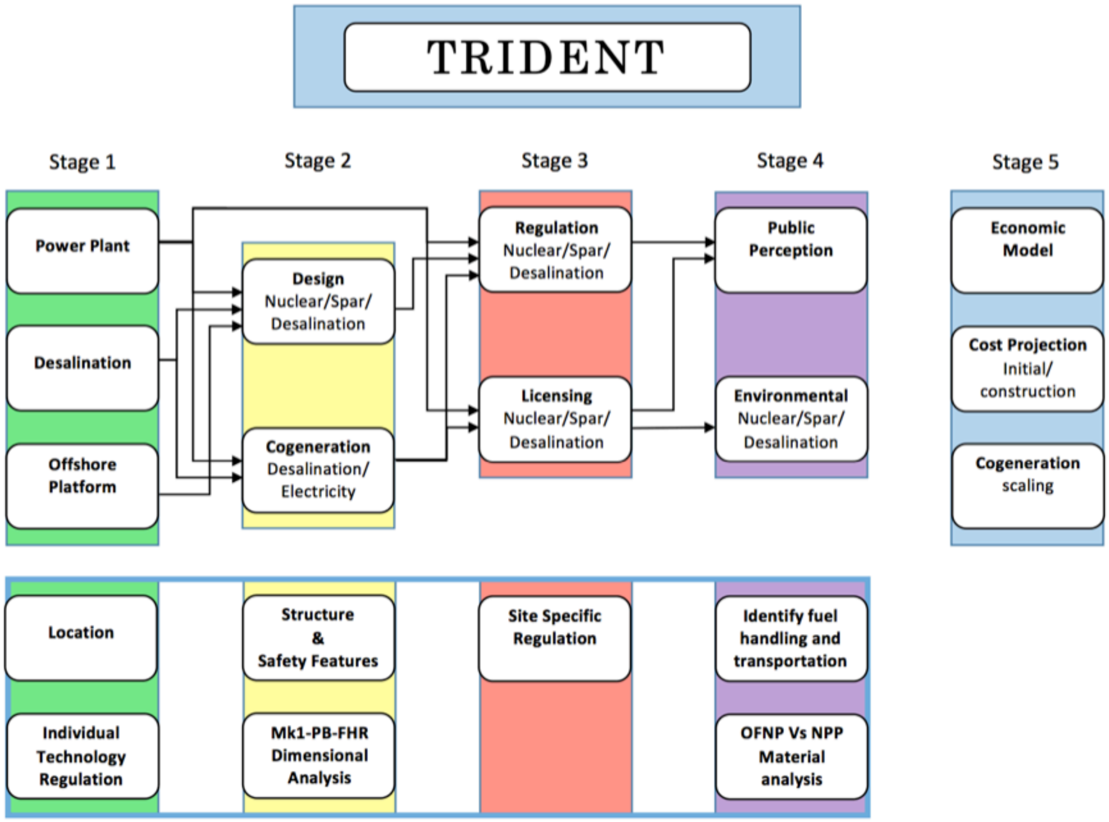


Figure 1. Flow chart of Trident capstone project

1.2. Problem Definition

The two most significant problems that this project faced were:

1. Integration and design of the floating platform

The offshore co-generation platform should integrate with nuclear power systems and SWRO facilities to achieve the goal of generating the electricity and desalination water. However, the space of the offshore platform was limited, since the cost of materials should be reduced to increase the market competitiveness. Moreover, the construction and installation of the platform should meet the criteria of existing naval transports and ship builders.

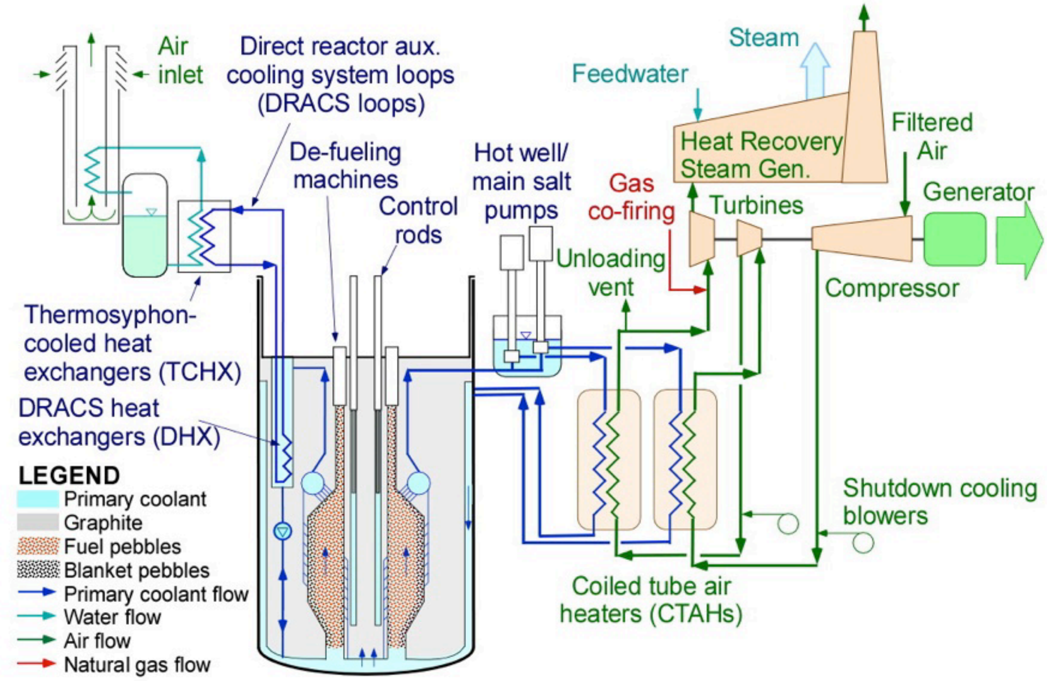
2. Identifying possible spent fuel canister transportation method

Since the platform was powered by nuclear and the site was in the middle of the ocean, the transport of spent fuel cannot depend on trucks or trains, which is the general way to transport spent fuel canisters. Moreover, the safety of spent fuel transportation also should be considered to reduce the possibility of dropping or damaging the spent fuel canisters, which might lead to the release of radioactive materials.

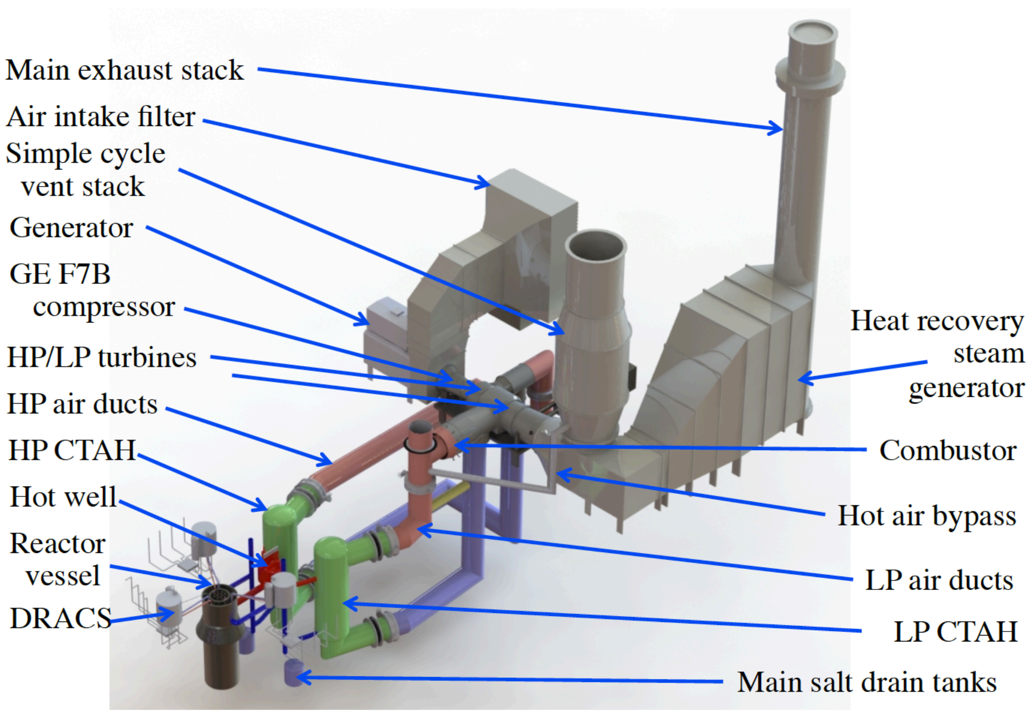
1.3. Literature Review

1.1.1. Mark 1 Pebble-Bed Fluoride-Salt-Cooled High-Temperature Reactor (Mk1 PB-FHR)

The Mk1 PB-FHR is a type of molten salt reactor designed by University of California, Berkeley and others[3]. Its flow schematic and the isometric view of the reactor and power conversion unit (PCU) are shown in Figure 2. Its base load was 100 MWe, and it can generate 242 MWe with a gas co-firing system for peak electricity generation. Different from light water reactor (LWR), the fuels used in Mk1 PB-FHR is 3.0-cm diameter pebbles, rather than pellets. The pebbles circulate between the reactor vessel and the pebble handling and storage system (PHSS) to separate the damaged and spent fuel pebbles. The heat generated by the fuel is carried by molten salt (flibe) through a hot well, which is in the main cooling loop, to two coiled tube air heaters (CTAHs). Moreover, then the air, which is circulated through the CTAHs, carries the heat to a modified General Electric 7FB gas turbine to generate electricity. Three direct reactor auxiliary cooling systems (DRACSs) remove decay heat using natural circulation under emergency conditions.



Mk1 PB-FHR flow schematic

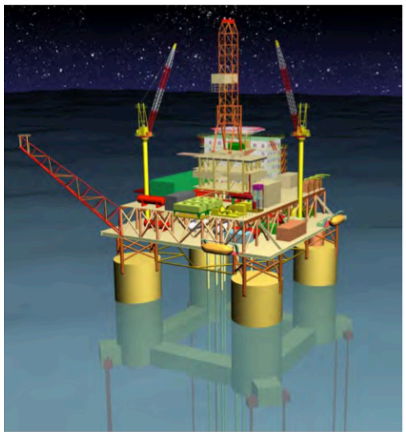


Isometric view of Mk1 PB-FHR

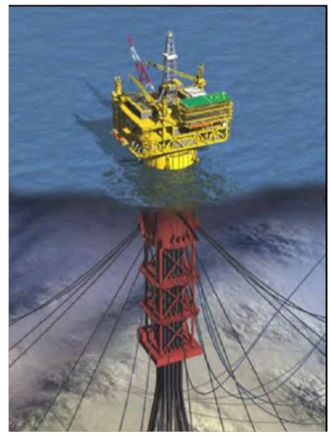
Figure 2. The flow schematic and isometric view of Mk1 PB-FHR [3]

1.3.1. Offshore Floating Platform

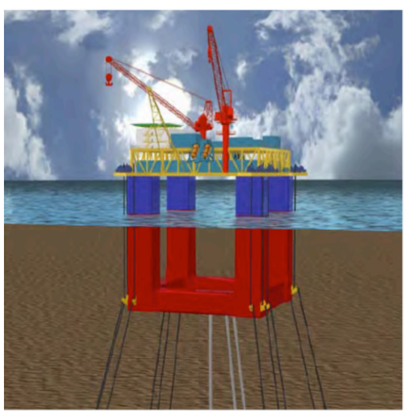
To reduce the effect of seismic impact and tsunami, the Trident should locate in relatively deep water. Four types of floating platform had been considered; they were Floating Production Storage and Offloading Vessel (FPSO), Semi-submersible, Tension Leg Platform (TLP), and Spar, as shown in Figure 3.



TLP



Spar



Semi-submersible

FPSO

Figure 3. Type of deep water floating platform[4]

TLP and Semi-submersible platform only had limited space, which located at the upper deck. However, for the Spar and FPSO platform, since both platforms could be applied to the storage facility, there was plenty space to accommodate extra facilities and equipment. Moreover, a large portion of the applicable space of both Spar and FPSO platform is located below the water line.

In addition to the Spar platform, it had the deepest draft and small water plane. Deeper draft could increase the stability since the fixed ballast, mainly consisting of iron ore, was placed in the soft tank[5], which located at the bottom of the Spar for lowering the centroid of the platform, as shown in Figure 4.

Mainly there were two types of Spar-classical-Spar, truss-Spar, as shown in Figure 4. This project selected truss-Spar as the offshore floating platform; Saiful Islam[6] indicated that truss-Spar compare advantageously with classical-Spar because the middle section of the spar is replaced by the truss, thus reducing the cost and amount of materials for construction. The heave plates were installed onto the truss, which improves the heave motion of the platform [7].

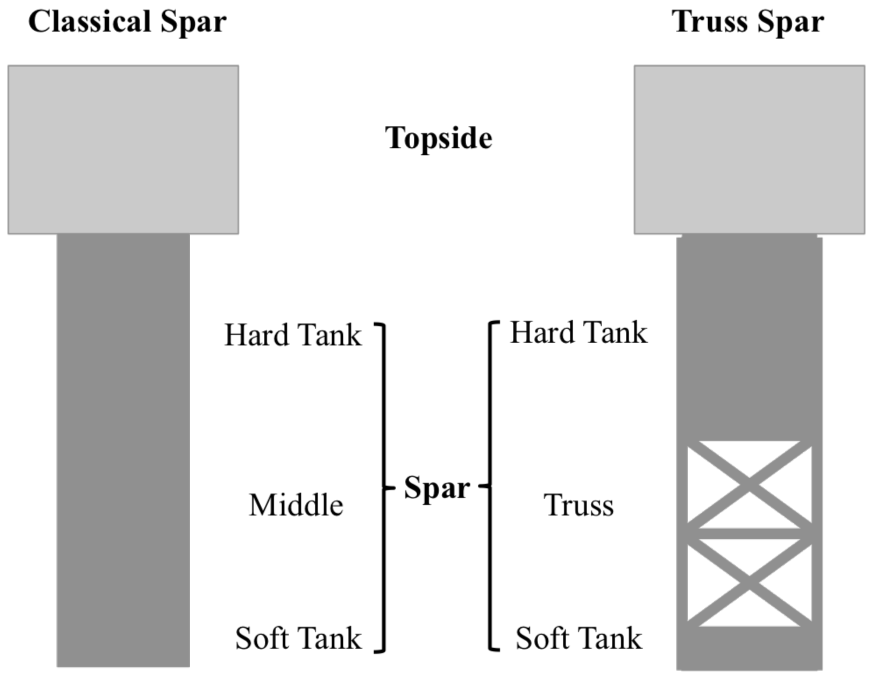


Figure 4. Classical spar and truss spar

As described in the Handbook of Offshore Engineering [8], the hull of a Spar is built horizontally in a shipyard. Different companies would manufacture the part of the Spar hull and shipped to the assembly site, as shown in Figure 5. More than half of the currently operated spar platforms have had their hulls assembled in Finland by Technip. The materials used to construct the spar hull mainly are steel. After the Spar hull was assembled, it will be shipped to the port nearby the final operation site by semi-submersible heavy vessel. The topside normal will be constructed in the country where the Spar would operate.

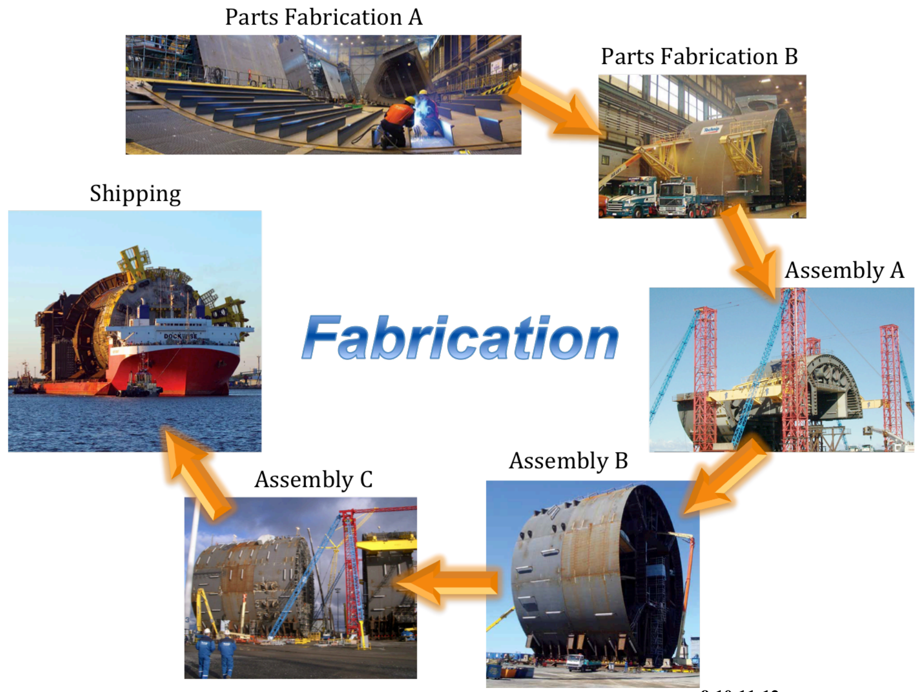


Figure 5. The fabrication of the spar hull[9,10,11,12]

Before the Spar arrives to the site, the anchors are preinstalled; this process might take months to finish. As shown in Figure 6, after the spar hull arrives the port, it will float horizontally and be towed to the site by the tugboats. At the site, the soft tank and the bottom of the hard tank will be flooded to make the hull upended. After placing the fixed ballast, the spar hull is connected to the anchors. The topside can be installed in two ways-lifted by crane or float over deck method[8]. These topside installation methods are shown in Figure 7.

Figure 6. The installation of the spar[11,13]

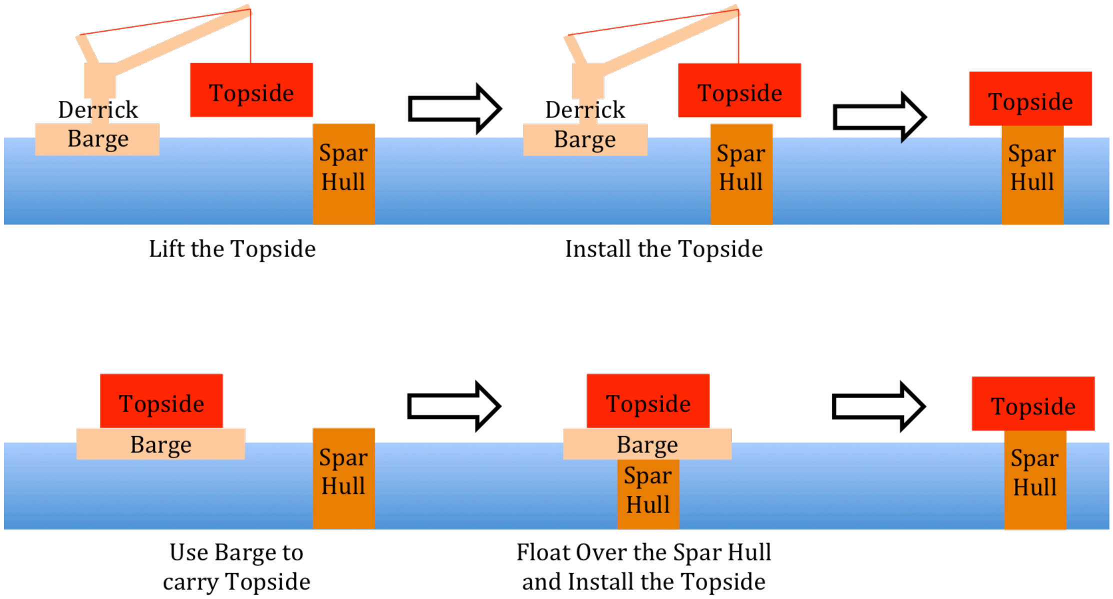


Figure 7. Topside installation method: life over and float over deck method

1.3.2. Offshore Transportation: between platform and vessel

There were mainly two ways to transport cargo and personnel between the platform and a transfer vessel - crane and bridge. Their schematics are shown in Figure 8. Both crane and bridge could transport the personnel, but only the crane had the capability to carry the cargo.

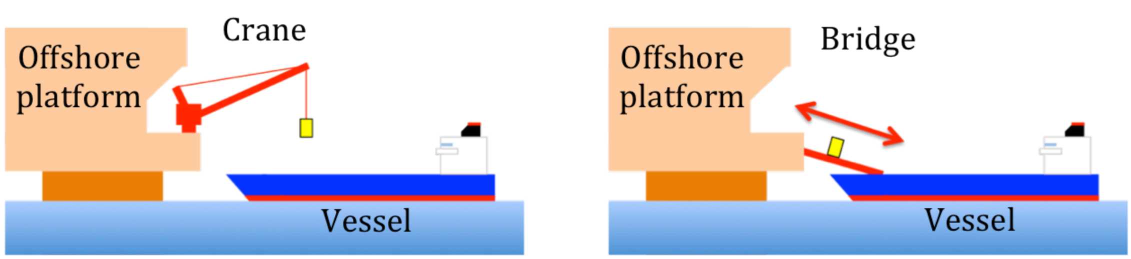


Figure 8. Schematics of crane and bridge transportation

Moreover, for the nuclear-safety related application of moving spent fuel canisters, the crane should have the single-failure-proof safety feature[14] to prevent dropping. The single-failure-proof cranes require auxiliary hoisting systems, electric control system, and emergency repair feature to hold the load if the crane is disabled. For an offshore crane, there did have the guideline that requested the crane should have brakes and fail-safe devices [15], which were similar to the single-failure-proof for nuclear applications.

Cranes and elevators were the two ways to transport from deck to deck. The elevators were considered as a safer way to carry cargo since it had the extra brake to stop the elevator from falling.

1.3.3. Offshore Nuclear Power Plant Design

The Massachusetts Institute of Technology developed two offshore floating nuclear power plant (OFNP) concepts in 2015[16]. OFNP-300 equipped a Westinghouse's AP300, which was a 300 MWe Small Modular Reactor (WSMR), and another one, OFNP-1100, equipped a Westinghouse's AP1000, which was a 1100 MWe pressurized water reactor (PWR). Both concepts are shown in Figure 9. Both platforms, as they described, were the type of Spar. However, the appearances look like FPSO.

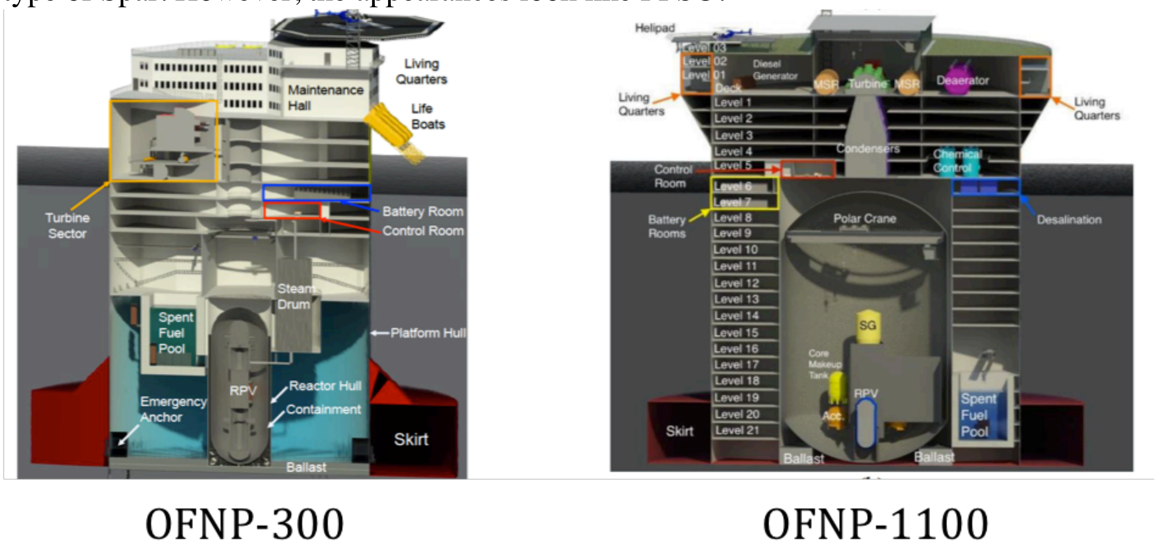


Figure 9. OFNP-300 and OFNP-1100[16]

They also developed a method for refueling and fuel transportation[17]. The concept is presented in Figure 10. The concept was using a semi-submersible barge to load and off-load the fuel canister under the water line. The fuel canister would go through a loading tube to the semi-submersible. To make the transportation possible, the OFNP should reduce its draft allowing the barge to go beneath it.

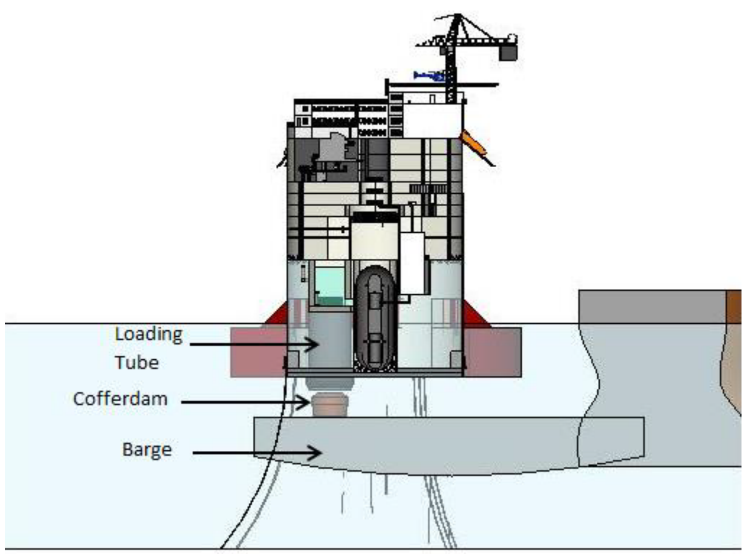


Figure 10. Elevation view of the OFNP and semi-submersible barge[17]

1.4. Approach

The sub-sector of the approach of the Trident's model was mutually influenced by each other since the size of the water production and generation of electricity depended on the number of Mk1 PB-FHR reactors and the scale of the desalination facility. However, the basic process is shown in Figure 11.

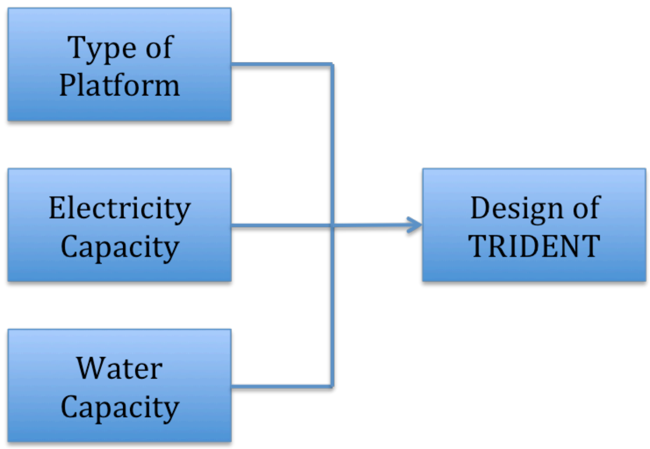


Figure 11. Flow chart of building model of Trident

For the determination of the spent fuel canister transportation method, the decision process is shown in Figure 12. After searching or creating types of transportation method, those methods will be assessed and be compared its frequency of dropping or safety devices. The final decision will depend on those safety feature assessments.

Figure 12. Flow chart of spent fuel transportation assessment

1.5. Design

1.5.1. The Approach of Trident's design

The truss-Spar platform was selected for the offshore platform design for Trident because it provides space to accommodate the nuclear power plant units and desalination facilities. For safety, the truss-Spar had intrinsic stability because of the low centroid of mass of the platform and its heave plates[5,7]. Also, compared with classical Spar designs, the truss-Spar has lower construction cost[6]. Moreover, the truss could act as a pathway to the topside for the electric cables, natural gas tubes, and fresh water tubes, which connected to the shore through the seabed.

To compete with MIT's OFNP-1100, the power output of Trident should be around 1000 MWe. This project had considered placing twelve units of Mk1 PB-FHR onto the platform. However, some of the girders in the Spar hull would block the reactor units and made the reactor impossible to access. Moreover, to make the design feasible, the reactor units would need maintenance pathway and space for extra equipment. Therefore, four units of Mk1 PB-FHR were removed. The remaining eight units of Mk1 PB-FHR could generate 800 MW of base load electricity and 1936 MW of peak load electricity.

The water capacity was flexible; it depends on the economic reason of operating a power plant. Thus, the basic model provided two areas on the lower deck of the topside for SWRO desalination facilities.

1.5.2. Basic Model Design

As shown in Figure 13, Trident is a truss-Spar type offshore platform that consists of the topside and the spar hull. The topside includes two towers, living quarters, power conversion units, and two SWRO water production facilities. The hard tank is modified to accommodate three levels - control room level, crane level, and reactor level. The skirt at the bottom of the hard tank could provide extra buoyancy during installation and stability during operation[16]. The last second section was VTS, which is short for the variable ballast tank, the truss, and the soft tank. The variable ballast tank in the VTS can adjust the draft to coordinate with the float over method during the installation of the topside and provide variable buoyancy to compensate the extra load during operation. The truss currently designs to construct with two heave plates. The VTS was consisted of 2.5-cm thick carbon steel plates.

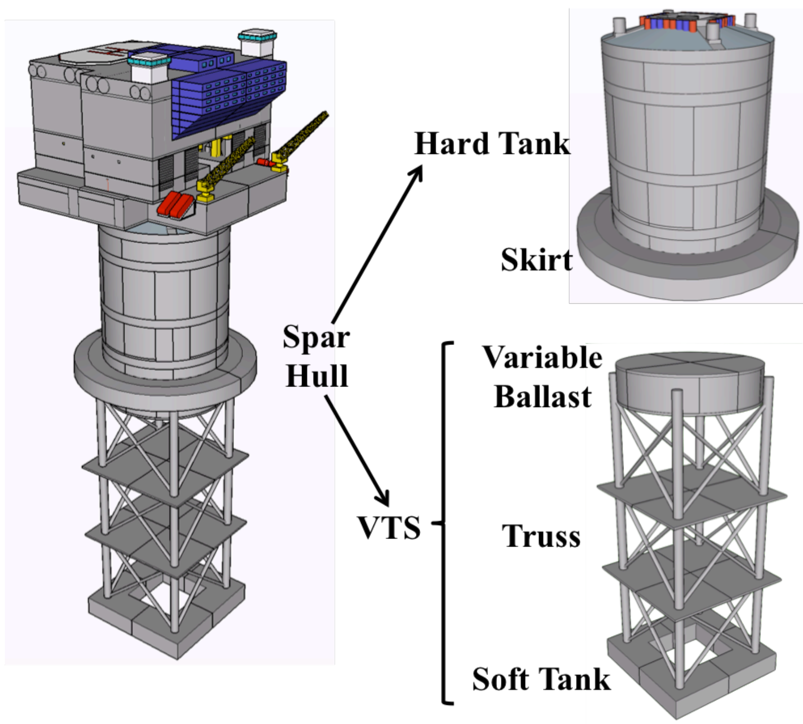


Figure 13. Trident: hard tank and VTS

The dimensions and the estimated weight of Trident are shown in Table 1. The weight included the structure steel of the platform, eight units of Mk1 PB-FHR[3], and two SWRO facilities. This project used Solidworks to estimate the structure steel required to construct the platform. Moreover, the result from the Solidworks was multiplied by 1.7 to estimate the steel for columns, stiffeners, and frames, which were not shown in the Solidworks model.

Table 1. Dimension and estimated weight of Trident

	Height (m)	Length/ Diameter (m)	Width (m)	Weight (MT)
Topside	70.56	91.20 ~ 73.66	91.20 ~ 73.66	26190
Hard tank	88.00	60.00	-	51117
VTS	147.00	60.00	60.00	18330
Total	305.56			95637

1.5.2.1. Topside

The cross-section of the topside is shown in Figure 14. The living quarters have nine stories, which provides housing and offices for workers. Eight power conversion units (PCU) are on the topside, each equipped with a generator, turbines, heat recovery steam generator, etc. [3]. These PCUs were co-fired units, which could convert heat, which was provided by the reactor and also by burning natural gas, into electricity. Besides the cranes on the outside-deck, three more cranes are located in the building. One of the three, which located at the center, can provide lift for elevator or transportation of equipment on the topside. The two remaining cranes are prepared for maintenance of PCUs. The walls of the PCUs and SWRO facilities are 2.5-cm thick carbon steel plates, and the walls of the living quarter and towers are 1.25-cm thick carbon steel plates.

RO facilities and transformers (it does not show in Figure 14) located on the lower deck. RO facility 1 measured at 91.2 m × 30 m × 9 m and RO facility 2 measured at 50 m × 25 m × 9 m. There are two units of transformer each measured at 25 m × 20 m × 9 m and distributed to two sides of the lower deck.

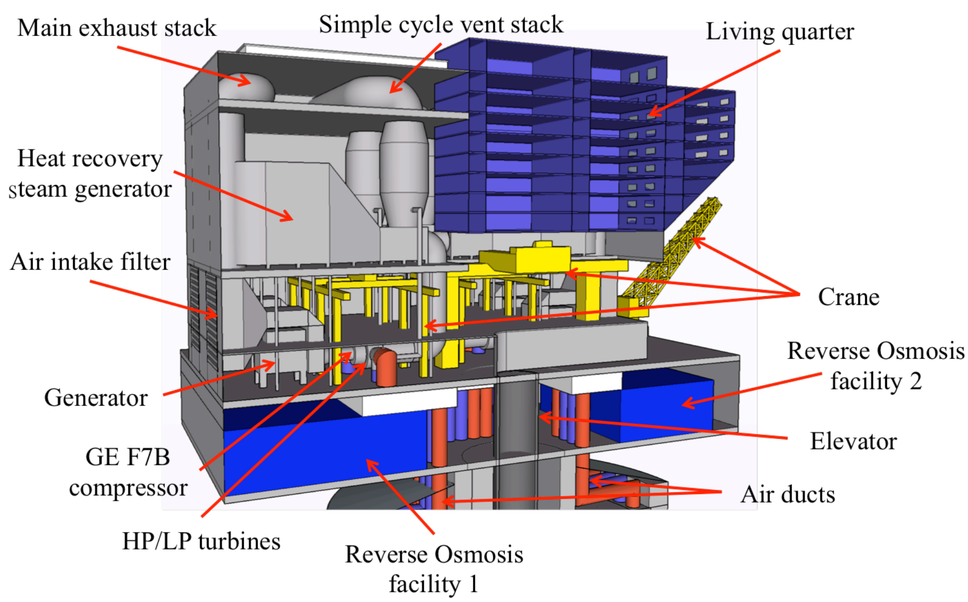


Figure 14. Cross-section of topside

1.5.2.2. Hard Tank

There are three levels in the hard tank - control room level, crane level, reactor level, and storage level, as shown in Figure 15. Each level is separated by containment gate to ensure isolation from outside environment. The elevator passes through the hard tank and reached the storage level; it is the only path for the transportation of equipment and spent fuel casks. The hard tank is designed as a double hull structure, and each level has different numbers of the watertight compartment to ensure safety, a plan view of each level are shown in Figure 16. The double hull structure, which is in red, can also act as a variable ballasts tank to adjust the draft during installation and operation periods. The green areas are the watertight compartments, which are divided into four or twelve sections depending on the level. These watertight compartments can contain the seawater during the flooding event and prevent further damage to the platform. The double hulls, watertight compartments, and skirt are constructed using 2.5-cm thick carbon steel plates. The rest of the hard tank is consisted of 1.25-cm thick carbon steel plates.

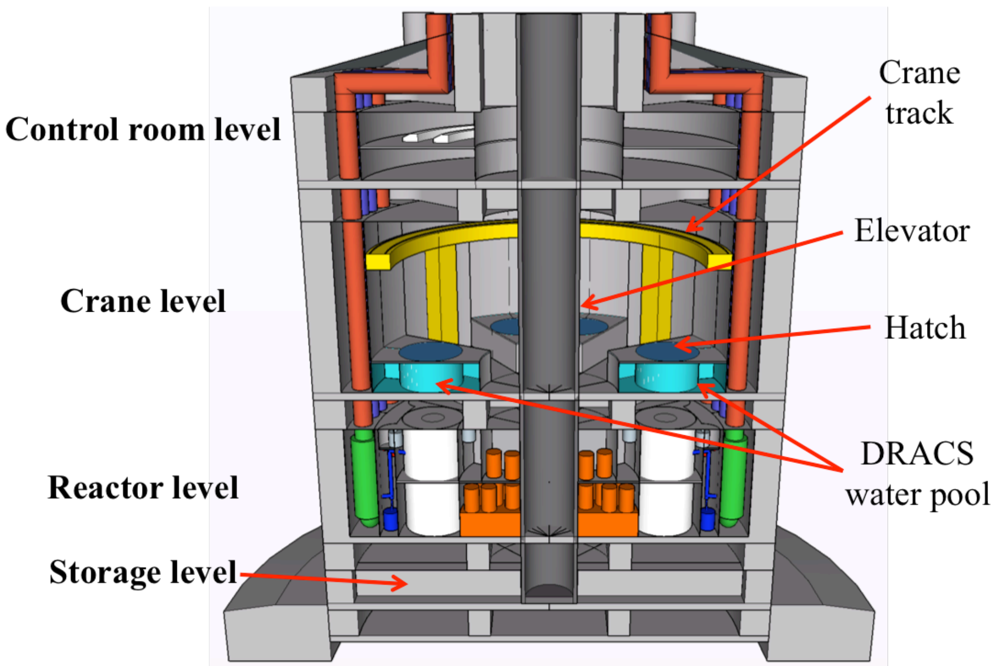


Figure 15. Cross-section of hard tank

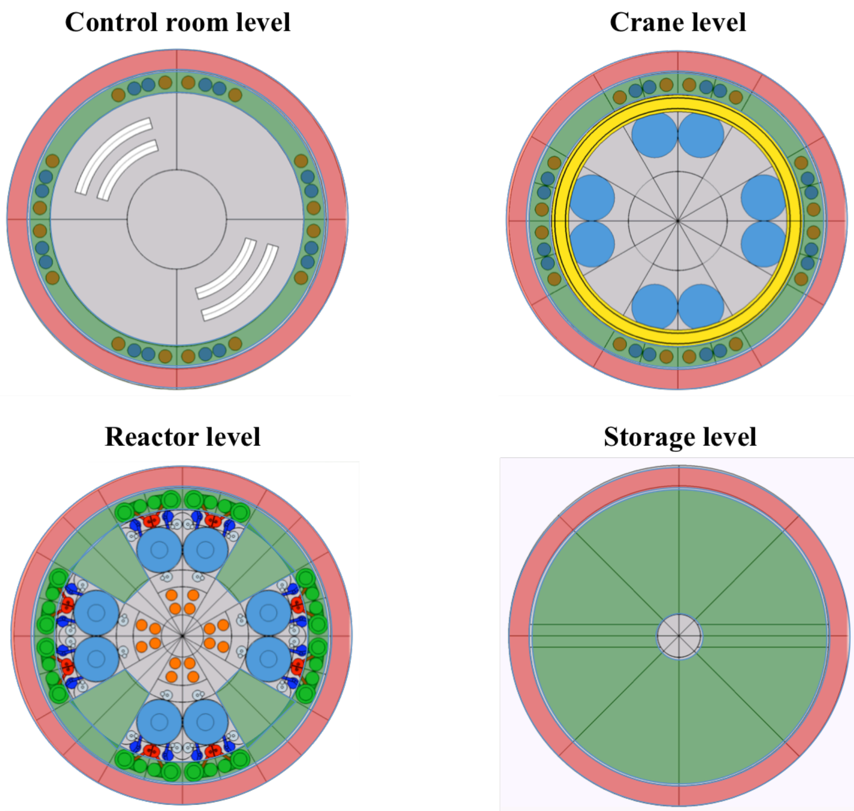


Figure 16. Plan view of levels in the hard tank.

The control room level consists of two control rooms on the upper level, only one of it will function during operation, and the other one will serve as a backup. The lower level provides a space for cable and other electrical equipment.

On the crane level, eight water pools provide water for the DRACS, which would be activated if the main cooling system were not working. The circular crane track is for the polar crane, which provides lifting capability during maintenance.

The cross-section of reactor level is shown in Figure 17. The reactor level consists of eight units. Each unit has one reactor cavity, one PHSS, one hot well, two drain tanks, two CTAHs, and three DRACSs. Figure 17 shows half of the units. The reactor vessel is in the reactor cavity, which is constructed with concrete and strengthened by steel, so it can also provide radiation shielding. The main cooling system is the hot well; it carries the heat of reactor by molten salt to the CTAHs, which exchange the heat from molten salt to air. The heated air goes through the air ducts to the turbine, which was part of PCU on the topside, to generate electricity. The fuel pebbles continuously circulate between the reactor vessel and PHSS. The PHSS, which consists of ten canisters, classifies pebbles and distribute them into the different canisters. Four of the canisters, which store the spent fuel, need to be periodically transported, so these canisters are located next to the central elevator. These spent fuel canisters will transport by the elevator to the storage level for temporary storage before it ships to a spent fuel storage facility on land. The spaces between units provide addition equipment and maintenance pathway.

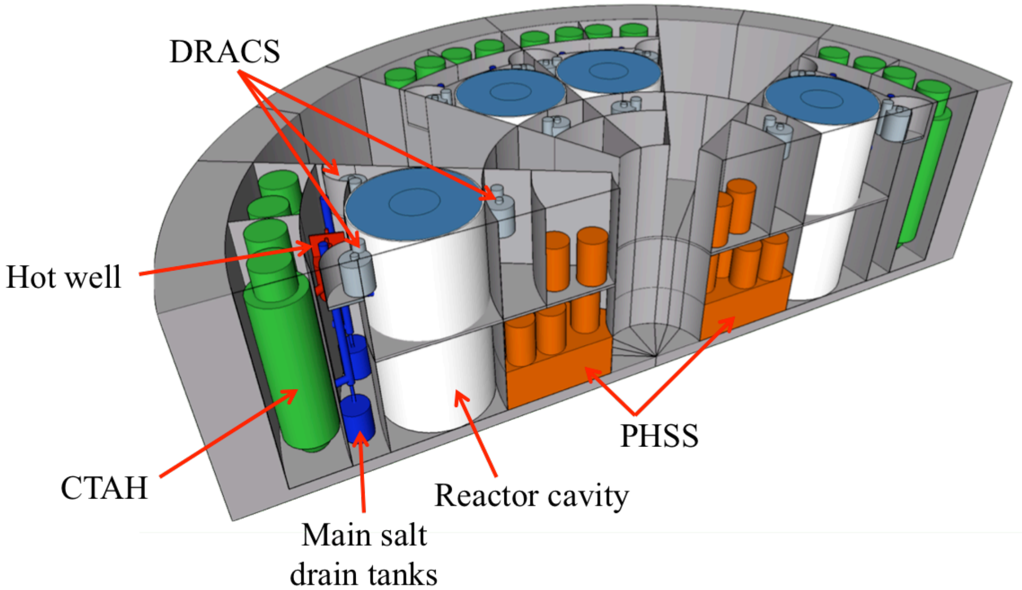


Figure 17. Cross-section of reactor level

To reduce the shipping frequency and the cost, the platform needed for storage enough fresh fuel and for space to store the spent fuel, which was produced in an operating cycle. Thus, an extra level is placed below the reactor level. The storage level holds an interim storage facility; it was designed to hold at least 180 spent fuel casks and 180 fresh fuel canisters. The fresh fuel canisters and the spent fuel casks would transport by the elevator to the storage level. After the casks or canisters reach the storage level, it will be moved by tracks to the location where the casks or canisters will be storage temporarily.

1.5.3. Fabrication and Installation

The fabrication and installation plan for Trident is different from the land-based power plants. Different companies will manufacture the parts of the spar hull and ship them to the assembly shipyard. The spar hull of Trident will be assembled in a vertical way, which was different from the general spar hull construction since the nuclear industry was not familiar with building a nuclear power plant horizontally and up-ended the plant after its construction. This vertical building process was similar to the manufacturing of Round Floating Production Storage and Offloading Vessels (Round FSPOs) [4], as shown in Figure 18. The materials used to construct the spar hull are mainly steel. However, Trident will need other kinds of materials, for instance, the reactor cavities are made of concrete, and other specialized components for the anti-corrosion purpose consisted of the superalloys. The fabrication process of Trident will be more complicated than traditional spar hull fabrication. The reactor vessels, CTAH, DRACS loop, etc., and cabling in each level of the hard tank will be installed during the assembly in the shipyard. However, the VTS will assemble horizontally as same as the general spar hull. In addition, the topside is planned to construct in San Diego to reduce the transportation cost and to provide jobs for the local community. After both the spar hull and VTS are assembled, they will be shipped to San Diego by semi-submersible heavy vessels.

Figure 18. Construction of Round FSPO [4]

Before Trident's arrival to the site, the anchors will be preinstalled; this process might take months to finish. The flow chart of the installation of Trident is shown in Figure 19. After the VTS arrives in San Diego, it will float horizontally and be towed to the site by the tugboats. Differently, the hard tank will be shipped to the site by semi-submersible heavy vessels. At the site, the soft tank and the bottom of the VTS will be flooded to make the VTS upended and submerged under water. After the hard tank has arrived at the site, the hard tank will be installed onto the VTS by float over deck method by the buoyancy, which was provided by the skirt. Before the spar hull is connected to the anchors, the fixed ballast will be placed into the soft tank. Since the topside of Trident is heavy, the installation of the topside will also use the float over deck method.

Figure 19. The installation of Trident

1.5.4. Spent Fuel Transportation

Two methods were considered to transport spent fuel canisters from the spar to a spent fuel transport vessel; one uses a crane, and the other is a method developed in this project.

The crane is a conventional method to transport cargo between a platform and a vessel. To apply the offshore cranes to a nuclear facility, the crane's frequency of load drops must be considered. This project only considered very heavy loads (> 27 MT) since the casks for spent fuel are heavier than 20 MT. From the U.S. Nuclear Regulatory Commission's (NRC's) crane operation survey of U.S. nuclear power plants[18], there were three very heavy load drops happened between 1980 to 2002, none of these drops resulted in radiation releases. In the report, they estimated the total number of very heavy load lifts for all US nuclear power plants during 1980 to 2002 were about 54000. Thus, the probability of load drops for each lift was about 5.55×10^{-5}. From the data directory of International Association of Oil & Gas Producers[19], the total dropped object probability for fixed installations per lift with load weight between 20 to 100 MT was 2.0×10^{-5}, which is lower than the probability of the US nuclear power plants. Thus, from regulation prospection, using an offshore crane to transport spent fuel casks was feasible.

However, Trident has about 365 spent fuel casks to transport each year for eight Mk1 PB-FHR units; the very heavy lift is more frequent than for land based nuclear power plants. Also, the reports from ABSG Consulting[20] and NRC[18] both indicate that human error was the major factor in earlier load drop incidents. Moreover, the cask might fall into the sea, which increases the difficulty in recovering the cask. Therefore, this project developed another method; this method uses an elevator to transport a barge, which carries the casks, from the deck to the sea level, and then uses a tugboat to tug the barge to a sub-submersible vessel. Finally, the sub-submersible vessel will carry the casks to the land. The sketch of the developed method is shown in Figure 20, and the concept of the elevator is presented in Figure 21.

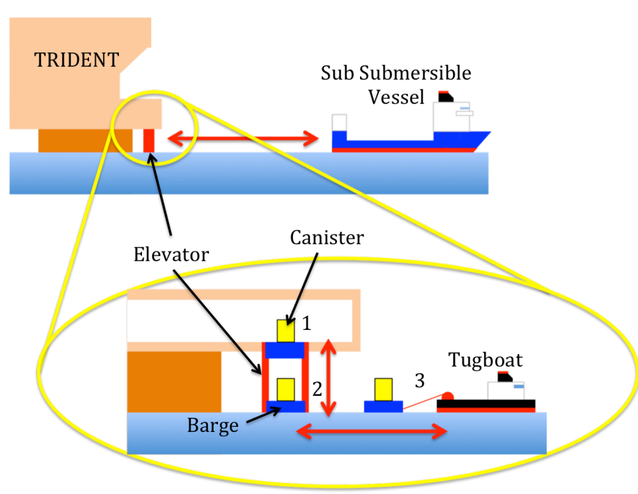


Figure 20. Transportation of canister by elevator, barge, tugboat, and sub-submersible vessel

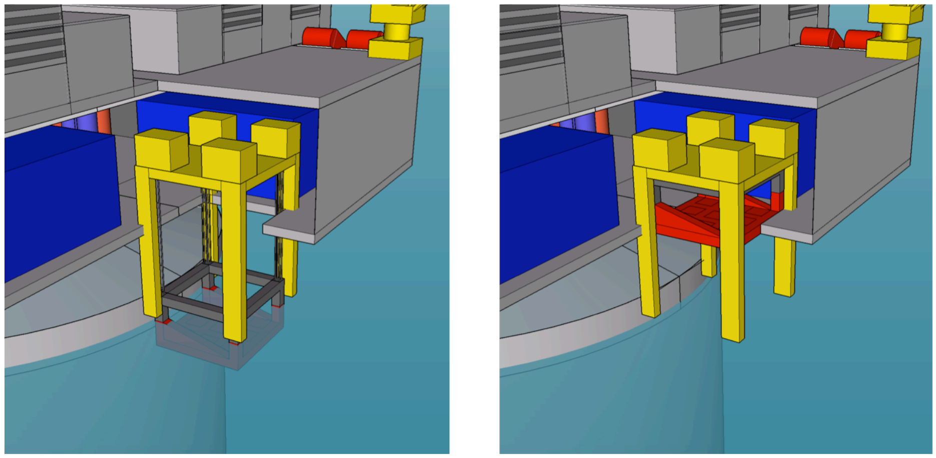


Figure 21. Section of elevator: at sea level and on deck

The developed method was considered as one of the potential methods since the heavy lift elevator is a mature technology, which has been applied to aircraft carriers. Moreover, controlling the elevator is simpler than operating the offshore crane; thus, reduced the possibility of the human error. Also, the elevator can be designed to have extra safety devices, which can prevent dropping of the loads. In addition, transport by barge and not using the crane can eliminate the possible failure of active wave movement compensation equipment for a crane. Finally, since the sub-submersible vessel is anchored distance away from the platform, the frequency of collision with vessel can also be reduced.

1.6. Summary

From the design, the project developed an offshore co-generation nuclear power plant - Trident, its main features are described as follow:

1. It is a Truss-Spar platform.
2. Eight Mk1 PB-FHR units are capable of generating 800 MW of base load electricity and 1936 MW of peak load electricity.
3. Two RO facilities on the bottom deck of the topside can provide desalinated water.
4. Double hull and multi watertight compartments can ensure the safety of the platform.
5. The skirt at the lower part of the hard tank can provide extra buoyancy and stability during installation and operation, respectively.
6. The vertical fabrication of hard tank is different from general spar hull horizontal construction.
7. A novel installation method was developed that allows the hard tank and VTS to be transported to the site separately.
8. Two possible spent fuel canister transportation methods have been developed - lifting by crane and elevator-barge-tugboat transportation.

Chapter 2 Safety & Environmental Analysis

2.1. Introduction

As like the post Chernobyl nuclear plant accident in 1986, recently, negative perceptions and concerns toward the nuclear energy are getting higher after Fukushima nuclear accident in 2011. Hereupon, researchers in the nuclear industry have tried to develop the innovative nuclear engineering technologies which are far more advanced than the existing nuclear technologies. We sometimes call them as a generation IV nuclear technologies and researchers put the major emphasis on the safety and sustainability. Nuclear specialists suggested six GEN IV nuclear reactor designs, VHTR, SCWR, GFR, SFR, LFR and MSR[i,21] and FHR (Fluoride salt-cooled High-temperature Reactor) reactor design which is the one of the MSR (Molten Salt Reactor) reactor design is studied in the nuclear engineering department at U.C Berkeley. Most of the existing nuclear power plants, however, were located on the land near the seashore in order to use sea water to cool down the heat from the reactor. Also territorial nuclear power plants are still not risk free from Tsunami which was the major cause of Fukushima accident. Therefore, we suggest the floating type of FHR. It can reduce the risk from natural disasters such as Tsunami and it can minimize the radiation expose level to the environment or the public on the land. So I discussed how floating FHR, Trident, is safer than the existing NPPs and I verified that Trident is radiologically safe enough to operate in the sea by analyzing the movement of Tritium which represents radioactive material in Trident.

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i Technology Roadmap Update for Generation IV Nuclear Energy System, OECD Nuclear Energy Agency, 2014

2.2. Description of Trident

Our capstone project, Trident provides both electricity and desalination water to the public from the offshore platform. For nuclear energy generation, FHR (Fluoride salt-cooled High-temperature Reactor, coolant is fluoride salt mixture) technology is adopted. For the floating platform, Spar that has a dimension with 200m depths, 60m widths will be used for containing NPP (Nuclear Power Plant) in it. For the desalination facility that will be installed on the top of the platform, RO (Reverse Osmosis) technology will be applied. During the normal operation, Trident produces around 800MWe. Some of this energy generates electricity and other energy is used for producing desalination water. The optimized energy consumption ratio of the electricity to the desalination is flexibly controlled by an economic model in order to maximize profits based on market price of the energy and fresh water. In the topside, other essential facilities would be installed as well as RO desalination plant. Living space which worker can stay at least for 6 months, main control room, dock for import/export of spent nuclear fuels and cranes, radiation detection system, helideck and control tower are planned to install in the topside. Fresh water from desalination plant and electricity from FHR would be transported across the center of hard tank and truss. And it would reach to the seabed and transport to the land through a submarine cable.

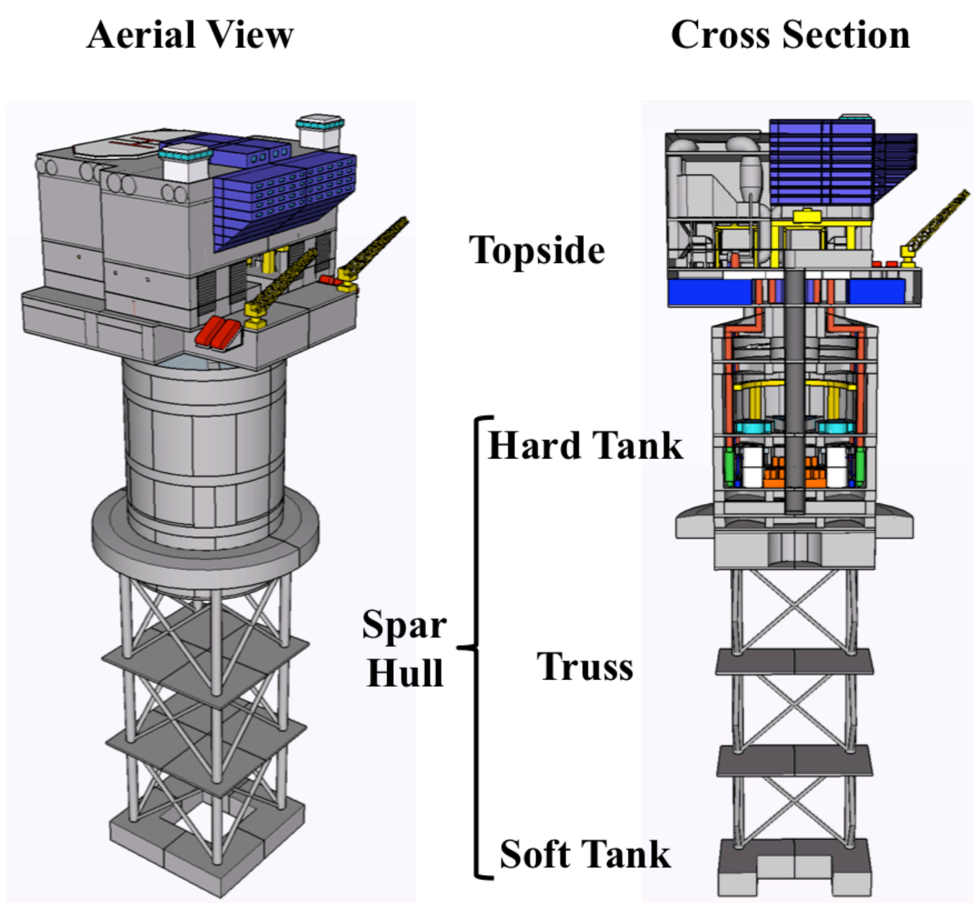

Figure 22. Projection of Trident

2.3. Safety Features of Trident

Safety features of Trident include intrinsic safety features of FHR and additional safety features brought on by installing FHR on the sea.

Traditionally, nuclear power plants were built near the sea in order to use the seawater as the coolant. Because of that, they are vulnerable to natural disasters such as earthquake or tsunami. In the aspect of nuclear reactor, we adopted the FHR (Fluoride salt cooled High temperature Reactor) technology not the LWR (Light Water Reactor, coolant is light water) because LWR design fundamentally needs to keep high pressure (150 bar, 150 times of atmosphere pressure) during normal operation whereas FHR can operate in the atmosphere pressure. Also FHR technology is the one of generation IV nuclear reactor designs that pursues the higher safety and sustainability than conventional NPPs have. There are couples of advantages when nuclear reactor is installed in the seawater. First, radiation from the reactor during operation is shielded by seawater (H_2O is the one of the best radiation shielding material). Second, the seawater can remove surplus heat from the reactor during normal operation and also in the case of the severe accident, the seawater is helpful to remove the decay heat rapidly (even after the reactor shut down, decay heat remains). Lastly, it can move to other location where it needs to be if cables are pre-installed in the location for the power transmission. In addition, FHR operates at a higher temperature (>1000ºC)[ii,22] than conventional LWR (>300ºC) for thermal efficiency and this thermal energy is also used for the desalination facility as the conversion energy from seawater to freshwater. Because Trident design is based on FHR, it is not significantly influenced by the resources (natural uranium ore) market price and consequentially it can supply power to the public with the low and stable cost. Also Trident has features of passive safety (automatically reactor shut down and cooling without external power during accident) system and sustainability (recycling of spent nuclear fuel) that is one of major criteria to differentiate new generation from conventional NPPs (generation III NPPs). Offshore floating design of Trident can also help to save construction time and cost by cutting expense of purchasing site and foundation work and by modularization.

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ii Fluoride-Salt-Cooled, High-Temperature Reactor (FHR) subsystems definition, Functional requirement definition and Licensing Basis Event (LBE) Identification White Paper, 2013

2.4. Radiation Safety

2.4.1. Tritium Dispersion into the Environment

We expected that the plant is located in the near sea of San Diego where 11 nm (Nautical miles) away from the land. Prospective installation location was indicated in Figure 23. One of strong points our plant has is low radiative materials release level to the public because the reactor is entirely submerged in the sea water. ^3H, however, is hard to shield to release from inside to outside of the plant. Therefore, understanding ^3H movement in the environment is one of major issues in the paper.

The air flow velocity and direction are shown in Figure 24. In the prospective installation location, wind constantly blows from north-west direction with about 5m/s. Surface sea current also moves constantly from west and north-west with around 0.07m/s. Current velocity and direction at prospective installation location (118.2W-116.2W, 32.2N-34.2N) are tabulated in Table 2 and 3. In the previous research, we found about 700 Ci per GW is released from FHR to the air and about 70Ci per GW is released to the sea water.

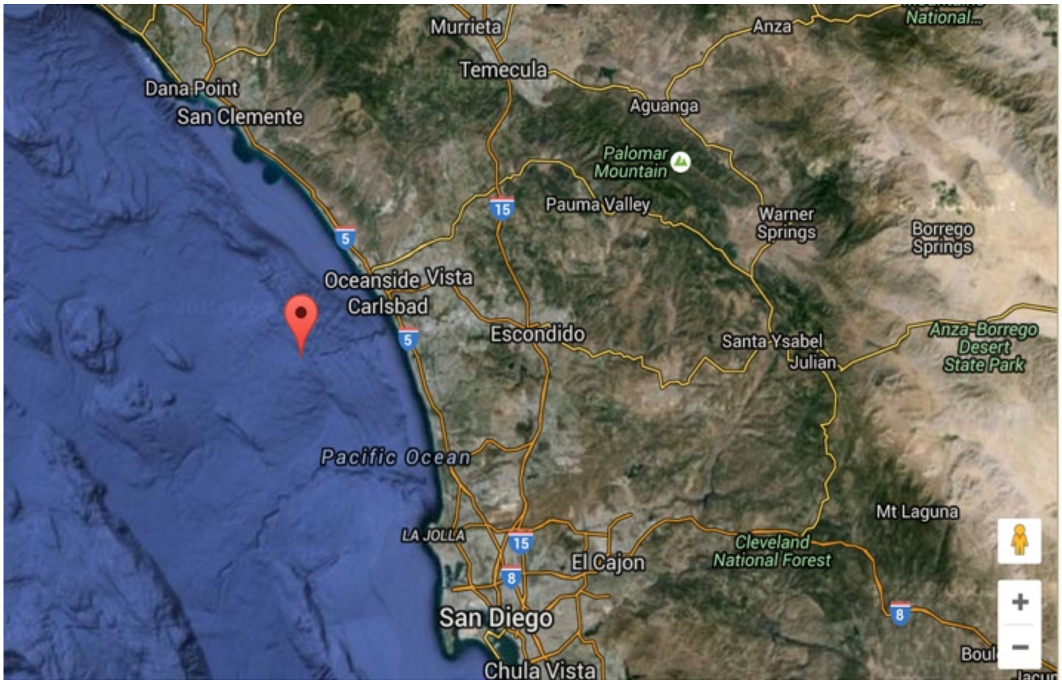

Figure 23. Prospective installation location (Coordination: 118.2W-116.2W, 32.2N-34.2N)

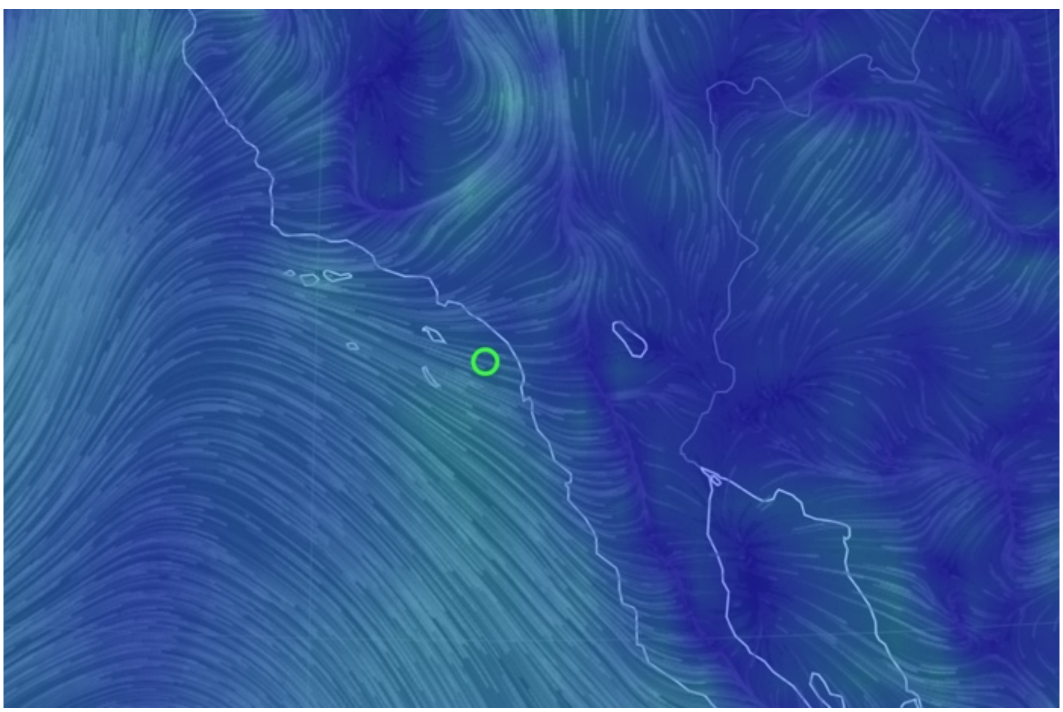

Figure 24. Wind flow direction at the prospective installation location (Coordination: 118.2W-116.2W, 32.2N-34.2N)

Table 2. Ocean surface current speed data (118.2W-116.2W, 32.2N-34.2N)

DATE	MEAN SPEED (M/S)	MEDIAN SPEED (M/S)
11/01/2014	0.0699000	0.0826000
11/06/2014	0.0685000	0.0846000
11/11/2014	0.0796000	0.0865000
11/16/2014	0.0924000	0.0955000
11/21/2014	0.0792000	0.0744000
11/26/2014	0.0644000	0.0592000
12/01/2014	0.0636000	0.0669000
12/06/2014	0.0548000	0.0475000
12/11/2014	0.0319000	0.0196000
12/16/2014	0.0464000	0.0555000
12/21/2014	0.0665000	0.0652000
12/26/2014	0.0716000	0.0780000
01/01/2015	0.0332000	0.0390000
01/06/2015	0.0469000	0.0463000

Table 3. Ocean surface current direction data (118.2W-116.2W, 32.2N-34.2N)

DATE	MEAN DIRECTION	MEDIAN DIRECTION
11/01/2014	6.70000	7.01000
11/06/2014	7.43000	7.01000
11/11/2014	7.34000	7.01000
11/16/2014	7.39000	7.01000
11/21/2014	7.22000	7.01000
11/26/2014	7.51000	8.01000
12/01/2014	7.15000	7.01000
12/06/2014	7.79000	8.01000
12/11/2014	7.76000	8.01000
12/16/2014	7.51000	15.0000
12/21/2014	10.4000	15.0000
12/26/2014	6.39000	6.01000
01/01/2015	6.23000	6.01000
01/06/2015	6.11000	6.01000

2.4.2. Tritium Dispersion through the Air

We used Gaussian atmospheric dispersion model to predict how ^{3}H moves through the air. We assumed that wind constantly blow with same speed from north-west direction. Gaussian atmospheric dispersion model is described in the equation 4.1. Gaussian model is a basic for the simulating and predicting ^{3}H dispersion at the initial stage. Simulated ^{3}H dispersion model in the air was shown in Figure 25.

$$C = \frac{Q}{u} \cdot \frac{f}{\sigma_y \sqrt{2\pi}} \cdot \frac{g_1 + g_2 + g_3}{\sigma_z \sqrt{2\pi}} \quad \text{Eq. 2.1}$$

[iii], [23]

$$f = e^{-\frac{y^2}{2\sigma_y^2}}$$

$$g_1 = e^{-\frac{(z-H)^2}{2\sigma_z^2}}$$

$$g_2 = e^{-\frac{(z+H)^2}{2\sigma_z^2}}$$

$$g_3 = \sum_{m=1}^{\infty} e^{-\frac{(z-H-2mL)^2}{2\sigma_z^2}} + e^{-\frac{(z+H+2mL)^2}{2\sigma_z^2}} + e^{-\frac{(z+H-2mL)^2}{2\sigma_z^2}} + e^{-\frac{(z-H+2mL)^2}{2\sigma_z^2}}$$

C is ^{3}H concentration of emissions, Q is a source pollutant emission rate, u is the horizontal wind velocity, f is a crosswind dispersion parameter, g_1 is a vertical dispersion with no reflections, g_2 is a vertical dispersion for reflection from the ground, g_3 is a vertical dispersion for reflection from an inversion aloft, σ_y is a horizontal standard deviation of the emission distribution, σ_z is vertical standard deviation of the emission distribution, H is a height of emission plume centerline above ground level and L is a height from ground level to bottom of the inversion aloft. For the infinite sum of four terms in g_3, because it converges to a final value rapidly, we used 1,2 and 3 for m values for the estimation.

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iii P. Aarne Vesilind, J. Jeffrey Peirce and Ruth F. Weiner. 1994. Environmental Engineering. Butterworth Heinemann. 3rd ed.

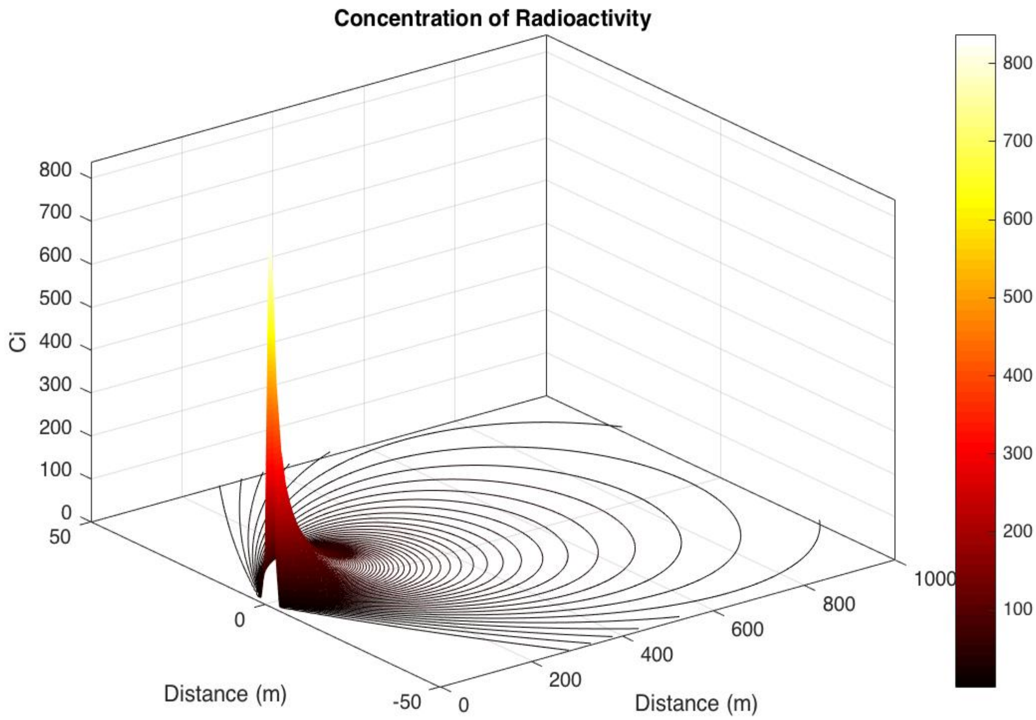

Figure 25. Tritium concentration dispersion model as a function of distance through the air (3D)

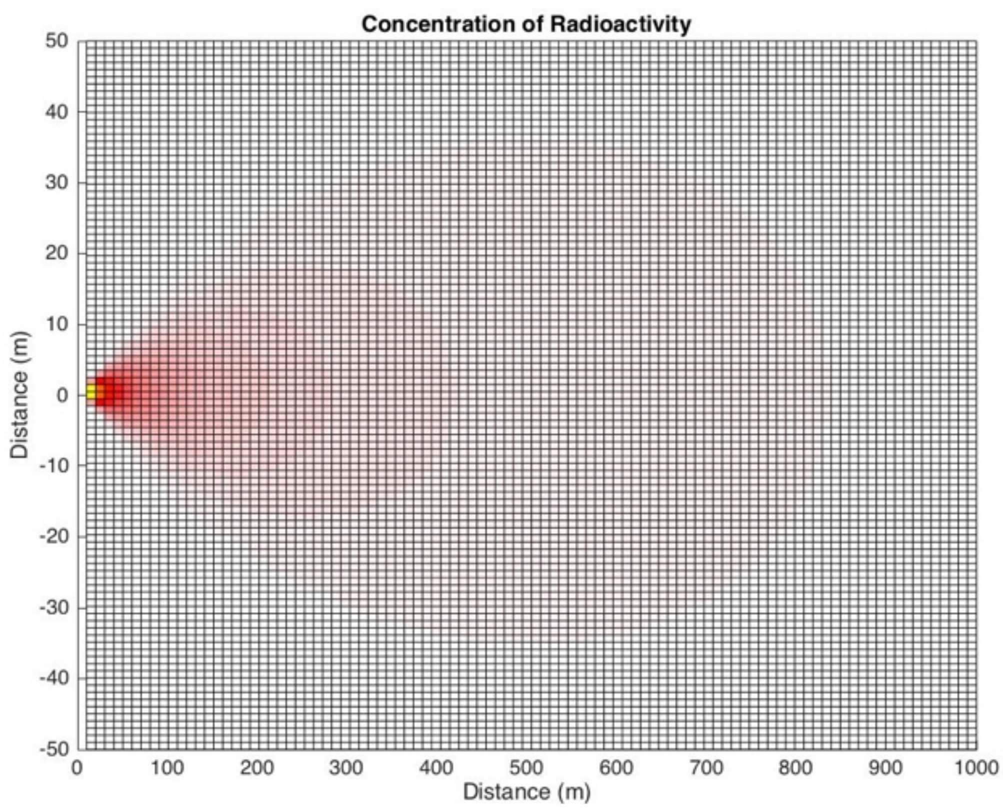

Figure 26. Tritium concentration dispersion model as a function of distance through the air (2D)

2.4.3. Tritium Dispersion through the Sea

^3H are produced not only from the reactor but also from the spent nuclear fuel storage and they are inevitably released into the sea and dispersed according to the current. In order to simulate ^3H movement in the sea water, we used the equation 4.2. M_0 and λ are a nuclide mass and decay constant it is the time and space dependent concentration distribution.

$$C(x,t) = \frac{M_0}{WH\sqrt{4\pi K_L t}} exp\left[-\frac{(x-Ut)^2}{4K_L t} - \lambda t\right] \qquad \text{Eq. 4.2}$$

$C(x,t)$ is ^3H concentration in the location x and time t. W, H and U are a width, height and flow velocity respectively. K_L is a longitudinal dispersion coefficient. ^3H concentration change in the sea water with regard to the time and distance from the platform was shown in Figure 27. According to the water dispersion model simulation, ^3H disappear rapidly by flowing with sea current and interacting with water. Therefore, the radiation level from ^3H is dropped to the safety level in an hour and within 100m.

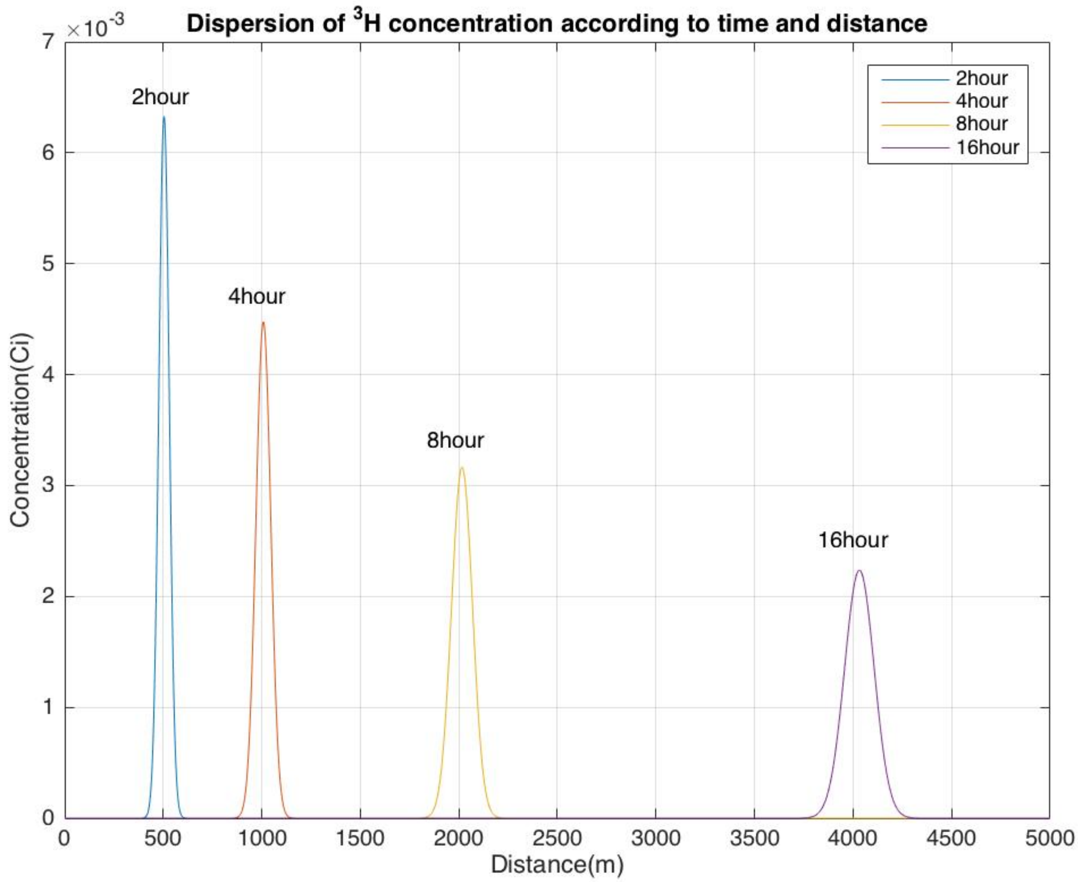

Figure 27. ^3H concentration change in the sea water with regard to the time and distance from the platform

2.5. Conclusion

According to equation 4.1, which describes the dispersion of tritium in the air. Gaseous tritium levels disperse and dilute to safe environmental levels of radiation once it moves around 200 meters away from the platform given a variable winds of up to .0955 m/s. Similarly, the dilution of aqueous tritium form the platform dilutes to background levels at roughly 10 meters. Therefore, we can minimize the radiation exposure to the public by installing Trident 11 nautical miles away from the coastline.

Chapter 3 Reverse Osmosis Economics

3.1. Project Definition

Terrestrial desalination is based around the methodology of creating the most potable water for the least cost. However, marine based desalination is accompanied with an additional challenge given the dimensional constraints of the marine structure the desalination plant is built on. Given this constraint, designing and adapting a desalination plant to synergistically couple with a nuclear power plant is a key component of the Trident system.

In order to evaluate a best-fit desalination system for Trident, a dimensional analysis must identify the available space and apply the desalination methodology.

In this way, a marine based desalination system should be chosen if it displays relative simplicity and a max production of water given the additional dimensional restrictions.

Finally, an analysis of the economic model for the desalination system coupled with a NPP will be evaluated. Identifying the total cost of adding and subsequently coupling the two systems, as well as identifying the total cost of producing potable water form multiple scenarios of power plant construction cost. Analyzing these factors will help identify the increased economic viability both systems can achieve.

3.2. Trident SWRO Model

Trident's desalination model requires the identification of the profitability for both electricity and water production. As multiple studies have suggested that coupling desalination to Nuclear Power Plants (NPP) improves economic performance for both nuclear and desalination plants[24,25,26,27,28], distinguishing these possible gains is high priority. In order to identify a best-fit economic model, factors for the salt water reverse osmosis (SWRO) dimensions and water production need to be evaluated.

3.3. SWRO Dimensions

The main challenge for coupling a desalination plant with an OFNPP comes in the form of its size constraints. In order to evaluate Trident's SWRO system, a dimensional analysis is applied to the first level of the top deck (Figure 28-29). With the structural design supplied by Chapter 1, a best-fit SWRO plant can be integrated into the proposed available space. Figure 28 demonstrates the positioning for two possible 25 MGD plants (red and blue boxes). Each box allows for a maximum square footage of 25,200 ft^2 for the SWRO plants (as seen in Figures 28-29).

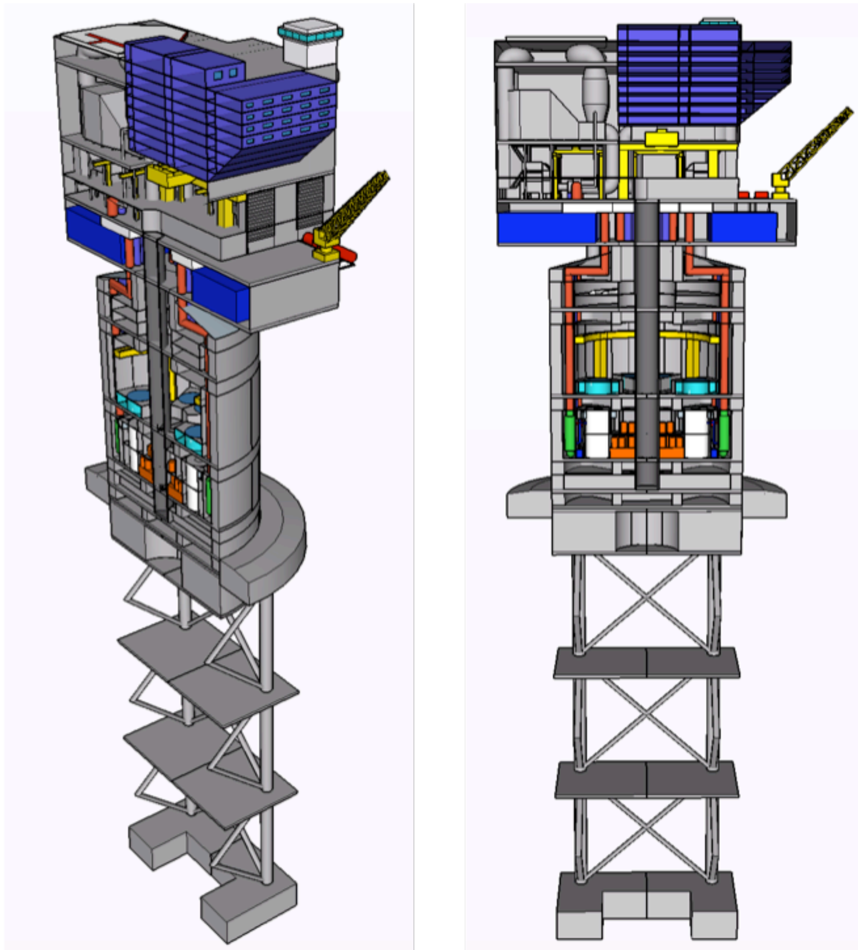

Figure 28. Cross-Section of Purposed Spar Design.

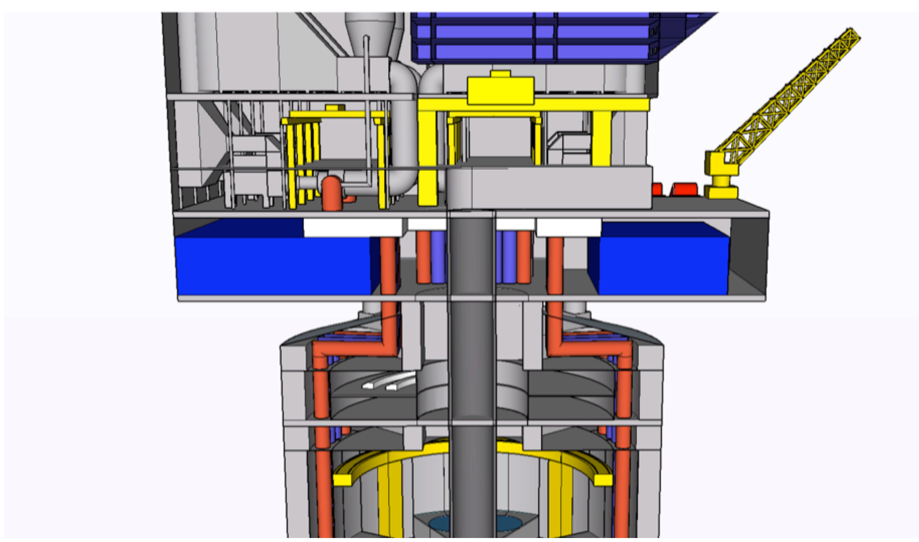

Figure 29. Desalination Deck.

This allows for up to two 25MGD RO plants with a total capacity of ~190,000 cubic meters per day (m^3/d). For continuity, we will be focusing on the current design as seen in Figures 28-29. Table 4 depicts the plant sizes implementing different RO membrane trains utilizing diameter sizes of 8", 12", and 16". Table 5 depicts the maximum capacities deployable for Tridents SWRO and NPP.

Table 4. Saltwater Reverse Osmosis Module Dimensional Analysis.

SWRO Dimensions	8-inch Diameter Elements	16-inch Diameter Elements	20-inch Diameter Elements
Train capacity, MGD	4.17	8.33	12.5
Number of Pressure Vessels	179	90	86
Train Size (WxLxH), ft	29x27x20	44.5x28x21.5	50.5x29x23.5
Height - Top Vessel Row, ft	16.5	17.5	19.5
Train Area (Footprint), ft^2	783	1,246	1,465
25 MGD Plant			
RO facility, 1,000 ft^2	25.1	25.3	23.9
% of 8" dia. area	100	101	95
1,000 ft2 area/mgd	1	1.01	0.96

Table 5. Saltwater Reverse Osmosis and Nuclear Power Plant Max Capacities.

SWRO Plant Capacity			Power Plant Capacity (Combined Cycle – Nuclear)		
Total Capacity	190000	m3/d	Reference thermal output	1888	MW(th)
Feed Salinity	35000	ppm	Reference electricity output + HRSG	1038.4	MW(e)
Combined Availability	0.81		Site Specific Electricity Production	7028.74	GWh/yr
Water Production	62.42	M m3/yr	Availability	0.9	
Power Used for desalination	26.5	MW(e)			

3.4. SWRO Coupling

A typical SWRO plant consumes 4 to 7 (kWh/m^3) of water. A plant's efficiency depends on several environmental factors, including - water salinity, temperature, and plant design, which, incorporates factors for permeate quality, plant configuration, recovery ratio, and energy recovery[29] (Table 6). When a desalination plant is integrated with or coupled to a NPP, the economic model can increase 20-50%[30]. In this way, electrical consumption costs are mitigated, creating improved production performance, lower water production costs, and lower power-to-production ratios[31].

The SWRO system utilized within Trident is defined as a preheat configuration[iv], which utilizes thermal waste produced from the Mk1 PB-FHR thermal process (figure 30). Given that the generation of electricity is an inefficient process, where roughly half of the thermal power produced is lost as waste heat, the SWRO preheat configuration utilizes this discharged waste heat via the Mk1 PB-FHR's condenser cooling system for the steam turbines that condense steam produced in the Heat Recovery Steam Generators (HRSGs). This use of waste heat to preheat the seawater, reduces its viscosity and greatly increases efficiency in the SWRO desalination process. Figure 30 illustrates schematically how the systems intake of feed-water is "preheated" within the nuclear condenser via the heat exchanger.

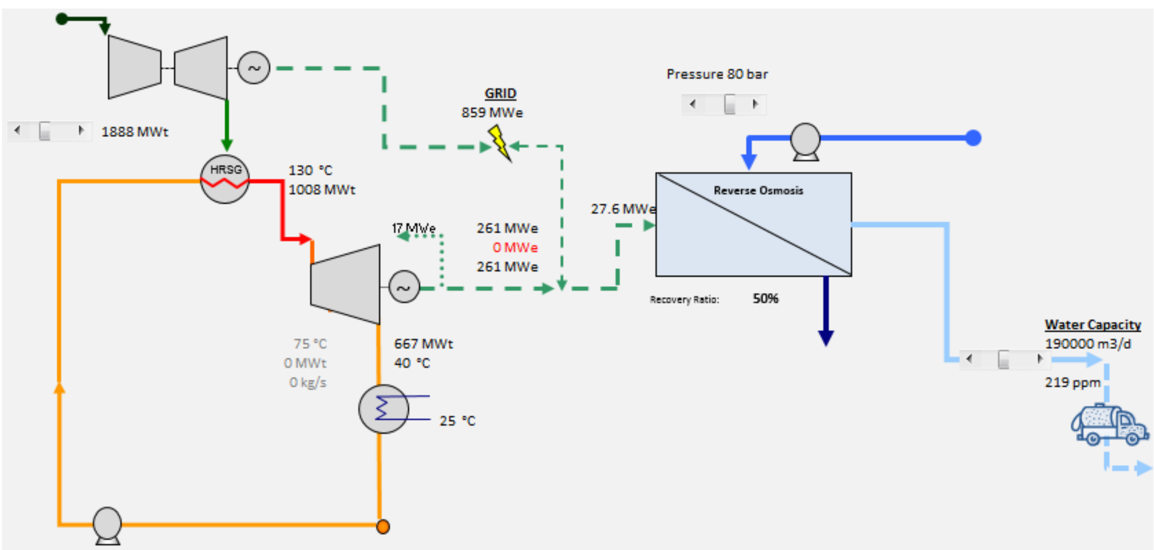

Figure 30. Desalination Schematic

[iv] Use of waste heat from a HRSG to rise of water temperature causes rise to its viscosity, which facilitates its permeability through the membrane. This allows a RO system to have a high capacity factor and is expressed via an Arrhenius style equation of temperature correction factor. DEEP 5 User Manual. (2013).

Table 6. Saltwater Reverse Osmosis Input Parameters

RO Technical parameters					
Maximum design pressure of the membrane (bar)	67.0	Specific gravity of seawater feed correction factor	1.02	High head pump efficiency	85%
Constant used for recovery ratio calculation	0.0	Specific gravity of concentrate correction factor	1.04	Hydraulic pump hydraulic coupling efficiency	97%
Design average permeate flux (l/m^2*h)	13.6	Pressure drop across the system (bar)	2	Seawater pump efficiency	85%
Nominal permeate flux (l/m^2*h)	27.8	Permeate pressure losses (bar)	1	Booster pump efficiency	85%
Polyamide membrane permeability constant	3500.0	Pump suction pressure(bar)	1	Energy recovery efficiency	95%
Nominal net driving pressure (bar)	28.2	Concentrate discharge pressure (bar)	0.5	Other specific power use (kWh/m^3)	0.4
Fouling factor	0.8	Seawater pump head (bar)	1.7		
Aggregation of individual ions correction factor	1.1	Booster pump head (bar)	3.3		

3.5. SWRO Economic Evaluations

In order to model Trident's desalination plant, the initial costs and capital associated with the plant are provided using the International Atomic Energy Association's (IAEA) Desalination Economic Evaluation Program (DEEP), an algorithm based spreadsheet program that calculates the cost to produce water and power used in coupled plants. DEEP provides levelized water and power costs, component cost breakdowns, energy consumption, and net saleable power for the specific plant being modeled. "This is the most common procedure used in the water desalination literature for reporting capital and operating costs of desalination plants"[32]. Further, "the overall gross investments in large seawater desalination plants are in the range of $1000 per unit capacity of (m^3/d) and roughly 50% to 200% more for nuclear power plants[33]." Thus, Trident's ability to accommodate a 100,000 (m^3/d) to 200,000 (m^3/d) SWRO plant will increase the cost of the Trident system anywhere from 200 to 800 million dollars.

3.6. Model

Our aim is to investigate the impacts of standardizing construction costs for a two-year lead-time via implementation of modularized shipyard construction. We modeled four scenarios for potential economic profiles that may be achieved with modularization and standardized shipyard construction for the Trident OFNPP-CDW system. The four scenarios address possible overnight cost and how these costs affect the OFNPP SWRO plant as a function of dollars per kWh ($/kWh). The model follows the DEEP Over Night Cost (ONC) of construction equations, which give an idealized estimate of similar sized 800 MWe NNP. We rely on this model as the proprietary nature of nuclear construction makes the ONC for current NPPs extremely difficult to derive.

Our model on how construction costs for fixed lead-times influence the total water cost of the OFNPP SWRO plant applies fixed variables in the NPP construction process. "Overnight costs are used instead of the actual construction costs for two reasons. First, financing costs depend not only on lead-time but also on the financial structure of the projects, including interest rates, debt–equity ratio and potential rules regarding capital costs recovery"[34]. Second, by fixing these variables, we create continuity between the study, which removes differences between various financial structures and regulations seen in utilities. Further, by fixing financing costs, we can prevent the role in which lead-time drastically changes the ONC for NPPs.

3.7. Data

Table 7. Overnight EPC Cost and SWRO Capitol & Operating Cost.

Power Plant Overnight EPC costs	Total SWRO capitol & Operating cost ($/m^3)	Levelized Capital Costs ($/m^3)	Base plant overnight EPC ($/m^3)	Other ($/m^3)	Levelized operating costs ($/m^3)	Electricity ($/m^3)	O&M ($/m^3)
Scenario 1 4000$/kW	.69	**0.25**	0.21	0.04	**0.44**	0.23	0.20
Scenario 2 3000$/kW	.65	**0.25**	0.21	0.04	**0.40**	0.20	0.20
Scenario 3 2000$/kW	.62	**0.25**	0.21	0.04	**0.37**	0.16	0.20
Scenario 4 1000$/kW	.58	**0.25**	0.21	0.04	**0.33**	0.13	0.20

The main susceptibility of any desalination economic model is due, in practice, to the amount of energy required for the process. Table 7 depicts the change in energy price afforded to the SWRO plant by changing Tridents power plant overnight EPC costs. This yields a total cost to produce water of 0.69 ($/m^3), 0.65($/m^3), 0.62($/m^3), and 0.58 ($/m^3) respectively. A percent decrease of 9%, 17%, and 25% can is observed with respect to scenarios 2, 3, and 4 versus scenario 1 ONC of the NPP. Figures 31 and 32 compares the economic profile change for the 4000($/kwh) and 1000($/kwh) scenarios respectively.

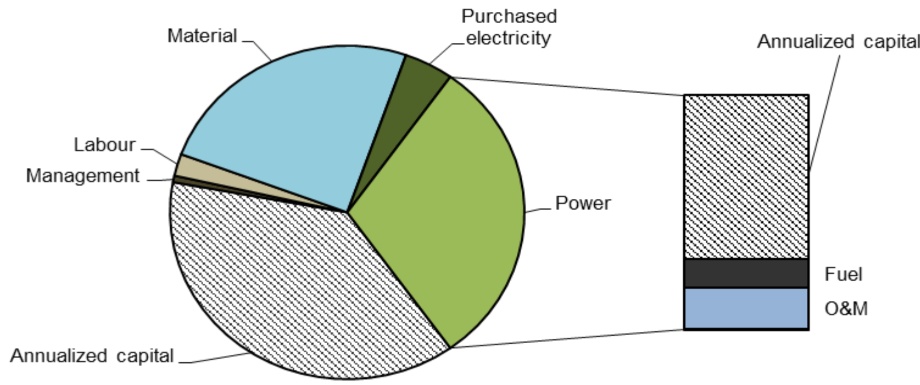

Figure 31. 4000($/kwh) Over night Desalination Cost Breakdown

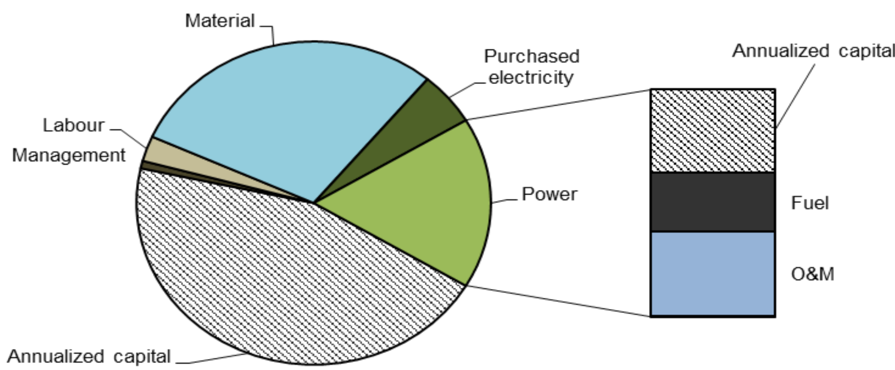

Figure 32. 1000($/kwh) Overnight Desalination Cost Breakdown

3.8. Nuclear Electricity and Water Evaluation

This section identifies the economics of the individual electricity and water production and usage for San Diego County, California. Similarly, in order to understand the logistical and economic benefits of producing energy and water via Offshore Platform, identifying current costs for both utilities will assist in ascertaining the enhanced economic value of an OFNPP coupled desalination plant to San Diego County.

3.9. California Energy and Water Use

The state of California generated 198,973 (GWh/y) of electricity in 2014 and consumed 52 billion (m^3/y) of water. Given the large geographic and demographic differences between the northern and southern parts of the state, California must distribute large percentages of its available water to the densely populated southern portions. Moving large volumes of water over large distances with significant elevation changes is extremely energy intensive. Water agencies accounted for 7 percent of California's total energy consumption[35]. For example, the State Water Project (SWP) is the largest single user of energy in California. SWP consumes an average of 5 billion (kWh/y), which accounts for 2 to 3 percent of all electricity consumed in California[36]. San Diego County individually consumed 19,908 (GWh/y) of electricity and 3.89 billion (m^3/y) of water. Roughly 85% of the water consumed was imported requiring 1.64 (kWh/m^3) of electricity or 5.5 (GWh/y). Identifying the economics of local co-generation and water desalination versus purchasing and importing water for San Diego County is a primary element.

The San Diego County Water Authority (SDCWA) purchases and imports wholesale water for 1,439 ($/AF) or 1.16 ($/m^3)[37]. Comparing this to scenario 1 through 4, the Trident SWRO model can produce water at a highly competitive rate in all scenarios (Table 7).

3.10. Trident Production Economics

Given that electricity prices fluctuate with demand, the wholesale price of electricity can change dramatically over a 24-hour period. These price fluctuations could cause the unit sales price for electricity versus water to change in favor of electricity. Thus, identifying possible water wholesale prices and electric unit prices for Trident is crucial.

According to Energy Information Association (EIA), the weighted average, wholesale cost of electricity for the southern California SP-15 electricity hub, in 2014, was 34.53 \$/MWh. The cost to produce a kW using current nuclear reactors is 0.022 (\$/kWh) or 22.00 (\$/MWh)[2]. Trident's modeled SWRO system has a power to water ratio of 17 MW/MGD, thus a 50 MGD plant will have a daily capacity of 850 MW. This translates to 4.3 kWh/m^3 or 233 (m^3/MWh) water produced. Figure 33 illustrates the wholesale price change for the SP-15 hub for 2014. Table 8 shows the compared values for scenarios 1-4 for the water versus electricity per MW.

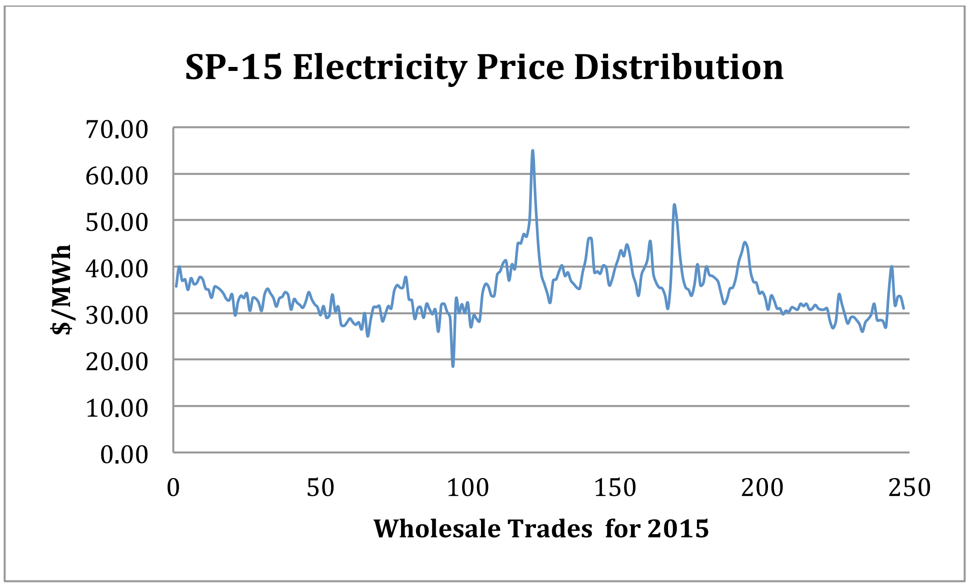

Figure 33. Southern California Whole Sale Price per Trade for 2015.

Table 8. Water versus Electricity (\$/MWh)

SWRO	Scenario 1	Scenario 2	Scenario 3	Scenario 4
\$/MW (water sales price)	\$106.54	\$115.48	\$122.19	\$131.13
NUCLEAR POWER PLANT	Average wholesale price	Low Demand	High Demand	
\$/MW (wholesale electricity price)	\$34.53	\$18.50	\$65.00	

3.11. Summary

While there are no commercial floating nuclear reactors, the coupling of a Salt Water Reverse Osmosis desalination plant is shown to improve the overall economic model of any OFNPP style system for regions where water scarcity exists, such as San Diego, California. And as the use of desalination plants will most certainly rise with increasing population and water shortage, Trident's design will prove immediately viable. The Trident system has the unique ability to couple the modular Mk1 PB-FHR, SWRO plant and offshore platform design to be portable and reach a much greater market. With the enhanced safety and flexibility of the Trident OFNPP design, this analysis demonstrates the ease and effectiveness of coupling a SWRO.

Engineering Leadership

Chapter 4 Engineering Leadership

4.1. Industry Technology Strategy

Traditionally, the electricity generation industry operated within a highly regulated market, where the standard model stipulated that investors, municipalities, and federally owned utilities received the rights to exclusively generate, operate, and distribute the retail wholesale of electricity. These utilities were vertically integrated into all residential, commercial, and industrial aspects, creating monopolies that set rates according to cost-of-service regulations[38,v].

4.2. Energy Industry Deregulation

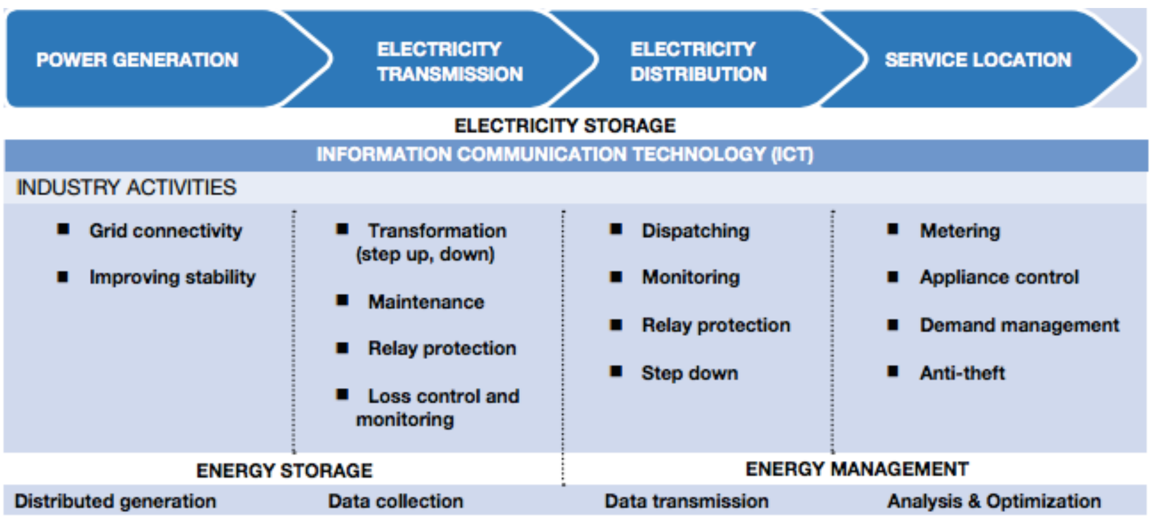

Figure 34. Energy Value Chain

In response to the limitations under cost-of-service, California, among others, deregulated its electrical markets. This separated electrical generation from transmission and distribution, disconnecting energy production from the main value chain (Figure 34). When applying a value chain analysis, deregulation created a single point of entrance; given this feature, any innovation[vi] in energy production could have a significant, disruptive impact on the industry.

The industry is a prime target for any forward integrating energy technology, as energy demand benefits from stable energy production correlating with a stable return on investment. Nuclear energy, with low marginal costs, is identified as a base load

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[v] Under cost-of service regulation, rates are set to allow utilities to recover their recurring operating expenses as well as earn a rate of return on all capital investments in generating equipment as long as that equipment is "used and useful" (F.P.C. vs. Hope Natural Gas Co., 320 U.S. 591, 1944). This creates little incentive for companies to operate their plants efficiently, including their nuclear reactors, because they receive this compensation regardless of the level of performance .

[vi] Energy innovations in the simplest form, are described as sources of energy production that can produce equal amounts of energy at a lower cost ($/KWh).

technology; meaning production is not limited during periods of low demand. This allows the energy to be sold at constant prices unaffected by supply and demand[39].

The energy sector is perhaps the most regulated segment in the US economy, with nuclear energy being regulated further. Regulations come in the form of - price, service quality, safety, reliability, efficiency standards, entry and exit of suppliers, environmental emission impacts, and DOD security. Combining these factors into a five forces model, a competitive landscape can be identified.

Government regulations are the largest barrier for new entrants to overcome. These regulatory barriers manifest in the form of huge upfront capital investments[vii] (Figure 35).

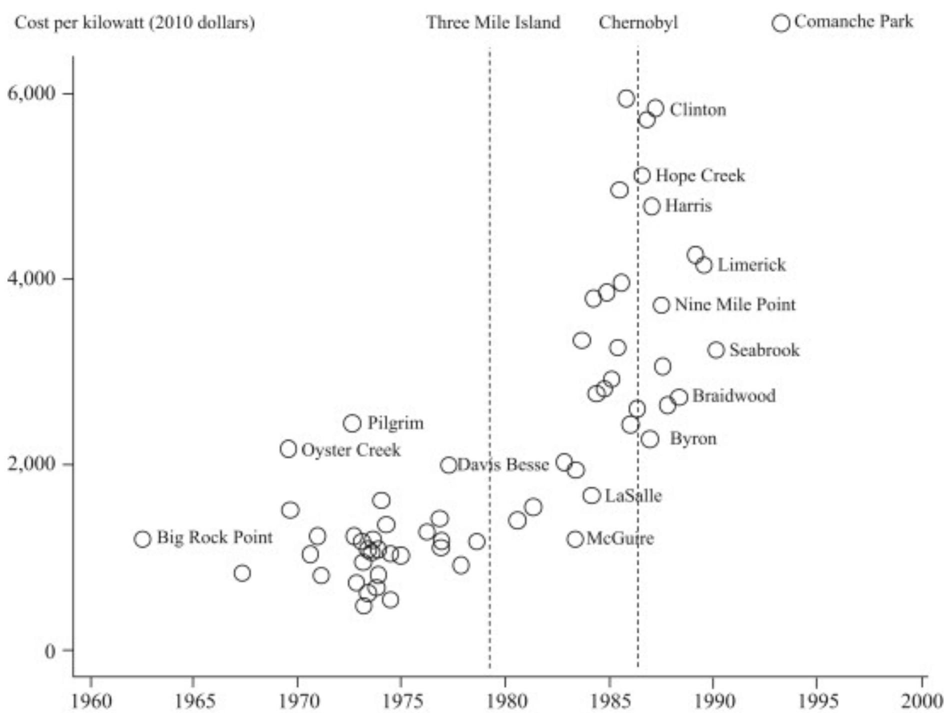

Figure 35. Price increases due to regulatory and safety design implementation after TMI and Chernobyl Accidents[40]

In deregulated electricity markets, buyers have the option to pick a preferred energy source. In general, wholesale bulk energy lots are purchased at the lowest price per kilowatt hour ($/kwh) from energy producers by utilities and then resold to end-users. The base load characteristics of nuclear establishes it as a constant preferred energy source.

Substitutes are defined as base load energy suppliers that can produce large scale

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[vii] "Frequent revisions of quality and safety regulations and backfit requirements – regulatory turbulence – had an even greater impact on construction times and operation patterns. Regulatory turbulence and unpredictability affected in particular the completion time of plants that were in the construction phase. In some cases, to comply with changing regulatory requirements, major components of nuclear construction projects had to be reworked and equipment, piping and cables that were already placed had to be re-engineered and repositioned" [23].

energy at lower $/kwh. Currently, the only base load technologies are oil, gas, and coal. However, the competitiveness of these energy sources are fuel dependent. Fuel price fluctuations destabilize economic profiles and are common with all energy sources except for nuclear[41].

With energy deregulation, nuclear energy producers consolidated into three main entities. These entities now control a third of the nuclear power capacity in the U.S., contributing to a non-existent rivalry. As such, base load whole sale prices are constrained geographically by boundaries between utilities and the deregulated markets.

4.3. Water Industry Opportunity

The San Diego Water Authority (CWA) and distribution market is primed for entry. Currently, San Diego must import the majority of its water to service its local population from the Metropolitan Water District of Southern California (MWD). The process of acquiring potable water is expensive and highly regulated, as water must meet both state and federal regulations for quality and safety.

To meet its water demands, San Diego is in the process of diversifying their water supply portfolio, with 24 retail water agencies currently selling potable water, the supply remains inadequate for the rising population and demand. Desalinated water from Trident will be a much needed addition to the water supply.

State and federal water regulations are low, thus the barriers to enter the market are low. While there are other retail suppliers, the nuclear plant is capable of producing significantly more water than other local municipalities.

As San Diego imports 80% of its water and serves 951,000 users, the buying power of San Diego is extensive. As MWD's water prices increase yearly, the city is in need of a water producer that can supply large quantities of water at stable prices. The nuclear reactor differentiates its water production profile from the other retailers as production costs will remain low and stable, thus limiting substitution[42].

California faces continuous struggle with its critical infrastructure challenges and energy supply (Figure 36). The highest point of stress the state must address is its water-energy relationship. "California's water-related energy use consumes 19 percent of the state's electricity, 30 percent of its natural gas, and 88 billion gallons of diesel fuel every year and this demand is growing"[43]. As population increases, the demand for water and energy linearly correlates in the respected geographical areas. As parts of the state grow rapidly, water and electricity demand stress the local infrastructure to failure resulting in a state wide program to develop new water supplies[43].

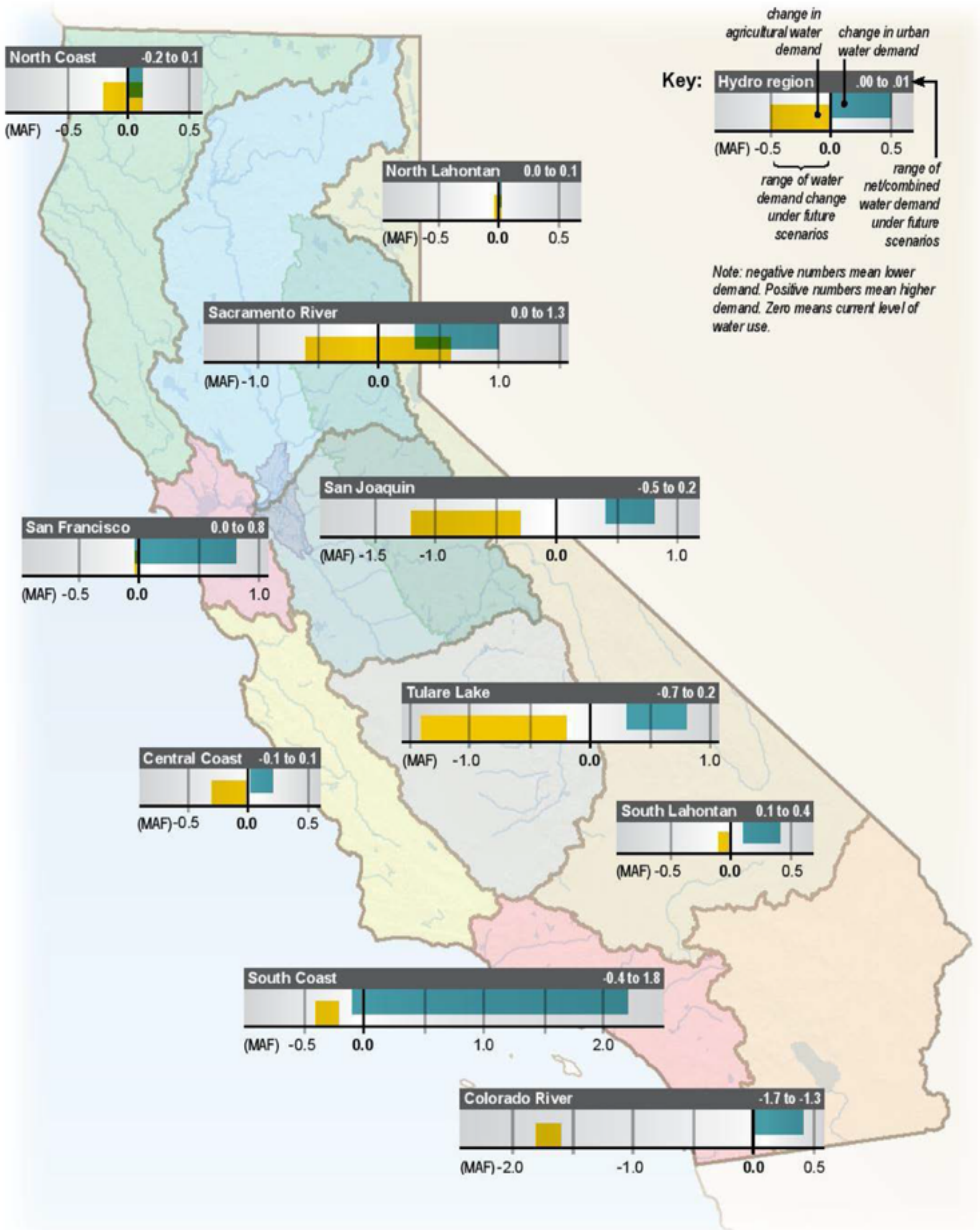

Figure 36. Change in regional water demand from 2006 to 2050 (million acre-feet/year)[44]

4.4. Energy & Water Technology Strategy

The technology strategy for Trident is to target California's geographical stressed resources. Unfortunately, the public's wariness of nuclear power complicates implementation. Positive publicity must be increased in order to garner support and identify Trident as a preferred source for increased government action to help utilities to secure the required funding. Trident must clearly communicate its value in order to change consumer perceptions.

As the energy sector continues to grow, emission regulations require power production to be greener, cleaner, and more efficient. And as utility demands rise so do the potential profits of these power plants. Further, the profitability of the desalination plant is directly proportional to the energy required for desalination. Unlike other desalination plants, the nuclear reactor platform is capable of producing potable water at significantly lower prices.

Energy production is a large and varied market, from solar to natural gas. While these technologies offer energy production, they fail to provide the secondary utility – potable water. A nuclear desalination plant is capable of covering not just the energy demands of a region, but the water demands as well. Trident offers a solution to two major problems facing not just California but large portions of the world.

Perhaps the most ingenious design aspect of Trident is the ability to scale the desalination plant according to a location's specific needs. The platform is capable of being built with one or up to eight MK1 PB-FHR reactors, allowing sites to regulate coverage needs and control costs. Additionally, as Trident is constructed offsite and delivered to the installation area, the construction process is streamlined and standardized for mass production; this allows for reduced construction times, from approximately 5 years to 2 years and potentially reduces construction costs considerably.

4.5. Market Entry Analysis

Marketing strategies for Trident and the process required to succeed in the energy industry were analyzed using a SWOT. Through SWOT, we begin to understand the market and devise a successful market penetration system via the 4Ps strategy.

Trident's strengths come from its significantly increased intrinsic passive safety and security features. Traditionally, nuclear power plants were built near the sea to provide water for coolant, unfortunately, this leaves the plants vulnerable to natural disasters. By applying a floating plant design and FHR technology, Trident will be installed 11km offshore, decreasing the risk of natural disasters. In addition, the Mk1 PB-FHR reactors of Trident offer an increased economic model over existing NPPs as, during high demand hours, the Trident system can switch to natural gas peaking.

And while floating nuclear plant technology has never been commercially operated, studies show the technology shows promise. However, it is the untested and unproven aspect that makes acceptance and production of this technology difficult.

4.6. Conclusion

With increasing demand for energy and water, utilities will be searching for innovation. New nuclear technologies and changing regulations have created the ideal time for new nuclear energy and desalination alike. Compounded by the threat of climate change, the desire and necessity of low carbon emission technologies will grow, boosting the desire for Trident.

Unfortunately, public education will be one of the largest threats for the adaption of Trident. While a NPP and desalination plant fulfills both energy production and desalination, the negative association of nuclear energy with catastrophic events overshadows the true benefits of nuclear. Without understanding the benefits and safety of nuclear power, the community, as a whole, will be largely against nuclear plants.

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