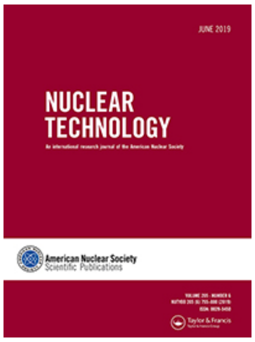


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# Economically Feasible Mobile Nuclear Power Plant for Merchant Ships and Remote Clients

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**Abstract —** *Recent studies point to a reduction of atmospheric pollution using nuclear energy for merchant ships. This work examines the development of an economically competitive nuclear power solution for merchant ship propulsion. The solution also addresses the requirements of a wider market, like islands, offshore oil platforms, and remote cities. System engineering and analysis at various product breakdown levels also propose architectural options to improve competitiveness of nuclear power in mobile nuclear power plants (MNPPs). Analyses include market research on clients and technical considerations on nuclear energy costs. The results show that an enterprise that delivers electric power to remote clients and dedicates to management of all nuclear aspects seems to be the best organizational and technical choice. Besides, ships should be of modular type and the MNPPs should be easily detachable at sea. Only container ships and remote islands demand enough power to justify the use of nuclear power. Nuclear power has high probability to be economically competitive for large container ships, however, only if public policies impose levels of risks akin to other industries.*

**Keywords —** *Nuclear merchant ships, nuclear energy, naval reactors, steam generators, system engineering.*

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

## I. INTRODUCTION

According to Ref. 1, in 2007 shipping worldwide was responsible for 2.7% of $CO_2$, 4% to 9% of $SO_x$, and 15% of $NO_x$ emissions. This fact alone allows the statement that shipping is a major source of air pollution. This fact led to restrictions on the types of maritime fuel oil in some countries, increasing shipping rates and reducing profitability. Along with uncertainties about the reserves of fossil fuels, these regulation changes have generated uncertainties in the shipping market. On the other hand, shipping has enormous impacts on the economy. In 2013, shipping carried about 95% of commerce worldwide.[2]

A feasible option for reducing air pollution is the adoption of nuclear energy for merchant ships. The design may manage the risks of radioactive leakage, and the use of nuclear power may reduce the frequency and gravity of oil spilled at sea, which is a much more frequent accident. From the energy security aspect, nuclear fuel has little price volatility because of long-term supply contracts, and the main suppliers are politically stable and dispersed in the world. Worldwide, by 2013 human kind had accumulated the experience of operating about 700 nuclear plants in ships,[2] mostly in navies.

The operation of nuclear power plants (NPPs) needs expensive competencies, and shore installations under control of nuclear authorities are too expensive for private investors. Finally, the use of nuclear energy finds fierce popular opposition in some countries, which is stronger after accidents like the accident at the Fukushima Daiichi plant that was caused by the 2011 Great East Japan earthquake and resultant tsunami. Such opposition led to the early retirement of nuclear-powered ships like N.S *Otto Hahn* and N.S. *Mutsu*. Even in the

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former Soviet Union where a fleet of nuclear-powered icebreakers has been active for a long time, authorities banned the container ship N.S. *Sevmorput* from ports following the Chernobyl accident.[3]

This work gives some insights on the technical options at many product breakdown levels: nuclear enterprise architectures, mobile nuclear power plant (MNPP) architectures, reactor coolant system (RCS) architectures, and steam generator architectures.

## II. LITERATURE REVIEW

Today nuclear energy is of little use in merchant shipping because of some issues that make its adoption too risky for private investors. One aspect is capital cost, which is much higher in nuclear plants than fossil fuel ones, making it difficult for a nuclear fleet to adapt to a dynamic market. Another problem is the lack of stable legislation,[2] resulting in huge cost increases in the 1970s and 1980s for civilian land NPPs.

In 2005 and 2006, studies from naval reactors (U.S. Navy) led to the conclusion that the global cost of nuclear energy for warships could be competitive (with oil) for high-energy-demand ship classes. Even with popular movements against the use of nuclear energy, currently U.S. nuclear-powered warships can stay in 150 harbors in around 50 different nations.[4]

The lack of stable legislation has made investors afraid of investing in a business where regulations become stricter over time. Further, such strict regulations impose expensive labor, which is a major cost driver in life-cycle costs.[5] On the top of all that, the operation of nuclear plants may ease nuclear weapons proliferation, which creates more safeguards the investor must pay.

On the other hand, the relative stability (obtained by long-term contracts) and the low cost of nuclear fuel reduces considerably the uncertainties of future expenses,[2] reducing the costs with hedging.

In the past, there were four merchant ships that used nuclear power: N.S. *Savannah*, N.S. *Otto Hahn*, N.S. *Mutsu*, and N.S. *Sevmorput*.[6] This work ignores the nuclear icebreakers because they are a specific application too different from typical merchant shipping.

The main issue with these ships (except for N.S. *Sevmorput*) was the lack of identification of requirements, adopting the nuclear option without taking into consideration the economic aspects. For instance, N.S. *Savannah* was built within the Atoms for Peace program as a symbol of good will. It was partly a passenger ship and a general cargo ship in a time when container ships started to dominate the market. Soon the Maritime Administration found that early disposal of the ship would be the best economic option, but from the point of view of technical feasibility the ship was a success.

Another important issue was the public rejection of nuclear power (except for N.S. *Savannah*, which found almost no opposition), which limited the ports that N.S. *Otto Hahn*, N.S. *Mutsu*, and N.S. *Sevmorput* could service.[6]

Driven by the air pollution issue and the volatility of fossil fuel prices, in the past few years there has been renewed interest in the application of nuclear power for merchant ships, with work focusing on possible solutions for solving the main issues.[7,8]

## III. METHODS

This work objective is to find a way to reduce energy costs at remote places and on merchant ships, considering the use of nuclear reactors in MNPPs to this end. The focus of this work is more in specification (problems identification) than in conceptual design (problem solution) aspects. The first step is to list the assumptions for this work.

The first assumption is about organization: nuclear-related activities (reactor production, operation, refueling, maintenance, emergency response, and fuel disposal) need competencies hard to get and expensive to keep. Therefore, the enterprise in charge of the MNPPs shall take care of all nuclear aspects, including licensing, spent fuel storage, and so on.

The second assumption is about the use factor: The achieved availability meets the requirement of 87% in Ref. 9, but during operational life, the average power is around 75% of nominal power, the same standard to calculate the energy efficiency design index.[10]

The third assumption is that the enterprise needs to give energy for merchant ships at a price equal to or inferior to the market prices of current fossil fuels, considering the life-cycle cost. The fourth assumption is the business model for this enterprise: an electric energy provider for remote clients—providing electric energy directly broadens the available market to any islands, isolated cities, and offshore oil platforms while keeping the ships as primary clients with the advance of integrated electric propulsion systems.

Because of the first and fourth assumptions, the enterprise would focus only on the nuclear and electricity generation part, as usual for nuclear vendors, needing little investment from a traditional vendor to enter this market. The enterprise would design, build, run, keep, and refuel MNPPs and could outsource some of those activities. Safety would be manageable as the MNPP may encapsulate all nuclear concerns inside.

This choice employs a technical solution very similar to a choice that Ref. 7 considered but did not choose as the main baseline. As it is like a proven business model, this work assumes that its risk is low. The business model of electric energy supplier is the best choice because it gives energy in a usual format and it has simple interfaces while keeping good safety management. Besides, it needs few competencies beyond nuclear vendors' knowledge, like barge construction, maritime power cabling, and ship movements.

Figure 1 presents a preliminary enterprise block diagram showing its interfaces and its main blocks along its internal functions or roles. This enterprise would have a fleet of MNPPs and some transport ships to deliver MNPPs to clients where they need electric power. Such transport ships deliver the MNPPs to islands, coastal cities, offshore oil platforms, and merchant ships far from the MNPP home port or base. In case of accident, those transport ships give complementary safety resources, if needed. Such ships need to have structural supports compatible with three-point couplings to stabilize mechanically the MNPP during its transportation.

The method that this work adopts is an adaptation of the onion model,[11] which studies architecture, behavior, and system-level requirements at each design level before passing to another level. This means that at each level (merchant ship level, MNPP level, nuclear steam supply system (NSSS) level, RCS level, and steam generator level) this work presents a block diagram like for the initial assumption for the enterprise level.

Such diagrams serve to guide the reasoning and to identify the main functional requirements. Additionally, at each level, this work adds some references about nonfunctional requirements and market considerations. This way, this work contributes more to the identification of problems to be solved than to the technical solutions.

At the end of Sec. IV, this work presents the main characteristics of the proposed MNPP and compares its size with a typical container ship. Such a solution is designed to solve all identified problems to make the use of nuclear energy in merchant shipping and remote places a real possibility.

## IV. RESULTS

In this section, this work identifies requirements and architectures at various levels of the product breakdown structure. The analyzed levels are merchant ship, MNPP, NSSS, RCS, and steam generator.

### IV.A. Merchant Ship–Level Analysis

As stationary clients at remote locations impose few requirements on the MNPPs, this work concentrated on the analysis on merchant ships that have complex behavior and nonfunctional requirements, as well. At any time, collisions may happen to ships, assumed to be about once in 100 years per ship.[12] Therefore, the NPP components need to be able to resist some level of shock to prevent nuclear accidents. This work assumes a value of 10 g in every axis because this shock level is achievable by many suppliers of electronic equipment, which seems to be one of the most fragile parts. With this level, the design achieves a good resistance while needing little extra expense.

It is desirable to have a long period of operation between refueling outages and to match refueling with the ship-planned maintenance periods, which occur each 2.5 years (Ref. 13) giving flexibility and reducing downtime. To reduce downtime due to unplanned maintenance, the architecture must allow detaching the entire MNPP within a few hours. Such a requirement lets another plant replace the faulty one, keeping the overall availability high. Furthermore, the deck officers and crew are employees of the freight company while the MNPP crew belong to the nuclear enterprise. Only the MNPP crew need to have nuclear competencies. The ship

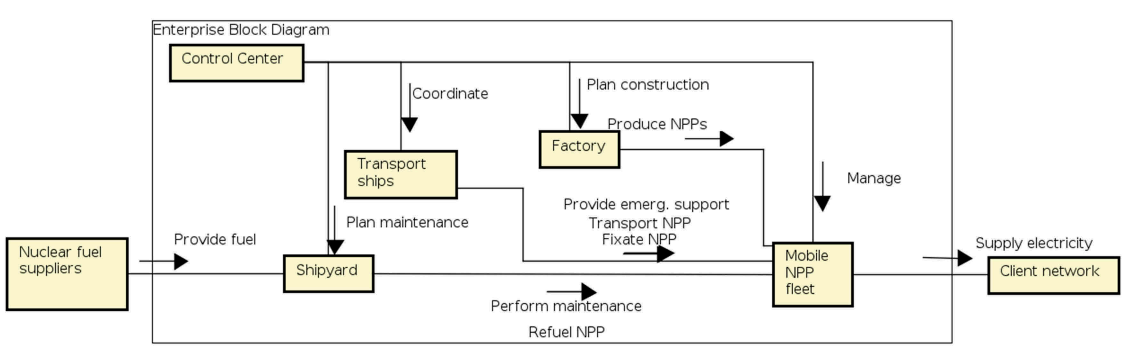


Fig. 1. Enterprise block diagram.

material also does not need to adhere to nuclear standards, as the MNPP is solely responsible for nuclear safety.

At navigating state, the ship demands nominal power to achieve cruising speeds. When approaching a port, the ship reduces speed to reduce collision risks, stopping the propulsion when she reaches the quay. At the quay, this work assumes the ship might need auxiliary power from the MNPP in a value up to 10 MW(electric) in case the electricity sold at that port is too expensive. This work assumes the ship has a block diagram like the one shown in Fig. 2, where the MNPP gives medium voltage for both propulsion and auxiliary loads. The ship hull and structures give a solution for physically attaching the MNPP, which must be compatible with three-point couplings (a sea-proven solution to make fast coupling and decoupling at sea). The ship crew give orders to the MNPP crew through the internal communications system. The orders may be to attach or detach the MNPP. Alternatively, it may be communication of the needed power levels.

There are three main large groups of merchant ships: bulk carriers, tankers, and container ships. Table I presents one class of ship for each type. This work does not choose the largest class of each type because they have few ships, which would restrict the market. For instance, Very Large Crude Carrier (VLCC) class is second in size behind Ultra Large Crude Carrier (ULCC) class and is responsible for 36.7% of total tanker ship deadweight, while ULCC handles just 0.8% (Ref. 14). Besides, according to Ref. 15, the Post Panamax class has 32% of 20-foot equivalent unit (teu) while larger classes have only 1% of teu of all container ships. The cause may be the lack of proper ports and routes, which limits the use of those huge ships that are more competitive at sea. However, recent ordering drives the advance of the New Panamax class, but this work does not count on the success of this trend, choosing the third class in size. The same reasoning goes for choosing the Capesize class (the second class, behind the Very Large Bulk Carrier class in size), which was responsible for 31.7% of deadweight of bulk carriers in 2007 (Ref. 16).

It is important to note that container ships need much more propulsion than other larger classes. The reason is their speed, around 25 knots, while other classes navigate at 14 to 16 knots. Besides, with the use of cooled containers (reefers), they may need high auxiliary loads, in the order of 10 MW(electric).

Because nuclear power needs scale to be competitive, this work proposes the use of nuclear power for container ships only, which are many and demand high power with increasing trend.[15] This work chose the Post Panamax class because it is more numerous than the biggest class, New Panamax. However, this may change in the future, which would make nuclear power still more competitive with nominal powers in the order of 100 MW(electric).

Container ships currently use fuel tanks that are about 9000 $m^3$ (Ref. 17), which means the nuclear solution should not have a volume beyond that to be competitive. High-quality components are more expensive and take more time to build. Even with modern reactor architectures, some components shall need complex, expensive, and lengthy qualification. A solution to overcome such issues is to extend as far as possible the lifetime, which should reach at least 60 years and which is far beyond ship life of 25 years (Ref. 15). Such aspect also calls for modular ship architectures, which allow the nuclear part to detach from an old ship and attach to a new ship.

Beyond operational availability, the capability to detach within 6 h from the ship also allows operation in countries that have banned nuclear energy, as proposed by Ref. 7. Of course, both the MNPP and the ship need to have their own independent crews because each crew works for distinct enterprises. With the use of modern three-point couplings, such fast detachment and reattachment is workable with low technological risks. In case of operation with the need for fast detachment,

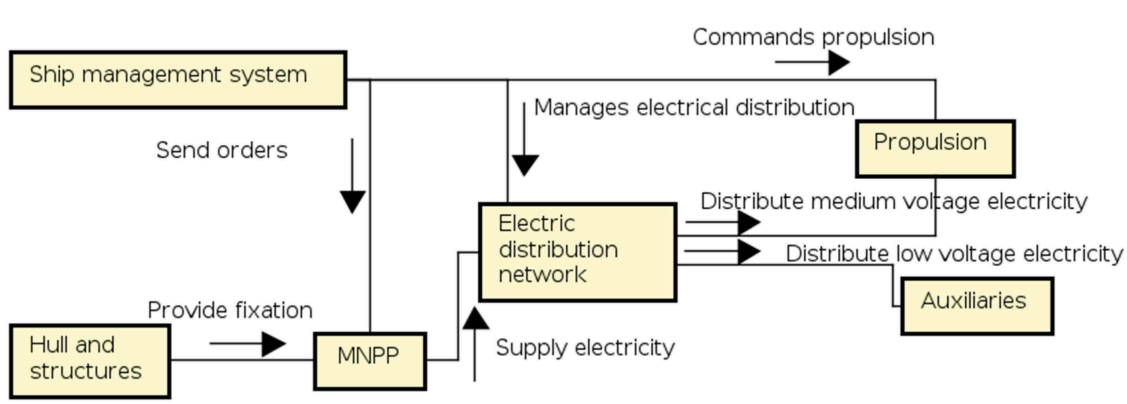


Fig. 2. Ship block diagram.

TABLE I

Comparison of Different Types of Merchant Ships

| Type | Displacement (ton) | Shaft Power (MW) |
|---|---|---|
| Tanker—VLCC (Ref. 14) | 280 000 | 25 |
| Container ship—Post Panamax[15] | 97 000 | 60 |
| Bulk carrier—Capesize[16] | 150 000 | 15 |

the MNPP shall need a retractable propulsion system driving the MNPP to speeds of 5 knots. Such propulsion would help in the coupling operations and allow the MNPP to stay in position (out of territorial sea of the country that has banned nuclear energy) while the ship enters the harbor. After decoupling, the container ship needs tugboats to enter in port and return to the rendezvous point where the MNPP waits. The MNPP propulsion needs to be retractable to reduce drag during normal operation. The failure of such a propulsion system could result in bottoming at shores and loss of cooling, resulting in a major loss-of-coolant accident. Therefore, this propulsion system should be redundant to mitigate such risk.

According to Ref. 10, a merchant ship stays the larger part of its life at open sea, needing 75% of nominal power in 280 out of 365 days per year. This work assumes that three-quarters of the other days (63 days) the ship is at quay, at either maintenance or unloading or reloading its payload. This work also assumes that she may need about 10 MW(electric) of electric energy at quay to drive container loads, for instance, cooled containers (reefers). These assumptions come with the possibility that the port energy could be more expensive (or even unavailable) than that provided by the MNPP. The rest of the time (22 days), she is at low speeds, navigating at channels, entering ports or on very crowded, traffic-intense sea regions, when she demands about 25% of nominal power.

The complete loss of electrical power may have catastrophic effects for a ship or sea environment, yet passive means may assure nuclear safety. Consequently, the frequency of complete electrical failure should be very small, while the design may define the reliability of electrical supply at nominal power following economic goals. A solution to achieve environmental safety goals while keeping the solution competitive is the adoption of graceful degradation (the frequency of total energy supply lost should be smaller than the frequency of not reaching the nominal power). To enlarge the target market, the MNPP should provide energy in a format compatible with international standards, like 13 kV/60 Hz, 11 kV/50 Hz. Prospective clients could be islands, isolated coastal cities, offshore oil platforms, merchant ships, navy ships, and desalinization stations. The generators should be able to give a wide range of voltage and frequency.

In case the ship sinks, the nuclear barriers must stay intact after bottoming, giving solutions to equilibrate internal and external pressures to prevent implosion, like N.S. *Savannah*.[18] From the ecological point of view, it should irradiate at sea noise levels inferior to 110 dB (with respect to 1 μPa at 1-m distance) in all frequencies.

## IV.B. MNPP-Level Analysis

The design must reduce production costs while keeping the safety goals. As MNPPs are smaller than stationary NPPs, serial construction at a factory-controlled environment may ease the quality control tasks and reduce costs for the same quality level. Experience shows that skilled people are a major driver for life-cycle costs.[5] Therefore, the crew must be small, and the plant must compensate for the lack of people with a high level of automation. The MNPP must be autonomous in terms of nuclear safety, and it shall not rely on any resource from the ship for accident scenarios. Such measures allow the ship (or remote client) and its crew to have few nuclear requirements or training.

The hull and structures must give resistance against collisions and shocks, both by keeping water tightness and decoupling fragile equipment from the outer hull with suspended cradles. In addition, the hull must have reinforcements at each one of the three coupling points, making it able to resist loadings caused by ship movement through the lifetime of the MNPP. Additionally, the hull gives the passive part of the nuclear containment system and, in case of accidents, it acts as the ultimate heat sink, transferring the residual heat to the sea water.

The platform systems give all auxiliary functions, like cooling water, air conditioning, and firefighting. To reduce costs, only the NSSS should have nuclear safety–related equipment, relying on passive safety to remove residual heat in the long term. The only exceptions are the hull and structures, which give the nuclear containment function and air conditioning function of the platform systems. Figure 3 presents the proposed block diagram for the MNPP, where the two nonsafety power sources are part of the electric distribution system. The only function of the NSSS is to give steam to the power conversion system (PCS), and it concentrates all nuclear-related equipment.

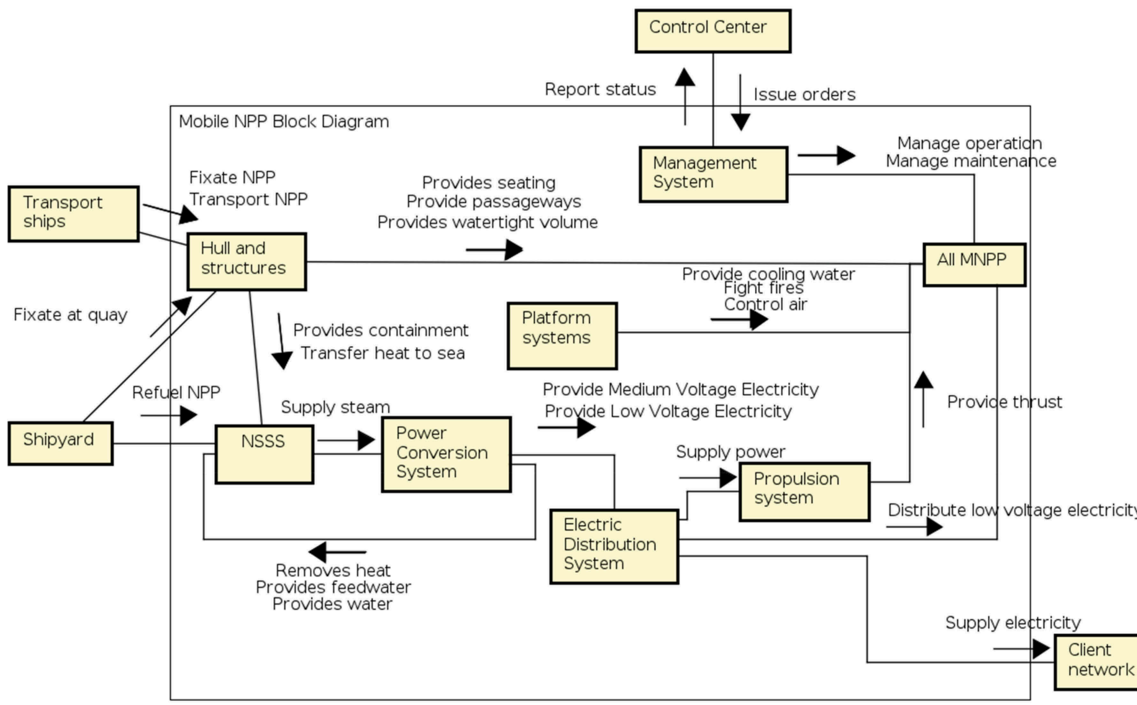


Fig. 3. MNPP block diagram.

Figure 4 presents the proposed arrangement for the MNPP. Note that the quantity of fuel oil to keep the client ship with a safe supply for 14 days is significant.

One of the key aspects is keeping the MNPP equilibrated in terms of center of mass and center of buoyance because the nuclear reactor and turbo generator are heavy.

### IV.C. NSSS-Level Analysis

There are many candidate technologies of nuclear reactors nowadays. This work assumes a pressurized water reactor (PWR) because it is the most successful design up to now due to a good compromise between safety, compactness, weight, and simplicity. Most

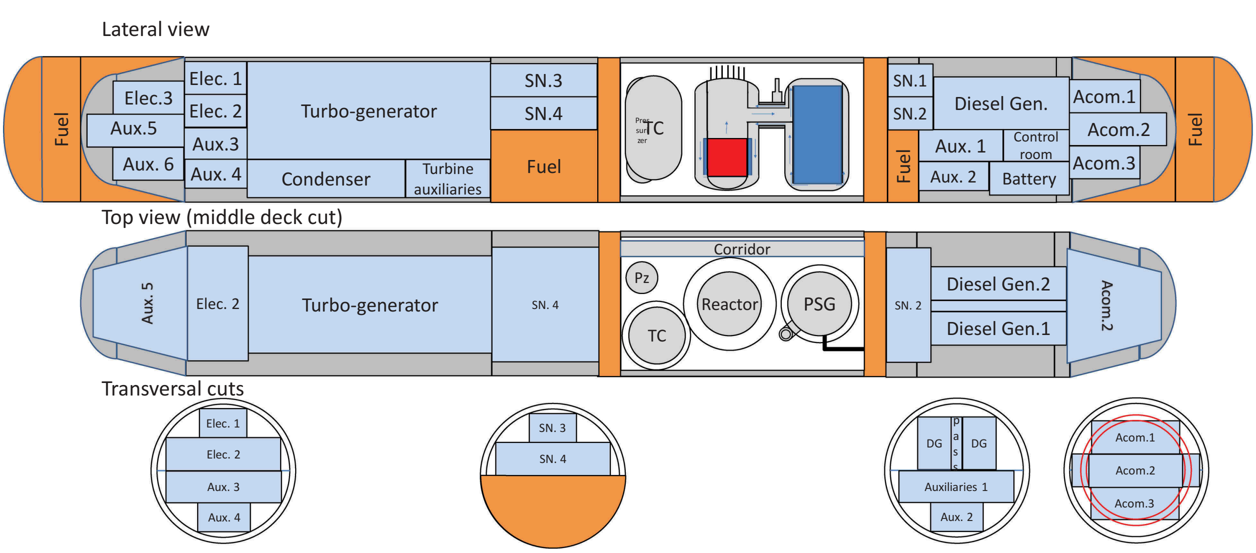


Fig. 4. MNPP proposed arrangement: Pz is pressurizer, TC is compensation tank, PSG is plate and shell steam generator, DG is diesel generator, SN is nuclear safety room, Aux is auxiliary room, Elec is electrical equipment room, and Acom is accommodation and habitability room.

military ships use a PWR and all merchant ships and icebreakers ever built adopted PWR plants. Compactness and light weight are important to give room for useful payload. With the advent of passive safety devices, PWR plants achieve safety levels far greater than older designs, and the construction and reduction of active (energy-powered) devices has reduced maintenance costs. The very fact that naval reactors are always at sea gives a readily available heat sink.

Once this work chose the PWR, it is interesting to profit from the PWR experience contained in Electric Power Research Institute (EPRI) requirements for passive advanced light water reactors[9] (ALWRs) as follows:

1. The safety features shall achieve safe shutdown of the use of energy (excepting single-action valves to set the configuration for the steady state). The design shall not employ rotating machinery (pumps or turbines) in accident scenarios.

2. Besides the nuclear-powered electrical energy sources, the plant shall include at least two nonsafety-grade sources of electric power. The goal is to achieve a frequency of event of total loss of electric power smaller than $1 \times 10^{-3}$ events per reactor year.

3. The core meltdown frequency shall be less than $1 \times 10^{-5}$ events per reactor year.

4. The cumulative frequency of radioactive leakage (more than 25 rem whole body doses over 24 h at .5 mile from the reactor) shall be less than $1 \times 10^{-6}$ per reactor year.

5. Containment leak tightness shall be enough to meet off-site dose limits for at least 72 h without the need for off-site help.

6. Only simple, unambiguous operator actions and easily made off-site help shall be necessary beyond 72 h to prevent fuel damage and to keep needed containment leak tightness.

7. The design shall include permanent features to ease connection and use of any portable equipment needed for off-site help. In addition, these features shall minimize radiation exposure during this connection.

Because the NSSS typically has many systems, Fig. 5 presents a simplified diagram for the sake of readability, omitting many systems and functions like the waste management system and reactor protection system. Some systems at interface are shown with only the functions related to the NSSS, omitting other functions. In this work, a single system performs the ANSI/ANS 51.1 (Ref. 19) emergency core cooling (core reflood) functions and emergency secondary heat removal (steam generator cooling) functions. Both functions are typically used together and with similar objectives, requiring high-quality

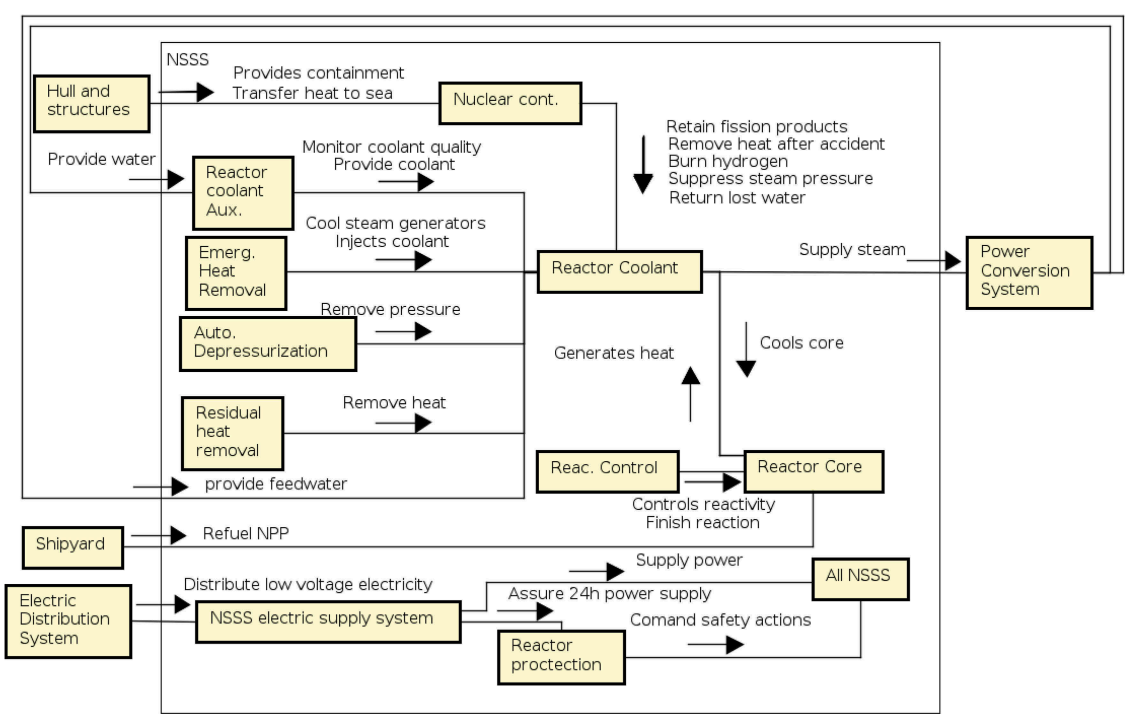


Fig. 5. Simplified NSSS block diagram.

equipment, so grouping both in a single system reduces the number of possible failures in accident scenarios. Besides, the electrical system assures power supply to the protection system for 24 h to make sure the RCS is depressurized and cooled by passive means.

Maintenance activities drive NSSS behavior, imposing the need for many states following the duration of maintenance tasks in progress. In case of accident, the NSSS tries to achieve the safe state, which causes less damage and minimizes downtime. For instance, in case of loss of coolant due a small rupture (an instrument line, for example), the NSSS tries to use normal means to remove residual heat and keep the core flooded. If it is not enough, the emergency heat removal system starts operation. If normal means are not able to keep the core flooded, the automatic depressurization system removes pressure in the primary circuit allowing gravity injection.

### IV.D. RCS-Level Analysis

For the RCS itself, this work adopts a pipe-in-pipe design, as it is an evolution of the loop reactor where the hot leg is inside the cold leg. Typically, the pipes are short and in straight lines between the pressure vessels. The KLT-40 employed this design successfully in many icebreakers and the N.S. *Sevmorput* containership, which gave service without failure for many years.[3] This work assumes the architecture in Fig. 6, where the steam generator feedwater regulation valves belong to the RCS to simplify the interfaces.

This design is intermediary between integral (pressurizer, steam generators, and reactor in a single pressure vessel) and loop (a distinct pressure vessel for each steam generator, pressurizer, and reactor) designs in terms of volume and weight, while keeping good safety characteristics and the flexibility to have high nominal powers. While it seems a little more complicated (than the loop design), it is not clear to the authors if it needs more design hours because the separations between the hot and cold legs are not pressure barriers and the cold legs are much shorter than in the design of loops. The pressure barrier design is complex, needing many calculations, including fatigue analysis following the American Society of

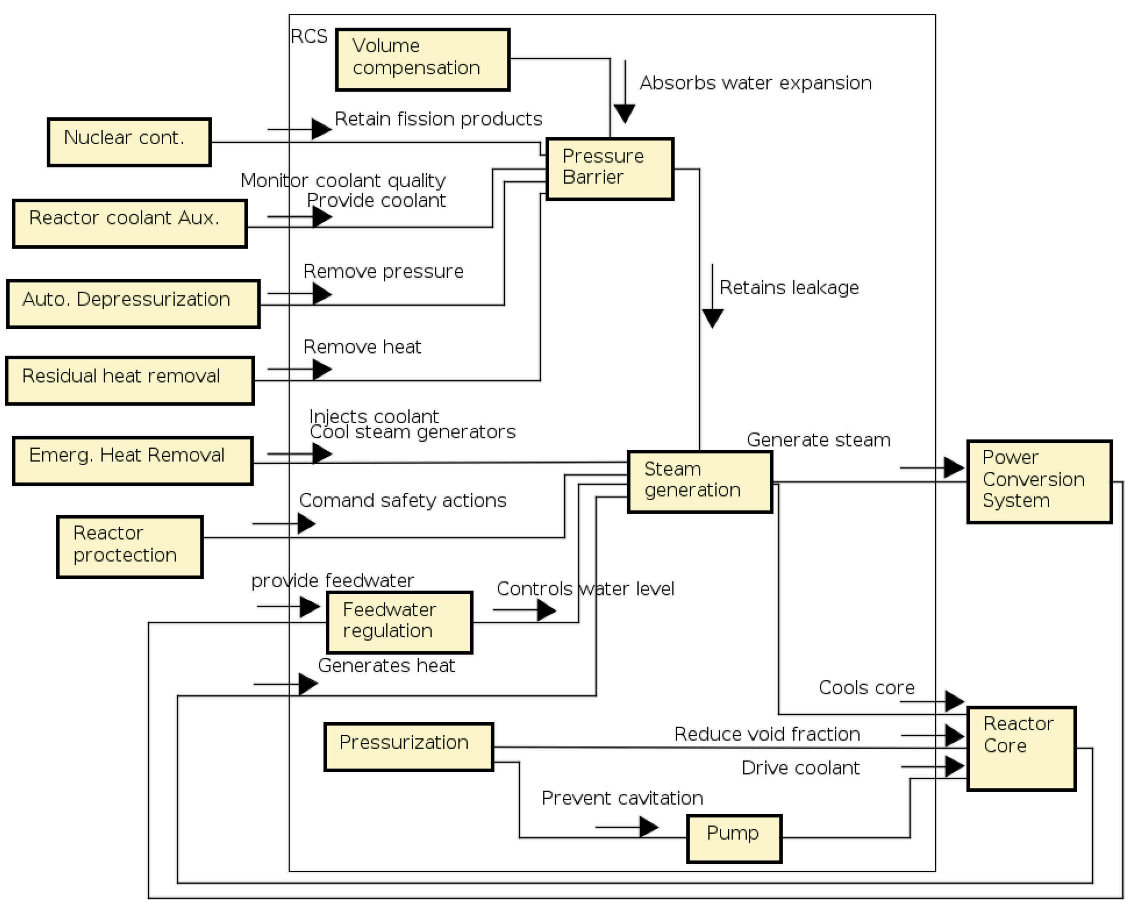


Fig. 6. Simplified RCS block diagram.

Mechanical Engineers (ASME) code for NPPs. So, although the conceptual design is more complex, it is not clear that total design effort is larger than for the loop design.

In case the reactor protection system trips the nuclear reactor, the RCS enters in safe shutdown mode, being susceptible to receiving cooling from the emergency heat removal system or depressurizing by the automatic depressurization system.

Figure 7 presents a proposal for the physical arrangement of the RCS, including pressurizer and compensating tank. The compensating tank is part of the volume compensation system and has the function to keep the water expanded from the RCS during heating and to keep any discharge from safety valves.

## IV.E. Steam Generator Analysis

The steam generator is a major part of a nuclear reactor and affects plant availability, efficiency, volume, and safety. According to Ref. 19, steam generators in activity have roles in normal PCS and accidental [emergency secondary heat removal system (ESHRS)] scenarios. The role performed on accident scenarios needs extra care throughout the life cycle of the plant. As an example, there are constraints in design, like the design of tubes following ASME B & PVC (Sec. III) and Subsection NB, which make the construction very expensive. The justification is that the failure of those tubes leads to loss-of-coolant accidents.

If a designer adopts the principle of functional segregation by needed levels of reliability, the resulting design would have different heat exchangers for the PCS and the ESHRS. This way the PCS could employ inexpensive industrial-grade heat exchangers and the ESHRS could rely on smaller (and less expensive) heat exchangers that do not suffer for normal-use wear and tear.[20] Reports show that normal operation has wear effects (for instance, fretting, fatigue wear, tube wear, and wastage) over the steam generator tubes, causing leakages and consequent plugging and leading to unplanned replacements and downtime. In 1995, steam generator problems ranked second behind refueling outages as the most significant contributor to lost electricity generation in nuclear power.[20]

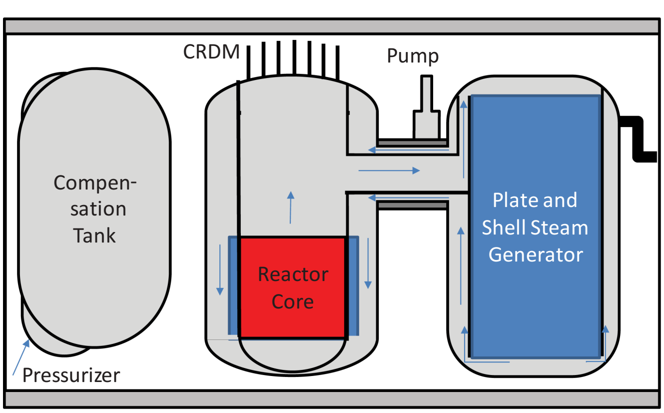


Fig. 7. RCS physical view. CRDM is control rod drive mechanism.

It is important to remember that the design must prevent failure of the reactor coolant pressure barrier (RCPB) due to the failure of nonnuclear safety equipment. A solution to meet this requirement while adopting the functional segregation principle is to place the PCS steam generator inside the RCPB. This way, once the steam-isolating valves close, no leakage rate in the heat exchangers may cause loss-of-coolant accidents.

This work advocates segregation of those functions in two sets of heat exchangers: one industrial-grade set for power conversion (normal steam generator), which is for plant nominal power, and two redundant Class 1 heat exchangers for removal of residual heat in emergency (safety steam generators). This work named this choice as a composite steam generator, and Fig. 8 presents its block diagram with a single safety heat exchanger, but the number may be multiple.

When normal cooling means are not enough, it enters in emergency cooling state, activating the shell and tube heat exchangers. If the RCS depressurizes, the composite steam generator injects coolant by gravity to keep the core flooded. Speaking now about the heat exchanger, there are new emerging technologies that could improve nuclear reactors in terms of cost, safety, and steam-cycle efficiency. Currently, most of the land steam generators are of the shell and tube type, using recirculation and steam dryers at the outlet. There are some once-through steam generators (Babcock & Wilcox design), which give super-heated steam, improving thermal cycle efficiency, however with the necessity of a better water quality to prevent turbine corrosion.[21] Another type is the helical coil once-through steam generators used in N.S. *Otto Hahn*, which also give super-heated steam.[22] Additionally, there are new types of heat exchangers based on plates and new fabrication methods. Such heat exchangers are smaller, reliable, and series-fabricated, and nowadays, they are already a mature technology in industry. They also reduce volume and are more reliable in theory than current steam generators. Another promising choice is plate and shell heat exchangers (PSHEs) from GESMEX, shown in Fig. 9. Compact PSHEs make it possible to place the plate packs inside

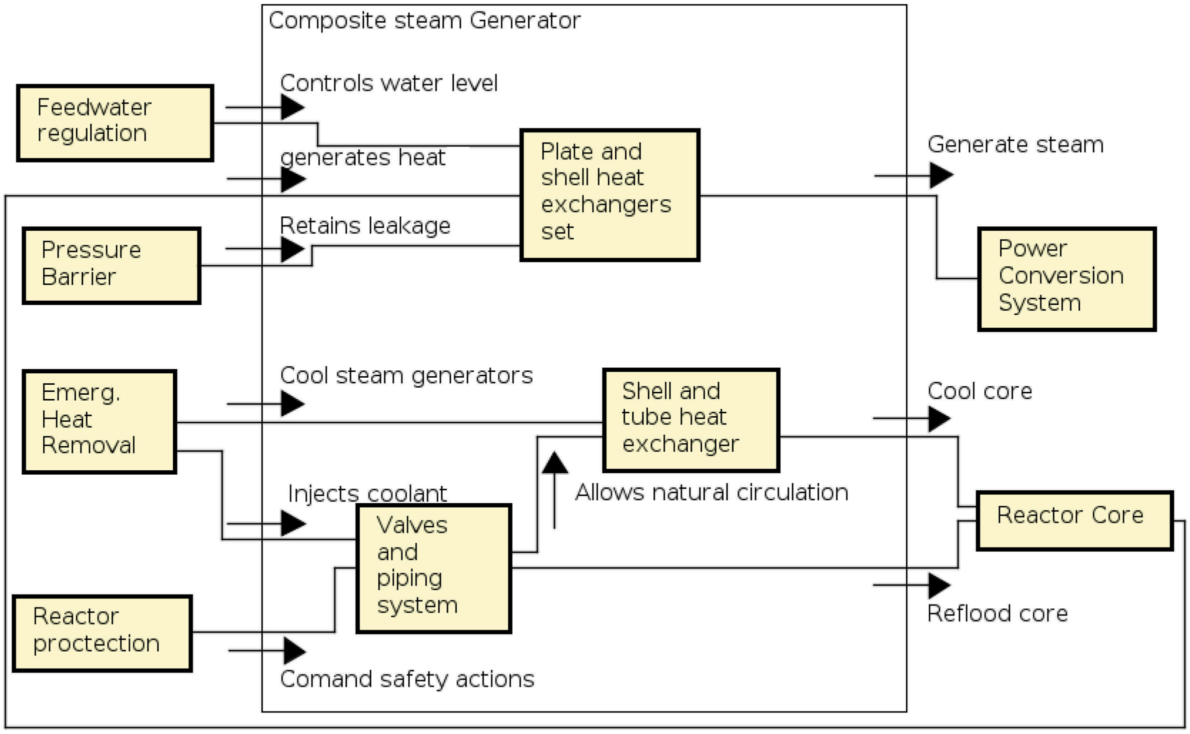


Fig. 8. Composite steam generator block diagram.

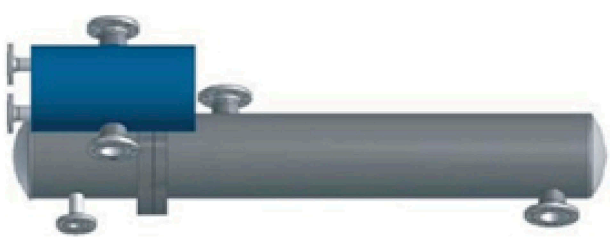

Fig. 9. PSHE compared with equivalent shell and tube heat exchanger.

the pressure vessel without enhancing much the volume of the reactor pressure vessel.

Figure 10 presents how such heat exchangers could be inside the reactor pressure vessel. The plate packs are in vertically and the steam would have three passes while the primary coolant would have only one to reduce charge losses on the primary side (pumping power and natural circulation). The vertical position is a normal arrangement for this type of heat exchanger.

To reduce heat exchanger volume and pumping power, it is advisable to adopt heat exchangers as small as possible,[23] like the XPS50 model of GESMEX. To maximize pressure resistance using tested materials, the plate material chosen was steel AISI 316L with 1.25-mm thickness. To reduce maintenance efforts, both feedwater and steam piping connect to the top of the plate packs. This way, when the control system detects leakages by increased radiation on the secondary loop, the design eases removal and replacement of the faulty plate packs.

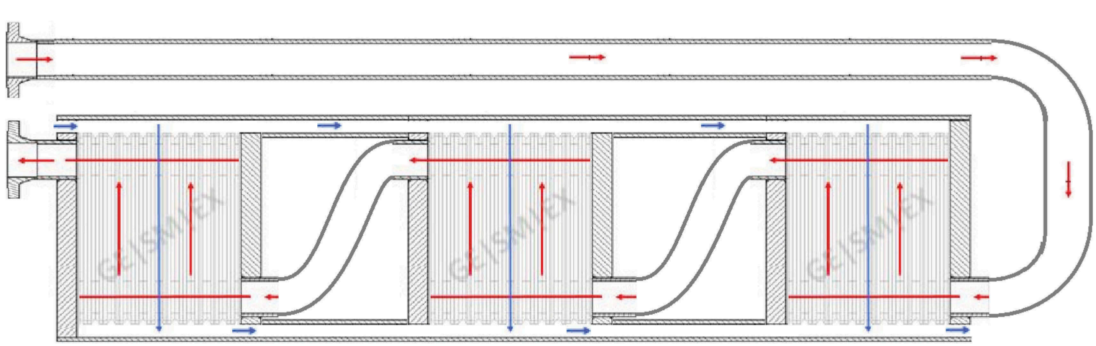

Fig. 10. Heat exchanger arrangement (inlet and outlet are oriented upward).

The PSHEs are very compact and allow flexibility in the design of the reactor pressure vessel. Compared to shell and tubes, the costs are smaller[24] and no quality control beyond industrial standards is necessary. The corrugated plates generate more pressure loss than the shell and tubes, but this is overcome using many small-diameter plates in parallel. However, the heat exchangers for residual heat removal in accidents must be Class 1 but small and of a known technology, and normal operation preserves them from wear and tear. In this architecture, once the steam-isolation valve closes, leakages or ruptures in the plate pack do not affect the leak tightness of the RCPB. Instead of relying on the quality of pipes working in traction stress (as in current designs), this proposal relies on passive safety (plates working in compression in most parts) to mitigate the frequency and gravity of leaks. In addition, no failure of the normal steam generator could disable any of the safety steam generators.

Additionally, the safety steam generators do not need to be at high pressure on the secondary side, allowing the designer to employ tanks opened to the nuclear containment atmosphere as recipients of the emergency secondary fluid. It is possible to arrange the containment physical layout to condensate the produced steam (transferring heat to seawater) and to direct the condensate back to the steam generator tank.

Overall, each safety steam generator is like the Westinghouse AP1000 passive core cooling system doing the passive residual heat removal. The main advantages of the composite steam generator are:

1. *Avoidance of ASME Nuclear Quality Assurance (NQA) quality on new industrial products*: This would be very expensive as new products did not pass nuclear qualification and would need large investments.

2. *Protection of safety steam generators from use*: The routine use of steam generators wears the tubes, reducing their reliability, needing the adoption of more than two heat exchangers in current designs, and increasing costs. The functional segregation improves system reliability by assuring safety components are in conditions to face the design basis accidents.

3. *Size reduction of safety steam generators*: As they are part Class 1 (tubes) and Class 2 (shell), reducing their size to meet the requirements only of emergency transients allows a cost reduction of one order of magnitude. Of course, this is true assuming the price is directly related to the heat exchange surface and the Class 1 material is one order of magnitude more expensive than industrial grade because of control quality costs.

4. *Use of shell and tube for nuclear-qualified functions*: The nuclear industry already has some shell and tube heat exchanger suppliers used for Class 1 equipment that will not charge the customer with the costs of setting an ASME NQA control quality program.

5. *Improvement of steam generator availability*: The compression tends to inhibit any crack propagation and creep has a high probability of stopping after some plastic deformation. Besides, the new methods of fabrication using laser and automated machinery have the potential to give high quality and repeatability in product characteristics. Of course, not all points will be at pure compression and localized failures may occur.

6. *Improvement of steam generator reparability*: The use of modular plate packs with both inlets in the upper part allows easy inspection of leakage paths once the reactor pressure vessel is open by pressurizing the secondary side with air (air bubbles will appear on the compromised packs). Besides, this arrangement allows easy replacement as both inlet and outlet are in the upper part.

Figure 11 presents how the PCS part of the composite steam generator is in the reactor pressure vessel.

It is interesting to note that industry has used successfully PSHEs for about two decades,[25] so it is a mature technology and its adoption incurs only risks of integration. Project management may mitigate such risks using system-engineering techniques.

## IV.F. Overall Solution

The results of this paper point to the adoption of an enterprise that sells electrical energy to remote clients, islands, offshore oil platforms, or merchant ships. This enterprise is the only institution that needs nuclear competencies and takes care of construction, maintenance, nuclear waste, and decommissioning of the MNPP, so clients do not need to manage such aspects. It is important to note that this enterprise could be helpful in case of war, supporting military bases or restoring electrical supply to key industries, besides powering war ships. Given its dual use, this enterprise could reduce the costs of maintenance of navy fleets because of economies of scale and competencies retention.

The enterprise has a command center that manages the delivery of the MNPPs to clients where and when they are needed using transport ships. Such transport ships may also give support following accidents and replace a faulty MNPP within a tight delay. The MNPP itself would have a cylindrical hull (the best form to

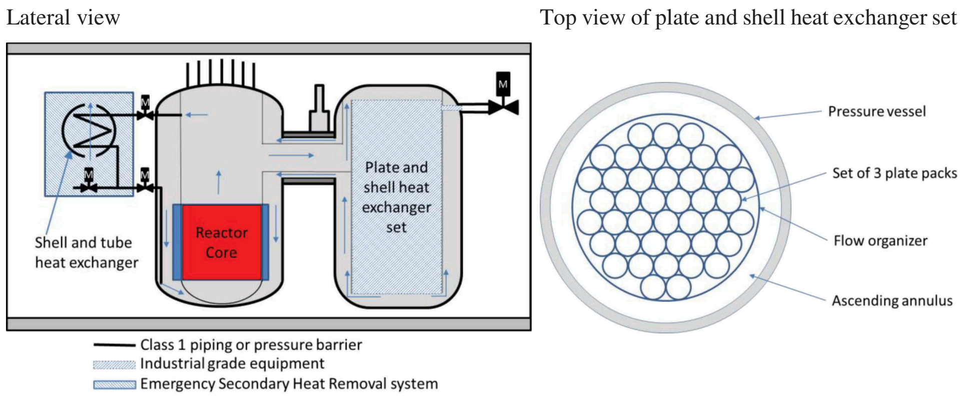


Fig. 11. Steam generators inside RCPB.

support shocks and pressure) and some limited propulsion to maneuver into the client ships or ports. The MNPP also would have two diesel generators (nonnuclear safety class) to keep the client ship with minimal steering capability after loss of the nuclear generation capability.

The chosen nuclear reactor technology is a fourth-generation PWR using passive safety to protect the core in the long term. The electrical network of the NSSS includes two redundant sets of batteries (nuclear safety classified) capable of supplying energy to the protection system and valves actuation for at least 24 h. The nuclear core is the same proposed by Ref. 26. The RCS uses a pipe-in-pipe architecture to be able to fit in a cylindrical hull. The steam generator employs both PSHEs (for power production) and shell and tube heat exchangers (for emergency scenarios).

To summarize the characteristics of the proposed solution, Table II presents the estimated main aspects of the reactor and the MNPP. For critical heat flux calculations, this work adopted EPRI correlation using a tool coded in Microsoft Excel worksheets. The core head losses were calculated adding the spacers and bare rod subchannel losses. For bare rod subchannels, the Cheng and Todreas model[27] was used for the bare rod subchannel friction factor constants in the square array with turbulent flow and pitch over diameter $P/D = 1.325$. The power distribution in the hot channel is a sine without axial offset, which is a conservative assumption from the point of view of critical heat flux. More details and assumptions are in Ref. 26.

To give an idea of size, Fig. 12 presents a lateral and cross-section view of a Post Panamax container ship along with the proposed MNPP. From a visual inspection, it seems the volume is reasonable and easily arranged inside a ship. Another conclusion is that the MNPP needs to have ballast tanks to achieve neutral floatability to reduce stress on the fixation points while the ship loads or unloads.

TABLE II

Results Summary*

| Nuclear Reactor Characteristic | Value |
|---|---|
| Number of fuel elements | 137 |
| Number of tubes per fuel element | 289 |
| Percentage of fuel rods | 90.25% |
| Tubes external diameter | 9,8 mm |
| Fuel rod length | 2.11 m |
| Element width | 0.2207 m |
| Core diameter | 3.04 m |
| Minimum departure from nucleate boiling ratio at hot channel | 2.05 |
| Output temperature | 323.7°C |
| Mean temperature variation in core | 25.7°C |
| Hot-leg subcooling margin | 22.1°C |
| Coolant mass flow | 1850 kg/s |
| Pressure loss at reactor | 4922 Pa |
| Water inventory in the RCS | 150 ton |
| RCS wet weight | 880 ton |
| Burnup | 30 MW(thermal)-day |
| Refueling interval | 5 years |
| Hull diameter | 11 m |
| Hull length | 80 m |
| Displacement | 7800 ton |
| Nominal electric power | 70 MW(electric) |

*Reference 26.

## V. DISCUSSION

This work concentrates on the economic and market aspects, ignoring externalities like public opinion and the possibility of protests, like in the case of the N.S.

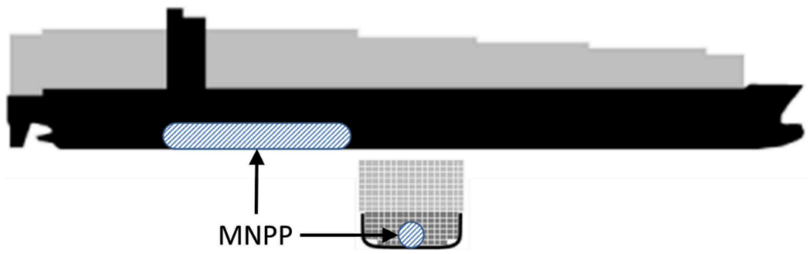


Fig. 12. Size comparison of proposed MNPP with a Post Panamax container ship.

*Sevmorput*[3] and N.S. *Mutsu*.[27] In part, the usual resistance to the recent technologies or ideas explains such protests. On the other hand, accidents in other NPPs have had an important role in the rejection of nuclear ships, like the banishment of the N.S. *Sevmorput* from ports following the Chernobyl accident. However, education is the key to solving the popular resistance against nuclear power, as a simple presentation of the advantages and disadvantages of nuclear power significantly changes people opinion.[28]

Another point is this work explores only a small part of the blocks composing the global solution. The chosen blocks were the critical ones (like a typical merchant ship) to identify the functional and nonfunctional requirements. Additionally, this work explored some blocks, like the steam generator, to show possible technological innovations. Overall, this work creates more questions than answers, as the authors believe that identifying the issues is yet more important than inventing new technical solutions.

Because of high capital costs, nuclear power needs economy of scale to be competitive. The cost of plants increases (with plant nominal power) at a power smaller than one, which means that the bigger the nominal power, the cheaper and more competitive it becomes. Innovative technologies may drive the cost versus nominal power curve downward but will not change its shape. Consequently, the best clients for nuclear power are big consumers. Because of its inherent enormous size to be competitive, nuclear projects are in the scale of mega projects, costing billions of dollars. This means any small mistake in design may easily reach the order of millions in financial damage. On the other hand, the fuel energy density makes huge dangers, demanding projects invest large sums of money in risk management. Currently, the best tools to break the complexity and to improve the design quality are system-engineering tools and methodologies. If a nuclear project starts from the beginning with a proven system-engineering method with adequate tools for model-based design, the management of risks would improve and the probability of success would rise sharply.

The authors' position is that it is not possible to say for sure that nuclear power is less expensive for merchant ships and remote clients. There is some solid evidence that nuclear power is at least competitive for plants with nominal electrical power of 60 MW(electric) and upward in ships, islands, and offshore oil platforms.[8] Given the strict quality requirements, the use of mass production and the effect of the learning curve are small, on the order of 7% to 15% according to Ref. 4. Of course, mass production is important to improve competitiveness, but it is not as game changing as the proper choice of clients. The modular construction favors nuclear energy because the MNPP may achieve a 60-year life while ships have a 25-year life, meaning a single MNPP may provide energy to 2.4 ships. Another fact is that countries with less-efficient power supply systems are going to lag in this competitive world, so disregarding this work proposition is also a risk.

Given the dangers incurred by the intrinsic energy density of nuclear fuel, governments across the world impose complex regulations on nuclear enterprises. Nuclear technology was, from the beginning, associated with nuclear weapons, so in many countries public opinion is afraid of this form of energy, which is quite new if compared with other power sources. This fear drives people and lawmakers into an attitude of over regulation on nuclear power when compared with other competing power sources. Additionally, other power sources labeled as green tend to receive much more public support and government incentives, regardless of their economic competitiveness. Therefore, the energy market is not a free market, but strongly controlled by governments by regulations and incentives. Consequently, in each country, the competitiveness of nuclear power is not a solely technical issue, but a political one.

The key point here is that government needs to engage in fair play, demanding from every industry the same safety level. Reference 29 gives historical data and analyses showing overregulation of the nuclear sector, while other sectors present underregulation in many countries. From a systemic point of view, this fact is negative because society abandons a choice that could bring safe, clean, and cheap energy. It is an error to think that atmospheric pollution is just a matter of comfort. There are many diseases caused by fossil fuel pollution that impair economic activity, resulting in fewer taxes and more health expenses and weakening the government. Therefore, for government, the advantages of fair play on energy are improvement in energy security, reduction of energy costs, improved voters' quality of life and political stability, general economic improvement, and increased taxes paid.

## VI. CONCLUSIONS

Functional segregation across organizations has the potential to improve nuclear power competitiveness, as nuclear qualification costs are diluted between many clients.

Modular ship architectures using MNPPs may improve competitiveness of the nuclear option because of the much longer life of the nuclear reactor compared to the ship life. Additionally, the capability of fast detachment and attachment may improve service availability and allow operation in countries that have banned nuclear energy. Anyway, due to high capital costs, nuclear technologies may only be competitive for clients demanding more than 60 MW(electric) of installed power.

This work demonstrates the technical feasibility of building a MNPP that has an external volume inferior to the typical container ship fuel oil tanks.

The use of plate and shell steam generators inside the pressure vessel may improve the safety, availability, steam-cycle efficiency, and overall life-cycle costs of NPPs.

The key to success is the capability to meet the needs of a large market at a competitive energy price. Earlier nuclear ship projects (N.S. *Savannah*, N.S. *Otto Hahn*, and N.S. *Mutsu*) failed because they built the wrong solution, not because nuclear energy is not affordable.

Last, but not least, this work shows a technical possibility, but without stable regulation, it is impossible to state for sure that nuclear power can beat fuel oil for ships and remote clients.

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