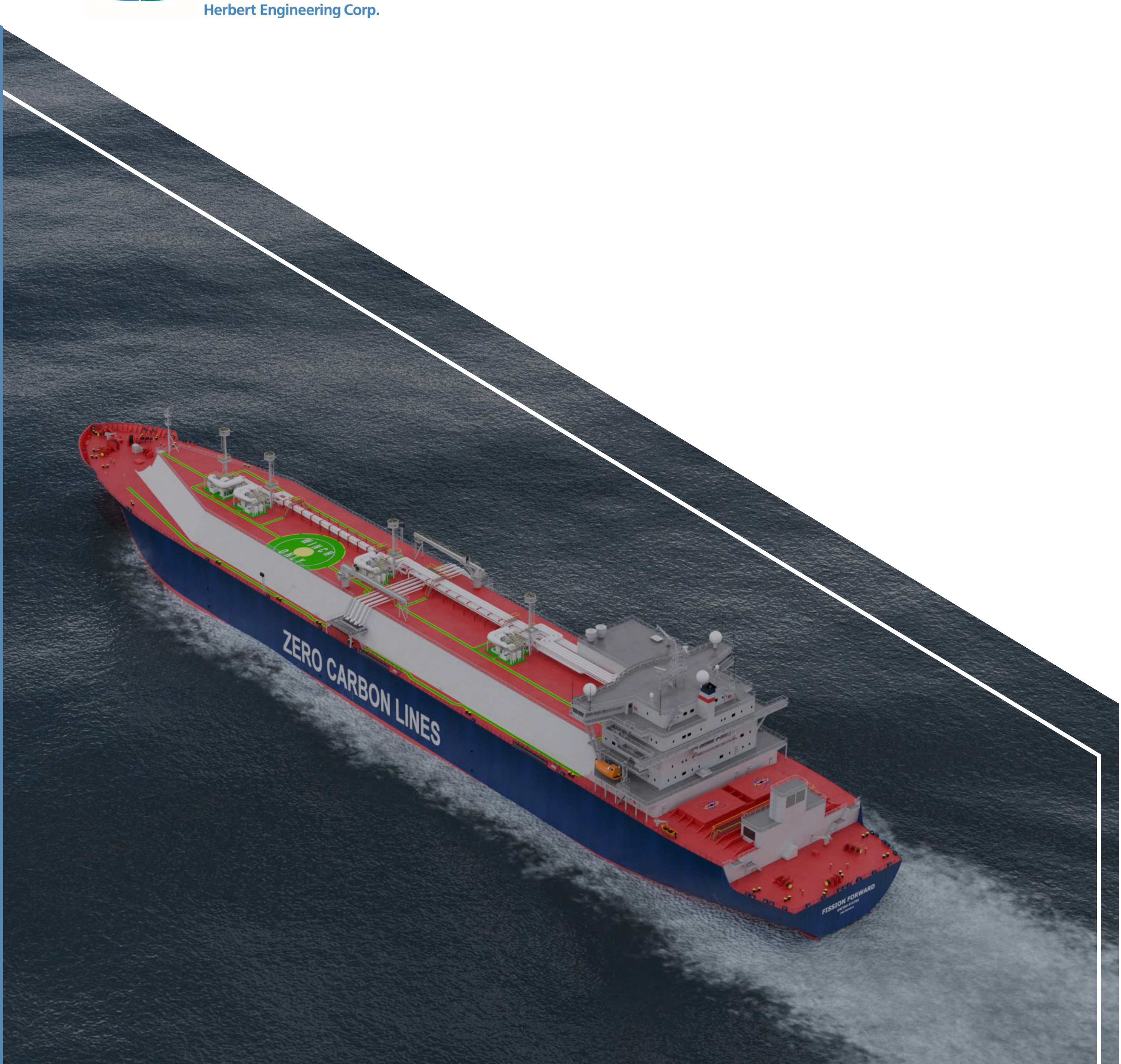
PATHWAYS TO A LOW CARBON FUTURE

LNG CARRIER NUCLEAR SHIP CONCEPT DESIGN

IN PARTNERSHIP WITH

Herbert Engineering Corp.



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FORWARD

With advancements in nuclear engineering and the development of many types of advanced nuclear reactors, there are many opportunities to implement the technology for commercial ship propulsion.

The American Bureau of Shipping (ABS) and Herbert Engineering Corporation often collaborate to investigate the application of new technologies for commercial vessels. The work leverages Herbert Engineering's expertise in naval architecture to incorporate novel arrangements and equipment into conventional vessel types. With insights from ABS on classification and regulatory requirements, the concept vessel designs are first looks at novel arrangements.

This forward-looking concept investigating advanced nuclear technologies is not intended to be aligned with IMO Resolution A.491(XII) at this stage. The goal of creating concept vessel designs is to begin the iterative design process at a high level, conceptualize the potential hazards of the new technology and prepare implementation of engineering solutions to address potential risks. The regulatory aspects of concept vessel design recommends that a risk analysis be used. As with all introductions of new technology, close collaborations with flag Administrations and port States will be necessary as the designs continue to evolve.

In addition to previous studies investigating a nuclear-powered containership and a Suezmax tanker, there was interest in investigating a nuclear-powered LNG carrier. These large vessels are increasing in demand as the international LNG trade remains important for global energy security. LNG is stored on board in large cryogenic tanks that maintain natural gas (primarily methane) in a liquid state around -165° C (-265° F). Benefits from nuclear propulsion include decarbonized high-power availability, reduced or eliminated bunker costs, and associated reduced bunker time in port. The typical energy demand for LNG carriers is between 30 to 75 MW.

Technical specifications of advanced nuclear reactors under development today, often referred to as small modular reactors (SMRs) for their scaled-down designs, are not widely available, or are not specifically designed for ship propulsion applications.

To conceptualize the possible design, the design team invited a reputable small reactor designer to provide information regarding the use of their reactor design for ship propulsion. This reactor design has been supported by the U.S. Department of Energy's Advanced Reactor Demonstration Program (DOE ARDP) to demonstrate the commercial viability of SMRs.

With these design arrangements in mind, ABS and Herbert Engineering are pleased to present a first look at a conceptual future zero-emissions LNG carrier.

We welcome your feedback through comments or suggestions.

Michael Kei
ABS Vice President, Technology, Americas

INTRODUCTION

The scope of this report focuses on the state of current advanced nuclear technology and how it could be modified, adapted and developed for commercial shipping. Basic assumptions on how the regulatory and commercial setup of nuclear-powered commercial vessels were required to serve as a basis for how the vessel design and the advanced reactor technology currently under development might come together to shape the nuclear vessels of the future.

1. SCOPE OF STUDY

1.1. STUDY GOALS

The intended scope of this study is to consider and discuss a standard liquefied natural gas (LNG) carrier design using nuclear power for propulsion and other primary energy needs.

Driven by the current ambiguous regulatory environment, market concerns and typical nuclear reactor designers' experience base and background, state-of-the-art advanced reactors are not yet designed for commercial marine use. On this basis, the high-level design of a standard LNG carrier is presented to illustrate how one type of advanced nuclear fission technology may be applied for shipboard power in the future, with an emphasis on what aspects of ship and reactor design may require further investigation to guide the development of the integrated technology and regulatory framework.

1.2. SUMMARY OF MAJOR TECHNICAL DESIGN ASSUMPTIONS

The design of this nuclear-powered vessel required several assumptions based on the perceived level of technical readiness and concept of operations that, at this time, are not defined. The reactors used in this concept study are intended for land-based applications. The primary design assumptions are:

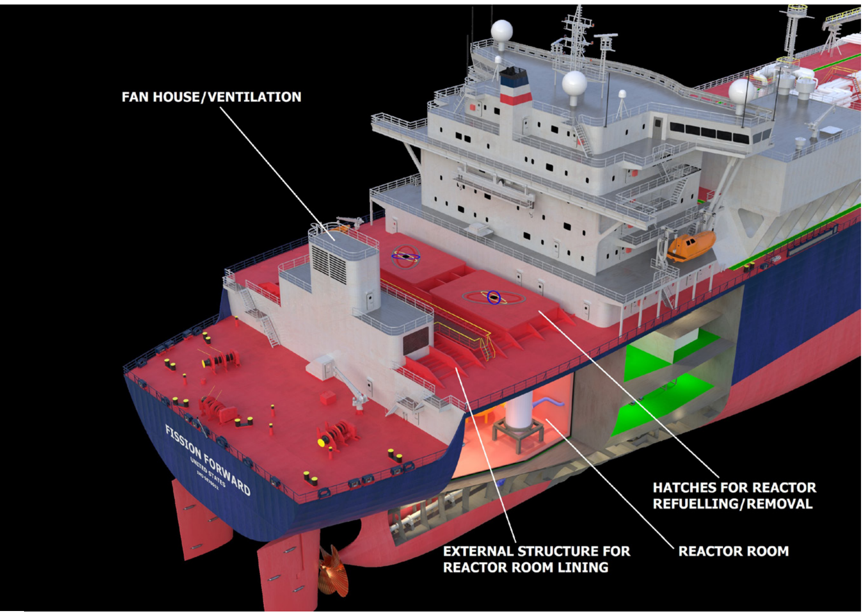
- The size of the reactors is relatively fixed so that they can be mass manufactured. For example, if a 30-megawatt (MW) reactor is chosen, only multiples of that size are permitted (i.e., 30 MW, 60 MW or 90 MW) rather than attempting to scale such a reactor up or down to a theoretical installed power level.
- The high-temperature gas cooled reactor (HTGR) used in this concept study is an advanced reactor with enhanced performance properties, including inherent safety and security features. Relatively high operational temperatures facilitate higher-efficiency energy conversion, while lower operating pressures permit smaller emergency planning zones (EPZ) when compared to conventional land-based nuclear reactors [1].
- A degree of redundancy more than what is normally present for ordinary commercial vessels is assumed to be required for a nuclear-powered commercial vessel. This includes the provision for alternative means of propulsion through redundant motors and power generation as well as emergency power provided by diesel generators for safe return to port in the event the reactors fail.
- The reactors are located aft of the accommodation block to shield the cryogenic cargo from the thermal load of the reactor compartment. For protection from collision, the reactor compartments are installed above the B/15 bottom damage line and within the B/5 transverse damage penetration extents [2].
- It is assumed that the nuclear reactors will be supplemented by battery power in an electric propulsion configuration for load-following and peak-shaving capabilities that are otherwise more difficult to meet with nuclear reactors that are typically designed for constant power generation services. This also provides continuous power to all vessel systems for a limited time in the case of main power plant failures before the emergency power diesel generators are started.

2. DESIGN BASIS

2.1. CONSIDERATIONS OF THE REACTOR TECHNOLOGY

The advanced nuclear reactor technology of interest for commercial marine applications is limited to small modular reactors (SMR) – designed to generate between 10 and 300 MWe, and microreactors – designed to generate up to 10 MWe. Both are envisioned to be factory-built according to a standard design to benefit from economies of scale and reduced licensing costs.

HTGRs, such as BWXT's Advanced Nuclear Reactor (BANR), are advanced reactors with lower thermal power ratings. HTGRs are one of several advanced reactor designs designated by the coolants, fuel types, and moderators used (if any). HTGRs are typically helium-cooled graphite-moderated nuclear reactors using fully ceramic TRi-structural ISOtropic (TRISO) coated particle-based fuels. These reactors are characterized by inherent safety features, excellent fission product retention in the fuel and high-temperature operation suitable for the delivery of industrial process heat. Although they may have limitations for onboard use due to the high temperature (for instance, in the case of an LNG carrier, it is imperative that the reactor heat dispersed through ventilation is released away from the cryogenic cargo), they imply a smaller EPZ than some other advanced reactor designs. However, the reprocessing or disposal arrangements of TRISO spent fuel are not fully developed and may need to be addressed to fully realize the benefits of the fuel.



2.2. SHIPBOARD NUCLEAR POWERING OPTIONS

In the following, an overview is presented of the HTGR concept used for the design.

HTGR – the chosen reactor is characterized as a modular, factory-fabricated system that is small and light enough to be transported via rail, ship or truck. It is helium-cooled and uses HALEU (19.75 percent enriched) uranium oxycarbide (UCO) TRISO fuel and graphite matrix as a moderator to produce 50 megawatts thermal (MWt) in the thermal neutron energy range. A nominal steam Rankine cycle of 35 percent efficiency is prospected to generate net 17.5 MWe. However, it should be noted that a higher core outlet temperature may enable direct Brayton cycle or combined cycle to increase efficiency from 35 percent to greater than 50 percent.

Advanced sensors enable semi-autonomous control, and a five-year nominal lifetime before core skid replacement would allow refueling at each ship's special drydocking. Coarse and fine reactivity control is provided through mechanical means. Passive decay heat removal is achieved by the large heat capacity of UCO TRISO graphite matrix and moderator block absorbing heat into the solids until reactor temperatures increase and radiated heat is dispersed to the ultimate heat sink while keeping the fuel and material temperatures below their design limits. This system feature is coupled with a negative reactivity temperature coefficient, providing inherent, engineered safety without the need for active safety features. TRISO fuel also contributes significantly to safety and security, as it is designed to be an accident-tolerant and proliferation-resistant fuel form.

Used with permission of BWXT

Figure 1: Example HTGR microreactor deployment application.

3. NUCLEAR POWERED SHIP DESIGN

3.1. SHIP DESIGN CONSIDERATIONS

The specific technical requirements of this nuclear-powered commercial vessel concept differ from navy nuclear vessels in the following ways:

1. Commercial vessels cannot have an extensive crew dedicated to managing the nuclear plant for administrative and cost concerns.
2. Commercial vessels cannot represent an increased threat to nuclear proliferation for security and safeguard concerns.
3. Commercial vessels cannot force the ports they visit to adopt special evacuation arrangements because of the nuclear plant used on board for public perception and safety concerns.
4. Commercial vessels need to be cost-competitive and should be designed with economy as a critical factor.
5. Commercial vessels need to maintain an acceptable level of safety even in all accident scenarios, including grounding and capsizing.

In addition to the above, there are other technical requirements to be satisfied by the power plant, which may showcase nuclear to be advantageous over other alternatively fueled power arrangements:

a. The power plant (including all ancillaries and fuel) needs to be as compact and lightweight as practicable for a given range and power requirement.
b. The power plant needs to be as easy to maintain as possible during short periods of drydocking.
c. The power plant needs to offer a range that allows the ship to operate along the proposed service route, i.e., the design should minimize the need for refueling.
d. The power plant needs to be flexible enough to adapt to the variable vessel load profiles, with longer-term oscillations such as those typical of time at sea, time in port and time in the yard, as well as transient power variations such as those occurring during maneuvering or cargo handling operations. This is known as load-following capability.

The above requirements impose a certain number of basic choices for the concept design. Other design considerations stemming from basic naval architecture and nuclear technology requirements can be summarized as follows:

1. A nuclear-electric plant is preferred over a direct drive take-off from the turbine for several reasons:
   a. It allows the reactor location to be decoupled from that of the main propulsion, thus allowing reactor safety optimization.
   b. It is easier to interface with alternative emergency power production systems/equipment.
   c. It is most flexible in terms of power management, particularly when associated with batteries.
   d. It lends itself to being redundant.

2. The location of the nuclear reactor is affected by the following:
   a. Radiation shielding characteristics, with particular emphasis on weight and volume in relation to the ship's trim, stability and structural strength.
   b. Structural or mechanical protection from collision, grounding and malicious attacks.
   c. Security arrangements for the protection from unauthorized access.
   d. Ship accelerations and vibration experienced under all operating profiles.
   e. Considerations of auxiliary power-generating machinery and explosion hazards.
   f. Consideration of the cargo areas and loading/unloading operations.
   g. Consideration of reactor maintenance and ease of installation/removal.

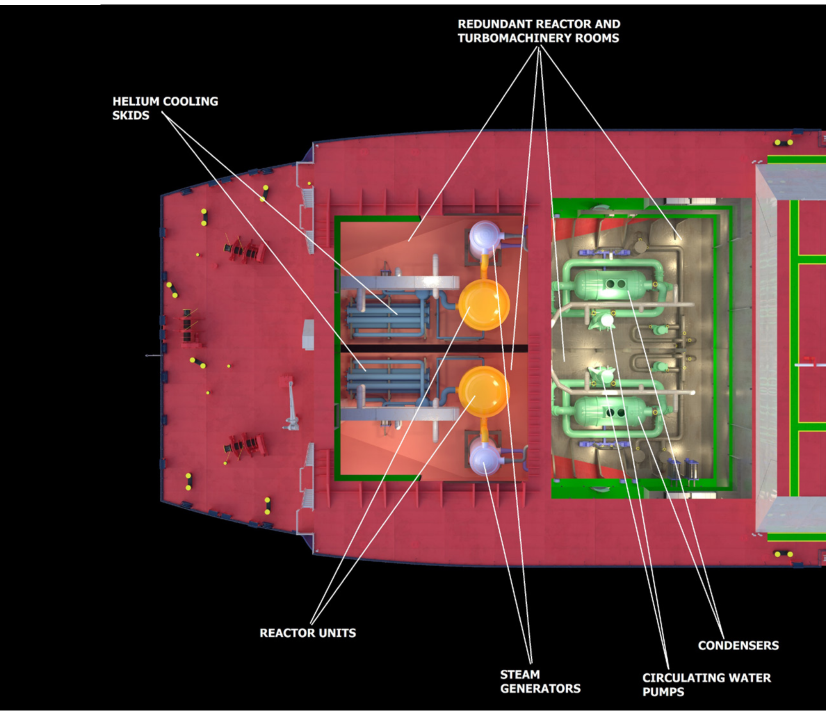
3. If the nuclear plant's load-following is supplemented by the inclusion of batteries for peak shaving, their location needs to account for fire and explosion risk, hazardous area requirements, monitoring, access, weight and replacement concerns.
4. The choice of the turbomachinery and electrical generation plant is mostly a consequence of the reactor's functional characteristics and operating temperatures, as the two need to be designed together. However, the type of electrical power generation plant will affect the surrounding ship arrangements and, consequently, its cargo capacity.

It is important to appreciate that the level of detail attainable at concept design is limited by the data available. For instance, nuclear waste generation, handling, storage and discharge arrangements cannot be addressed in detail at this stage. Similarly, other nuclear plant characteristics cannot be defined in detail, such as shutdown and startup process, capacities and performance of insulation and shielding materials, reactor room ventilation requirements, etc.

3.2. THE 145K M³ LNG CARRIER, HTGR

Figure 2: 145k m³ LNG carrier, HTGR ship profile.

The HTGR electrical power capacity reasonably matches the overall installed power requirements of a standard 145k m³ membrane LNG carrier. The total installed power requirement for this type of vessel is estimated to be approximately 35,000 kilowatts (kW); 11,650 kW of which would cover the hotel load and associated redundancies, while the remaining 23,350 kW are needed to power the ship propulsion to achieve the design speed of 19.5 knots.

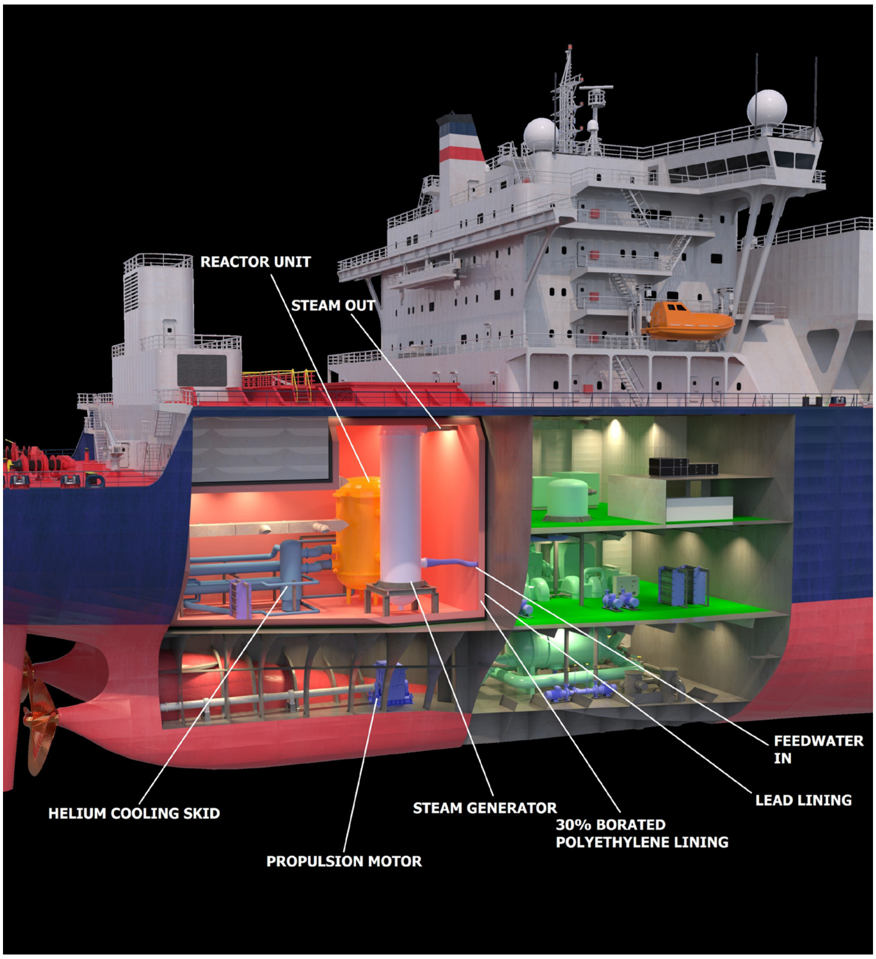


This power requirement can be satisfied by two standard nuclear power plants using two steam turbines per reactor, each with an assumed 35 percent power conversion efficiency. For this design, two steam turbines per reactor provide power management flexibility to the plant. Assuming this limit is 60 percent of maximum power output, having two reactors and four turbines allows the plant's output power range to go from a minimum of 5,250 kWe to the full 35,000 kWe. This setup also provides some redundancy and improved resilience to turbine breakdowns, albeit at the cost of increased capital expenditure (capex) and plant complexity. When propulsion is not required, the lower level of required power would be attained by shutting two or three of the four turbines and recharging the ancillary battery set. Alternatively, the vessel could reverse-cold iron (providing power to the shoreside grid) if relevant facilities were available in port.

Excess reactor heat would be rejected through reactor cooling vent stacks. The original land-based designs envision these reactors as air-cooled, so substantial fan rooms, air supply ducting and exhaust piping have been fitted to the deck above the reactors and extended above the hazardous area zone to provide the necessary airflow. The excess heat venting would need to handle the entire maximum reactor load. However, the heat supplied to the Rankine steam cycle would be partly utilized by the turbo generators, and partly rejected through standard, seawater-cooled steam condensers, effectively using the ocean as the main heat sink.

At this concept stage of design, providing detailed information about the size of reactor room fans, air supply ducting and exhaust stacks is not possible. However, the size of the steam condensers and associated circulating pumps is likely to require approximately the bottom one-third of the power generation rooms. It is conceivable that some of this heat might be reclaimed to reduce the overall hotel electrical load requirement. Also, it should be noted that, in an emergency, the reactors can be brought to a reduced power state or shut down, where the thermal energy produced is substantially reduced. In this event, ancillary batteries and emergency diesel generators would power the ventilation system.

LNG carriers are designed to transport liquid methane around -163° C. This is achieved by advanced cryogenic insulated cargo tanks, so the concept is sensitive to heat sources close to the cargo block area. For this reason, the reactor rooms (the radiation-shielded compartments containing the reactors, primary coolant loops, intermediate heat exchangers and steam generators) are placed aft of the accommodation block and the power generation rooms. Reactor compartment ventilation stacks could then be placed far aft and well away from the cargo block. Unlike the reactor rooms, the power generation compartments do not need radiation shielding since they contain turbo generators, steam condensers, associated condensate and circulating water pumps, emergency diesel generator sets, and the reactors and power plant control rooms. These spaces are not expected to create or manage radioactive conditions in normal conditions. The power generation rooms were located in the portion of the hull directly below the accommodation block where the engine room of a standard design would typically be.

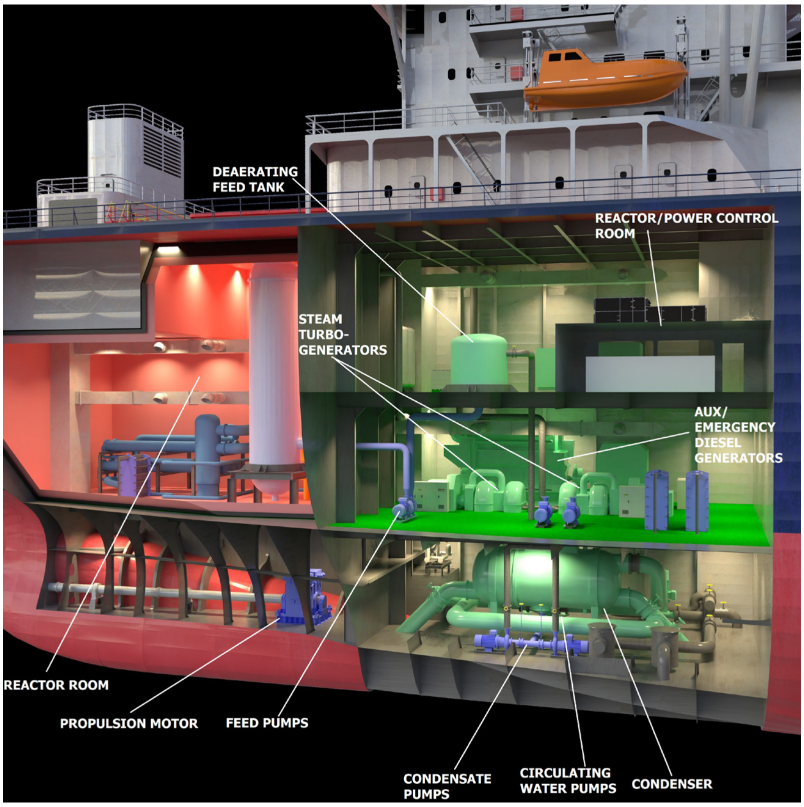


Each reactor compartment is 23 m long, 15 m wide and 15 m high. All boundary surfaces are covered with 120 mm thick 30 percent borated polyethylene for neutron shielding and 60 mm thick lead for gamma ray shielding. It is assumed that the HTGR is designed with increased shielding directly around the reactor, reducing the overall compartment shielding needs. This primary shielding adds approximately 300 MT to the reactor weight but helps reduce the neutron and gamma ray shielding materials for the enclosing bulkheads and decks. This results in a total weight of shielding equal to 2,900 MT, which is additional to the 2,300 MT of the reactors and associated power plants. The reactors are placed well above the double bottom and the B/15 maximum grounding damage limit and within the B/5 collision damage limits to maximize safety. Furthermore, each reactor is in a separate compartment with primary and secondary shielding. This allows one reactor to operate even when access to the other reactor compartment is needed.

The power generation compartments are more extensive, each being approximately 22 m long, 22 m wide and 26 m high. Similar to the reactor rooms, two power generation compartments are provided and separated by a longitudinal bulkhead at CL, providing improved redundancy (and therefore enhanced safety and reliability) in case of flooding or fire in one of the two compartments. Electric motors drive this LNG carrier's main propulsion. At the ship's stern is a standard twin-screw, twin-rudder "gondola" design, which provides sufficient room for two 11,675 kW motors near the propellers under the reactor room. Like the reactor room and power generation room, the motor room and the steering gear room are also split at CL. The bulkheads and decks separating the steering gear room, motor room and power generation room from the reactor room are all lined with 500 mm thermal insulation.

In addition to preventing undesirable heating of the LNG cargo, the chosen location for the reactor room allows the deck immediately above the reactors to be free from equipment, facilitating the extraction of the core (i.e., the pressure vessel and everything in it) every five years during special drydocking for refueling. Furthermore, this configuration works reasonably well in terms of weight management since the weight of the reactors, shielding and power generation equipment is roughly in the same longitudinal location as the engines, machinery, main fossil fuel tanks and funnel stack of a conventional LNG carrier. This means that the ship's cargo block configuration for this nuclear-powered design would remain identical to that of the conventional ship equivalent, implying no cargo capacity loss.

It should be noted that no re-liquefaction plant is explicitly assumed for this ship, as these plants would likely imply an increase in the power demand and would be harder to meet with the chosen HTGR design. Typical boil-off gas (BOG) rates for a GTT Mark III membrane system for a ship of this size can be estimated to be in the range of 200 m^3/day, requiring some 3,000 to 3,500 kW (about 25 to 30 percent of the total hotel load capacity installed) to reliquefy. Including a BOG re-liquefaction plant might imply that the nuclear plant would need to attain increased power generation efficiency, perhaps employing a closed gas Brayton cycle instead of a standard steam Rankin cycle. Alternatively, it may be possible to accommodate the additional electric load of a re-liquefaction plant, reducing the hotel load flexibility margin. This setup would need a careful, detailed analysis of the vessel's operational profile to verify its feasibility beyond the scope of the current study.



If both reactors fail, power for a safe return to port is provided by two sets of standard diesel generators that would not be used during normal operations. An alternative to marine diesel oil (MDO) could be biofuel or LNG, and the latter design choice would have the additional benefit of a smaller MDO capacity requirement, potentially allowing room for a larger ancillary battery set. However, the use of LNG for the emergency generators may increase the complexity of the plant (due to the equipment for gas fuel treatment) with only minor emission reduction benefits since these generators are meant for an emergency to return safely to port.

Although the HTGR is capable of load-following at a rate of change of a few percentage points per minute, this may not deemed sufficient to deal with the rapid load changes typical of ship maneuvering. For this reason, a small ancillary battery set of approximately 54 MWhr capacity was placed at the bow and would be used only to complement the reactor load following capabilities. These batteries are for peak shaving, to compensate for sudden load increases and to serve as a power sink when the vessel is in port and propulsion is not necessary. These batteries cannot be used as an alternative power source for a safe return to port since the total endurance at full power would be less than 2 hours. Similarly, sizing the battery set to provide sufficient energy to provide a reasonable range for the safe return to port would imply an unrealistic volume and weight requirement. Battery recharging would likely be done in port when turbine power is minimal. This would allow a full recharge in approximately 12 to 24 hours, depending on other hotel loads. However, insufficient information is available in this design stage to provide further details on battery charging.

This design configuration implies two main drawbacks.

First, since the weight of reactors, shielding and power generation equipment exceeds that of the engines, machinery, main fossil fuel tanks and funnel stack of a conventional LNG carrier by approximately 700 MT, the balance of trim needs to be at least partly restored by placing the ancillary battery sets (weighing around 270 MT) at the bow, where the remaining fossil fuel of a conventional LNG carrier would typically be stored. This implies a modest increase in the empty ship hogging bending moment that would require a slightly more robust hull structure. It should be noted that the location of the battery set far from the main power generation machinery is not an issue, as this does not produce any significant electrical loss or delay in the charging and discharging of the batteries.

Second, the reactor location aft implies higher ship motion accelerations than those experienced at or near the midship section (MS). For this reason, the local accelerations were estimated using the IGC Code Regulation 4.28.2 "Guidance formulae for acceleration components." These acceleration values correspond to a probability level of 10-8 in the North Atlantic and apply to ships at or near their service speed. The calculated maximum values (ax = 0.14 g's, ay = 0.59 g's, and az = 0.64 g's) were judged to be reasonably low to allow the installation of their reactors in this location for normal operations.

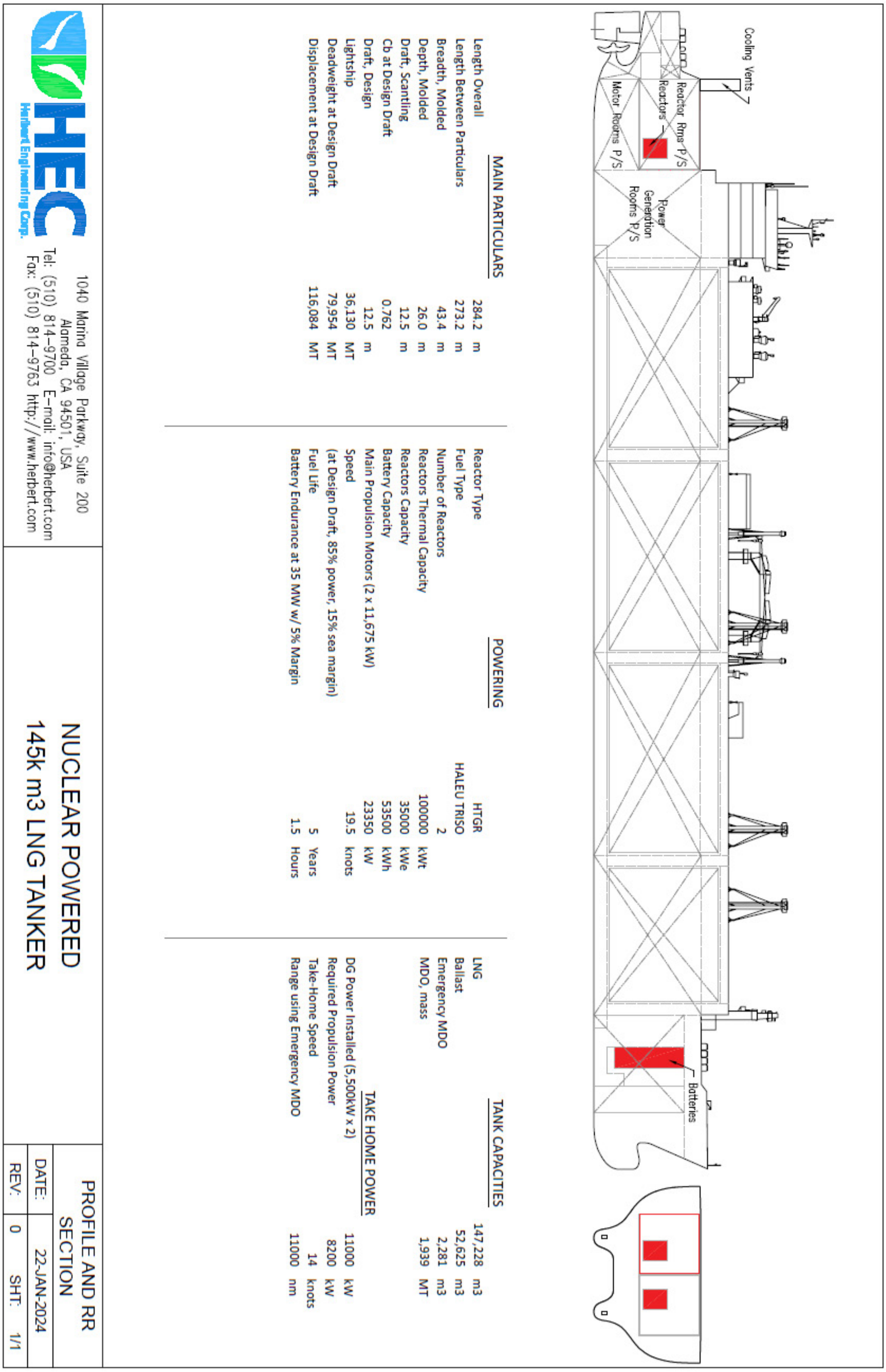
Finally, a constraint of the HTGR is the need to refuel every five years. This implies opening the reactor room and removing the reactors, and this can only happen in shipyards or other facilities equipped to deal with radioactive material. Although this is possible in a few shipyards worldwide, the limited choice implies a distinct challenge compared to conventional LNG carriers. The HTGR maintenance and refueling would need to be achieved within the normal special survey drydocking time.

4. SUMMARY AND CONCLUSIONS

The main conclusions of this study of nuclear-powered commercial vessel designs are:

- Nuclear power would be an ideal means of drastically abating shipping emissions, but significant hurdles remain in public perception and international regulations before this can be achieved.
- The use of nuclear power on board commercial vessels can contribute to significantly more efficient ships in terms of transportation capacity.
- The maturity of advanced nuclear technologies that may be implemented for ship propulsion is low. Therefore, the level of detail provided in this study is limited to engineering information available from the design of terrestrial applications for engineering postulation and recommendations for future design optimization.
- The modular reactor philosophy imposes significant restrictions on ship design. The modularity concept imposes a fixed maximum SMR power output per reactor, corresponding to a set lifespan of its core. Although it is possible to operate an SMR at a lower constant power level, its core will last longer. This may cause the reactor end-of-life to not line up with the ship's standard drydocking schedule, thus imposing significant additional operational costs. This means that SMRs would be better suited for just a few sizes per ship type (mostly larger ships). For instance, in the design presented here, the SMR is considered to have an output capacity of 17.5 MWe associated with a core lifespan of five years. This matches well the total power requirement of a 147k m^3 LNG carrier, imposing the use of two reactors and a core switch at each special survey. However, if the same SMR were considered for a QMax LNG Carrier (262k m^3) with a total energy need of approximately 56 MW, four SMRs would be needed, operating at around 80 percent of their maximum power. This would imply a core switch approximately every six years and three months, which does not match well any of the vessel's scheduled drydocks. This SMR feature may impose limits to ship capacity that can be offered to the market.
- The ability of nuclear power plants to tolerate higher accelerations due to ship motions and vibrations can allow for flexibility in the overall design. While there are significant safety benefits to keeping the plants at midships, for specific vessel types like oil tankers and LNG carriers, the midships location would not be feasible or would significantly penalize cargo capacity.
- It is advantageous if the nuclear power plant equipment and fueling lifecycles align with the vessel's life. Challenges with access to suitable shipyards or other support facilities and the physical removal of the reactors are major concerns, which would be simplest to avoid by addressing the issues in the design stages.
- The degree of redundancy required by a nuclear-powered vessel may be higher than a more conventionally powered vessel for safety, which causes a decrease in performance. The presented nuclear vessel design has two separate power, propulsion and steering plants, which provide a high level of redundancy compared to no redundancy typically accepted of single screw vessels driven by marine diesel engines. Opportunities for optimization exist on many levels for future design iterations.

APPENDIX A — DESIGN SKETCH



END NOTES

[1] NRC Reference below reports: "For planning purposes, the NRC defines two emergency planning zones around each nuclear power plant. The exact size and configuration of the zones vary from plant to plant due to local emergency response needs and capabilities, population, land characteristics, access routes, and jurisdictional boundaries. The two types of EPZs are:

- The plume exposure pathway EPZ extends about 10 miles in radius around a plant. Its primary concern is the exposure of the public to, and the inhalation of, airborne radioactive contamination.
- The ingestion pathway EPZ extends about 50 miles in radius around a plant. Its primary concern is the ingestion of food and liquid that is contaminated by radioactivity."

More generally, an EPZ is the area around a nuclear plant that would require planning of concerted actions aiming to prevent or relieve the exposure of the public to radiation.

[2] The International Maritime Organization (IMO) has defined through an extensive statistical analysis the maximum damage penetrations due to grounding (B/15 or 1/15th of the breadth above the ship's bottom line) and collision (B/5 or 1/5th of the breadth transversally, from the ship's sides).

REFERENCES

"Backgrounder on Emergency Preparedness at Nuclear Power Plants", NRC - https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/emerg-plan-prep-nuc-power.html#zones

ACRONYMS AND SYMBOLS

B	Ship's beam; the vessel's width
BANR	BWXT Advanced Nuclear Reactor
BOG	Boil-off gas
capex	Capital expense
CL	Ship's center-line; the vessel's plane of symmetry
CO_2e	Carbon dioxide equivalent or CO_2e means the number of metric tons of CO_2 emissions with the same global warming potential as one metric ton of another greenhouse gas
EPZ	Emergency planning zone
HALEU	High-assay low enriched uranium (up to 20 percent of ^{235}U)
HEU	Highly enriched uranium (^{235}U above 20 percent)
HTGR	High-temperature gas reactor
IAEA	International Atomic Energy Agency
IMO	International Maritime Organization
kW	Kilowatt
LEU	Low-enriched uranium (up to 7 percent ^{235}U)
LNG	Liquefied natural gas
MDO	Marine diesel oil
MS	Midship location
MW	Megawatt
MWt	Megawatts thermal, a unit of power used for the thermal output of a reactor before conversion to electricity
MWe	Megawatts electrical, a unit of power used for the electrical output of a nuclear plant
NRC	Nuclear Regulatory Commission in the United States (U.S.)
opex	Operating expense
P&I	Protection and Indemnity insurance, as provided by a P&I Club
SMR	Small modular reactor, typically in the 20 to 300 MWe range
TRISO	Fully ceramic TRi-structural ISOtropic coated particle-based fuels
UCO	Uranium oxycarbide

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