Nuclear Propulsion in High-Performance Cargo Vessels

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It has been about forty years since nuclear powered merchant ships were seriously discussed in the naval architecture community. But recent developments in commercial shipping include bigger, faster, and more powerful ships, where nuclear propulsion may be an option worth considering.

The development of advanced ship designs opens an opportunity for high-speed maritime transportation, that could create new markets and recover a fraction of the high value goods currently shipped only by air. One of the vessels being considered is FastShip, a large monohull ship that would require 250 MW in 5 gas turbine-waterjet units. An estimate of the operation cost of FastShip reveals that its success relies heavily, among other things, on the fuel price, a single factor that comprises more than one third of the total operating cost. The alternative, a nuclear FastShip, would save, per trip, almost 5000 tons of exposure to fuel price fluctuation, and about half of this savings would further be available for additional cargo and revenues. Nuclear power results in a more stable operation due to the relatively constant low price of nuclear fuel.

The nuclear power option is suitable for high power demand and long haul applications and a reactor pack could be available within the decade. A candidate design would be the helium-cooled reactor, which has been revisited by several nuclear reactor design teams worldwide. For the Fastship a suggested plant would consist of two Modular Helium Reactors, each one with two 50 MW Helium Turbines and compressors geared to waterjet pumps, plus a single 50 MW Gas Turbine. This vessel becomes more expensive to build but saves in fuel, and still provides margin for cost, weight and size optimization.

This paper discusses general characteristics of a FastShip with such nuclear power plant and also highlights the benefits, drawbacks, pending issues and further opportunities for nuclear powered high-speed cargo ships.

INTRODUCTION

In the last years, marine transportation has shown an evolutionary trend in the high-speed transport segment, with a marked consolidation in fast ferries, and an encouraging innovation potential in other markets.[1] [3] This evolution has been possible due to the joint emergence of new hull designs, high performance propulsors and highly compact power plant packages.[2]

A remarkable proposal, this time in the containership segment, has been the FastShip concept, which has attracted the attention of shipping business actors and the media. Both the magnitude of this commercial venture and the size of the vessels are breathtaking, particularly taking into account the current technology advantages of highly capable and reliable cargo airplanes, the shipping industry's main competitors in the higher cargo value segment. The anticipated overall features of this ship design, the logistic system and the commercial strategy are known within the marine industry.

This article intends to demonstrate the economic viability of nuclear propulsion as an alternative power source for a large high-speed cargo ship, using the FastShip as a case study. We are confident that the general results of the study are applicable to other vessels with comparable fuel consumption patterns, but data on such other vessels is not as readily available as data on FastShip. Please note that this paper is about the new generation of nuclear power plant, and uses FastShip only as an example of a suitable ship type. The authors acknowledge that FastShip itself is controversial, and wish to emphasize that the FastShip serves in this case merely as a "platform of convenience." We are also confident that there is enough controversy to be found in the idea of nuclear power propulsion, that we would ask our readers to look beyond any particular controversy to the FastShip.

For the purpose of this work, the economics of the original project will be assessed firstly, and then the economic viability of the nuclear version will follow. A brief description of a suitable power plant, its attributes and limitations is included. The economics of both propulsion options will be compared, for the same service, route, speed profile, hull shape and propulsors.

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3 Numbers in brackets designate References at end of paper.

THE FASTSHIP PROJECT

The "FastShip" concept consists of a high-speed marine transport system that relies on a fleet of four semiplaning monohulls (SPMH) -geometry typical of smaller fast vessels- with large installed power and efficient propulsors. The FastShip will reliably travel from Philadelphia to Cherbourg, in less than 4 days, due to a deep-V hull, a relatively full waterplane, flare, wide transom, and other features for good seakeeping.

The ship was conceived by Thornycroft, Giles & Co. for FastShip Atlantic Inc. of Virginia,[3] with assistance of the MIT Department of Ocean Engineering for hull design and seakeeping simulation, and the MIT Center for Transportation Studies for market aspects. Figure 1 shows the expected hull shape and Table 1 the characteristics of the reference ship.

FastShip's prime movers will be 25% more powerful than those of the Nimitz-class nuclear powered aircraft carriers. With such installed power, fuel consumption per turbine would be about 240 tons per day, or the equivalent of $850,000 per trip. Therefore, even with very low specific fuel consumption (SFC) turbines, fuel would represent more than 30% of the total operating cost of the ship. This item becomes critical in such a project, because its profitability practically vanishes with a 30% increment in fuel cost.

Table 1 Characteristics of the Reference FastShip

Hull Type:	SPMH
Overall Length:	262.0 m
Length b.p.:	245.0 m
Maximum Beam:	40.0 m
Maximum Draft:	10.0 m
Displacement:	30,750 tons
Cargo Capacity:	1,432 TEU (~10,000 ton)
Port Turnover:	6 h
Cruise Speed:	37.5 kn
Maximum Speed:	42.0 kn
Atlantic Crossing Time:	4 days
Installed Power:	250 MW in 5 Gas turbines
Daily Fuel consumption:	960 tons @ SS3
Reference Unit:	RR Trent GT @ 3600 rpm
Reference Propulsor:	KaMeWa 3.25 m waterjet
Reference Reduction:	Two-stage 1:18
Anticipated Unit Cost:	above $200 million

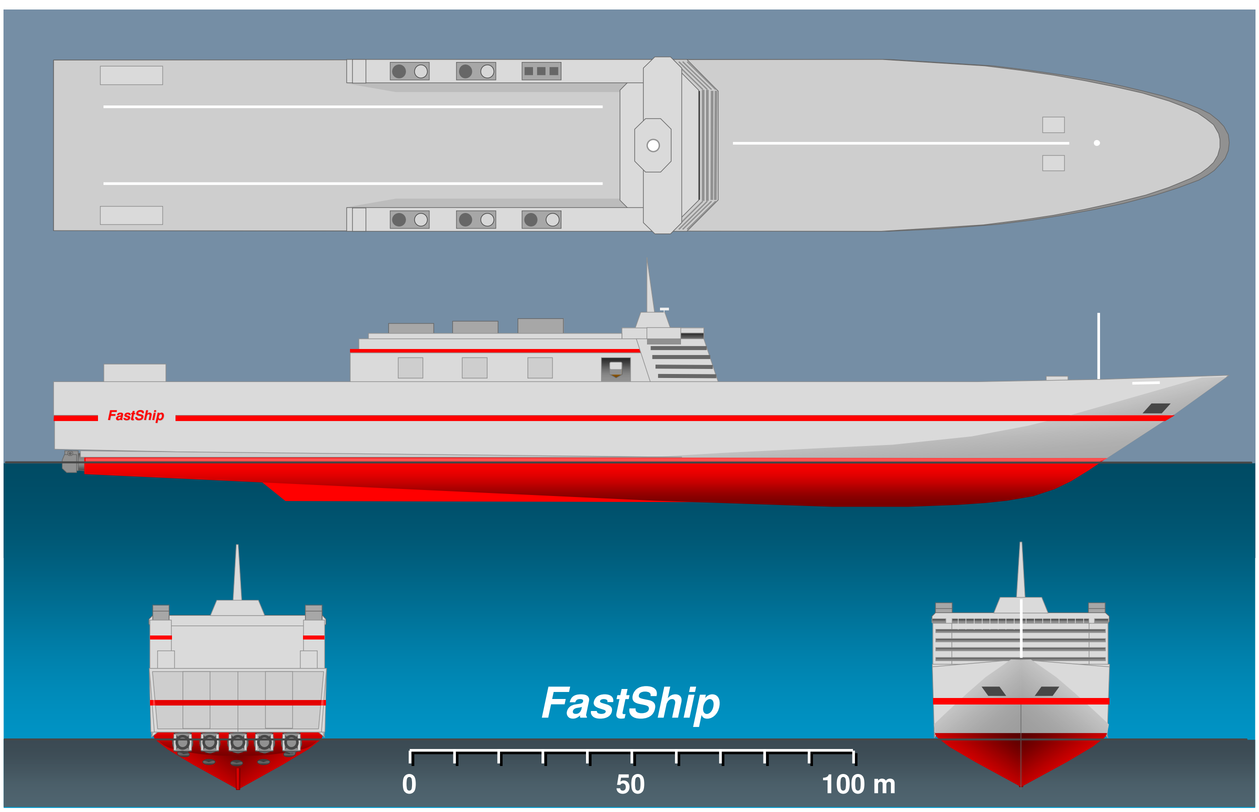

Figure 1 ***FastShip*** **Profile and Hull Shape**

ECONOMIC VIABILITY OF HIGH-SPEED CARGO

FastShip´s business strategy is based on a) high speed, for a transatlantic non-stop cargo delivery between hubs in less than four days, b) high reliability due to a relative independence of the sea state with enough extra power to recover from eventual climate-related delays, c) expedited efficient customs procedures and fast ship turnaround, and d) a synchronized fleet of trucks, trains and transfer docks for a maximum 7-day door-to-door delivery.[4]

The first challenge is to generate enough demand to justify this service. Currently, there is a basic demand for fast shipping of large-packages cargo (130-4,500 kg); however, there are minor switching costs to overcome. With anticipated cargo fares markedly lower than aircargo fares, there is a chance for such a switch. In addition, under current globalization and enhanced foreign trade, there is a clear potential for overseas shipping of goods, which are relatively heavy or bulky for commercial airplanes, such as computers, electronics and most house appliances. On the other hand, a broad variety of new market flows can appear, such as higher value foodstuff and perishable goods, over large distances. FastShip Atlantic Inc. expects to obtain a 7% market penetration in North Atlantic transportation.

The expected annual profit per ship, with revenues at a preferential rate of ¢38/kg, with a 90% service factor. a 70% load factor and 7.25 tons/TEU, is around $30 million. This value considers operation costs of about $192 million, 35% of which are fuel costs, at 90% of the nominal power.

We have assumed two rotating crews of twelve per ship and advanced automation for cost evaluation.[5] The estimated IRR was 12% before taxes, a value that anticipates only a moderate attractiveness in a hyper-competitive-to-be business. Nevertheless, there seems to be a market potential for this project, that encounters the most attractiveness in those goods currently not covered by conventional maritime or air transport.

For comparison, a regular containership service at 16.5 knots, subject to weather-related delays and to load unavailability, with revenues at a rate of ¢22/kg for a service factor of 90%, a load factor of 62%, and 8.2 tons/TEU, would have a profit of US $8 million per year and an IRR of 7.4%. This value considers operation costs of about $43 million.

NUCLEAR PROPULSION FOR FAST TRANSPORT

Before assessing nuclear propulsion viability, we summarized the nuclear applications in naval and merchant propulsion, as well as their attributes and limitations.

Nuclear power was born in the SSN "Nautilus" in 1955, with an enriched uranium-fueled, pressurized water coolant-neutron moderated reactor (PWR), to exploit the particular nuclear power advantage of containing an enduring energy source in a small volume. In fact, a suitable reactor with about one ton of uranium can run for several years. A naval reactor usually operates more than one thousand effective full power days (closely equivalent to a million nautical miles with a single fuel load). Moreover, Rolls Royce and GE are about to assure a single load for lifetime in submarine reactors. On the other hand, commercial nuclear power plants (on land) typically reload one third to one fourth of the core every 18 months.

Nuclear propulsion has been utilized in navies of six countries (USA, Russia, France, UK, China and India) in submarines for air independent stealth and in large aircraft carriers for high power demand and maximum jet fuel capacity. A few cruiser types have adopted nuclear power due to the conceptual similarity to the steam propulsion plant. Nevertheless, it can be assumed that under the current gas turbine consolidation, future cruisers will be powered by fossil fuels, unless enhanced power demands are required, i.e. beyond 100 MW_s (shaft), or unless fuel costs increase dramatically.

Commercial marine nuclear power experience has been rather scarce.[6] It was applied for a brief period of time on two general cargo and one experimental ships, without a practical commercial option, or perhaps as an exercise to demonstrate technology leadership. Currently, nuclear marine propulsion is only justified for high power demands and long hauls, and should be an option for such applications, and as a progressive substitute for fossil fuels as they become expensive or restricted by environmental reasons. Nuclear propulsion has also been used in several Russian icebreakers, in which range and persistance in the ice sheet have been imperative.

Nuclear propulsion would be appropriate for FastShip or ships with similar demand patterns and service factors. It would eliminate typical disadvantages of aeroderivative gas turbines and Diesel engines, such as fuel consumption rate and environmental offense.

Almost all naval and marine reactors have been conceptually similar to that of the SSN "Nautilus", with technology evolution at the component level, and with the intrinsic limitations of such reactor type, mainly the excessive weight required for an efficient steam cycle in single-phase flow and shielding. An exception has been the liquid metal cooled reactor (LMR) that takes advantage of the large heat transfer capacity of liquid metals, i.e. lead-bismuth eutectic, enabling compact reactors. LMRs have been used in high performance Russian submarines (Alpha class), and was proven firstly in the second nuclear submarine (SSN "Seawolf") of history, but it was earlier converted to PWR due to concerns of chemical reactivity of liquid metal, i.e. sodium, with water ingress.[7]

Nuclear technology, despite the broad innovation potential in the field, has been conservative, and newer reactors are only rational evolutions of proven designs. A main reason of this lethargy, has been the safety culture, which manifests itself in two forms. On one hand, in many redundant systems to avoid any eventual power excursion leading to a loss of cooling that might melt and release radioactive materials beyond the reactor core physical barriers (cladding, vessels, containment, etc.) to the environment. On the other hand, it implies the use of a heavy and voluminous shield to prevent the exposure of plant operators to the effects of radiation (neutrons and gamma) during normal operation. These reasons result in a heavy and expensive reactor, and an extremely redundant plant, which might in turn configure a vicious trap toward complexity and systems interference instead of the desired safety. Moreover, the plants become expensive to operate under stringent quality requirements, and are complex to license. An inconvenience of nuclear power propulsion, especially the one based on the Rankine thermal cycle, is the necessity of core residual heat removal. Even after shutdown, the reactor core remains hot and requires a cooling flow, with several auxiliaries in service.

In summary, nuclear power offers a potential in the propulsion of ships, but has not evolved as it should. There are two factors that might have created its current stigma, which has hindered its commercial use. The first one is public perception, which has been able to restrict nuclear power, sometimes influenced by pressure groups, usually in the name of ecology with little scientific basis. It is difficult to face this factor, especially after a few cases of negligence occurred within the nuclear industry. The second argument is the indirect relationship between nuclear fuel and weapons proliferation, which has resulted in technology controls with the practical consequences of any monopoly. Therefore, as an overregulated industry, it becomes difficult to achieve competitiveness. Hopefully, technology development worldwide would force a more innovative industry.

NUCLEAR PROPULSION TECHNOLOGY

The dominance of PWRs in nuclear power generation and propulsion is a consequence of the early selection of water as a coolant, due to its moderation properties, heat transfer capacity, pumping versatility, chemical stability, availability and cost.

PWRs are robust and proven reactors for aircraft carrier and submarine propulsion; however, specific volume and weight seems to be prohibitive for merchant ship propulsion. This emerges from the choice of the coolant, which demands massive high-pressure vessels and components for a satisfactory thermal efficiency in liquid phase, and which are subjected to in-service degradation. Also, unless these reactors become radically simplified, they would remain relatively expensive under 500 MW_e (electric) per unit.

Boiling water reactors (BWR) were supposed to offer slight investment reductions, but this design has not found justification in marine propulsion, because of phase changes and heaving accelerations that would impair reactor power control, plus the requirement for extensive shielding, due to radiochemical carryover.

A convenient reactor choice for commercial marine applications appears to be a derivative of the gas-cooled reactor (GCR). This reactor evolved from the first nuclear reactor, Enrico Fermi's CP-1 (Chicago Pile-1). It has been extensively used in power generation, in particular in the UK, where these reactors dominated while PWRs did so in other countries. Original commercial GCRs were Magnox type reactors (a magnesium-aluminum-berilium cladded fuel, and CO_2 cooled reactor), and later a few advanced gas reactors (AGR) came into the scene.[8] In spite of the PWR prevalence, several countries built GCRs, including the high temperature gas reactor (HTGR), for higher thermal efficiency. These reactors had gas-water heat exchangers for steam generation, offsetting their efficiency potential. Currently, there are two prevailing choices of advanced gas reactors in multinational efforts, the PBMR (Pebble Bed Modular Reactor) led by Eskom, South Africa, and the GT-MHR (Gas Turbine Modular Helium Reactor), proposed by General Atomics. Both concepts are arranged in a closed Brayton thermal cycle for even higher thermal efficiency, but differ basically in the nuclear fuel system.[9]

Variants of the GCR have been proposed for special ships.[10][11] Among those with the highest prospects, the GT-MHR would be suitable for marine nuclear propulsion, because it would result in a lighter and simpler plant, plus other features.[12] It combines the experience of the HTGR and compact heat exchangers, with the ample experience of aeroderivative and industrial gas turbines. New GCRs have attracted the attention of utilities, governments and engineering schools, due to their high thermal efficiency, chemical fuel-coolant affinity, and fuel burnup.[13] A marine GT-MHR would be less sensitive to ship motion than a PWR, while its power conversion units would provide direct torque as helium expands in the turbines.

What is the GT-MHR? Conceptually, this plant is similar to an aeroderivative gas turbine, except for the existance of a nuclear reactor instead of fuel burners, and the choice of a closed helium cycle, resulting in a decrease in the compression ratio. Helium is heated by the nuclear reaction and expands across the blades of the turbine. The helium is recompressed and redelivered to the hot side of the engine. The turning turbine produces torque, and in some cases is directly coupled to a generator (within the containment shell) for direct delivery of electrical power.

To further improve the thermal efficiency from that of a simple cycle, a heat recuperator recovers residual energy from the turbines, thus reducing the reactor size, while a precooler and an intercooler reduce the compression power demand. Figure 2 shows closed thermal cycle options for ideal and real components. The choice of an ICR cycle is apparent (i.e. a nuclear version of the upcoming Northrop-Rolls Royce WR-21), and a low compression ratio of 2.7 is recommended using two compressors. The use of an independent power turbine provides better reactor control and propulsion thrust. With such characteristics, a nuclear power plant could achieve a 47.6% thermal efficiency.

Helium is the best coolant. This monoatomic, low molecular weight gas allows to peak in efficiency at a relatively low compression ratio, imposing small loading to turbine blades. The specific heat capacity, gas constant and thermal conductivity are relatively high, properties with which compact components are possible. In addition, its low density and high gas constant allow high flow rates without Mach restrictions as in gas oil turbines. Its inertness reduces radioactivity within the turbomachinery.

Fuel cost of a nuclear FastShip should be less than $150,000 per trip, due to the low “nuclear” SFC rate. Furthermore, since uranium cost is only about one third of the assembled nuclear fuel element cost, this plant would be stable to resource price fluctuations. If fuel oil cost increases 40%, operation cost of a fossil-fueled FastShip would rise by 15%, risking profitability. In contrast, if uranium cost doubles, operational cost of a nuclear FastShip would rise less than 1%.

NUCLEAR POWER PLANT DESCRIPTION

There are many possible GT-MHR arrangements, with two extreme configurations:

a) A marinized commercial 540 MW_t (thermal) nuclear power plant with a reactor vessel (RV) and a parallel power conversion vessel (PCV) with turbocompressors, heat exchangers and a 257 MW_e vertically mounted generator, connected through concentric high-pressure ducts, with both vessels inside a radiological container. The generator would provide electric power to four 62.5 MW_s (shaft) motors coupled to waterjets.

b) Two 270 MW_t compact RVs, each one with a vertical PCV and two horizontal power turbines, fed through manifolds, and coupled to two 62.5 MW_s waterjets.

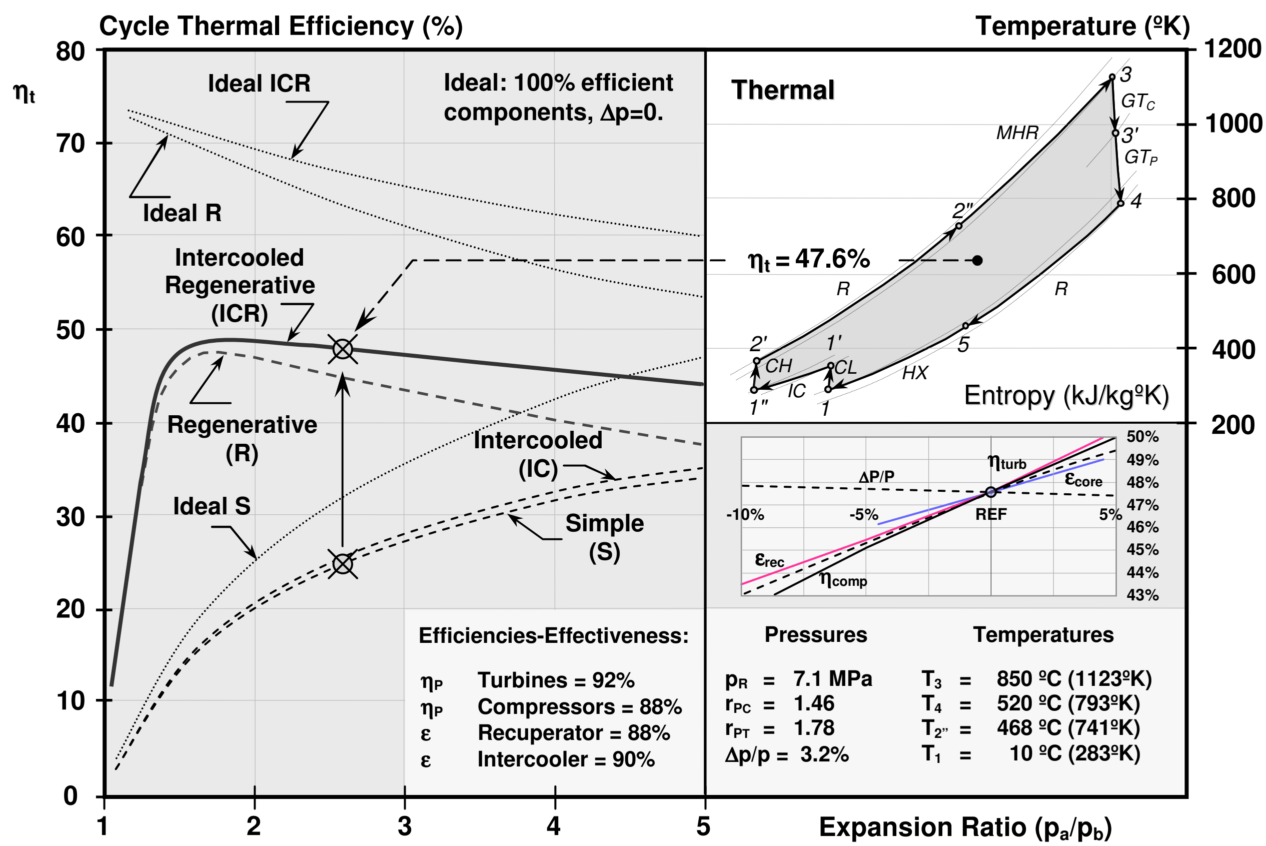

Figure 2 Thermal Efficiencies of Brayton Helium-Closed Cycle Options

Plant a) would be very expensive, due to high electric motor costs. Option b) would be underutilized, in order to operate at cruise speed. A more feasible plant for the FastShip, would be a concept similar to plant b), with two standardized 210 MW_t MHRs at the longitudinal center line, each one coupled to a pair of 50 MW_s horizontal PCVs and waterjets for cruise speed, plus a central 50 MW_s gas turbine and waterjet booster, which is also useful for port maneuvering and take-home. This hybrid power plant, shown in Figure 3, would be cheaper to invest than plant b), although it would be somewhat more expensive to operate due to gas turbine fuel consumption. Nevertheless, it would be convenient for the expected speed profile, with a large 50 MW_s gap between cruise and maximum power.

The main attribute of a GT-MHR, provided that it has a low power or a low power density, is its capacity to tolerate a full loss of coolant without core meltdown (a critical factor in reactor licensing) and the stability of the coolant. Safety resides in a microencapsulated fuel that can retain fission products during such an accident, its capacity to passively shut down the reactor if temperature increases (Doppler effect), and a safety-related favorable core geometry. Each fuel element is a hexagonal-prismatic graphite matrix of 0.8 m high and 0.3 m between faces, with 3000 fuel compacts in 94 channels, plus 108 cooling channels. The elements are arranged in an annular core with internal and external reflectors. Each fuel compact is 5 cm high and 1.2 cm in diameter, and contains about twenty thousand tiny refractory particles (615 µm), with uranium encapsulated in several layers of porous carbon, silicon carbide and pyrolytic carbon (TRISO). This fuel design has been proven at high temperatures for about 3 decades, and tested to almost its theoretical burnup. Figure 4 shows the RV, a core section for a power density lower than 5.5 MW_t/m^3, and the fuel geometry.

The alternative reactor is the PBMR. Conceptually, this reactor is mostly equivalent to the GT-MHR, but it has a pebble bed core, which consists of a stack of thousands of 6 cm diameter graphite balls with the TRISO uranium microparticles within them. Suitable for power generation, it can be refueled on-line with a fuel recharging and monitoring system which could even provide a reflected annular core configuration. However, such fueling system puts an additional complexity to propulsion power plant operation, and to international safeguards.

To remove fission heat, helium is injected to the RV at 7.1 MPa, from the PCV. The gas ascends through the RV periphery, and descends cooling the reactor annular core.

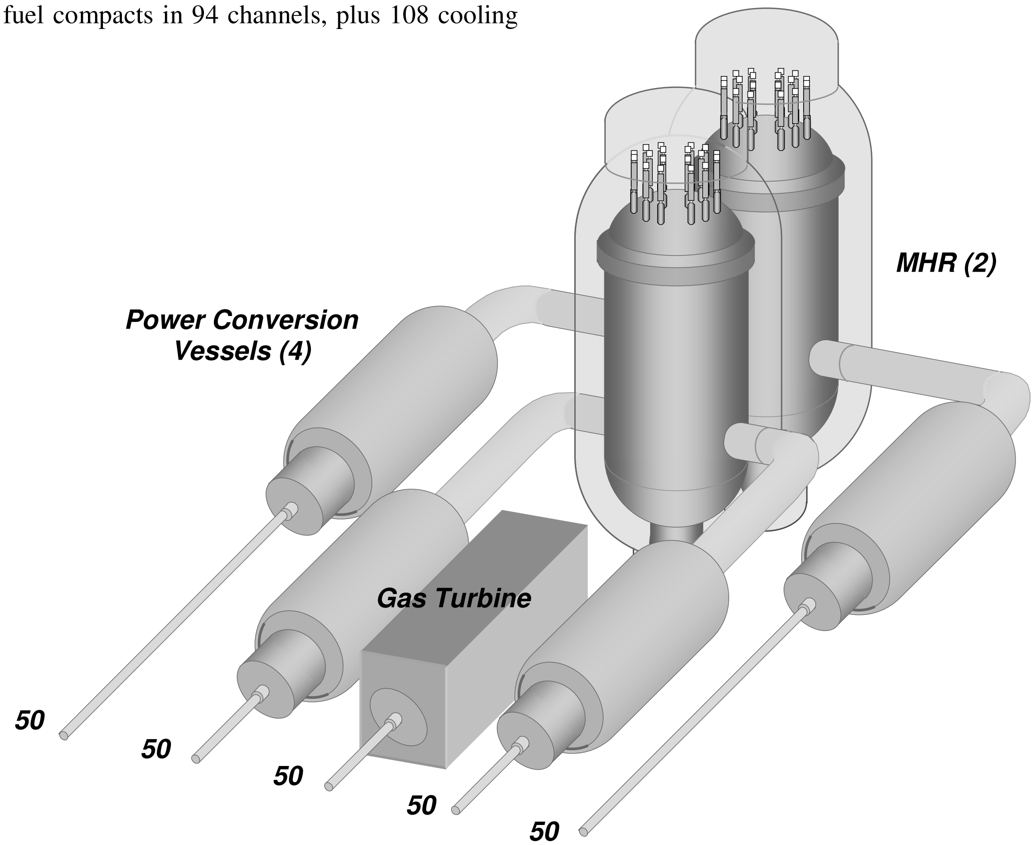

Figure 3 Hybrid Propulsion Plant (Nuclear-Gas Turbine)

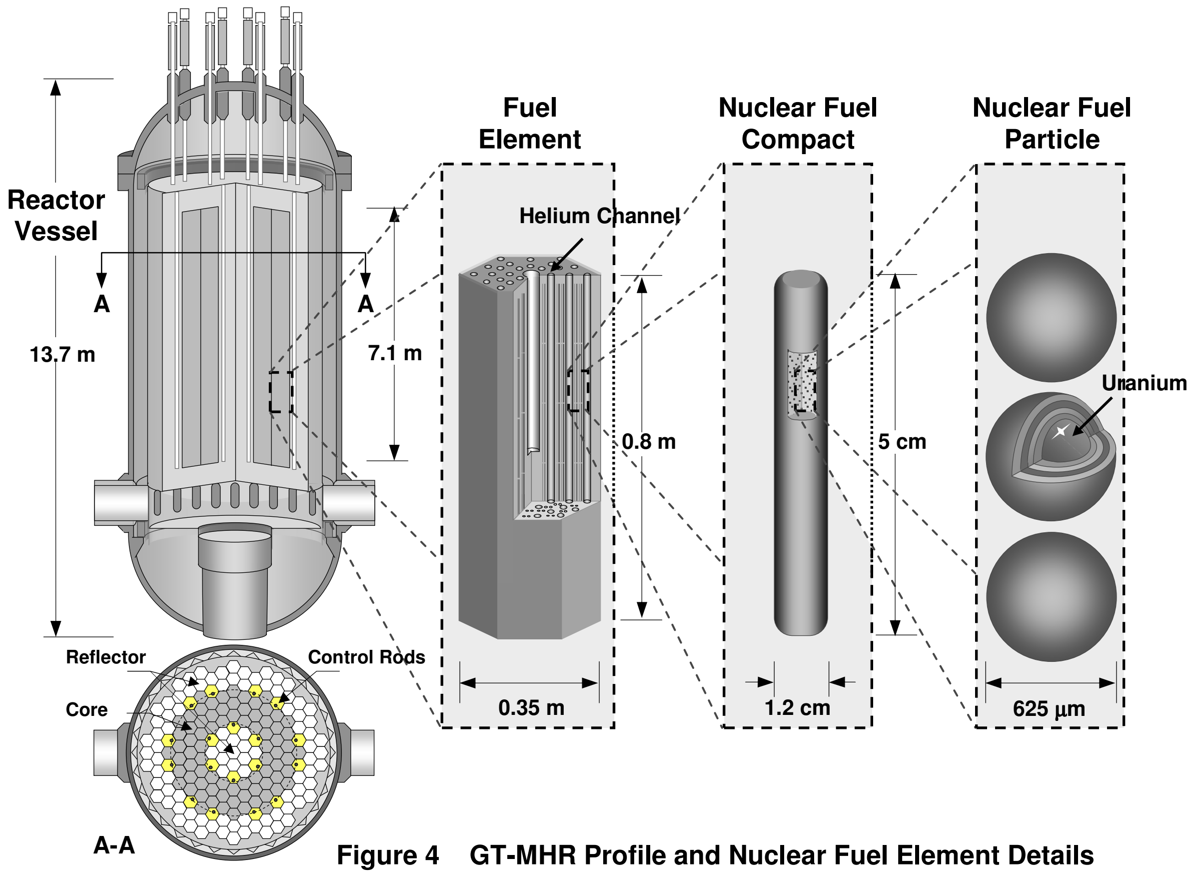

Figure 4   GT-MHR Profile and Nuclear Fuel Element Details

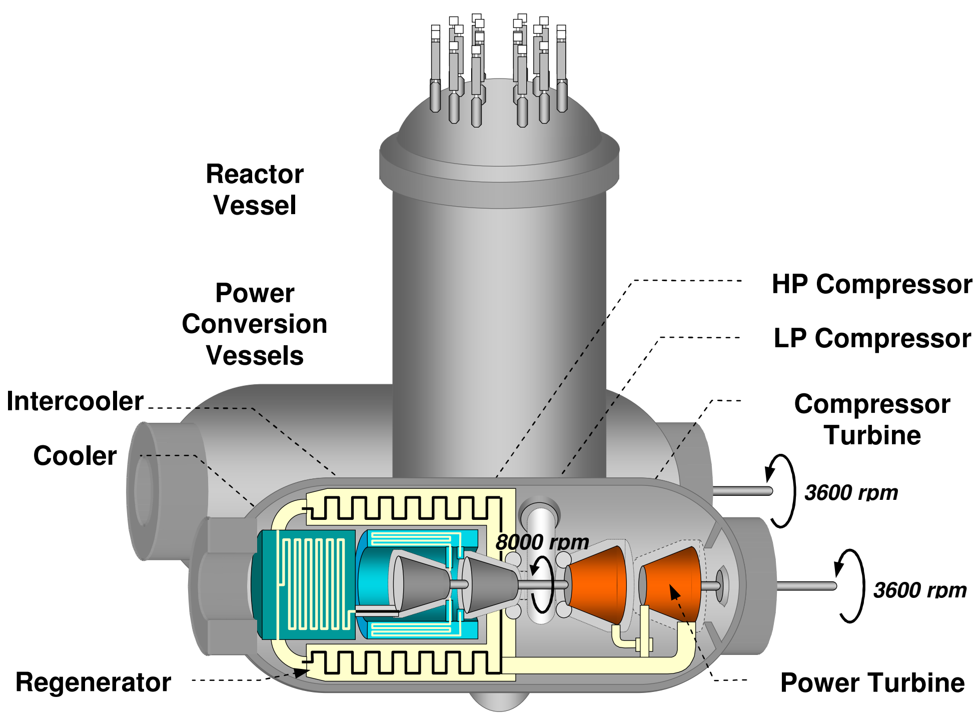

Figure 5   Power Conversion Vessel Components

Figure 5 represents the internal arrangement of a PCV, in which the gas expands through the compressor turbine spinning at about 8.000 rpm, and through a power turbine. Power level control is provided by gas pressure adjustment at nominal efficiency, and by a power turbine by-pass.

The ICR cycle is used for a better thermal efficiency, and two helium compressors make up for expansion and friction pressure drop. Figure 6 schematizes the gas flow for one of the GT-MHR modules as applied to FastShip

The specific weight of a nuclear part of the propulsion plant for FastShip, composed of two reactors and four 50 MW_s power conversion units is close to 11 kg/kW, which includes radiological shielding, structural reinforcement and collision barriers, according to Table 2. If gas turbines and fuel weights are removed and nuclear weights added, there is a net balance of almost 2.600 tons that could be spared for additional cargo, provided that original LCG and VCG are not compromised. Only 90% of that amount was assumed to be useful cargo capacity in our economic analysis. Furthermore, if the power plant is sufficiently automated and controlled from the bridge, the radiological shielding thickness could be redefined for additional cargo, based on Dose-Equivalent Limiting Recommendations.[14]

Table 2 Relative Power Plant Weight Estimation

Components	Added weights (tons)	Removed weights (tons)
Reactor Vessel (2)	270	
Reactor Core (2)	380	
Shield and Structures	1050	
Power Conversion Units (4)	290	2240 tons @ 11.2 kg/kW
Helium Control	40	
Cooling Systems	15	
Spare Helium	5	
Auxiliary Equipment	150	
Decontamination	40	
Gas Turbines and Auxiliaries	50	(250)
Air ducts and Exhaust	20	(150)
Fuel Oil	300	(4800)
Totals:	2610	(5200)
Net Weight Advantage:	2590	

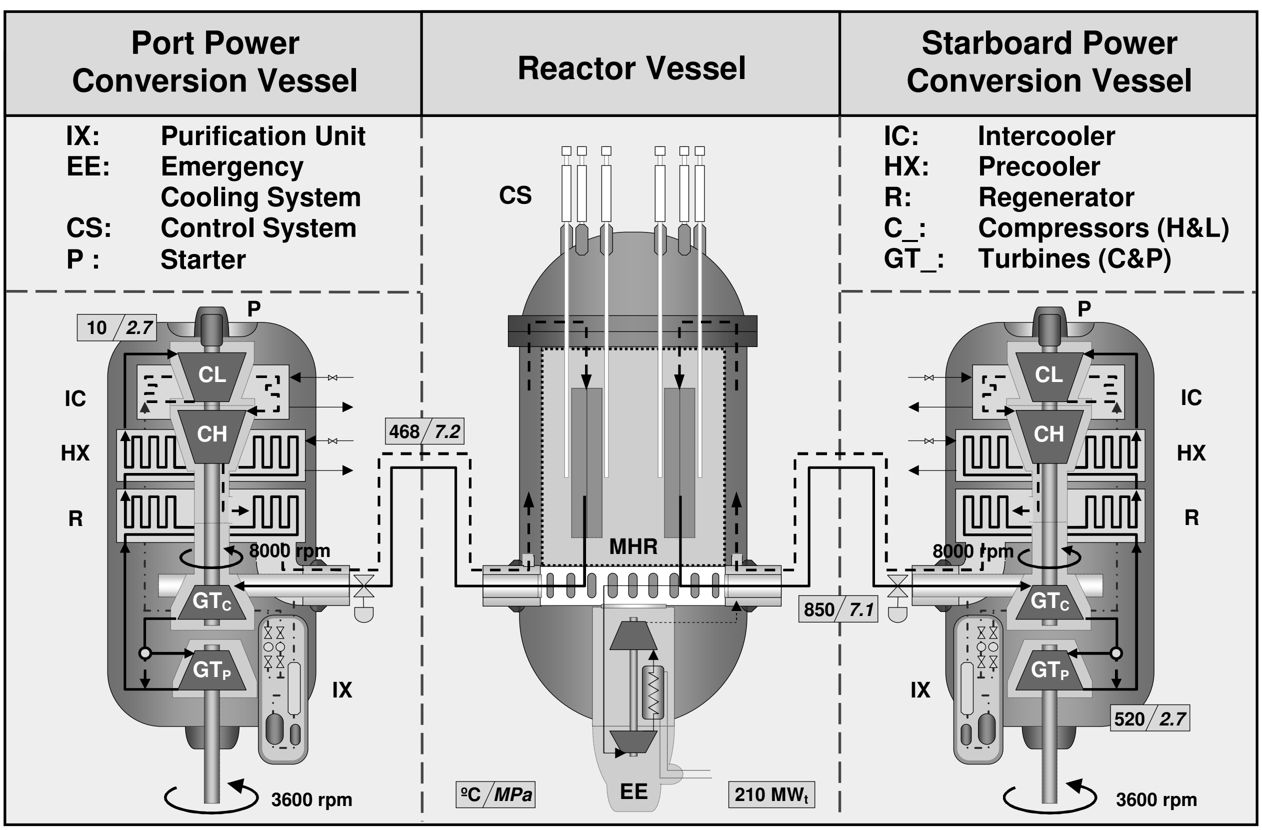

Figure 6 Helium Flow Circuit in a GT-MHR Propulsion Plant Module

Figures 7 and 8 represent the hybrid power plant and cargo layouts, respectively. A fully nuclear plant, for a nominal power of 250 MW_s in 4 waterjets, would have a nuclear plant specific weight closer to 10 kg/kW, but the net weight advantage would be similar. This plant should incorporate a Diesel-electric auxiliary propulsion system.

The relatively constant displacement, due to low fuel consumption, offers advantages for planing control and stability, with small draft and planing centroid changes during the trip. Therefore, heavy trimming control and ballast would not be necessary.

NUCLEAR PROPULSION ECONOMIC VIABILITY

Nuclear propulsion viability is assessed for the original FastShip business strategy and the same speed, range, seakeeping behavior, and loading system, with the benefits of a low fuel consumption and the weight drawbacks of radiological shield and pressure vessels.

The net benefits per ship, considering revenues at a preferential rate of ¢38/kg with a service factor of 87%, and a load factor of 70% with 7.25 tons/TEU, would be $65 millions per year, due to the larger cargo capacity. That value considers operation costs of almost $200 millions (now the investment cost takes one third of the total), with enhanced insurance and maintenance costs, as well as increased terminal costs due to the required nuclear fuel handling facilities, plus the increment in land transport and container investment. It also considers an additional reactor engineer, and better qualified personnel. The IRR would be 9% before taxes.

An inconvenience of nuclear propulsion is the reactor cost. The GT-MHR-turbogas plant cost for this ship would be around $586 millions, for a total of $686 millions per ship, assuming a conservative specific cost of $2,800/$kW_s$, including both reactors, containment, auxiliaries, etc.. The estimated power plant costs, for the hybrid and nuclear power plants, are given in Table 3.

This value has a large potential for cost reduction, since reference reactors (i.e. advanced PWRs and GCRs) are being redesigned to achieve specific costs closer to a $1,000-1,200/$kW_e$ range, for unit sizes of 110-350 MW_e. The expected specific cost of the commercial PBMR (and GT-MHR) is about 40% of the assumed value, for a 112 MW_e unit size reactor. The relative sophistication of high temperature materials and the technological challenges are well compensated with plant simplicity, thinner pressure vessels, and absence of corrosion induced effects.

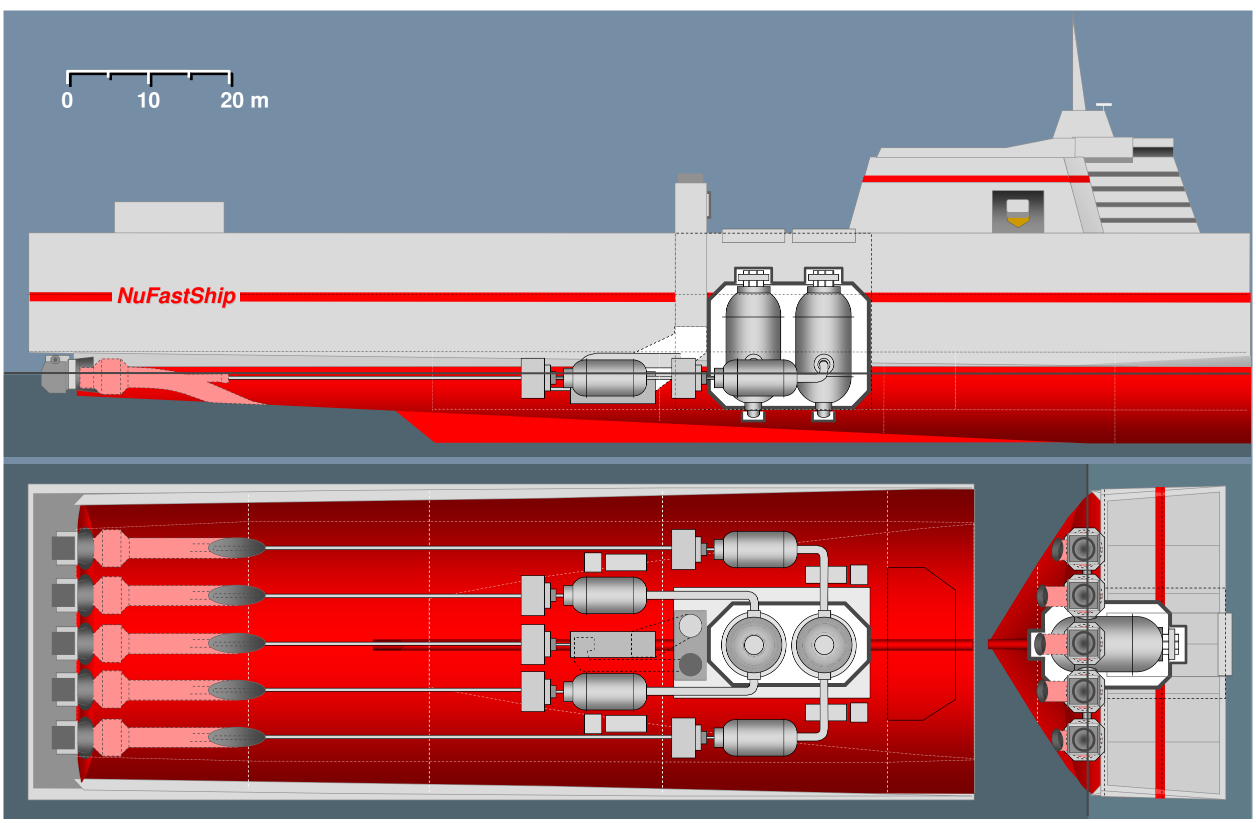

Figure 7 Nuclear-Gas Turbine Propulsion Plant Layout for "FastShip"

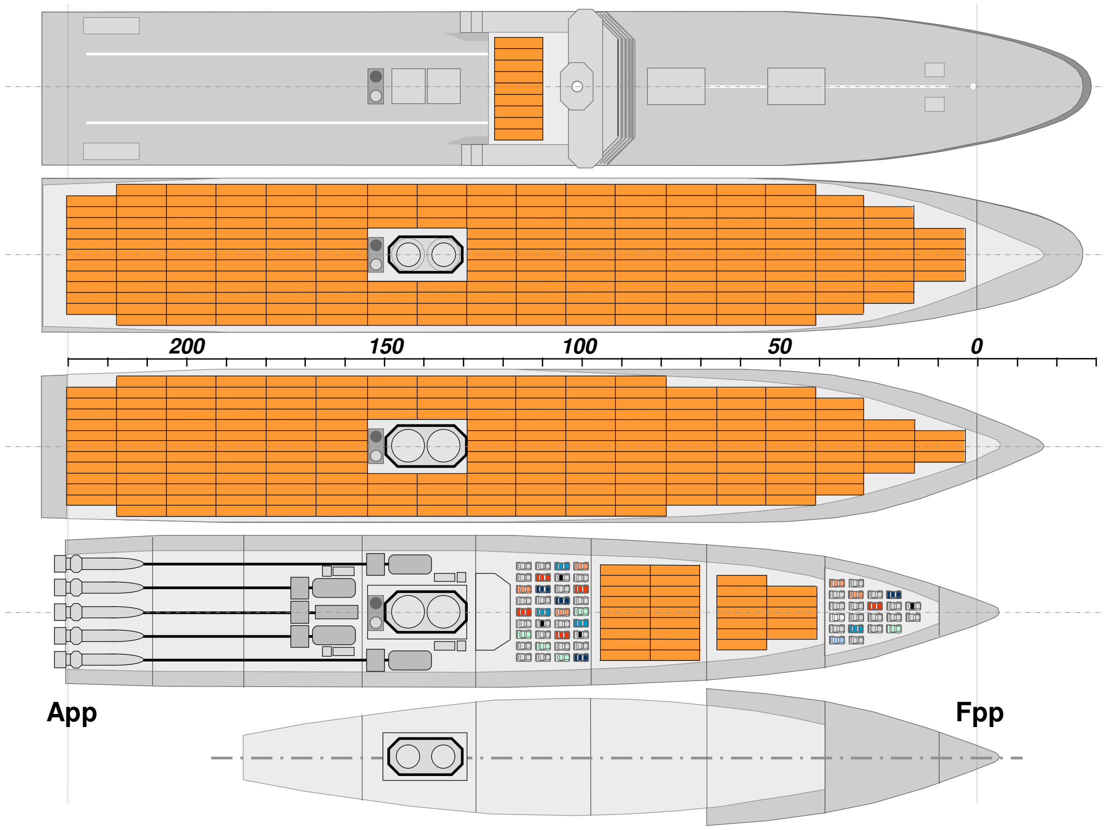

Figure 8 Cargo Arrangement for the Hybrid "FastShip"

Table 3 Estimated Power Plant Cost (US$ million)

Cost Component	Hybrid	Nuclear
Structures and reactor shield	90	125
Reactor and 1st core load	110	138
Fuel mgt and rad. protection	10	12
Instrumentation and control	15	18
Gas treatment	10	12
PCV and heat exchangers	155	183
Shafts, gears & waterjets	40	50
Miscellaneous	25	32
Engineering	65	65
Construction items	40	45
Nuclear Power Plant	560	680
Gas Turbine (or take home)	26	20
Power plant Cost	586	700

Therefore, the cost of a hybrid ship would be 3 times as much as that of the gas turbine version, with a fuel cost 4 times lower, but stable to any energy resource fluctuation (the fully nuclear ship would be 3.5 times more expensive, but it would have about one sixth of the fuel cost, with a near-total price stability).

The use of two terminal hubs for FastShip represents an advantage for handling the nuclear stigma, and allows for the buildup of an increasingly more positive perception towards nuclear power. Another confidence building way to improve perception would be through the use of the central gas turbine in addition to bow and stern thrusters for port maneuvering.

We acknowledge that such power plant arrangement breaks the deck continuity. Solutions for such interference are bow entrance for the forward container lines or internal rail switching, for which we anticipated a slightly lower service factor in our cost estimation. We cannot discard other alternatives such as reactors with lower aspect ratios or even horizontal gas reactors, although these dismiss the competitive benefits of standard reactor designs.

RELATIVE PROPULSION PROFITABILITY

Figure 9 shows the most relevant differences in cost partition and potential for the FastShip propulsion modes (gas turbines, hybrid and nuclear). A sensitivity analysis is included for each option, including reactor costs.

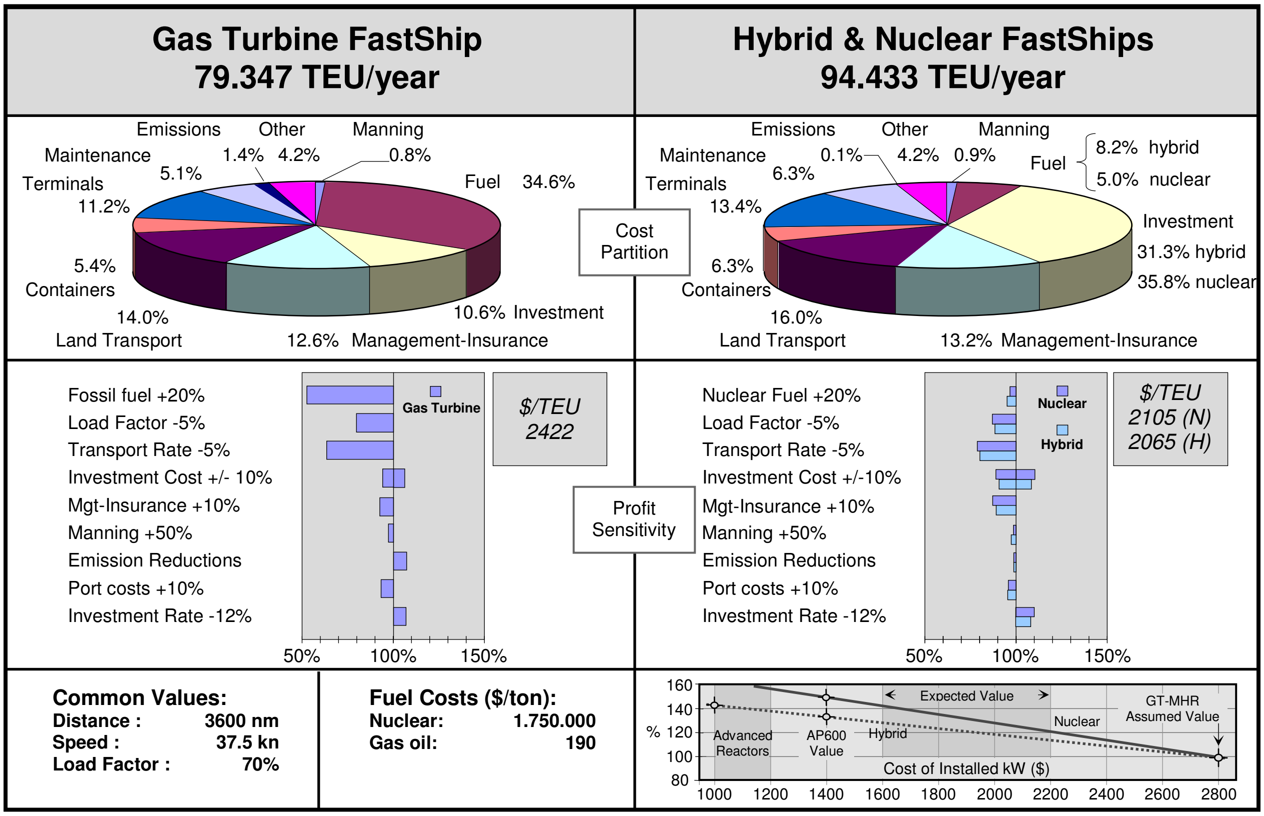

Figure 9 Cost Distribution and Profit Sensitivity for FastShip

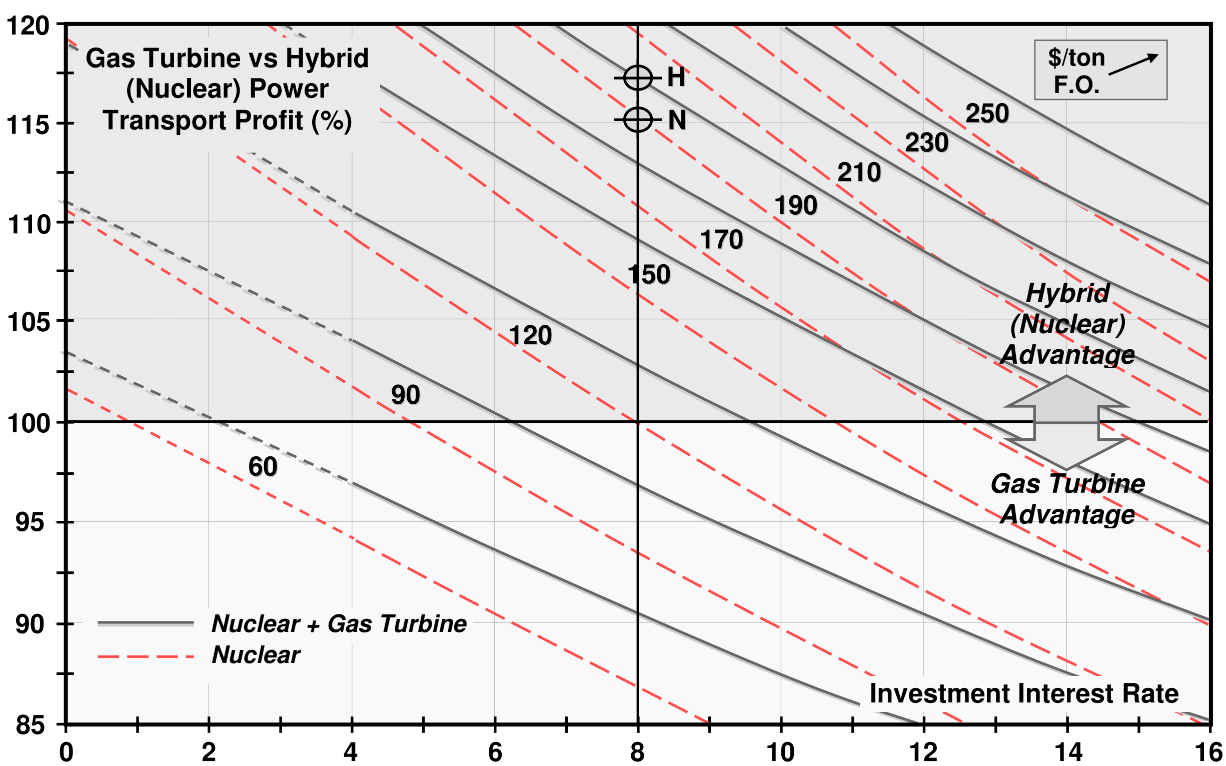

Figure 10 Relative Nuclear and Hybrid Propulsion Transportation Costs

Nuclear propulsion viability relies strongly in the cost relationship between nuclear reactor investment and fossil fuel price. Figure 10 shows a relative profit figure of merit with respect to investment interest rate. It can be noticed that there is ample room for nuclear propulsion viability. The gas turbine FastShip would not be profitable if its fuel is increased by 40%, while the hybrid version becomes unprofitable if both fuels increase 450% (700% in the fully-nuclear version). Furthermore, typical nuclear range is somewhat between 400,000 and 500,000 nm, depending on the adopted nuclear fuel cycle, so that commercial routes beyond the North Atlantic could be explored, i.e. Asia to America and Europe to South America.

Calculations so far consider an increase in deadweight capacity of 2,400 tons for nuclear propulsion despite a predicted weight advantage of 2,600 tons, from Table 2. The reactor cost is a critical factor; however, conservative values were used throughout this work, disregarding the cost reduction potential. The hybrid FastShip would equal the original IRR with a reactor specific cost of \$2,400/kW_s (\$2,150/kW_s for the fully nuclear ship). The impact of crew wages in the operation cost is small, so a superior crew qualification is possible.

RELATIVE ENVIRONMENTAL IMPACT

Nuclear reactors are environmentally friendly with respect to fossil-fueled plants, since these units do not release combustion products to the atmosphere, a particular advantage that might revitalize nuclear power if global warming proves to be as severe as anticipated.

Table 3 Relative Environmental Impact (yearly basis)

Factor/Emission	Gas Turbine	Hybrid	Nuclear
Fuel feed (Tons)	350,100	33,900	
Nuclear feed (Tons)		5.0	5.6
SO_2 (Tons)	6,700	645	
CO_2 (Tons)	1,000,200	96,700	
NO_X (Tons)	8,300	806	
Particulate (Tons)	500	48	
Nuclear HLW (T)		4.7	5.3
Persistent N. waste		0.18	0.21
Thermal efficiency	41%	46.9%	47.6%
Heat waste (MW)	323	256	247
Noise	high	Intermed.	low

According to Table 3, a gas turbine FastShip would emit about one million tons of CO_2 and fifteen thousand tons of other gases per year. The environmental impact of a nuclear FastShip would be a few tons of solid spent fuel per year, of which most could be recycled, leaving less than a ton per ship-year confined for long-term decay. The environmental response of GT-MHR is expected to be better than that of LWR´s due to enhanced uranium utilization, better uranium confinement, potential direct nuclear waste disposal forms plus a few other advantages, which have not yet been confirmed.

MARINE REACTOR SAFETY

Reactor safety is a stringent requirement within the nuclear community in order to ensure that the general public and plant operators would not be exposed to high radiation levels or contamination. Regulatory offices are required to determine the required level of safety.

Detailed GT-MHR safety is under evaluation,[15] but in principle there are several advantages over current reactor designs. Some elements pertain to the reactor system, and others to the particular marine application. This reactor has the unique capability, which is embedded in the fuel concept, of withstanding a total loss of coolant without the release of radionuclides from the fuel particles, provided that the power density is low enough. Furthermore, helium is an inert gas, so that corrosion is of lesser concern than in typical water-cooled reactors. Nevertheless, very high temperature operation imposes a non-trivial aggressive environment for structural materials.

Nevertheless, there are a few accident categories that must be considered to gain acceptance. These are: i) loss of load, ii) loss of flow, iii) water ingress, iv) turbine deblading, and v) collision, grounding and sinking.

Loss of load events may be minimized by having independent power turbines directly coupled to waterjets, a propulsor that generally operates at a constant load (even backing). A relevant concern is waterjet inlet emergence, to be minimized by proper inlet design and heavy seas sailing procedures. A few innovative features, such as inertia disks and coordinated helium flow valves might be considered. The effects of a loss of flow incident are constrained by design limits in reactor power density.

Water ingress poses effects in reactivity control and fission product release by fuel coating failure. The potential sources of water during operation are water coolers within the system and auxiliaries coupled with reactor depressurization. Otherwise helium would leak out instead of water entering the system.

Turbine deblading, and the more unlikely compressor deblading, may result from overspeed, manufacturing defects, creep and/or fatigue. Potential consequences are differential pressure buildup leading to high flow rates, pressure loads and possibly flow reversal, in addition to stator damage and coolant leakage. Deblading may be reduced by decoupling the power turbine and by proper PCV architecture design. However, blade loading and environment severity would be relatively low compared to typical open cycle gas turbines.

Finally, collision, grounding or sinking are potential events for any vessel, although nowadays they are almost fully avoidable. The reactors must shut down safely in any case and the probability of radioactive release should be minimized. The plant layout and ship structural design must reduce the probability of damaging the reactor. In case of sinking, the reactor would have to balance pressure in order to avoid a destructive collapse. The carbon based fuel element should have a release slow enough to keep the environment radiation level close to the background level.

In general, it could be said that under proper design practices and operation procedures, nuclear power can be regarded as a safe power technology. GT-MHR safety should rank very high among reactor designs.

INTERNATIONAL COLLABORATION

In our opinion, this type of reactor could be available in less than a decade if it recovers R&D inertia and a working prototype is built. Although research in direct gas turbine cooled reactors is found back in the mid fifties, no technology flow occured. Development of a commercial GT-MHR was strongly supported by the US government for almost a decade, until a sudden arrest a few years ago. A relatively modest return is observed in a few programs, such as the joint MIT-INEEL project, with emphasis in a thorough fuel particle evaluation, nuclear fuel cycle, thermohydraulic and core performance.[13] However, it is encouraging that high temperature gas reactor R&D continues at good pace in other countries, such as France, Germany, Japan, China, Russia, and a few other countries, apparently led by perseverance and technical competence of South Africa.[14] This combined effort, with the close assistance from the International Atomic Energy Agency, may result in new reactor design features.

Similarly, a collaborative propulsion project may be set-up for marine propulsion, as proposed in Table 4. Currently, the most critical part is the power conversion vessel. The main mechanical issues to be determined are rotating magnetic bearings and dry seals. The performance of large helium heat exchangers must also be determined. In the nuclear field, fuel response and integrity, and reactor dynamics must be proven. A working prototype is thus required to demonstrate the anticipated reactor features.

The cost figures given in Table 4 represent an order of magnitude of the development cost for the first hybrid ship from ground zero, based on a conservative logic, similar to that used in Figure 9. Such OOM rests on a value which is 280% of the "anticipated" per kW cost of a land-based GT-MHR, plus an equally conservative value of $200 millions for R&D, and the first vessel. Note that the lower threshold should be closer to $500 millions per ship, including a still conservative R&D cost allocated to each unit of a fleet of just four ships.

Table 4 Nuclear Propulsion Project Programme

PHASE	I	II	III	IV
Period	2002-2003	2003-2005	2005-2008	2008-2012
Researchers & Engineers	10	50	500	2,000
Reference Budget	~$500,000	~$2,000,000	~$20,000,000	~$800,000,000
Phase Purpose	Market Potential Confirmation for Fast Ships beyond the FastShip fleet. Candidate Ship Design Study. Fuel Microparticle Analysis and Optimization. Preliminary public Accept. Studies. Flow Simulation.	Candidate Ship Design. Fuel Element and Core Design. Power Conversor Prel. Design (ICR) Bearing-Seal R&D Preliminary Power Plant Design. Nuclear Related Port Infrastructure Design.	Nuclear Reactor Detailed Design. Nuclear Ship Detailed design. FastShip-Reactor Integration Design. Power Conversor Detailed Design. PCV Prototype Testing Public Acceptance Final Study.	Prototype Reactor Construction. Nuclear Reactor Commissioning. Nuclear Fuel Manufacturing Port Infrastructure Completion. Ship and Power Plant Building, plus Integration. Service Start-Up

However, the main cost attributed to the ship owner should not be a design from ground zero, but integration costs of a “land-based proven reactor” to a “standard” FastShip. The spare weight and volume per ship is high enough to provide a solution to the integration equation.

SPIN OFF TO NAVAL PROPULSION

Once naval propulsion gave birth to the dominant commercial nuclear power reactors. Now, the advances in innovative reactor designs may pay back.

Based on the GT-MHR´s advantages just described, in particular simplicity, costs and safety, there should be, in principle, no objection for the introduction of such system as the next generation of naval reactors, specially in future aircraft carriers and heavy cruisers (i.e. above 15,000 tons of displacement). High-speed aircraft carriers and cruisers, tuned for a potential fast ship environment and enhanced mobility in logistic and combat fleet, with enhanced power availability and stealth properties (reduced waste heat for low IR signature and low noise), would benefit from such innovative power source.

Moreover, PCVs should be compatible with very large waterjets, for higher silent speed than current propulsors and enhanced cavitation performance, avoiding their size limitations. Thus, a new generation of stealth propulsion for large naval ships is a possibility, providing improved defensive capability and mobility.

CONCLUSIONS

The economic viability of a hybrid GT-MHR-gas turbine propulsion plant for FastShip is anticipated. A fully nuclear plant would also be viable, but the former is preferred, due to the large power difference between cruising and maximum speed, with additional benefits, i.e. better investment to operation cost balance and power source redundancy, advantages that become appreciable at higher interest rates. We conclude that nuclear power propulsion would provide competitiveness to FastShip Atlantic, with greater capacity and a more stable operation cost to fuel volatility, load factor and transport rate fluctuations, even with very conservative figures. Also, it could open markets beyond the one foreseen with gas turbines, due to increased range. Nevertheless, it is sensitive to reactor investment cost or investment rate, and also sensitive to other intangible factors.

The GT-MHR power system could revalue nuclear propulsion for commercial ships, and influence future naval nuclear propulsion plant designs.

REFERENCES

[1] Phillips S., Jane´s High-Speed Marine Transportation 1998-99, Market Review, Jane´s Transport (www.janes.com).

[2] Kennell C., Design Trends in High-Speed Transport, *Marine Technology*, Vol 35 Nº3, July 1998.

[3] Giles D.L., Faster Ships for the Future, *American Scientific*, October 1997.

[4] MergeGlobal, Inc., Fast Ships, Cargo Analyst, 1995.

[5] Landsburg A.C. et al., *Marine Technology*, Vol 27, Nº3, May 1990, pp.129-152

[6] Harrington K.L., Nuclear Marine Propulsion, Chapter VII, in *Marine Engineering*, SNAME, 1992.

[7] Simpson J.W., *Nuclear Power from Underseas to Outer Space*, American Nuclear Society, 1995.

[8] Lanning D., Modularized High-Temperature Gas-Cooled Reactor Systems, *Nuclear Technology*, Vol 88, November 1989, 139-158.

[9] IAEA, Current Status and Future Development of Modular High Temperature Gas Cooled Reactor, IAEA-TECDOC (electronic version), 2000.

[10] Mahoney D.P., An Evaluation of a Nuclear Power Plant for a Surface Effect Ship, M.S. Thesis, MIT, 1977.

[11] Brooks R.M., Light-Weight Nuclear Propulsion Applications to High Performance Naval Ships, O.E. Thesis, MIT, 1976.

[12] Zgliczynski J.B. et al., The Gas Turbine-Modular Helium Reactor (GT-MHR), High Efficiency, Cost Competitive, Nuclear Energy for the Next Century, Atomics Project 7600 (GA-A21610), April 1994.

[13] IAEA, Design and Development of Gas Cooled Reactors with Closed Cycle Gas Turbines, TECDOC-899, August 1996.

[14] International Commission on Radiological Protection (ICRP) Publication 60, 1990.

[15] Dunn T.D. et al., Preliminary Safety Evaluation of the Gas Turbine-Modular Helium Reactor (GT-MHR), GA Project 7600 (GA-A21633), July 1994.

[16] Kadak A.C., Ballinger R.G., and Ryskamp J.M., Modular Pebble Bed Reactor Project, Advanced reactor Technology, MIT-INEEL, July 1999.

[17] Silverstein A.J., The Gas Turbine Modular Helium Reactor. An International Project to Develop a Safe, Efficient, Flexible Product, IAEA HTGR Technical Committee Meeting, Petten, Netherlands, 1997.