Center for the Commercial Deployment of Transportation Technologies

ALTERNATIVE POWERING FOR MERCHANT SHIPS

Task 2 – Survey of Available Alternative Powerplants for Container Ships

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FINAL

for:

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1 INTRODUCTION

1.1 Administrative Background

This report was produced by Chris B. McKesson for the Center for Commercial Deployment of Transportation Technology (CCDOTT). The report documents a project to study the economic impact of alternative powering systems for container ships. The concept of the project is to assess whether there is economic incentive to develop alternative powering systems for container ships: Would such systems result in improved shipping economies?

This investigation is referred to as the CCDOTT Alternative Powering for Existing Ships project.

There is a similar CCDOTT project conducted simultaneously which considers the application of alternative powering schemes to proposed very-fast ships, specifically using the Fast Ship Atlantic project as a technology baseline. This larger project looks further over the horizon than does the present project, but there is nevertheless a significant similarity between the two projects. The larger project is a contracted effort being performed by John J. McMullen Associates, Inc.

1.2 Purpose and Organization of this report

This report is the second of three deliverables of this project. This report discusses the range of powerplants available for propulsion of container liners. The report begins by recapitulating a discussion of diesel engines which appeared in report #1 of this series. This diesel engine discussion forms the baseline for discussion of alternative powerplants. The subsequent chapter of the report then presents discussions of the characteristics of a variety of alternative powering systems.

2 CURRENT POWERPLANT BASELINE – The Diesel Engine

The following discussion is repeated from Report #1 of this project. It is repeated here because the diesel powerplant forms the basis of comparison against which all of the subsequent alternative concepts are evaluated.

Container ship powering demands two characteristics: Reliability and Economy. Due to excellent economy the diesel engine remains predominant. The diesel driveline chosen for most line-haul container ships consists of a low-speed two-stroke diesel turning a direct-connected single propeller. Such a propulsion plant consists of a single large engine turning the propeller at shaft RPM with no intervening reduction gear.

A leading manufacturer of such engines is MAN B+W, who in fact trace their corporate origins directly to Rudolf Diesel himself.

2.1 Diesel Engines

MAN/B+W have provided an excellent summary of the development of container ship diesel propulsion:

"A substantial number of recent large container ship contracts have called for main engine outputs up to a the highest ratings available, and for a period, most large container ships were thus specified with main engine MCR outputs of some 65,000 bhp

However the launching of ratings up to about 75,000 bhp per unit changed the picture. Now units with such outputs exist and in anticipation of a market for above 8000 TEU container ships, engines with even higher outputs have been introduced.

The change in ship size does not in itself explain the substantial increase in the average engine power seen in recent years. Hence it can be assumed that the design speed has increased. Increase in the average engine size is an indication of a changed demand pattern toward higher powered ship types.

The propulsion power requirement is considerably higher for a container ship sailing with high-value commodities than for bulk carriers and large tankers transporting raw materials, for which the sailing time is of less economical consequence. Hence, the propulsion power requirement for a Post Panamax container ship is 2-3 times the power requirement for a VLCC.

The increasing containerization and competition in this market, together with demands for the lowest possible freight cost per TEU, will imply a continued race for transporting as many TEUs as possible on the long-haul routes. This means that an increase in the average power requirement for container ships is to be expected."

The “flagship” of the MAN B+W product line, and an engine often chosen for container ship propulsion, is the K98-MC engine. This engine is 980mm bore, and produces up to 90,000 horsepower (12-cylinder version.) The first of these monster engines was tested in 1999 at Hyundai, Korea – see Figure 1.

Other manufacturers have reported their intent to introduce engines larger than the K98. Examples include IHI’s representation of their intent to introduce a 140,000 hp engine.

RINA reported in June of 2001 that “the two leading designers of low-speed diesel machinery, Wartsila (Sulzer) and MAN B+W have both launched extended-cylinder inline versions of their most powerful models. This is being done to provide suitable plants for future generations of container liners without branching into twin-engine/twin-screw variants.”

Specifically, “Sulzer can now offer a 14-cylinder RTA96C engine capable of developing 80,080kW, while MAN B+W has just announced 13- and 14-cylinder versions of its K98MC and K98MC-C models. These will provide 74,360kW and 80,080kW (K98MC) and 74,230kW and 79,940kW (K98MC-C). (The MC-C designation indicates a shorter stroke and slightly faster running speed.) Even more remarkable, this latter designer says both types could be built with up to 18 cylinders and outputs of nearly 103,000kW, if necessary!”

These future engines are not yet in existence, and it appears that when they do emerge, they will be very similar to the existing K98. Thus for the purposes of this study we may use the particulars of the K98 series to derive engine parameters representative of all low-speed container ship diesels. The principal characteristics of the K98 are given in the MAN B+W catalog, reproduced as Figure 2.

We should note that, of course, much more detailed information is available on this engine. In the next section of this report, however, comparisons will be made against much less mature powerplants. For these less-mature powerplants the only available information will be top-level data similar to that in Figure 2. Therefore, in order to provide a level field of comparison for all engine options this report will consider the diesel only at the same high level.

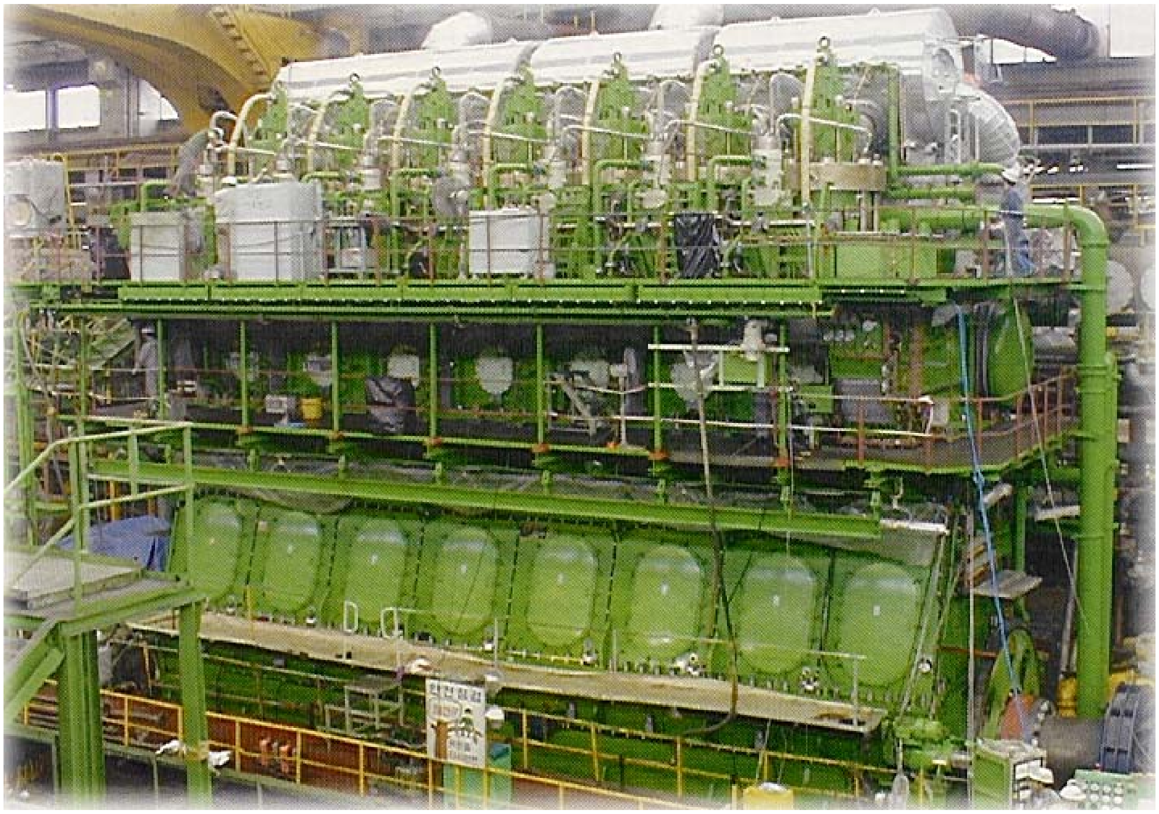

Figure 1 - The first MAN B+W 8-cylinder K98 engine, on test at Hyundai

Bore: 980 mm, Stroke: 2 660 mm **K98MC**

Layout points	L1		L2	L3	L4
Speed r/min **mep** bar	94 18.2		94 14.6	84 18.2	84 14.6
	kW	*BHP*	kW	kW	kW
6 K98MC	**34 320**	*46 680*	27 480	30 660	24 540
7 K98MC	**40 040**	*54 460*	32 060	35 770	28 630
8 K98MC	**45 760**	*62 240*	36 640	40 880	32 720
9 K98MC	**51 480**	*70 020*	41 220	45 990	36 810
10 K98MC	**57 200**	*77 800*	45 800	51 100	40 900
11 K98MC	**62 920**	*85 580*	50 380	56 210	44 990
12 K98MC	**68 640**	*93 360*	54 960	61 320	49 080

Specific Fuel Oil Consumption (SFOC)

	L1	L2	L3	L4
g/kWh	171	162	171	162
g/BHPh	126	119	126	119

Lubricating oil consumption: approximately 7.5-11 kg/cyl. 24 h
Cylinder oil consumption: 0.8-1.2 g/kWh ~ 0.6 - 0.9 g/BHPh

Cyl. No.	6	7	8	9	10	11	12
L_{min} mm	12 865	14 615	17 605	19 355	21 105	22 855	24 605
Dry mass ton*	1 152	1 318	1 528	1 678	1 856	2 006	2 157

* The mass can vary up to 10% depending on the design and options chosen.

H_1: Vertical lift
H_2: Tilted lift
H_3: With electrical double jib crane

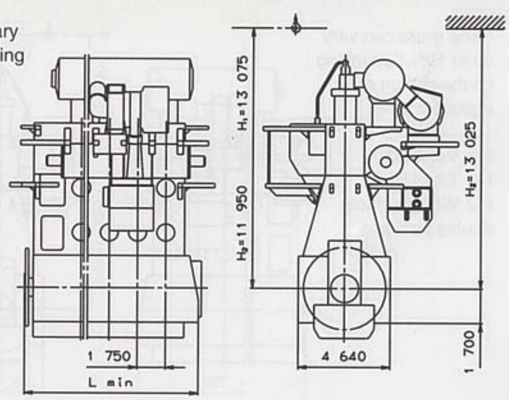

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Figure 2 - Page from MAN B+W sales catalog describing the K98 series

3 AVAILABLE ALTERNATIVE POWERING OPTIONS

The preceding section of this report identified the MAN B+W K98 series low-speed diesel as the example of the current state of the art for container ship propulsion. This next section will examine what alternatives to diesel propulsion exist. These alternatives include Gas Turbines, Nuclear power, and Fuel Cell power. The Nuclear and Fuel Cell options both use electric transmission, which is separately addressed.

3.1 Gas Turbine Engines

During the period of the 1960s the world enjoyed an affair of preference for new and "space age" devices. During this period aeroderivative gas turbine engines saw service in some limited merchant shipping activities. It was during this time, for example, that the Golden Gate Ferry district first procured gas turbine-driven high speed ferries to serve San Francisco. However, the Oil Embargo of 1973/74 and the skyrocketing fuel prices associated therewith almost eliminated gas turbines as prime movers for merchant ships because of their inferior fuel economy compared to medium and low-speed diesel engines. Today however there has been a resurgence of interest in gas turbine propulsion.

Gas turbines are small and compact for their power level – especially when compared to low-speed diesels. They have recently enjoyed a revival as a prime mover for the growing number of fast ferries that are subject to severe space and weight restrictions and which transport a "cargo" that appreciates reduced traveling time. Gas turbines have also seen success in cruise ships, because their very high operating RPMs result in a nearly vibration-free machinery plant and thus a potentially quieter, smoother ride.

It is not evident, however, that these virtues of the gas turbine are sufficient to qualify it for the propulsion of the greater part of the merchant fleet. Its disadvantage in terms of its preference for high quality fuel and its relatively low fuel efficiency, in particular at part load, surely detract from its acceptability. This is recognized clearly by the turbine manufacturers, and thus a significant part of their efforts is devoted to increasing the fuel efficiency of their gas turbines. The U.S. Department of Energy has also recognized this and has sponsored several cost-shared Advanced Turbine Development programs to boost the efficiencies of U.S gas turbine engines. Additionally while the gas turbines have a much lower power-to-weight ratio, they do require a greater amount of interior space for intakes and exhaust which also becomes a design tradeoff issue.

The latest generation of marine gas turbine – including engines which are still slightly "over the horizon" – includes intercooled, recuperated or regenerative gas turbines. These machines capture heat from the turbine exhaust and recover the energy in order to increase the overall thermal efficiency of the machine. As a result the fuel consumption per unit power generated is reduced and part load efficiencies are increased as well.

The recuperators increase the size and weight of the machine and thus somewhat erode the machine's advantage in these areas. Turbine manufacturers also claim their engines to be of greater reliability than a diesel. The absence of reciprocating parts brings to mind the Mazda car commercials of the 1970s, wherein we were enjoined to consider that "whirr" was better than "bounce bounce bounce." In similar fashion turbine manufacturers state that a modern gas turbine will run for many thousands of hours with only periodic inspections. Indeed, in fast ferry applications and land-based stationary power applications the machines are run completely unattended for hours at a time.

Recent RINA reports suggest that the experience "from the first gas turbine-powered cruise ships now in service seem to confirm a number of benefits offered by this form of main propulsion over conventional diesel-mechanical and diesel-electric systems. The vessels in question are Celebrity Cruises' *Millennium* and *Infinity*, both built by Chantiers de l'Atlantique, and Royal Caribbean International's *Radiance of the Seas*, very recently completed by Meyer Werft. Each of these three ships is powered by two GE LM2500+ gas turbines.

"In the early stages of winning these orders, GE believed (as reported in a paper presented at the Seatrade Miami conference) that both the owner and the shipyard would be concentrating most heavily on the following power plant issues when considering new ship designs:

- space utilisation aboard ship
- environmental friendliness
- passenger comfort
- maintenance costs
- reliability.

"General Electric's original estimates claimed that as many as 50 additional passenger cabins could be realized as a result of installing a COGES plant (combined gas turbine and steam turbine with integrated electric drive) in the original engineroom space designed for a diesel plant. In both *Millennium* and *Radiance of the Seas*, the designers did, in fact, find this much space and the cabins were added. Additionally, Meyer Werft is refining the design of the follow-on ships, *Brilliance of the Seas* and sisters, to move the engineroom aft, which will result in considerably more public space along with an increase in passenger cabins.

"Another approach that has come about as a result of the compact and lightweight design of the GE gas turbine package is placing the gas turbine generator in the funnel. This is being done on two classes of P&O Princess Cruises vessels, also onboard Cunard's new *Queen Mary 2*. On the latter ship, the extremely high power requirement dictated the use of gas turbines in addition to four Wartsila diesel engines. Once again, because of the light weight and compactness of the gas turbine package, the designers were able to place two gas turbo-alternators in the funnel."

In addition, significant environmental attractions exist for gas turbines. According to RINA "Royal Caribbean's decision to utilize gas turbines in its next generation of cruise liners was heavily driven by its desire to lead the industry in the construction of environmentally friendly ships. In 1998, GE claimed that its LM2500+ gas turbine would reduce emissions by 98% from that of current diesel technology. During the hand-over of Millennium to Celebrity (today a Royal Caribbean associate), actual exhaust stack emission measurements were taken. Not only was there no visible smoke, but the NOx emissions were found to be only 5g/kWh. This is less than half the minimum level targeted by IMO.

"Of course, diesel engine manufacturers have not been standing idly by during the past three years. MAN B&W has its 'invisible smoke' technology which incorporates fuel/water emulsification, auxiliary blower, and special turbocharger. Meanwhile, Wartsila NSD is developing its 'smokeless diesel' which incorporates a new ultra high-pressure common rail fuel system. In addition, the Finns use direct water injection to reduce NOx emissions. 'Both these technologies are not new and add a considerable amount of complexity to the installation and operation of these engines,' claims David Whisenhunt, general manager of commercial marine systems at S&S Energy Products (part of the GE Group). 'On *Millenium*, we have proven that our gas turbines operate without visible smoke and actually meet the 5g/kWh target that we quoted in 1998. No new development was necessary to accomplish this,'"

Regarding reliability and maintenance, it is reported "Although there have, as yet, been no major gas turbine-related repair, events on *Millenium*, the jury is really still out. It will probably take another year for crews to wholeheartedly believe what GE has been saying all along about how simple gas turbines are to maintain onboard.

"As opposed to changing or repairing major components on a set schedule, which is normally the case with diesel engines, repairs to the LM2500+ sets are carried out based on condition observed during regular borescope inspections. These are normally done approximately once every 2500 hours.

"The last borescope inspection on *Millenium* was carried out in January this year [2001]. The service engineer stated that internal components still 'looked like new' after 5000 hours of operation. At that rate, it is the opinion of GE experts that the predicted 15,000 hour hot-section repair interval will be easily passed.

"Royal Caribbean elected to enter into a long- term maintenance agreement with GE for its gas turbines. This contract covers all scheduled maintenance activities, including hot section repairs. GE has been told by the owner that the cost of the contract was comparable to its diesel engine maintenance at the time on a cost/MW basis. Today, as diesel engines become somewhat more complex because of emission requirements, their maintenance cost seems likely to increase. This could make gas turbines even more attractive in the future."

Regarding reliability, the RINA article goes on to say: “Another operational aspect that has been rarely debated by opponents of gas turbine technology is reliability. With more than 25 years of operating history in the US Navy, the LM2500 has a proven track record. Because of this, the LM2500 and the LM2500+ are recognized as the standard for modern gas turbine design technology when it comes to reliability.

“The turbines aboard *Millenium* should prove no exception. It is now more than a year ago since they were first started up in the shipyard, and both units are reported to have operated flawlessly, requiring no repairs to date. The entire COGES system is claimed to have operated continuously without any event causing a delay in the ship's schedule.”

The activity of the cruise ship industry in the adoption of gas turbines may have important applicability for the container industry as well. Both industries are conservative and highly competitive. Also, both industries face pressure to reduce the environmental impact of their service. The RINA article notes “Because of an emphasis on environment friendly ships, both owners and yards have changed their attitude towards gas turbine power since the concept was first considered in 1995 and Royal Caribbean took the lead with the first orders in 1998. Many major cruise shipping companies have now placed orders for ship with GE LM2500 and LM2500+ gas turbine onboard, Owners appear to have recognized that gas turbines fulfill the need for cleaner propulsion plant emissions without adding significantly more complexity. Yards such as Chantiers de I'Atlantique, Meyer Werft, and Fincantieri are reported to be convinced that gas turbines are actually easier and less costly to install.”

“S&S Energy Products' David Whisenhunt believes that after a few more years' experience in operating gas turbines, crews will plead for a total change-over to this machinery. 'They will find their lives much simpler in the face of increasingly stringent environmental regulations for waste and sludge, not to mention the chore of keeping the newer, more complex diesel engines tuned to limit visible smoke and emissions,' he says.

Marine gas turbines generally are developed either from land-based power units or from aircraft engines. Since land-based units, such as the Westinghouse 501, are designed from the beginning to operate on land, weight usually isn't an important design criterion so most (but not all) units tend to be very large and very heavy. Aero-derivative turbines, as the name implies, are developed from engines designed for aircraft use. These units are smaller and lighter than the land-based units, but their durability is not as good. Since weight and volume traditionally are important considerations when selecting a ship powerplant, and since marine engines operate for much fewer hours and at lower power levels than do land-based units, most large marine gas turbine engines are of the aero-derivative type. However it is important to note the similarity of evolution of the land-based turbine and the marine low-speed diesel. In both of these machines the evidence points to an emphasis upon reliability and efficiency, with little attention given to weight or size.

Marine gas turbines have power turbines that are either mechanically coupled or aerodynamically coupled to the gas generator section. Each configuration has its advantages and disadvantages. Mechanically-coupled engines, such as the General Electric LM6000, typically are more efficient than the aerodynamically-coupled engines. One disadvantage, however, is that minimum power turbine rotational speed is fixed at a relatively high level because the same shaft also drives the low-pressure compressor stages, which cannot turn too slowly or the engine will stall. The aerodynamically-coupled engines are the opposite: the efficiencies are slightly lower but the power turbine can operate at very low speeds since the power turbine is not directly coupled to the compressor. Another advantage of mechanical coupling is that some engines that have it allow power takeoff from the compressor end as well as from the exhaust end. Most marine gas turbines also are simple cycle, having only compression, combustion, and expansion processes typical of a Brayton open cycle. The Northrop Grumman WR-21 engine now in development, however, is not simple cycle. It has an intercooler and recuperator (also called a regenerator) so it often is referred to as the ICR engine. The ICR cycle provides good fuel efficiency even at low power levels, but it does so at the expense of added complexity, size, and weight. Reliability is unknown at this time, however, since its development has been primarily for military naval applications it is assumed to be high.

3.1.1 Current State of the Art Size

In the power levels of interest for container shipping (50-100+ MW) the turbine options available currently or in the near future are listed below. Note that there are other turbine manufacturers than those listed, but these are arguably the leading ones in marine propulsion:

- GE LM2500+
- GE LM6000
- GE 90
- GE Frame 6B
- GE Frame 7
- Rolls-Royce V2500
- Rolls-Royce Trent
- Westinghouse 501

The characteristics of these engines are given in Table 1. They are described below:

<u>General Electric LM2500+</u> - An upgrade of the LM2500 aero-derivative engine, the LM2500+ is a simple cycle gas turbine engine with an introductory ISO continuous rating of 27,050 kW and a U.S. Navy rating of 26,100 kW. Initially derived from the TF-39 engine used on DC-10 wide-bodied jets, the two-shaft design has an output speed of 3600 rpm to

permit direct coupling to a 60 Hz generator. This engine has been used several times for cruise liner electric propulsion. The two-shaft design consists of a gas generator and power turbine. The gas generator consists of a variable geometry compressor, an annular combustor, high pressure turbine, an accessory drive gear box, controls and accessories. The 16-stage compressor is of the high-pressure-ratio, axial flow design. The LM2500+ also utilizes a "zero stage" on the compressor with a resulting increase in airflow, which allows for the upgraded power rating from the base LM2500. The 6-stage low pressure power turbine is aerodynamically coupled to the gas generator and driven by the gas generator exhaust.

General Electric LM6000 - This engine is derived from the GE CF6-80C2 aircraft engine used in the Boeing 747 and 767, the McDonnell Douglas MD-11, and the Airbus A300. Being designed for simple-cycle, combined-cycle and cogeneration installations the LM6000 has an output speed of 3600 rpm and can be directly coupled to an electric generator for 60 Hz applications. The LM6000 has an ISO rating of 43,860 kW. The concentric two-shaft arrangement has the low pressure compressor and low pressure turbine on one shaft, forming the low pressure rotor, and the high pressure compressor and high pressure turbine on the other shaft, forming the high pressure rotor. Utilizing a 5-stage low pressure section and a 14 stage high pressure section results in a compression ratio for each section of 2.4:1 and 12:1, respectively. The combustion system is of the annular type and can be operated with natural gas, liquid fuel, or dual fuel. The combustion gases expand through a 2-stage, air-cooled, high pressure turbine and a 5-stage low pressure turbine. Over 160 LM6000 units are currently in shore-side operation for simple-cycle, combined-cycle or cogeneration projects worldwide.

General Electric LM9000 - The LM9000 is a nomenclature assigned to a nominal 125 MW aero-derivative engine which could be developed from either the CF6-880C2 or from a GE90 core (the engine is currently in service in the Boeing 777 aircraft.) Although some preliminary studies have been completed by the manufacturer concerning the possibilities of such development, no decision has yet been made to proceed with further development. According to the manufacturer, any decision to proceed with the development would depend upon assessment of the market for an aero-derivative gas turbine in this power class.

General Electric Frame 6B – The GE Frame 6B is currently used in 60 Hz industrial power cogeneration applications worldwide. With a manufacturer's nominal rating of 38 MW, the Frame 6B has an estimated navy continuous rating of 34,525 kW for specified marine applications. This simple-cycle engine has a 17-stage axial-flow compressor with modulated inlet guide vanes resulting in a compression ratio of 11.8:1. It is equipped with a reverse flow, multi-chamber (can annular), single nozzle combustion chamber with its exhaust expanding into a 3-stage power turbine.

General Electric Frame 7 – This engine, like the Frame 6B, is also designed specifically for 60 Hz power generation. Designed to be directly coupled to a generator, the Frame 7 has a manufacturers rating of 85.4 MW. For proposed naval applications, however, the Frame 7 has been de-rated at approximately 77.9 MW. This simple-cycle engine has a 17-stage axial-flow compressor with modulated inlet guide vanes resulting in a compression ratio of 12.2:1. It is equipped with a reverse flow, multi-chamber (can annular), single nozzle combustion chamber with its exhaust expanding into a 3-stage power turbine. This gas turbine is available primarily for electric utility applications, this fuel-flexible power generator is used in cogeneration and combined-cycle power plants.

Rolls-Royce V2500 - This family of aircraft engines is used exclusively in the Airbus A319, A320 and A321. Currently, the V2500 is only available in the aero form and there are no immediate plans by the manufacturer to convert this engine for use in marine or industrial applications.

Rolls Royce Marine Trent - The Marine Trent is based on the on the Rolls-Royce Industrial Trent power generation gas turbine which, in turn, is a derivative of the Trent 700 and 800 aero engine. The result is a mature powerplant having a marine rating of approximately 47.5 MW. The three-shaft design Marine Trent engine replaces the industrial dual gas/liquid fueled combustion system with a simplified liquid-only system. The engine is equipped with a 2-stage, axial configuration low pressure compressor with variable inlet guide vanes, an 8-stage intermediate pressure compressor and a 6-stage high pressure compressor. It has an annular combustion system. The low pressure turbine consists of 5-stages of high aspect ratio rotor and stator blades. The low pressure turbine is followed by a single stage intermediate pressure axial turbine and a high pressure turbine. In addition, due to the power turbine being able to run down a typical cube law power/speed curve to idle, the large low pressure compressor handling bleed and ducting needed in synchronous power generation applications is not required and has been removed.

Siemens/Westinghouse 501 – The 501 engine has been the key element of a self-contained electrical power generating system termed ECONOPAC, which is nominally rated at 160 MW. For naval applications the 501 engine has a reduced rating of 145.4 MW using a conventional combustor with distillate fuel. Commercial marine rating would likely be similar. The engine is designed for simple-cycle and heat-recovery applications. The single-shaft engine has a 16-stage axial flow compressor yielding a compression ratio of 14:1. The combustion system is composed of 16 single-nozzle combustors in can-annular arrangement. The power turbine is a 4-stage reaction turbine. This engine primarily has been installed in industrial power generation applications, and is not currently used in any marine applications due to its large physical size and weight. Note, however, that it is not far from the power being discussed in future generation 10,000+ TEU ships.

Table 1 - Characteristics of Major Gas Turbines

	General Electric LM2500+	General Electric LM6000	General Electric Frame 6B	General Electric Frame 7	Rolls-Royce TRENT	Westinghouse 501
AERO-DERIVATIVE ENGINE	YES	YES	NO	NO	YES	NO
CURRENT MARINE APPLICATION	YES	NO	NO	NO	YES	YES
FUTURE MARINE APPLICATION	YES	YES	NO	NO	YES	YES
MAXIMUM RATED POWER OUTPUT	35,000 hp (26,100 kW)	50,000 hp (37,285 kW)	46,300 hp (34,525 kW)	104,465 hp (77,900 kW)	63,700 hp (47,500 kW)	195,000 hp (145,410 kW)
FUEL CONSUMPTION	0.373 lb/hp-hr (227 g/kW-hr)	0.345 lb/hp-hr (210 g/kW-hr)	0.455 lb/hp-hr (277 g/kW-hr)	0.437 lb/hp-hr (266 g/kW-hr)	0.337 lb/hp-hr (205 g/kW-hr)	0.433 lb/hp-hr (263 g/kW-hr)
FUEL FLOW RATE	13,010 lb/hr (5901 kg/hr)	17,453 lb/hr (7917 kg/hr)	2,320 lb/hr (9217 kg/hr)	45,965 lb/hr (20,849 kg//hr)	22,000 lb/hr (9979 kg/hr)	18,750 lb/hr (8505 kg/hr)
EXHAUST GAS TEMPERATURE	948 °F (509 °C)	878 °F (471 °C)	1015 °F (546 °C)	1022 °F (550 °C)	800 °F (428 °C)	1112 °F (600 °C)
EXHAUST GAS FLOW RATE	658,800 lb/hr (298,800 kg/hr)	1,008,000 lb/hr (457,200 kg/hr)	1,045,000 lb/hr (474,000 kg/hr)	2,162,200 lb/hr (980,757 kg/hr)	1,263,600 lb/hr (573,120 kg/hr)	3,335,520 lb/hr (1,512,966 kg/hr)
UNIT WEIGHT	50,706 lb (23,000 kg)	63,934 lb (29,000 kg)	210,000 lb (95,255 kg)	353,500 lb (160,345 kg)	57,000 lb (26,000 kg)	748,000 lb (339,287 kg)
DIMENSIONS	27.6 x 8.7 x 9.8 ft (8.4 x 2.7 x 3.0 m)	36.1 x 11.8 x 13.1 ft (11.0 x 3.6 x 4.0 m)	22.9 x 10.5 x 12.5 ft (7.0 x 3.2 x 3.8 m)	37.9 x 11.7 x 12.8 ft (11.6 x 3.6 x 3.9 m)	36.1 x 13.1 x 13.1 ft (11.0 x 4.0 x 4.0 m)	33.7 x 11.9 x 13.8 ft (10.3 x 3.6 x 4.2 m)
SPEED OF OPERATION	Power Turbine 3600 rpm	Power Turbine 3600 rpm	Power Turbine 5133 rpm	Power Turbine 3600 rpm	Power Turbine 3600 rpm	Power Turbine 3600 rpm
MAINTENANCE REQUIREMENTS	N/A	N/A	TBO – 48000 hrs	TBO – 48000 hrs	TBO – 12000 hrs	TBO – 38500 hrs
ENGINE EMISSIONS DATA	N/A	NOx levels below 25 ppmvd	NOx levels below 25 ppmvd	NOx levels below 25 ppmvd	NOx levels approx. 650 ppmvd	NOx levels approx. 42 ppmvd
AUXILIARY POWER	N/A	159 kW	532 kW	792 kW	470 kW	870 kW
LUBE OIL FLOW RATE	N/A	N/A	N/A	N/A	N/A	600 gpm (136 m^3/hr)
INTAKE AIR FLOW RATE	N/A	225,000 scfm (362,800 Nm^3/hr)	N/A	N/A	N/A	N/A
COOLING AIR REQUIREMENTS	N/A	60,000 scfm (96,800 Nm^3/hr)	N/A	N/A	43,225 scfm (73,330 Nm^3/hr)	N/A
COOLING WATER REQUIREMENTS	N/A	120 gpm @ 95 F (27.3 m^3/hr @ 35 C)	N/A	N/A	N/A	N/A
STARTING REQUIREMENTS	N/A	Electro-Hydraulic (200 hp)	Electric Motor (660 hp)	Electric Motor (1200 hp)	Hydraulic	Electric Motor (2200 hp)

N/A - Information not available from manufacturer.
ppmvd – parts per million, volumetric (dry).

TEST CONDITIONS FOR ABOVE INFORMATION

	General Electric LM2500+	General Electric LM6000	General Electric Frame 6B	General Electric Frame 7	Rolls-Royce TRENT	Westinghouse 501
AMBIENT AIR TEMPERATURE	100 °F (38 °C)	100 °F (38 °C)	100 °F (38 °C)	100 °F (38 °C)	86 °F (30 °C)	95 °F (35 °C)
LHV OF DISTILLATE FUEL USED	18,357 BTU/lb (42,700 kJ/kg)	18,357 BTU/lb (42,700 kJ/kg)	18,546 BTU/lb (43,137 kJ/kg)	18,550 BTU/lb (43,147 kJ/kg)	18,450 BTU/lb (42,915 kJ/kg)	18,450 BTU/lb (42,915 kJ/kg)
INTAKE / EXHAUST LOSSES	4" / 6" w.g.	4" / 6" w.g.	2.5" / 5.5" w.g.	2.5" / 5.5" w.g.	4" / 6" w.g.	3.6" / 4.2" w.g.
ELEVATION	Sea Level	Sea Level	Sea Level	Sea Level	Sea Level	Sea Level
RELATIVE HUMIDITY	60%	60%	60%	60%	60%	60%

w.g. – water, gauge.

3.1.2 Current State of the Art Efficiency

Table 1 presents physical and fuel consumption data on the listed engines. As will be seen, the fuel consumption for the turbines ranges from 205 to 277 g/kW-hr. This compares to the diesel's 171 g/kW-hr as a 20% to 60% penalty in fuel consumption. Further, since these engines prefer a lighter grade of fuel, there is an additional cost increase per pound of fuel that may be approximately 50%. The net result of this is that the turbines may cost as much as twice as much in fuel costs, as compared to the diesels. This of course adds to the total life cycle cost of the gas turbine propulsion plant alternative as well as a modification of the world-wide bunkers infrastructure.

3.1.3 Current State of the Art Weight

The weight of the turbines is given in Table 2 This weight is for the gas turbine alone, not including the required reduction gears. Most of the listed turbines turn at about 3600 rpm. Thus a double-stage reduction gear is required to reduce the rpm to the 100-200 at the ship's propeller.

Gears of this power and ratio will be large and heavy, often as heavy as the turbine engine itself. Indeed, a reduction gear weight of about 1 tonne per MW is likely. Thus the weight of the turbine engine must be increased from, say, 20% to 100% to account for the weight of required reduction gears. (A greater weight penalty with the lighter aeroderivative engines.)

The result of this is a range of engine-plus-gear weights as follows. As may be seen, despite large gear weights these engines are still substantially lighter than the thousand-tonne-plus diesels. This weight reduction might in some services be converted into extra revenue capacity. However, due to the noted fuel consumption penalty, this weight reduction will be completely eliminated by an increase in the required fuel capacity. The result is that there is no net reduction in machinery weight, no net increase in ship revenue, and a substantial increase in recurring fuel costs.

These economic considerations will be developed in the next chapter of this report.

Table 2 - Gas Turbine Weight Characteristics

	GE LM2500+	GE LM6000	GE Frame6B	GE Frame7	Rolls Royce Trent	West'h'se 501
Power	26.1 MW	37.3 MW	34.5 MW	77.9 MW	47.5 MW	145.4 MW
Engine Weight	23 t	29 t	95 t	160 t	26 t	339 t
Gear Weight	26 t	37 t	35t	78 t	48 t	145 t
Weight, Eng+Gear	49 t	66 t	130 t	238 t	74 t	484 t

3.1.4 Barriers to scaling to Container Ship size

There are no scaling barriers to using gas turbines in the propulsion of container ships. Turbine power is one option that will be assessed from the transportation efficiency point of view, in the next section of this report. As previously mentioned, the barriers to adoption of gas turbine propulsion in container ships arise from the relatively poor (compared to low-speed diesels) fuel economy of these engines.

3.2 Electric Drive

Electric drive is an alternative transmission methodology rather than an alternative prime mover/power generator. This methodology consists of using a steam, diesel, or gas turbine prime mover, or an alternative power generator (fuel cells or nuclear reactor) to drive a large electric power producer (alternator). The electricity is then sent via wiring to a propulsion motor that turns the propeller. This system would more properly be called an electric transmission, as the prime drive power is still diesel or turbine produced. As may be imagined, the system introduces some losses, as mechanical energy is converted into electricity and then back into mechanical energy. Further, the large alternators and motors required may significantly drive up the weight of the system as compared with a mechanical transmission, especially when compared to the directly coupled low-speed diesel engine configurations.

The attraction of electric drive lies primarily in the ability to distribute power demand over multiple prime movers. Thus several engines may be working together to drive one propeller. This in turn offers the possibility of adjusting load factors so that the engines operate at their most fuel-efficient points throughout a relatively wide range of ship speeds. Cruise ships are increasingly turning to electric drive, with the *Queen Elizabeth II* being a notable example. Electric drive is also of interest for ships with large hotel electric loads, such as cruise ships and warships, because it offers the possibility of having one large machinery "bank", and tapping power off for propulsion or hotel loads equally.

As has been mentioned, electric drive begs the question of how the electricity is produced – whether by diesel, turbine, or other means. In this section of this report we will address only the propulsion motor & generator portion of electric drive. Sections below will address a variety of propulsion power generation options. In this way, the present discussion of electric transmission forms a building block for subsequent discussion of Fuel Cells and Nuclear Power.

3.2.1 Current State of the Art Size

Among the largest electric drive motors currently deployed are those on the passenger liner *Queen Elizabeth II*. These motors have the characteristics given below:

- Length 4.4m
- Width 8.74m
- Height 8.4m
- Weight 285t
- Power 44 MW
- RPM 144
- Power 10kVolt 3 Phase 60 Hz

Additionally, published US Navy reports indicate that the next generation of naval surface combatant – designated DD 21 – will be electrically driven. Based on current destroyer-sized warships we may thus expect the DD-21 to be fitted with two shafts each having 50-70,000 hp electric drive motors.

Limited data is available on a 35MW GEC Alstom motor, having the following characteristics:

- Length 11.2m
- Width 4.25m
- Height 3.75m
- Weight 230t
- Power 35 MW

A developmental motor is the superconducting homopolar motor currently being developed by General Atomics (GA). The following description is taken from a General Atomics data sheet on this project: "General Atomics is performing an assessment of superconducting homopolar motors for ship propulsion as part of the U.S. Navy's quiet electric drive effort. Homopolar motors are simple in design and offer the potential for a large weight reduction when compared to conventional motors.

Because there are no multipole components in the motor it is expected to be acoustically quiet enough to permit hard mounting directly to the ship's hull, thus greatly simplifying integration.

In order for the homopolar motor to fully exploit the advantages of reduced size and weight, the field coils must be superconducting. The coils will be conduction cooled using compact reliable devices called cryocoolers, which do not require the use of bulk liquid cryogens. GA has developed and demonstrated the reliability of conduction-cooled superconducting systems for the Navy under high shock and vibration environments that are suitable for full-scale homopolar motors. Ongoing research and development efforts by the Navy are now focusing on improving the performance and reliability of the motor's current collectors or "brushes." Dry current collectors presently under development show promise for reduced wear rates that may result in no maintenance between ship overhaul cycles.

The conceptual design of the 40,000 HP, 150 RPM motor was developed by the Naval Surface Warfare Center, Annapolis, MD, and is significantly smaller in diameter than any other kind of electric drive propulsion motor of equivalent speed and power, and is expected to have between 1.5% and 2% higher overall efficiency."

The physical characteristics of these motors may be approximately as follows:

- Length 4.1m
- Width 4.3m
- Height 4.3m
- Weight 113t
- Power 31 MW
- RPM 100

3.2.2 Current State of the Art Efficiency

The efficiency of an electric drive system depends upon a number of factors. Not least of these is the type of rectifier / inverter used, and how hard one has "pushed" the rating. For example, adding forced air cooling to some of the components will increase their rating as much as a third, but at lower efficiency.

For a general-purpose efficiency estimate it is not unreasonable to expect electric drive to have a net system efficiency of 90%. This is the ratio between installed engine power and net delivered propeller power.

3.2.3 Current State of the Art Weight

The paragraphs given above provide some characteristics for existing and future ship propulsion motors. From this limited data it is possible to extract a menu of weight vs power, as shown below.

Table 3 - Electric Drive Weight Characteristics

Motor	Technology	Weight	Power	kg/kW
QE-2	Conventional AC	285 t	44 MW	6.47
GEC / Alstom	Conventional AC	230 t	35 MW	6.57
General Atomics	Superconducting	113 t	31 MW	3.65

For the purposes of the present study, then, it appears reasonable to state that current technology motors are available at about 6.5 kW/tonne, and that future technology motors may become available at about 4kW/t. (The author has rounded the figure of 3.65 to 4 in order to reflect the developmental status of the motors. It would be unrealistic to use a prototype figure to three significant digits to represent a production unit that may be ten years away.)

3.2.4 Barriers to scaling to Container Ship size

There are no barriers to scaling electric drive technology to container ship size, at least not when using current state of the art motors. Indeed, the drives on the QE 2 are very nearly of the size required for container ships. Further, ongoing R&D programs including those motivated by the DD-21 and other Navy acquisition programs, will assuredly result in advances and developments of electric motor drive technology for marine propulsion.

3.3 Nuclear – Electric Propulsion

Nuclear power has not been considered since the NS *Savannah* in the 1950s. The Savannah experience is complex and cannot be adequately summarized here. In brief it was that the manning requirements, due to the high degree of training required, and fearful port regulations impaired further development of nuclear merchant ships.

A new type of nuclear power plant has been recently proposed, designated the gas turbine modular helium reactor (GT-MHR). In this type of reactor the heat of reaction causes helium gas to expand. The helium is “blown” across a turbine coupled to an electric alternator. Because of the balance of the reaction this type of reactor is fail-safe: If left uncontrolled it will “wind down” to an idle mode.

The GT-MHR has suggested to several observers an application for shipboard use. Indeed, a parallel CCDOTT project is studying the application of the GT MHR to the FastShip Atlantic vessel.

Conceptually the GT-MHR is similar to a gas turbine, except for the existence 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 recondensed and redelivered to the hot side of the reactor. 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, reducing the reactor size, while a precooler and an intercooler reduce the compression power demand. With such characteristics, a nuclear power plant could achieve a 47.6% thermal efficiency.

Helium is the preferred working fluid for several reasons. This monatomic and low-molecular-weight gas peaks in efficiency at a relatively low compression ratio, imposing small mechanical loading on the turbine blades. It has a high

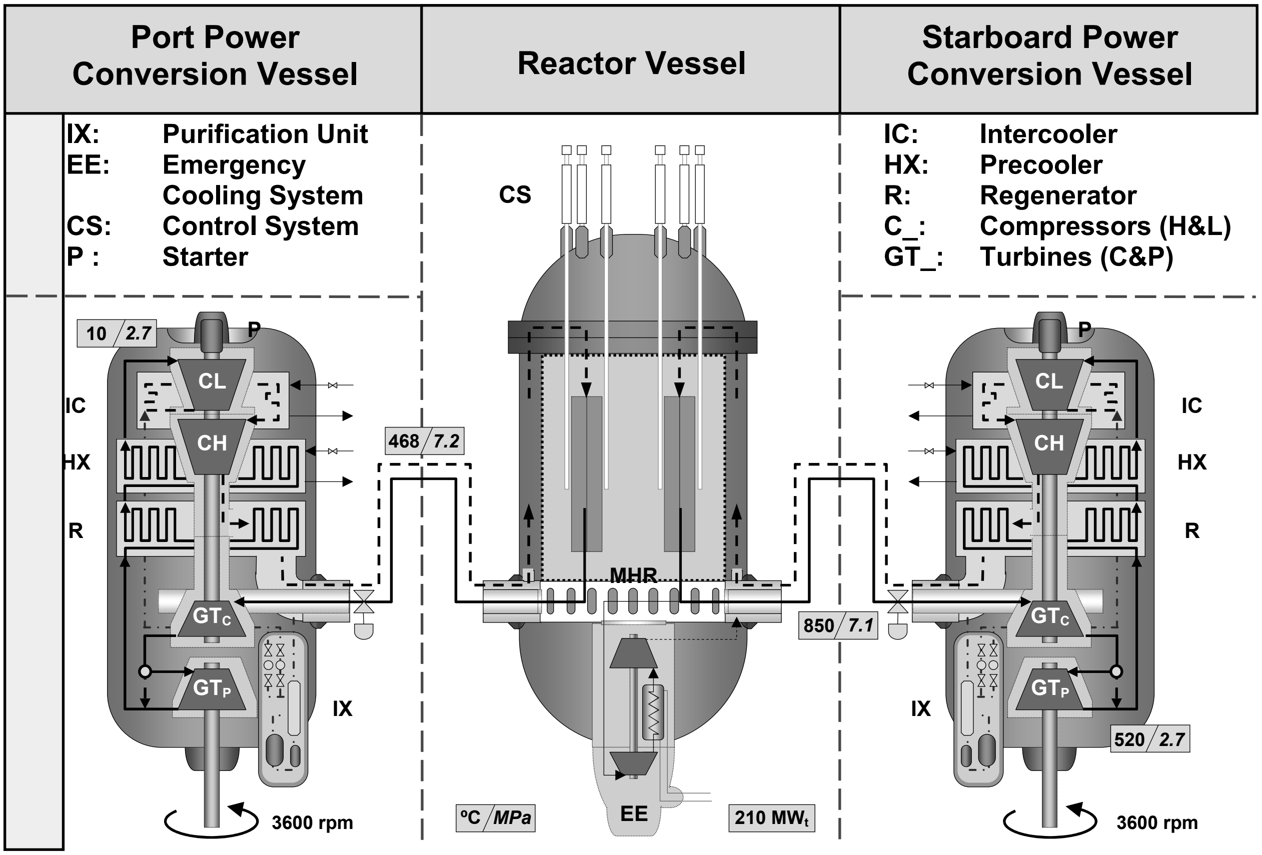

Figure 2 - Helium Flow Circuit in a GT-MHR Propulsion Module

specific heat capacity, high gas constant and a relatively high thermal conductivity, properties which make compact components possible. On the other hand, its low density and high gas constant allow high flow rates without Mach restrictions as in conventional turbines. Its inertness reduces radioactivity within the turbomachinery. The main limitation of helium is cost.

The conceptual container ship GT-MHR powerplant could be as depicted in Figure 2. The plant depicted shows a configured envisaged for two-shaft operation, with one reactor vessel (RV), and two power conversion vessels (PCV). Both the RV and the PCV are located within a radiological containment perimeter. The PCV would produce electric power, which would then be fed to the ship's propulsion motors. Container ship versions of this system would probably utilize a single PCV, for a single shaft ship.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. In the General Atomics GT-MHR, each fuel element is a hexagonal-prismatic graphite matrix 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 hundreds of thousands of 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 three decades, and tested to almost its theoretical burnup.

To remove fission heat, helium is injected to the RV at 7.1 MPa, from the PCV. It ascends through the RV periphery, descends cooling the reactor core, and returns to the PCV, expanding through the compression and power turbines. The ICR cycle is used for a better thermal efficiency, and two compressors make up for expansion and friction pressure drop. Power level control is provided by gas pressure adjustment at nominal efficiency, and by a power turbine by-pass. Figure 6 schematizes the gas flow for one of the GT-MHR modules as applied to FastShip.

3.3.1 Current State of the Art Size

GT-MHRs, and nuclear reactors in general, experience significant economies of scale. Thus most development attention is focused on the deployment of large land-based power generation capabilities. This is in contrast to most alternative propulsion concepts where the problem of scaling up to ship size exists. In nuclear power we are challenged to scale down to ship size.

In the USA the greatest advocate of the GT-MHR has been General Atomics Corp, in San Diego CA. General Atomics is, on a program parallel to the present one, developing a conceptual description of a GT-MHR power plant for the FastShip Atlantic (FSA) cargo ship. This ship application requires about 250 MW total. The GA concept for the FSA application is a two-reactor plant, with two RV/PCV units operating in parallel. This is a fortuitous development decision as it allows the present project to use just one-half of this system for a conventional type container ship.

3.3.2 Current State of the Art Weight

The weights for a complete GT-MHR powerplant, including propulsion motors, is given in Table 4. Added to that table is a column of comparable line item weights for a direct drive low speed diesel powerplant. Note that the diesel plant includes fuel for an estimate 6000 nm range. The nuclear fuel is included as well, but this is not so closely tied to a particular range.

What is surprising is that the nuclear plant is competitive in weight with the diesel plant. And, in addition, it produces 83% more power. In other words it has a substantially improved weight per MegaWatt as compared to the diesel. Of course, it shares this attribute with a gas turbine, which is also lighter than a diesel, but as will be explored later the nuclear plant has no additional fuel weight, whereas the gas turbine plant loses nearly all of its weight advantage due to an increase in the associated fuel weight.

3.3.3 Barriers to scaling to Container Ship size

The barriers to application of the GT-MHR are not technological barriers associated with scaling the powerplant. As has been mentioned the scaling involved is a scaling down to be small enough for a container ship. And the barrier to this scaling will be economic, more than technological.

Of course, a nuclear powered container ship will face barriers in the form of regulation, port admissibility, and public acceptance, but these factors – vitally important though they are – are outside the scope of this project.

Table 4 - GT-MHR Propulsion plant weight, compared to diesel plant weight

Nuclear Plant		Diesel Plant	
Description	1/2 FSA		MAN B+W K98
Reactors	450t		
Shielding	1250t		
Generator	800t	Engines	2157t
Foundations	250t		
Motors	400t		
Motor Control	100t		
Helium System	7.5t		
Heat Exchange	50t	Margin	216
Cabling	50t		
Margin	336t	Fuel	2817t
TOTAL	3693.5t		5190t
Power	125 MW	Power	68 MW
Note	Nuclear plant is one half of plant being conceived for FastShip Atlantic Diesel plant estimates are intentionally optimistic		

3.4 Fuel Cell – Electric Propulsion

Fuel cells are an emerging technology. A fuel cell converts hydrogen fuel into electricity directly. There are no moving parts – the electricity is released when the hydrogen molecule is broken up.

As such, a fuel cell may be thought of as an alternative to a diesel generator. It is indeed such an alternative, with the advantage of having no moving parts and a very high fuel conversion efficiency.

The fuel cell reaction works only on the hydrogen in the fuel. When running a fuel cell with a hydrocarbon liquid fuel it is necessary to first reform the fuel into hydrogen and CO2. As part of or prior to the reformation, it is also vital to remove the sulfur from the fuel before it is used. This process represents an ancillary load on the cell, and requires additional space and weight.

Also, the fuel cell reaction is chemically the same as combustion: Hydrogen is combined with oxygen and released as H2O vapor. Fuel cells thus have the same air intake and exhaust uptake requirements as combustion engines. They also produce waste heat, which is dissipated to cooling water. In all these senses the fuel cell is a direct replacement of a diesel generator.

The advantages of fuel cells are that they lack moving parts, which implies reliability. This is only true, however, for the fuel cell itself. The fuel reformer will certainly be mechanically complex. As will be shown below fuel cells also demonstrate high power density and high thermal efficiency. Use of fuel cells may potentially result in a reduction in plant weight, a reduction in plant complexity, and a negligible reduction in fuel consumption. These advantages may be enough to draw electric propulsion into the ranks of container ships.

3.4.1 Current State of the Art Size

There are no fuel cells on the market specifically configured for ship propulsion. However, fuel cells by their very nature are assembled out of "stacks" of cell elements, in a fashion similar to the way batteries consist of assembled cells. Because of this inherently modular design fuel cells can relatively easily be assembled to almost any size. Nevertheless, there are at present no known fuel cells over 1 MW.

3.4.2 Current State of the Art Efficiency

Net fuel cell plant efficiency (from the VINDICATOR project discussed below) ranges from 42% at 10% load to 51% at most-efficient load. This translates to an equivalent Specific Fuel Consumption of 165 to 200 g/kW-hr. This compares quite favorably with a low speed diesel at a catalog (presumably "best case" fuel consumption of 171 g/kW-hr. Thus total ship fuel consumptions will be similar between fuel cells and low speed diesels.

3.4.3 Current State of the Art Weight

Current fuel cells have power densities slightly better (denser) than generator sets. The hydrogen fuel cell stack is smaller and more compact than the portable generators they replace. However, the fuel cell reaction works only on the hydrogen in the fuel. When running a fuel cell with a liquid hydrocarbon fuel it is necessary to first reform the fuel into hydrogen and CO2. This process represents an ancillary load on the cell, and requires additional space and weight.

Perhaps the most mature fuel cell demonstration project was a project to install fuel cell propulsion generators on the USCGC *VINDICATOR*. The *VINDICATOR* is a former T-AGOS monohull ship, driven by two 800 hp motors energized by four 600 kW diesel generators. The project, performed by JJMA under contract to the US Coast Guard, was to replace the diesel generators with Molten Carbonate fuel cells.

The project concluded that the replacement was feasible, but that the fuel cell power plant would be slightly larger and heavier than the medium speed diesels they were replacing. The figures given in the JJMA final report are as follows:

- Length 26 ft (7.9m)
- Width 7 ft (2.1m)
- Height 11.5 ft (3.35m)
- Weight12,000 lbs (Stack only)
  est. 24,000 lbs complete module (11 t)
- Power 625 kW

Note that the *VINDICATOR* project was replacing medium speed diesels, whereas the present project on container ships considers slow speed diesels as the baseline. As a comparison, consider Table 5 which expresses the baseline low speed diesel and the *VINDICATOR* fuel cell, both in terms of kW / tonne. The fuel cell plant is approximately half to two-thirds the weight per kW of the diesel plant. Indeed, as will be explored later, the weight reduction of the fuel cell is enough to "pay for" the weight addition due to use of electric transmission.

Table 5 - Comparison of power densities of Fuel Cell and Low Speed Diesel

VINDICATOR FUEL CELL	LOW SPEED DIESEL
625 kW	68000 kW
11 t Power generation total	2157 t Diesel Engine
Net: 56.8 kW / tonne Net: 17.6 kg/kW	Net: 31.5 kW / tonne Net: 31.7 kg/kW

3.4.4 Barriers to scaling to Container Ship size

There are two primary barriers to fielding fuel cell propulsion systems on container ships: Size and Reliability. While the fuel cell chemistry is very simple and attractive, at the present time this chemistry is supported by a complex system of fuel reformers, fuel cell controls, and other ancillary systems. As a result the reliability of the fuel cell system is not up to the standards needed. In addition, the manufacturing infrastructure is geared toward much smaller production.

The fuel cell stack itself has an MTBF estimated at 65000 hours (*VINDICATOR* Project), but the system MTBF for the total plant in that project is only 1385 hours.

The research efforts to date have advanced the chemistry of the fuel cell stack. The next step in development and deployment of fuel cells will be to refine their necessary ancillary systems.

Of course, the other barrier to deployment of container ship fuel cell plants is the absence of units of 50-100MW on the market. Indeed, the largest known units are less than 1 MW. However the fuel cell industry is aggressively pursuing the fixed site domestic power utility market, and units of container ship size may be expected in the next five to ten years.

4 CONCLUSIONS

The preceding paragraphs described a variety of alternative propulsion systems for container ships. The table below summarizes the leading naval architectural parameters of these systems.

Concept	**Maturity**	**Weight**	**Fuel Consumption** (68MW / 25kt ship / 6000 nm)
Diesel Baseline	Mature	31.7 kg / kW	2800 t
Gas Turbine Mechanical	Mature	1.5 – 3.8 kg / kW	3377 – 4564 t
GasTurbine /Diesel Electric	Fairly Mature	1.5 – 3.8 kg / kW 6.5 kg / kW alternators 6.5 kg / kW motors 14.5 – 16.8 kg / kW total	3700 – 5000 t (~10% inferior to turbine mechanical)
Nuclear Electric	Immature	29.5 kg / kW	None
Fuel Cell Electric	Immature	17.6 kg / kW FC 6.5 kg / kW motors 24.1 kg / kW total	<2800t