POSSIBLE POWER TRAIN CONCEPTS FOR NUCLEAR POWERED MERCHANT SHIPS

E. Dedes[1], **S.R. Turnock**[1], **D.A. Hudson**[1] and **S. Hirdaris**[2]

[1] Froude Building (28), Faculty of Engineering and the Environment, University of Southampton, University Road, Southampton SO17 1BJ, UK, srt@soton.ac.uk
[2]Lloyds Register of Shipping, 71 Fenchurch St, London EC3M4BS, UK, Spyros.Hirdaris@lr.org

ABSTRACT

Nuclear propulsion has many potential advantages in terms of reduced emissions, as nuclear fission itself has zero CO_2, NO_x, SO_x and PM emissions, although the whole nuclear fuel cycle has an amount of emission associated with it. An overview of current and future reactor technologies suitable for marine propulsion is presented. A comparison in terms of efficiency and technology used is performed and technical and constructional aspects for surface non - military applications are discussed. A debate of feasible ship types is made and proposals of propulsion layouts are highlighted including the use of all electric ship concepts. The actual engine loading and the efficiency of propulsion components have great importance in propulsion behaviour and fuel consumption, which imply further constraints in merchant nuclear propulsion applications in terms of refuelling intervals. The social impacts and constraints in operation of such vessels, orients the designers towards large DWT vessels that can load and unload outside the ports.

Keywords: Nuclear Propulsion, Rankine cycle, Emissions, Hybrid systems, reactor technologies

NOMENCLATURE

$\eta_{Rankine}$: Rankine cycle efficiency
$\eta_{overall}$: Turbine system overall efficiency
W_T : work in the Turbine
W_P : work required at pressuriser
Q_1 : energy supplied by the nuclear reactor
h_i : enthalpies at certain temperature and dryness
$\dot{m}$: steam mass flow
h_p : enthalpy at condenser
P_{total} : the required voyage propulsive power
$\eta_{reactor}$: nuclear reactor efficiency

1. INTRODUCTION

Approximately 80% of world trade by volume is carried by sea (UNCTAD 2008). In 2007 it is estimated that international shipping was responsible for approximately 870 million tonnes of CO_2 emissions, or 2.7% of global anthropogenic CO_2 emissions. By way of comparison this level of emissions is between those of Germany and Japan for the same year. Domestic shipping and fishing activity bring these totals to 1050 million tonnes of CO_2, or 3.3% of global anthropogenic CO_2 emissions. Despite the undoubted CO_2 efficiency of shipping in terms of grammes of CO_2 emitted per tonne-km, it is recognised within the maritime sector that reductions in these totals must be made (IMO, 2009). Shipping is responsible for a greater percentage share of NOx (~37%) and SOx (~28%) emissions (AEA, 2008) and recent legislation is aimed at reducing these emissions through the introduction of emission control areas and requirements on newly built marine diesel engines (MARPOL, 2005). The expected changes in CO_2 emissions from shipping from 2007 to 2050 were modelled for the International Maritime Organisation with reference to the emissions scenarios developed for the UN IPCC. These scenarios are based on global differences in population, economy, land-use and agriculture (IMO, 2009). The base scenarios indicate annual increases of CO_2 emissions in the range 1.9-2.7%, with the extreme scenarios predicting changes of 5.2% and -0.8%, respectively. The increase in emissions is related to predicted growth in seaborne transport. If global emissions of CO_2 are to be stabilised at a level consistent with a 2°C rise in global average temperature by 2050 it is clear that the shipping sector must find ways to stabilise, or reduce, its emissions – or these projected values will account for 12% to 18% of all total permissible CO_2 emissions. CO_2 emissions from world shipping are directly related to the fuel consumption of the fleet.

In 2007 approximately 277 million tonnes of fuel were consumed by international shipping. Three categories of ship account for almost two thirds of this consumption. The liquid bulk sector accounts for ~65 million tonnes fuel/year, container vessels for ~55 million tonnes fuel/year and the dry bulk sector for ~53 million tonnes fuel/year (IMO, 2009, p. 59). Figure 1 depicts the actual share of Carbon dioxide per vessel category which is the most important GHG emitted by ships.

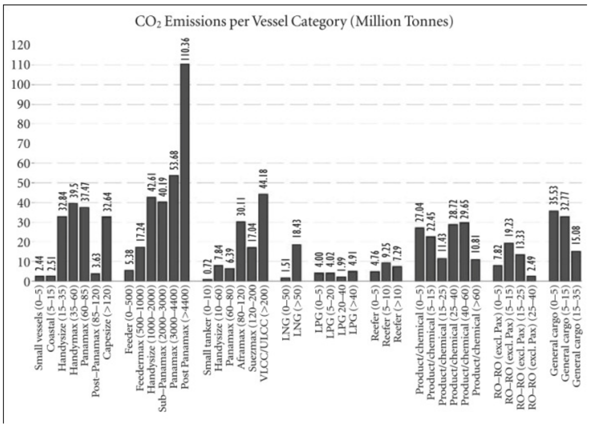

Figure 1: World fleet CO_2 emission share (Psaraftis and Kontovas, 2009)

Both in terms of quantity and of global warming potential, other GHG emissions from ships are less important and current European framework projects, aim in abatement technologies for Nitride Oxides and Sulphur oxides, with promising results (Wright, 2000). These measures if implemented, could increase efficiency and reduce the emissions rate by 25% to 75% below the current levels (Gupta and Batra, 2009). Many of these measures appear to be cost-effective, although financial barriers may discourage their implementation (IMO, 2009).

There are currently 600 nuclear reactors in service globally, of which one third are marine applications of which all but a few are military based. However, the possibility of much lower GHG emissions may lead to a renaissance in the development of a next generation of nuclear powered merchant ships.

The energy in nuclear propulsion comes from the released energy of the fission of ^{235}U which comes from, kinetic energy of the charged fission fragments, the gamma rays due to fission, the subsequent beta and gamma decay and the energy of neutrinos. As it can be extracted, no chemical reactions as in hydrocarbons occur and the energy is considered clean and carbon free in terms of operation. Nevertheless, the mining and the re-processing of spent fuel link nuclear energy with ultra-low GHG emissions.

This paper considers the historic development of nuclear powered ships and their possible re-introduction for marine applications associated with alternative on-board energy management systems.

2. NAVY NUCLEAR PROPULSION

After World War II, Admiral Rickover received the assignment to the division of Reactor Development and the Atomic Energy Commission which his role was to develop the first nuclear powered submarine. The USS Nautilus (SSN-571) was a successful final design which was launched in 1955 and formed the Era of naval nuclear propulsion.

Concerning marine nuclear propulsion, the world's first nuclear powered surface vessel was the 20,000 DWT icebreaker Lenin. Refuelling issues and the unique operational profile of these vessels, which had to break ice up to 2.5 meters thick, made nuclear propulsion attractive. Consequently six more Arktika class icebreakers of approximately 23,500 DWT were launched from 1975 until 1994.

The US-built Savannah was commissioned in 1962 and decommissioned 8 years later. This design was impressive with high safety records, the fuel economy remarkable and the absence of smoke exhaust gases were her undoubted advantages. Although she was a technical success, the ship was not designed to be economically competitive (Pocock, 1970).

Three more civil cargo vessels have been built. The German ore and passenger carrier Otto Hahn (1964), the Japanese research vessel Mutsu (1972) and the Russian container vessel Sevmorput, launched in 1988 which operates in the arctic region and is one of the few remaining operational nuclear powered vessels. The Japanese vessel Mutsu, contributed to the field of marine nuclear propulsion. All the engineering data of design, construction, operation and the decommissioning were systematically arranged and preserved as a database. Furthermore, the reactor responses such as power output to changes in sea state (required Thrust increase) are available.

The previous mentioned commercial designs became actual vessels; two more did not have the chance to fruit. The Vickers design and the "dozen giants plan" dated around 1973. Both scenarios investigated the installation of nuclear reactors in tanker vessels. The Vickers plan was developed by the RnD department of Vickers Armstrong's Naval Construction work. The design was made for a 63000 DWT tanker vessel equipped with Advanced Gas Reactor (AGR). It was believed that Pressurized Water Reactors (PWR) were economically unfeasible due to the need for highly enriched Uranium (HEU). Of particular concern was the reactor placement, the motion behaviour of the rector at high sea states and the necessary crew shielding. The reactor compartment was enclosed by double bulkheads. Deep tanks and collision absorbent mattresses covered the sides. The reactor compartment was gas shielded since at that period AGR design did not offer protection in the case of radioactive CO_2 leakage. Despite the existence of the shielding the vessel was equipped with an exhaust piping system, so that radioactive stream could escape at high velocity to the atmosphere, without affecting the crew and the rest of the vessel structure. The "dozen giants" project involved a combined nuclear – oil fired boilers which could provide super-heated steam (MER, 2011).

3. REACTOR TECHNOLOGIES

In the last decades, many reactor designs have been established, either in stationary civil applications, or for naval vessels. The basic quantities for comparison are the thermal to electric efficiency, the moderator and coolant types and the fuel, in terms of supplying quantity and its lifecycle. This paper will focus only on reactor designs that are applicable to marine propulsion.

The most successful design is the Pressurised Water Reactor (PWR), which was developed by United States for submarine and aircraft carrier propulsion. It is consisted from 200 - 300 fuel rods and installed fuel quantity usually reaches 100 tonnes. The core temperature is on average at 325 degrees Celsius while the pressure is kept at 155 BAR. It has two separate circuits which prohibits the contaminated coolant, which is water and acts as a moderator as well, to reach the turbines. The heat exchange takes place in a high efficiency heat exchanger located inside the reactor compartment and the secondary circuit supplies lower quality steam than a conventional oil fired boiler to the turbines (Lamarsh and Baratta, 2001). The propulsion can be achieved by turbines and large gear boxes that are connected to the propulsion shafts or by generating electric energy (Carlton, et al., 2010). The fuel is highly enriched Uranium. However, in civil applications, enrichment is limited to less than 20%.

Advanced Gas Cooled Reactors (AGR) were found only in the design of Vickers. Although the British design to replace the magnesium alloy cladding (Magnox) allows higher fuel and coolant temperature that leads to better thermal efficiency 40%, thus steam quality, it is not believed that this type follows the current trend for compact and small dimensional designs that new vessels dictate.

Fast reactors were fit to the vessels of the soviet navy. The unique characteristics are that nuclear fission reaction is sustained by fast neutrons while there is no neutron moderator, something that implies highly enriched material (Uranium or Plutonium). Nevertheless, by applying neutron economy, a number of neutrons can breed more fuel or transmute long life waste, parameters that are crucial for the modern success of nuclear energy.

3.1 NOVEL REACTOR TECHNOLOGIES

A new technology of nuclear Reactors is proposed by various manufacturers such as Toshiba, Mitsubishi or Hyperion Energy. This is called Small Modular Reactor (SMR) which is more like a nuclear battery than a reactor propulsion layout. It has a 36% thermal to electrical efficiency, competitive to the European Pressurised Reactor (EPR) design of the French Areva company.

These reactors are modular, can fit into a twenty-foot container (TEU) and weigh approximately two tonnes per installed MWe. The fuel is Low Enrichment (<20%) Uranium (LEU). Details for example of the SMR design of Hyperion energy are presented in Table 1.

Table 1: Hyperion Energy, Small Modular Reactor (SMR) basic commercial characteristics

Reactor Power: 70$MW_{thermal}$
Electrical output : 25$MW_{electrical}$
Lifetime: 8 - 10 years
Size: 1.5m w by 2.5m h
Weight: Less than 50tons including pressure vessel, fuel and primary coolant LBE
Structural material : Staineless steel
Coolant: PbBi
Fuel: Stainless clad, uranium nitride (U_2N_3)
Enrichment: %U-235 less than 20%
Refuel on site: No
Sealed core: Yes
License : Design certification
Passive shutdown : yes
Active Shutdown: Yes
Transportable : Yes; intact core
Factory fuelled : Yes
Safety and Control Elements: 2 redundant shutdown systems & reactivity control rods

3.2 REACTOR DESIGN COMPARISON

The reactor comparison will be based on the following parameters. The first and important is the burn-up. This term describes the energy produced per unit of mass fuel [GW days/tonne]. A typical Value of a PWR design is 45000GWdays/tonne compared to a gas fired boiler which is 0.4GWdays/tonne. The second parameter is the thermal to electrical efficiency. This efficiency comprises the steam generator efficiency and the electric generator efficiency which varies according to the load. Other important parameters for the consumption of fuel are the operating temperatures and pressures. In general PWR designs operate at the temperature range around 320^{0}C and 155bar pressure with a temperature drop equal to 30^{0}C and 9bar pressure drop due to the operation of the secondary steam cycle. Table 2 contains a comparison of civil reactor designs in general. In marine applications as it was mentioned PWR and fast Reactors have already been installed on naval vessels. Gas reactors, despite their high efficiency and operating temperatures, are not viable due to their low power density.. Advanced boiling water reactor (BWR) designs, should however be investigated in the future.

Table 2: Characteristics of civil reactor commercial designs (HMS-Sultan, 2008; Bocock, 1970)

Reactor	PWR	BWR	MAGNOX	AGR
Fuel:	3% LEU	2.2% LEU	Natural Uranium	2% LE UO_2
Cladding	Zircalloy	Zircalloy	Magnesium alloy	St. Steel
Moderator	Light Water	Light Water	Graphite	Graphite
Coolant	Light Water	Light Water	Carbon dioxide	Carbon Dioxide
Outlet Temp.	318	318	360	620
Steam Temp.	285	286	345HP 330LP	540
Steam Pressure	69	75	150	40HP 11LP
Efficiency	32%	32%	33%	42%
Power Density	High	High	Low	Low
Burn-up	High	High	Low	Low

4. SPECIAL MARINE ENGINEERING CONSIDERATIONS

The marine environment is a dynamic with continual variation in load applied to the vessel structure with resultant motions. Unlike commercial nuclear power plants, marine nuclear reactors must be rugged and resilient enough to withstand several decades of rigorous operations at sea, subject to a ship's pitching and rolling and rapidly-changing demands for power, keeping the vessel speed close to that required by the operator. These conditions, combined with the harsh environment within a reactor plant, which subjects components and materials to the long-term effects of irradiation, corrosion, high temperatures and pressures, necessitate an active, thorough and far-sighted technology effort to verify reactor operation and enhance the reliability of operating plants. A nuclear reactor is a device which should not operate under non-stable structural conditions. The nuclear reactor should be placed near the amidships where the longitudinal centre of buoyancy is found at design or scantling draft. The reactor compartment has to be shielded and protected from groundings, collisions and impacts. Nonetheless, these parameters are crucial for the safety of reactor, the scope of this paper will focus on the implied power load fluctuation from the marine environment and ship operation which create the actual operation profile of the reactor.
Unlike other shore based electric generator plants, the marine reactor have to operate at continuous fluctuating load. Depending on the sea state, a rise of total resistance may lead to a power change of ~10%. A typical data set of voyage engine loading fluctuations can be found in Figure 2.

Although the rapid load change is the least important aspect in modern nuclear reactors in respect of accident probability, as designs are under-moderated and have always negative temperature coefficient, the operation of turbo-machinery in non-optimum conditions increase the fuel consumption either the fuel is a HFO or nuclear. Despite the fact the Uranium price is constant the last decades, with the exception of recent problems in mines of Canada which actually increased the price of ^{238}U up to four times, it is important in our opinion to have fully optimised an least energy intensive systems from the early design stage. Minimising fuel usage will either reduce or even completely remove the need for through life refuelling with potentially large cost savings.

The world's economy is volatile and some nations have already deployed an energy self-sufficiency strategy. Currently, the Uranium price is a minor component as it represents only the 7.5% of the total cost, with another 7.5% associated with the fuel enrichment and the rest 85% is the reactor and secondary circuit component cost (double gears, turbines and generators) (Abram, 2011).

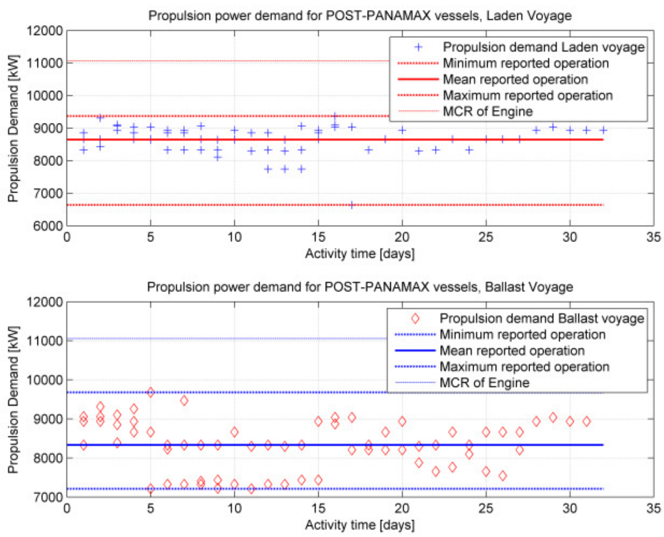

Figure 2: Engine loading based on noon-report data as edited in the work of Dedes, et al. (2011).

Therefore, at the initial stage of a modern nuclear study, the cost of Uranium will be assumed low. Meanwhile, in terms of refuelling, shipping sector requires the vessel to operate most of the time. A 20 day dry-docking on average per year is assumed. According to class regulations, intermediate and special surveys occur while the ship is dry-docked, and repairs and planned hull and machinery maintenance occur. While refuelling in Nuclear Reactors is not an easy and fast process, refuelling has to be performed during special surveys (intervals of 5 years) and depending on the extent of repairs to be completed by the end of dry-docking. As a result, 30 days for refuelling and general repairs at 10 years special survey is ideal. Nonetheless, the refuelling period can be extended as the ship during the period of 10 years, could have skipped the bunkering process that sometimes occurs in bunker stations that actually stop the vessel and thus increase the available voyage time. As a result, saved days could be added at the one or two nuclear refuelling per vessel's life time intervals, without affecting the operational availability of the nuclear powered ship.

In our view, if a large nuclear fleet become a reality, fuel availability and prices have to be investigated thoroughly. According to Deutch et al. (2003) updated by Ansolabehere et al., (2008), the supply of Uranium ore can withstand demand of up to 1000 reactors of 1000MWe without accounting any new deposits or the construction of fast breed reactors. The global growth scenario projects that by 2050, 1000GWe of Nuclear power will share the 19% of global electrical power generation.

4.1 RANKINE CYCLE AND PROPULSION COMPONENTS EFFICIENCIES

Although, nuclear fuel is cheap compared to oil and gas propulsion the power train should run at or near optimum conditions for most of the operational time in order to achieve sustainability. Reactor technology however still limits the possibility for drastic improvements in steam generation efficiency. The following graphs explain the steam cycles occurring in conventional and nuclear steam power plants. Figure 3 depicts a steam cycle with superheating.

z

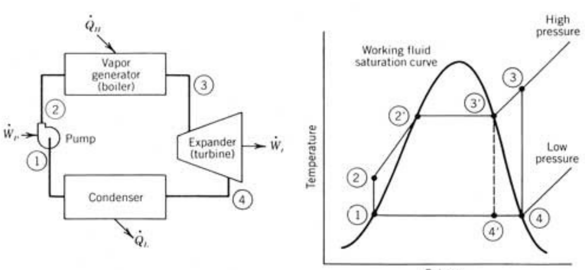

Figure 3: Steam Cycle with superheating 3'-3 and one expander (turbine).

Superheating is a better way to increase Rankine efficiency by the extra area of (3' 3 4 4') (Van Wylen and Sonntag, 1978). Superheated steam ensures longer turbine life because of the absence of erosion from high-velocity water particles that are suspended in wet vapour (Rajput, 2009). Moreover, the Rankine cycle efficiency can be improved by increasing the average temperature (2' - 3') which heat is supplied (2- 3') or by decreasing the temperature which heat is rejected (points refer to Figure 3). Figure 4 represents the actual nuclear cycle where no superheating is possible as the cycle has to operate at lower temperatures due to reactor constraints (Nuclear cycle typical values are: $T_{3'}$= 285^{0}C, $X_{3'}$ ~=0.9975, $P_{3'}$= 69bar, while typical steam, T_3=600^{0}C, X_3>1, P_3= 80bar).

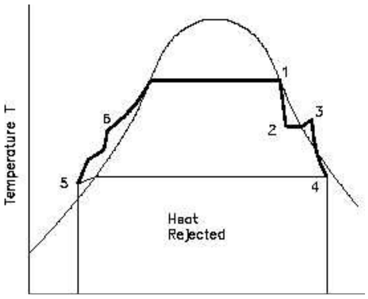

Figure 4: Nuclear steam cycle using two expanders, with reheating (2-3) between high pressure (HP) (1-2) turbine and low pressure (LP) turbine (3-4) and preheating (5-6)

To increase efficiency and to protect the low pressure turbine from operating with steam of dryness <0.9 (X<0.9), reheating accurs after the high pressure turbine (HP) and the steam efficiency increases.

If the coolant and moderator is light water (H_2O), in order to keep it in a single phase, the reactor maximum temperature should always be under 550^{0}C. Although operation with two-phase coolant is possible (in BWR designs), it is very difficult to control, therefore BWR designs have lower safety limits. Thus, operational risk increases and other methods for Rankine efficiency increase have to be examined. It has been observed that by increasing the secondary steam cycle boiler pressure, the cycle efficiency tends to rise and reaches maximum value at about 166bar. Thermal efficiency of the cycle increases if the T_{max} (without superheating) is higher and by keeping the T_{min} lower or equal to the initial cycle. This means too that high temperature reactors have increased efficiency.

The net efficiency of the Rankine cycle is given by equation (1.1)

$$n_{Rankine} = \frac{W_T - W_P}{Q_1} = \frac{(h_1 - h_2)\cdot(h_{f4} - h_{f3})}{(h_1 - h_{f4})} \qquad (0.1)$$

where,

W_T : work in the Turbine
W_P : work required at pressuriser

Q_1 : energy supplied by the boiler (nuclear reactor)
h_i : enthalpies at certain temperatures and dryness
Turbo-generator work can be defined by the following equation (1.2):

$$\dot{W} = \dot{m} \cdot \left(h_0 - h_p\right) \cdot \eta_{overall} \qquad (0.2)$$

where:

$\dot{m}$: steam mass flow
h_0 : enthalpy before expansion (in Figure 4, 0 ≡ 1)
h_p : enthalpy at condenser (in Figure 4, p ≡ 4)
η_{overal} : overall efficiency of the turbo-generator system.

The mass flow, pressure drop and the efficiency of the turbine is described by manufacturer system maps. Usually these systems are optimised for a broad range of operation and at high loads, but in every other load, their efficiency drops. Typical turbo-generator efficiency values for example for an LNG operated LNG carrier vessel vary from 0.93 to 0.96.and remain almost constant at high loads (Vakasi, 2009).

5. HYBRID NUCLEAR PROPULSION

For a better understanding of the actual operational constraints the application of nuclear propulsion to a specific voyage based ship operation is made. The work of Dedes et al. (2011) shows that according to the vessel characteristics, mainly described from overall displacement, the fluctuation of engine loading depends on the sea state although less so when vessel displacement exceeds 140,000 tonnes. In smaller vessels, the average voyage power loading variation can exceed 10%, as shown in Figure 2. In the case of conventional nuclear reactor technology, the reactor in order to alter the output, the reactivity ρ(equation 1.3) has to increase so the reactor can become critical again (ρ=0).

$$\rho = \frac{k-1}{k} \qquad (0.3)$$

where,
k : multiplication factor

When k>1 reactor is supercritical and when k<1 reactor is subcritical. At constant load, k=1 (critical condition)

Although modern reactors can rapidly change load (in seconds), the operation of the secondary steam system (turbo-machinery) is affected. Depending on the load, efficiency fluctuates. Ideally, the system should always run under optimum and favourable conditions. However, the propeller loads affect the demand and force the system to react by altering the mass flow and the temperature and pressure drops. The latter are directly connected to the operation of the nuclear reactor. Other parameters affecting loading, hence turbo-machinery operation are the auxiliary loads. Cruise ships, ferries and containerships have notable auxiliary loads with many peak values. A nuclear reactor can either slow down the reaction by part lowering the control rods which absorb a greater proportion of neutrons and 'semi poison' the reactor. However, peak demands and significant drops should be avoided for safety reasons. In conventional ships, the use of slow steaming is considered to be a solution against high fuel consumption. Although specific fuel oil consumption (SFOC) [g/kWh] in Diesel engines increases due to off-design operation, the total consumption is reduced [tonnes/day]. In the nuclear reactor itself the fission decay of the Uranium fuel just depends on the level of allowed reactivity allowed and hence the heat generated. , Efficiency issues arise in the secondary steam cycle and are the same for a conventional ship using steam cycle propulsion. Therefore a new approach of the machinery should be performed. Carlton et al., (2010) states that complex steam based cycles that increase cycle efficiency are not favourable in marine applications due to the necessity for astern propulsion. Reheating is mentioned as a way to increase efficiency but this cannot be performed as while the ship is in astern movement, the re-heater is not protected from overheating tubes. Marine boilers though, are separately oil fired, but in terms of zero carbon emissions, this solution should be avoided.

5.1 THE HYBRID MACHINERY COMPONENTS

Hybrid nuclear propulsion combines the advantages of direct steam propulsion, the flexibility of electrical systems in manoeuvring and while ship is at berth, the safety features in case of main propulsion unit failure and enhanced secondary system safety in case of ship black – out, involving energy storage devices. The coupling of electric propulsion and direct propulsion turbine requires a gearbox with two inputs (the first connected to the propulsion turbine and second to the electric motor). All the power generation comes from a nuclear reactor which produces steam through the steam generators attached to the primary circuit.

The main characteristics on the steam are the low quality, due to the absence of superheating, and the existence of reheating between the HP and LP turbines at all stages of operation.

The ship will be considered to operate in four normal and one emergency modes of operation.

(1) The first is identified as normal where the main propulsion turbine provides the power to the propulsor and a secondary turbo-generator which utilises a part of the steam flow provides at sea basic loads only.

(2) The second mode is called 'slow steaming' in which no propulsion occurs from the main turbine. The ship uses the electric motor to cover the propulsion demand. However, while the electric loads are significantly higher than the auxiliary, a second turbine which will be optimised for this operation has to be installed. In this scenario, steam oriented for the main turbine will pass thought the main propulsion generator and the rest through the turbo-generator for auxiliary "at sea" loads as in scenario one. In this operation load levelling has to be investigated as described in the work of Dedes et al. (2011). Although slow steaming is achieved by having optimised electric production, the trade-off between conversion losses and main propulsion turbine efficiency drop has to be investigated in detail. However, due to lack of turbo machinery data, no further investigation was performed.

(3) The third scenario is while the ship is manoeuvring. This scenario is identical to the second; however, due to significantly less propulsion loads than at slow steaming but with higher electric loads, the main propulsion generator should operate only. In case of reactor limit operation, the ship should be able to withstand operation using energy storage devices only. Because the propulsion is performed by the electric motor, steam re-heating in the turbo-generator can be performed again having increased efficiency.

(4) The fourth scenario is when the vessel is berthed. According to the port restrictions, either the nuclear reactor can operate at low loads driving only one turbine (preferably the electric propulsion turbine, as electric loads are higher than at sea, but lower than manoeuvring (refer to Table 3).

Table 3: Examined ship electrical load analysis.

Scenario:	Total Load [kW]	Continuous Load [kW]	Internment Load [kW]
Normal sea going	522.5	402.7	363.1
Manoeuvring with ballasting	991.2	961.1	151.7
Manoeuvring without ballasting	765.4	715.3	151.7
Cargo Handling	823.0	655.5	507.5
At Harbour	478.2	370.4	326.4

For the emergency scenario where the main propulsion turbine fails, the electric motor directly connected to the gearbox and fed by electricity produced again by the nuclear reactor can provide propulsion. In the case of nuclear reactor emergency shut-down (scram), propulsion can be achieved by the independent diesel emergency generators and as a back-up the battery storage. The system is now more flexible retiring any component matching issues. Nonetheless, conversion losses do exist. Conversion issues are not a primary concern as inevitably electricity is needed to cover auxiliary loads and astern propulsion is performed for very short periods over the life time of the vessel compared to a-head or manoeuvring operation where ship can operate using higher quality steam. In accident conditions consumption is not of importance as primary goal is not to damage the ship or harm crew or the environment.

In general an energy storage system offers greater flexibility in load handling. Any peak demand, either it is an auxiliary load or a propulsion load as shown in Figure 2 can be treated without altering constantly the load applied on the reactor. The sizing of the reactor can be performed in a manner that the final reactor size is downscaled, thus the initial cost could drop significantly. A cost comparison between a conventional containership (Emma Maersk) and a nuclear powered is performed in Marcus et al. (2009). According to Hori (2008) the estimated cost is between 2500 – 3500 $/kW depending on ship type and installed power. Installed power is directly connected to refuelling intervals.

6. BULK CARRIER SIMULATED VOYAGE

A ship voyage simulator was developed initially to investigate the performance of the fleet in real voyages, correlate the reported consumption with the expected, judging from actual propeller – engine matching and thrust requirements. This simulator which is built in Matlab/Simulink environment is modular and further blocks can be implemented which represent, energy storage devices, turbo-machinery, thermodynamic process and a simple reactor operation, based on manufacturer maps. For the purpose of this paper, a Post-Panamax bulk carrier 93,000DWT was selected (basic ship data can be found in Appendix I). It should be noted that this is considered the minimum size vessel were nuclear propulsion is applicable for berthing at shore only.

The resistance approximation is performed using the Hotrop - Mennen method (Holtrop and Mennen, 1982) which was reviewed by Holtrop (1984), the added resistance uses Aertssen (1963) and Kwon (2008) methods, for the wind resistance Isherwood (1973) and Blendermann (1994) statistical equations. For the propeller, no K_T K_Q polynomial approximations were used, but the actual open water characteristics of the ship's propeller. For an overall discussion of available semi-empirical ship powering estimation see Molland et al (2011).

6.1 COMPARISON OF FUEL CONSUMPTION

In order to calculate the nuclear fuel consumption the following assumptions are made:

1. ~ 85% of reactions leads to fission
2. 1 fission releases ~ 200MeV energy
3. 1 mol of U_2N_3 weights 518.078g
4. Avogadro number = 6.02×10^{23} atoms/mol
5. Small Modular Reactor efficiency = 36%

The examined voyage time is 32 days. The departure port is Dalrymple Bay coal station in Australia heading to Taranto port in Italy, sailing 9,535 sea miles. The 'as measured' fuel consumption for the main engine is equal to 1348.9 tonnes.

$$A = \frac{P_{total}}{\eta_{\text{reactor}} \cdot 3.2 \cdot 10^{-11}} \quad (0.4)$$

$$No_{atoms} = \frac{A}{85\%} \quad (0.5)$$

where,

P_{total} : the required voyage propulsive power
$\eta_{reactor}$: nuclear reactor efficiency
A : number of fissions
No_{atoms} : the required number of atoms to achieve the number of fissions.

Total mean daily power P_{total} is calculated by the ship simulator. It was determined by the Thrust – Resistance match for self-propelled ships. Thus, P_{total} is the required shaft power to achieve the reported speed at specific sea state. This power comes either from a Diesel engine or from a steam turbine (nuclear power plant). The values are plotted in Figure 5 along with the engine loading.

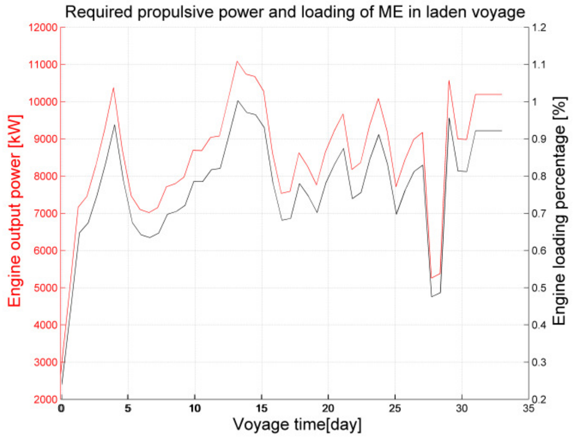

Figure 5: Simulated engine loading and engine power output during the examined laden voyage

The simulation result converge with the published data of Dedes, et al. (2011) and it can be observed from Figure 5 that load fluctuation is significant and exceed regularly the optimum point of operation, leading to decreased fuel economy, hence increased exhaust gas emissions.

By dividing the No_{atoms} with the Avogardo number, the amount of spent nuclear fuel is calculated. The following Table 4 contains the results of the simulation and the consumed nuclear fuel. The CO_2 emissions of the nuclear fuel are whole lifecycle estimates. Emissions occur through plant construction, Uranium mining and milling and plant decommissioning (Sovacool, 2008). In this paper, 1.4g CO_2e/kWh was selected.

Table 4: Simulation results for HFO and Uranium consumption and GHG emissions of the examined voyage. Values are in tonnes.

Fuel	Consumption	CO_2	NO_x	SO_x
HFO	1354.1	8585	117.8	3067
U_2N_3	0.0022	8.5	-	-

7. SAFETY AND RELIABILITY

The safe operation of ship requires the availability of propulsion power, steering capability, navigation, auxiliary power generation. Currently, this is mainly secured by ensuring that each component complies with the general standards having enhanced reliability and performance. In nuclear powered ships, due to the high initial cost of the reactor, it is believed that only one nuclear reactor proving enough output for the propulsion and auxiliary loads will be installed. In case of a reactor failure, a back-up propulsion system should be fitted, to ensure that the ship can return safely to a convenient port and all the emergency functions can run. A combination of diesel generator and batteries is the suitable solution. Although Diesel generators can provide enough power to propel and provide enough electricity for cooling the decay heat of the reactor, as in land based power plants, a second back-up system is required. Integrating the solution of Hybrid Nuclear, batteries seem to offer both load levelling in terms of demand, can actually down scale the reactor installed thermal power and can offer at the same time a back-up system in case of total failure.

The basic principles to design the secondary safety systems are the diversity (different principles of operation), redundancy (multiple components and systems to guard against the individual failure of components), independence (systems have to be physically separated), be failsafe and be testable (tested without disrupting operation, or with redundancy).

Modern reactor designs are always under-moderated and they operate with a negative reactivity coefficient. In case of rapid or extreme load change, turbine failure or loss of primary coolant, the reactor will self-shut down to avoid damage. In terms of the ship accelerations imposed on the reactor, the designer has to calculate the operational margins and match the design with the operational profile of the ship.

In terms of radioactivity, in PWR designs (where SMR are part of that category), the safety system must protect the three barriers to release of radioactivity which are the fuel cladding, the primary cooling circuit and the containment. It is an obvious risk that ship is a small system. There is fear that there might be an exposure to radioactive material by radiation or by inhalation of particles. Based on long design experience coming from more than 800 years of PWR operation, this risk in modern reactors which operate under normal conditions is considered low (DNV, 2010).

In the case of a ship, the containment compartment, is shielded and protected with double bulkheads, double bottom and double skin in case of collision and grounding. The probability of collision to the amidships is increased compared to the stern. Unfortunately, there is a trade-off between the risk of exposing the reactor to high accelerations and the risk of collision and potential breach of the containment compartment.

The possible environmental impact of nuclear powered vessels (submarines or surface ships) requires assessment, however it is noted that a number of submarine accidents have occurred and no major nuclear contamination reported. In May 2011, a Russian icebreaker reported excess of radioactivity. IAEA categorised the event at scale 0 (IAEA: news centre, 2011).

8. SOCIO-ECONOMIC ISSUES

In the last decades terrorist attacks and nuclear major accidents in Chernobyl and Fukushima, have ensured a general public awareness of the potential hazards associated with the use of nuclear power.

In shipping, another aspect arises as harbours are usually located close to areas of large population density. Although the risk of terrorist threat may be limited in secured ports, and the LEU fuel is not suitable for nuclear weapons, still the political implications and the general public opinion is believed to be against the entrance to the harbours of nuclear powered ships. Hence, at least initially, the ship types which seem attractive are bulk carriers and tankers. They are capable of loading - unloading away from the shore and as shown in Figure 1, share a significant proportion of CO_2 emissions. Furthermore, due to the high initial cost which is 2.5 times the cost of conventional vessel, the HFO consumption of these ships should be high.

Concerning the operation of such vessel some implications arise. Firstly, not all ports can accept these vessels. Secondly, in transatlantic or transpacific voyages which usually large vessels operate as liners, decrease the flexibility for chartering. Thus nuclear powered vessels with port restrictions obstruct free economy. Furthermore, the construction and repairs of such ships is limited to licenced shipyards which again bound the economy and potentially the construction and repair cost would remain high due to the inexistence of competition.

The manning and operational costs of such vessels are still an issue. Nuclear ships will require fully qualified and thus expensive personnel on board. The rest of the crew can be as it is currently. However, specialised crew increases the operational cost of the vessel.

From the shipping company view, the daily performance monitoring of the fleet and the maintenance surveying that superintendent engineers perform in dry-dockings, should change. Superintendent engineers have to attend continuing professional development (CPD) courses in nuclear engineering so they can understand the principles of operation and of course be aware and identify any failures in materials that radioactive exposure causes. Nevertheless, small modular reactors can be considered as black boxes and might be property of the developing company, so no company engineers have to attend such an inspection but rather as in the early days of radio the nuclear company provides the operators.

The limitations that currently seem to exist in nuclear merchant shipping dictate that a potential ship-owner has to be willing to be a first mover, to have a strong financial position and decide that is going to be a long term investment. Due to the fact that the acceptance of a ship might be limited and hence trade restrictions might occur, the ship-owner must be willing to accept the high risks of an unknown territory. However, in case of success the benefit of the prime mover can be significant.

Traditional P&I clubs cover the liability to third parties in case of accidents. When having a nuclear fleet, a new trust would probably be required to cover any radiological pollution that might occur after a serious accident. As a general comment it can be said that the situation will be volatile and a lot of steps are required before the actual operation of nuclear powered merchant vessels can occur.

Finally, the spent fuel of global nuclear powered shipping should be considered. PWR designs create hazardous depleted fuel. In terms of fuel economy, the worst thing to perform is to bury the spent fuel. The study of Deutch et al. (2003) showed that the discovered Uranium resources are sufficient for the next 70 years, without including the needed reactor power for shipping. Therefore, fuel recycling has to initiate before any nuclear renaissance. Technological improvements in fast reactor technology (Lamarsh and Baratta, 2010) should allow the depleted fuel to be re-used, and thus the nuclear fuel cycle can close and the actual burnt fuel can breed more, having practically unlimited fuel for 1500 years. However, it needs almost 40-50 years to breed more fuel with the current technology.

9. CONCLUSIONS

A nuclear ship will face many constraints in the early stages of its application. The very high initial vessel cost which is estimated to be up to three times the cost of conventional ships, the increased manning cost, the high insurance and the decommissioning cost would make the typically conservative and cost-conscious ship-owner sceptical. Harbour restrictions may pose constraints to the applicable vessel type and ship types which are capable of loading and unloading outside the harbours seem to be a favourable start point.

Despite the socio-economic issues discussed in this paper, in terms of emissions, these ships have zero GHG emissions during their operation. Recent technological improvements in nuclear reactors, demonstrated that fast reactors can breed more fuel and recycle the used in conventional installations, offering great flexibility in dealing with long life nuclear waste reducing significantly the environmental impact and increasing the Uranium resources for 1500 years of reactor operation.

In terms of secondary steam propulsion system efficiency, the proposed hybrid propulsion has great potential in the flexibility of ship operation, while it exploits the advantages of direct propulsion, the flexibility of electric propulsion and the operation of systems which increase the Rankine cycle efficiency. Moreover, energy storage devices can supply energy when ship is operating at high sea states for a short period of time, eliminating the need for over dimensioned nuclear reactor designs. Furthermore, it offers load levelling and can be used as backup of the emergency cooling system of the reactor.

The developed ship voyage simulator gives a noteworthy aid in the calculation of the energy requirements of a specific route using only the weather characteristic data during the examined voyage and the basic ship dimensions. Thus, fuel consumption and emissions can be calculated along with the efficiency of the propulsive system. In this paper, Uranium fuel consumption was demonstrated and compared to HFO consumption for a single voyage.

Marcus et al. (2009) demonstrated the feasibility study of a container vessel similar to the largest conventional (Emma Maersk). Thus container ships > 8000 TEUs with the current price of HFO are feasible.

ACKNOWLEDGEMENTS

The authors wish to thank Lloyd’s Register of Shipping UK, Hellenic Lloyds Register and the Foundation Propondis for the financial support of the PhD project. Moreover, Lloyd’s Register Research and Development Group UK for the scientific support and the Greek Maritime corporation which provided the case study data of the conventional bulk carriers.

REFERENCES

Abram, T. (2011). ‘Water Cooled Reactors - lecture notes SESG6026’, University of Southampton MSc, Dalton Institute, The University of Manchester.

AEA Energy & Environment. (2008). ‘Greenhouse gas emissions from shipping: trends, projection and abatement potential’, Didcot, Final Report ED43808, Issue 4.

Aertssen, G.J. (1969). ‘Appendix V, Report of Performance Committee’, 12th ITTC, Rome. International Towning Tank Conference, www.ittc.sname.org .

Ansolabehere, S., et al (2008). ‘The future of nuclear power: an interdisciplinary mit study’.

Blendermann, W. (1994). ‘Parameter identification of wind loads on ships’, Journal of Wind Engineering and Industrial Aerodynamics Vol. 51, No 3, pp. 339-351.

Carlton, J.S., J.V., and R.S. (2010). ‘The nuclear propulsion of merchant ships’, The Royal Academy of Engineering .

Dedes, E., Hudson, D. and Turnock, S. (2011). ‘Assessing the potential of hybrid energy technology to reduce exhaust emissions from global shipping’, Under Review Energy Policy.

Deutch, J., et al (2003). ‘The future of nuclear power, an MIT Interdisciplinary Study’, http://web.mit.edu/nuclearpower.

DNV. (2010). ‘Nuclear powered ships: Technical Report 2010-0685’, Det Norske Veritas, (DNV).

Gupta, C. & Batra, L. (2010). ‘Marine Engine Emissions and their Control: Present and the Future’.

HMS-Sultan. (2008). 'Sustainable energy Nuclear Power', - lecture notes SESG6026, University of Southampton MSc, HMS Sultan, Nuclear Department Defence Academy.

Holtrop, J. (1984). 'A statistical re-analysis of resistance and propulsion data', International Shipbuilding Progress Vol. 31, No 363, pp. 272-276.

Holtrop, J. & Mennen, G. (1982). 'An approximate power prediction method', International Shipbuilding Progress Vol. 29, No 335, pp. 166-170.

Hori, H. (2008.). 'Feasibility of a nuclear ship at crude oil price 100 per barrel'.

IAEA: news centre. (2011, May 6). Retrieved May 2011, from International Atomic Energy Agency: www.iaea.org

IMO. (2009). 'Second greenhouse gas emission study', Technical report, International Maritime Organisation.

Isherwood, R. (1973). 'Wind resistance of merchant ships', RINA Supplementary Papers 115.

Kwon, Y. (2008). 'Speed loss due to added resistance in wind and waves', The Naval Architect March, pp. 14-16.

Lamarsh, J. & Baratta, A. (2001). 'Introduction to nuclear engineering', Prentice Hall.

Marcus, H., et al. (2009). 'An early conceptual design and feasibility analysis of a nuclear-powered cargo vessel', PhD thesis, Massachusetts Institute of Technology.

MER. (2011). 'Early nuclear tankers', Marine Engineers Review pp. 27-29.
MARPOL. (2005). MARPOL 73/78 revised ANNEX VI, MEPC59. IMO.

Molland, A.F. Turnock, S.R. and Hudson D.A. (2011). 'Ship resistance and propulsion: practical estimation of ship propulsive power', Cambridge University Press.

Pocock, R. (1970). 'Nuclear ship propulsion', Ian Allan.

Psaraftis, H. & Kontovas, C. (2009). 'CO2 emissions statistics for the world commercial fleet', WMU Journal of Maritime Affairs, Vol. 8, No. 1), pp. 1-25.

Rajput, R. (2009). 'Engineering thermodynamics: A computer approach (si units version)', Jones and Bartlett.

Sovacool, B. (2008). 'Valuing the greenhouse gas emissions from nuclear power: A critical survey', Energy Policy, Vol. 36, No. 8, pp. 2950-2963.

UNCTAD. (2008). 'Review of Maritime Transport', United Nations Conference on Trade and Development, United Nations.

Vakasi, V. (2009). 'Simulation of the Steam Propulsion System of a Liquefied Natural Gas Carrier', Master's thesis, School of Naval Architecture and Marine Engineering, National Technical University of Athens.

Van Wylen, G. & Sonntag, R. (1978). 'Fundamentals of classical thermodynamics', SI version, John Wiley and Sons, New

York.Wright, A. (2000). 'Exhaust emissions from combustion machinery', Institute of Marine Engineers.

APPENDIX I

FLAG / PORT OF REGISTRY	GREEK / PIRAEUS
YEAR OF BUILT	2007
CLASSIFICATION	L.R.S.
GRT / NRT	49973 / 30679
SUEZ	52763,44 /48045,08
GRAIN / BALE [M3]	109037,9 /103586,0
DWT (MT) / DRAFT (M)	92451,85 /14,7255
L (OA) / L (BP) / B (MLD) / D (MLD) / LIGHT WEIGHT	229,50 /221,60 / 36,92 / 20,50 / 15515,85 MT
No OF DECKS / HOLDS/HATCHES	ONE / 7/7
MAIN ENGINE TYPE BHP / RPM	MAN STX B&W 7S50MC-C 11060kW / 127
D / GENS TYPE KW / RPM	YANMAR 6N21L-UV 3 X 660 /720
EXH GAS BOILER	KANGRIM 200KG/HR
PROP/BLADES DIAM / PITCH MM WEIGHT MATERIAL	SILLA METAL CO. / 4 BLADES KEYLESS 7.000 / 3.9336 (at 0,7 R) 23.50 / NI-AL-BRONZE (cu3)