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Performance Analysis of a Naval Reactor for Nuclear Powered Ship

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Abstract: Nuclear power-driven ships are becoming progressively more popular in advancing ship technology. Nuclear ships use naval reactors, which have lower fuel costs and last for many years and have almost zero emissions. The working of a Nuclear Ship is derived from the simple nuclear fission reaction. One more important factor that has spurred on the continuous investigates of nuclear power generation within ships is the irregular cost of flammable fuels. The unfavorable effects of burnt fuel being dispelled into the sea are also a concerning factor for green and sea life activists. Nuclear power applications have been limited due to safety concerns, but the new war against global warming is perched to drive its progress. In a span of a few years, safety risks may be minimized and nuclear power for power generation, in medicine and aboard ships and even in cars—may be the norm. The paper focuses the analysis of design for a nuclear-powered ship and the subsequent safety analysis of that ship in comparison with its fossil fuel ship. The final result of this paper shows that a suitable naval reactor for developing nuclear powered ship, while being technically feasible, will alternative to a fossil fuel powered ship.
Keywords: Fuel Cost, Naval Reactor, Nuclear Propulsion and Ship Designs

I. INTRODUCTION

Possibly the most important factor regarding the probability of a nuclear powered ships is the industry model and its appeal to potential investors. It is believed that with the rising oil prices and taxes on carbon emissions, the maritime industry will be looking for new, more efficient propulsion systems to introduce to the new fleets. It may be possible that with a much cheaper fuel cycle, a nuclear powered ship will be much cheaper to run, however, a nuclear naval reactor is a significant initial cost to the investment which could overshadow these savings. In terms of day to day costs of running a fossil fuel ship, fuel is by far the highest proportion of cost. A nuclear powered ship would use less than 4% of the bunker fuel of a conventional ship of the same capacity assuming the nuclear reactor would not be suitable to run at certain proximity to shore. Clearly, the savings on fuel costs will be substantial however these savings could be dominated by the vast costs associated with building and implementing the infrastructure to cater for a moving nuclear reactor. Therefore, aside from the clear environmental benefits, there needs to be an assessment of the potential savings that this nuclear proposal may have to create as an incentive for further work to be done on this project. Since there are no current nuclear-powered commercial vessels in service presently, costing of the fuel, ship and maintenance of the nuclear proposal is difficult and relies predominantly on other studies into the economic feasibility of nuclear powered ships and publicly available military information. Due to the secretive nature of military institutions and the nuclear industry these cost estimates are mostly speculative and unreliable. However, this model only aims to quantify the feasibility of nuclear propulsion and the significance of any differences in profit margins, if this proposal were to be taken further. Also, due to cost estimates being taken from military data, it is likely that some costs are overestimated since military projects will have no profit incentive. Thus, if this proposal were to be taken further, cost reduction in some areas is certainly a possibility. This model has been created as a comparison between the current costs of the seven year life of the Eugen Maersk and the nuclear powered proposal, which is estimated to be of similar capacity and weight as the Eugen Maersk but with a slightly larger power output. Therefore, an important assumption for the economic feasibility of this proposal is that the design would be taken up by a private sector business rather than a national or even global effort. The model takes a 20 year life time for both ships as a minimum life span for the ship and reactor and also as the cut-off time after which ship depreciation slows and yearly expenditures will become relatively constant. A remarkable proposal, this time in the containership segment, has been the NuShip concept, which has attracted the attention of shipping business actors and the media. The anticipated overall features of this ship design, the logistic system and the commercial strategy are known within the maritime industry. We are confident that the general results of the study are applicable to other vessels with comparable fuel consumption patterns, but data on such other vessels is not as readily available as data on NuShip.

II. NUCLEAR PROPULSION TECHNOLOGY

The science of atomic radiation, atomic change and nuclear fission was developed since the mid-fifties. From 1945 attention rotated to the peaceful purposes of nuclear fission, notably for naval propulsion and power generation. The first nuclear-powered submarine, USS Nautilus, put to sea in 1955. Naval reactor is mainly suitable for vessels which need to be at sea for long periods without refueling, to ensure the safe and reliable operation or for powerful ship propulsion. The various designs use different concentrations of Uranium for fuel, different moderators to slow down the fission process, and different coolants to transfer heat.

Table 1: Composition of highly enriched fuel for naval reactors design

Isotope	Composition (percent)	Activity (curies)	Decay Mode	Exposure Contribution (μR/hr)
$_{U}234$	0.74	6.1	Alpha decay	Unappreciable
$_{U}235$	97.00		Decay gammas	Appreciable
$_{U}238$	2.259		Spontaneous fissions	Appreciable
$_{Pu}239$	0.001		Alpha decay	Unappreciable
Total		6.5		19.9

A. The NuShip Project

The basic design approach for the naval reactor is optimization of the capital and operational costs. The reactor adopts design strategies for minimizing mass and overall dimensions, feasibility to deliver Reactor Pressure Vessel by sea. Therefore, single-reactor power units are the most desirable designs. From the economic point of view it reduces the startup capital costs, construction and payback periods. Structural optimization of main equipment allows for delivery of the power units at the base site through water with minimum technological issues.

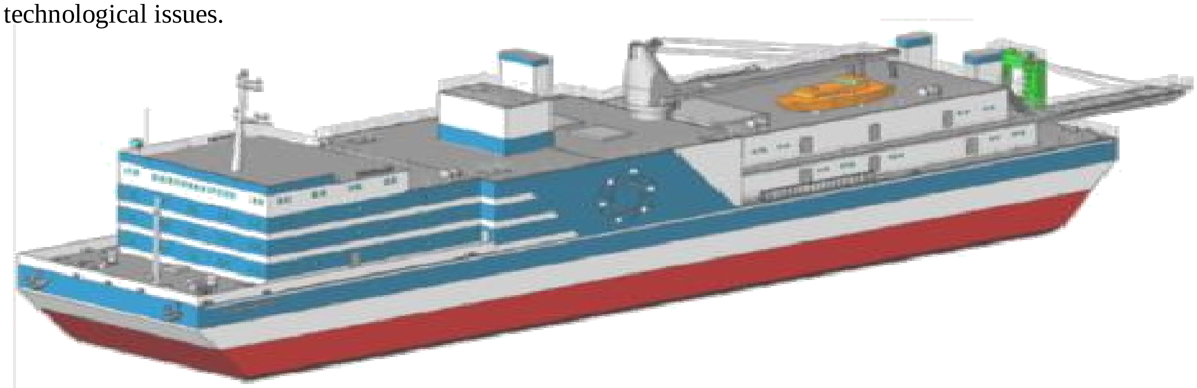

Figure1: The conceptual view of the NuShip with Naval reactor

III. DESIGN PHILOSOPHY

The Naval Reactor is a pressurized water reactor (PWR); its design incorporates the following main features:
Negative feedbacks and enhanced thermal inertia;
Passive and self-actuated safety systems;
Increased resistance to extreme external events and personnel errors;
Use of nuclear fuel with the enrichment of less than 20% by weight (maximum enrichment 19.7%).

Reactor type	Integral PWR
Electrical capacity (MW(e))	50
Thermal capacity (MW(th))	175
Expected capacity factor (%)	65
Continuous operation period (hr)	26000
Design life (years)	40
Coolant/moderator	Light water
Primary circulation	Forced circulation by pumps
System pressure(MPa)	15.7
Core inlet/exit temperatures (oC)	277 / 313
Core flow rate (ton/hr)	3,250
Steam generating capacity (ton/hr)	248
Steam temperature (oC)	295
Pressure (MPa abs)	3.82
Neutron fluence at the end of life time (neutron/cm2)	5.2 x 1019
Main reactivity control mechanism	Control Rod Drive Mechanism (CRDM)
RPV height (m)	8.5
RPV diameter (m)	3.3
Module weight (metric ton)	1100
Configuration of reactor coolant system	Integral PWR
Power conversion process	Indirect Rankine cycle
Fuel type/assembly array	UO2 pellet/hexagonal
Fuel assembly active length (m)	1.2 – 1.65
Number of fuel assemblies	199
Fuel enrichment (%)	< 20
Fuel burnup (GWd/ton)	68.4 / 51.2
Fuel cycle (months)	54 – 84
Approach to engineered safety systems	Combined active and passive
Number of safety trains	2
Refuelling outage (days)	40
Seismic design (g)	3g
Core damage frequency (per reactor-year)	0.9E-6

Table 2: Major Technical Parameters of a Naval Reactor

IV. TECHNICAL ANALYSIS

A. *Technical risk factors on a naval reactor*

When a nuclear reactor is to be used as the primary means of population for a ship, the following factors should be considered:

1) The reactor should be small, light, and safe and stable in performance regardless of motion of the ship..
2) Propulsion output varies when approaching a port and berthing. In addition, it should respond to navigation requirement, and thus the operability of a nuclear reactor on board should be flexible
3) Reactor system including structure, piping, component should take into account the load from acceleration due to ship motion. In addition, the impact load due to collision or stranding, and penetration due to collision, grounding and consequent sinking are importan
4) Damage stability and immersion of the engine room to be considere
5) Sufficient shielding against radioactivity should be provided, and an entry permit system to allow access to qualified persons only should be established and implemente
6) Loss of coolant (LOC) has been the cause of tragic accidents due to its high pressure and high temperature, as well as radioactive contamination. Thorough risk assessment and mitigation planning regarding LOC are essential

7) Emergency preparedness when Scram is initiated must be well-established.

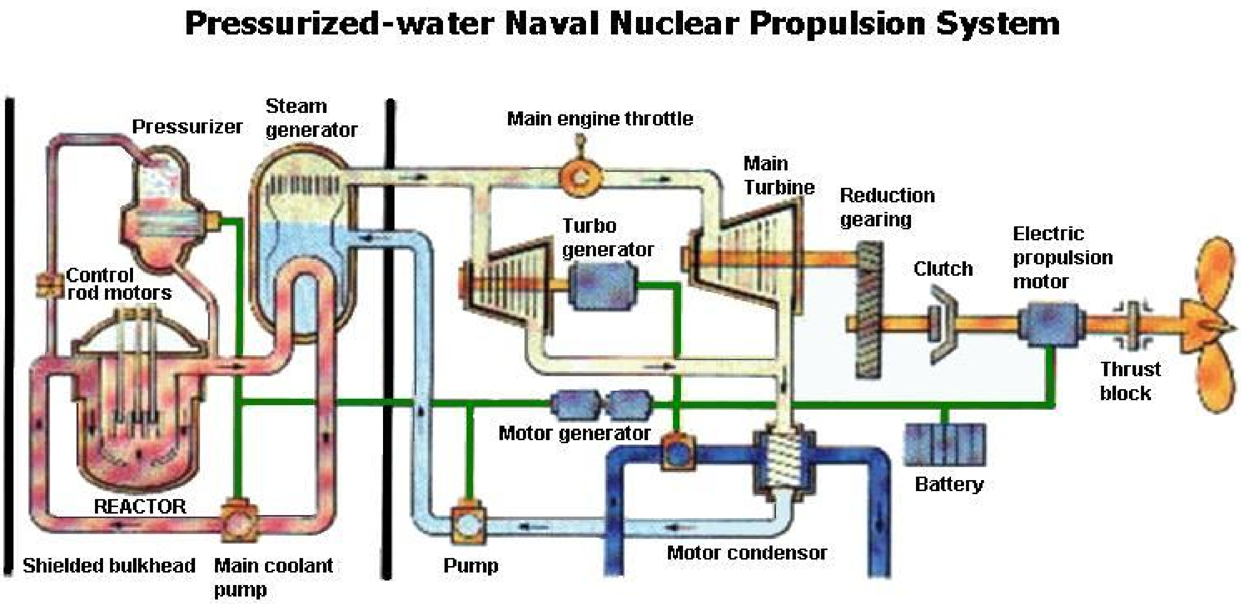

Figure 2: Naval Pressure water reactor Propulsion system for NuShip

V. NUCLEAR REACTOR ECONOMIC ANALYSIS

There are several economic similarities between the proposed nuclear-powered ship NuShip and the actual Eugen Maersk. Also, the arrangement analysis clearly shows that both the nuclear-powered NuShip and the actual Eugen Maersk have roughly the same estimated cargo-carrying capacity, so the profitability of each ship based on hauling cargo is roughly equivalent. The main difference in the economics comes from the actual day-to-day operations of the two different ships. The nuclear-powered NuShip has significantly higher upfront costs but lower actual operating costs while the actual Eugen Maersk has a higher operating cost but lower upfront costs. A summary of all costing data is shown below in Table 3.

Table 3: Comparison of Costing for Nuclear powered ship (NuShip) and Conventional Ship

Costing Data	Nuclear-Powered Vessel (NuShip)	Eugen Maersk
Ship Acquisition Cost	$1.2 billion	$145 million
Maintenance and Repair	$1.6 million per year $2 million every 5 years for turbine overhaul & reactor maintenance	$800,000 per year
Dry-docking/Class Inspections	$1.25M every 2.5 yrs. $1.75M every 5 yrs	$1.25M every 2.5 yrs $1.75M every 5 yrs
Fossil Fuel Burn Rate	4,000 metric tons/yr	350 metric tons/day
Nuclear Refueling	$115 million to replace Reactor Core	N/A
Spent Fuel Disposal	$3 million/yr beginning 10th year	N/A
Manning	$25,000 per day (35 crew)	$10,000 per day (20 crew)
Security	$3 million per year	$1 million per year
Insurance	1% of value of the vessel per year	1% of value of the vessel per year
Scrap Value	$20 million steel and copper	$10 million steel only
Decommissioning	$20 million	None
Slot Charter Expense Refueling/Dry-docking	$71.1 million per 5 year period	$19.5 million per 5 year period

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VI. RESULT

When diesel propulsion cost is compared with nuclear propulsion cost, there are two variables that play a significant part: the oil price and interest rate on capital expenditure. The interest rate plays a significant role in the cost of the nuclear option, while the oil price plays a large role in diesel propulsion option. The sensitivity to these two variables is analyzed in this section. These cost items were compared as a function of interest rate and fuel cost. The result is shown in Figure 3. From this graph it can be seen how the annual cost of the two alternatives change as a function of interest rate and Heavy Fuel Oil cost.

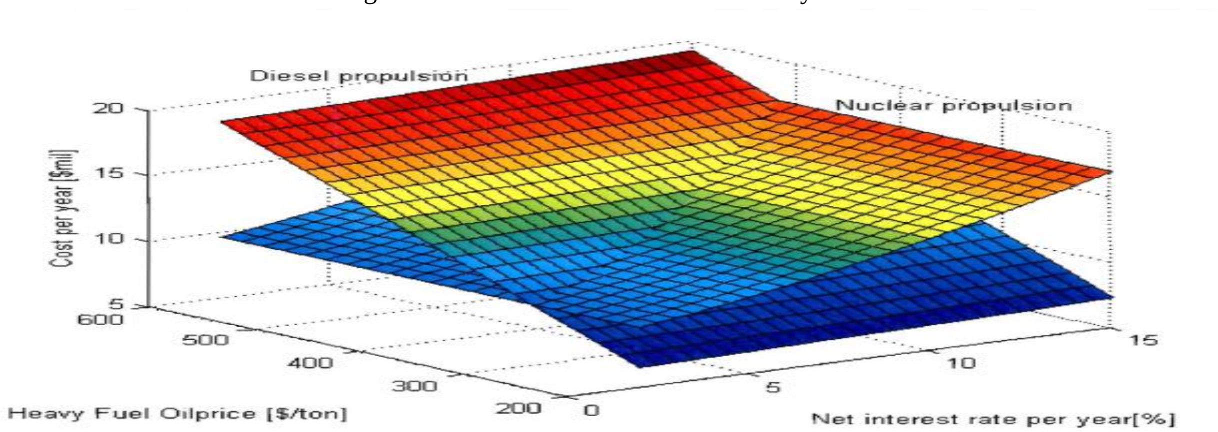
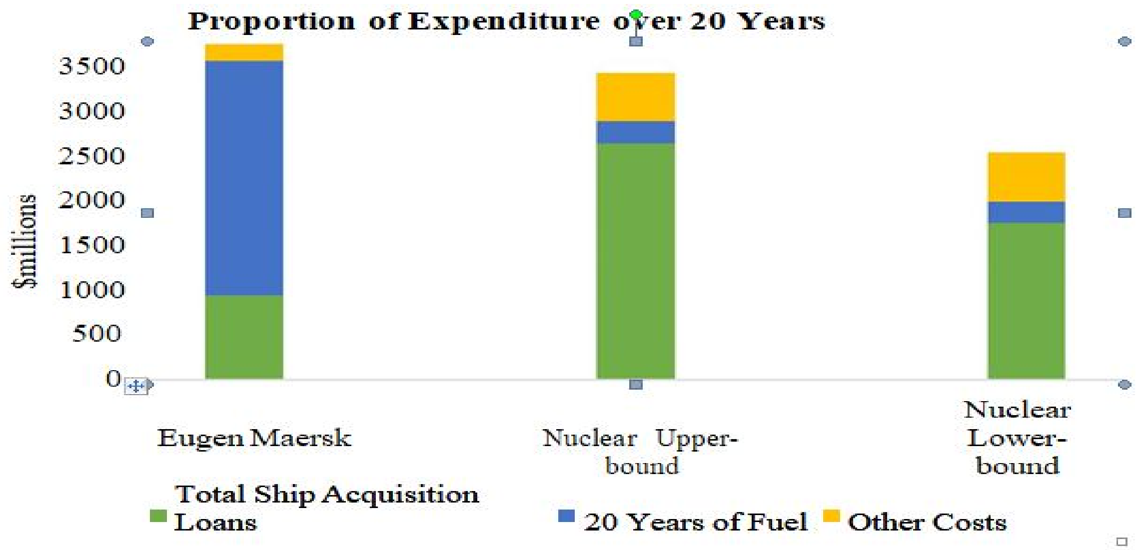


Figure 3: The maps the relative cost competitiveness of diesel propulsion versus nuclear propulsion.

Figure 4: Annual Cost Comparison between Nuclear and Diesel-propulsion Options



A. *Carbon Dioxide Emission Tax:*

As an example of the costs of current carbon trading, an approximation was made of the annual amount both the Eugen Maersk and its nuclear powered equivalent would have to pay if the shipping industry was not exempt from carbon emission controlling measures in the maritime industry.

Table 4 – Difference in carbon emissions between Eugen Maersk and NuShip

Vessel	Fuel use (tonne/day)	CO2 emissions (tonne/year)	Potential carbon tax ($mill/year)
Eugen Maersk	350	405 000	10590
NuShip	11	12 680	0.331

The table shows an alarming difference in carbon taxes between the vessels if maritime industry taxes were applied to the shipping sector and although this scale of tax is unlikely to be introduced it still shows that with the increasing global focus on 'green' energy and fuels, a nuclear powered ship could gain a dramatic economic advantage over conventional fuel in the future. These taxes may also begin to rise as the threat of climate change becomes more extreme and climbs up the global political agenda thus rendering fossil fuel powered cargo shipping even less profitable.

VII. CONCLUSION

The paper could be done into the possibility of extra revenue that the nuclear propelled vessel could earn compared to conventional fuel ships. The potential revenue the ships make has not been analysed in this project and could contribute significantly to the model in concluding if the nuclear powered vessel is more profitable than the Eugen Maersk. Since it is the financial feasibility of nuclear-powered ships that will decide whether they are ever implemented in the future, it is important for a reliable estimate to be produced in order to attract investments into what could be a successful industry. The performance analysis of nuclear naval propulsion plant for NuShip is anticipated. The technical viability of a nuclear engine is investigated, by comparing the several operating parameters including costing, capacity, fuel price change, carbon dioxide Emission, and so on to conventional propulsion systems. We conclude that nuclear powered ship NuShip, with greater capacity and a more stable operation cost to fuel volatility, load factor and transport rate fluctuations, even with very conservative figures.

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