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Considerations on the potential use of Nuclear Small Modular Reactor (SMR) technology for merchant marine propulsion

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ABSTRACT

International shipping has a well established reputation as the most energy efficient mode of freight transport. However, treating shipping within the context of global environmental concerns has gained significant momentum over the last 10 years, particularly in relation to the generation of Green House Gases (GHG) and other contributions to air and water pollution. Shipping relies on fuel oil and this implies that understanding the potential of alternative non-carbon marine propulsion technologies is necessary as the industry moves forward with its longer term decarbonisation efforts. Without any intend to underestimate the potential environmental and economic benefits of renewable, natural gas or non-fossil (e.g. biofuels) energy resources, it would be only sensible to add on the nuclear engineering option as a possible alternative. As successful as traditional nuclear propulsion has been in the naval and ice breaker ship segments, one aspect of the industry that escaped attention in the commercial sector is the use of modern small and medium size reactor technology on-board ocean going vessels. This paper reviews past and recent work in the area of marine nuclear propulsion and for the purpose of demonstration outlines the technical considerations on the concept design of a Suezmax Tanker powered by the Gen4Energy 70MW Small Modular Reactor (SMR). It is shown that understanding the technical risks and implications of implementing modern nuclear technology is an essential first step in the long term process of developing knowledge and experience.

1. Introduction

The ocean is the highway for international trade, with 90% being seaborne. Despite the long lasted reputation of the shipping industry as the most energy efficient mode of freight transport, treating shipping within the context of global environmental concerns gained significant momentum over the last 10 years. The Kyoto protocol legacy that bunker fuel emissions produced within international waters may be excluded from national targets, the increasing effects of globalisation and the global 2 °C temperature target decrease (UNFCCC, 2009) imply that the international maritime community should consider the strategic technology paths for energy decarbonisation by 2060. Over the medium to long term stabilisation of CO_2 concentrations at a level that prevents dangerous anthropogenic interference with the climate system would require a radical innovation regime. The later should aim toward the implementation of advanced energy systems and growth of some new technologies. Considering shipping's reliance on heavy fuel oil and the expected high rates of growth (Lloyd's Register et al., 2013), it is fare to accept that alternative sources of energy could help with this transformation. Hirdaris and Cheng (2012) suggest that some decarbonisation solutions may be

Abbreviations: ABWR, Advanced Boiling Water Reactor; AECL, Atomic Energy of Canada Ltd.; BWR, Boiling Water Reactor; CRP, Contra Rotating Propeller; C4TX, Centre for Tankship eXcellence; DCNS, Direction Technique des Constructions Navales of France; EFPY, Effective Full Power Years; EHFA, Early Human Factors analysis; FOI, Floating Offshore Installations; FNPP, Floating Nuclear Power Plant; FNR, Fast Neutron Reactor; G, Generator; GBS, Gravity-Based Structures; GHG, Green House Gas; GFR, Gas Cooled Fast Reactor; HAZID, Hazard Identification Study; HTR, High Temperature Reactor; HP, High Pressure turbine; IACS, International Association of Classification Societies; IAEA, International Atomic Energy Authority; ICLL, International Convention for Load Lines; IEA, International Energy Agency; IMO, International Maritime Organisation; INF, Irradiated Nuclear Fuel; LCA, Life Cycle Assessment; LFR, Lead-cooled Fast Reactor; LNG, Liquefied Natural Gas; LP, Low Pressure turbine; LWR, Light Water Reactors; M, Shaft Motor; MARPOL, Marine Pollution Prevention; MEPC, Marine Environmental Pollution Protection Committee; MRG, Marine Reduction Gear; NI, Nuclear Inspectorate; NP, Nuclear Powered; NS, Nuclear Ship; OECD, Organisation for Economic Co-operation and Development; ONPP, Offshore Nuclear Power Plants; OPA'90, Oil Pollution Act 1990; PB, Brake Power; PCA, Product Chain Assessment; PS, Shaft Power; PSMR, Propulsion and Steering Machinery Redundancy; PT, Thermal Power; PWR, Pressurised Water Reactor; QAP, Quality assurance Programme; SFR, Sodium Cooled Fast Reactor; SMR, Small Modular Reactors; SOLAS, Safety of Life at Sea; UNFCCC, United Nations Framework Convention on Climate Change; USANC, United States of America National Commission; USSR, ex Union of Soviet Socialist Republics; WNA, World Nuclear Association

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Nomenclature

B	Ship beam
BHP	Brake Horse Power
CO_2	Carbon dioxide
D	Ship
HT-9	High Tensile stainless steel (12Cr1MoVW; ASTM Ferritic/Martensitic steel)
L	Concept SMR ship length
L_{OA}	Ship length overall
L_{PP}	Ship length between perpendiculars
LBE	Lead Bismuth Eutectic coolant
LCG	Ship longitudinal centre of gravity
Na	Sodium
NO_x	Nitrogen Oxides
P	Engine power
Pb	Lead
^{239}Pu	Plutonium-239 fissile an isotope of plutonium
^{241}Pu	Plutonium-241 isotope of plutonium
SO_x	Sulphur Oxudes
T	Ship draft
U	Uranium
^{235}U	Uranium-235, fissile isotope of U making up about 0.72% of natural U
^{233}U	Uranium-233 fissile isotope of U (bred from Thorium-232)
^{238}U	Uranium-238 natural non-fissile common isotope of U
UN	Uranium Nitiride
UO_2	Uranium Oxide
V	Ship normal service speed
B_4C	Boron Carbide shutdown rods
∇	Ship displacement volume
η	Efficiency

associated with substitution of renewable energy (e.g. wind, solar) for fuel oil. Other solutions may involve alternative energy resources that are dependent on fossil carbon (e.g. natural gas) or the harvesting of non-fossil carbon resources (e.g. biofuels). Without any intend to underestimate the benefits of those, it would be only sensible to also consider the nuclear engineering option as a promising alternative with minimal detrimental emissions (CO_2, NO_x, SO_x).

Nuclear powered ships, operated by the international naval and Russian icebreaker sectors, have been a reality for over 50 years. Since the first nuclear submarine, about 700 nuclear reactors operated at sea on various vessels. Whereas the limited or unknown safety records of Russian nuclear fleet raise some concern (Reistad et al., 2008; Ølgaard, 2001) it is estimated that the western world, primarily led by the USA Naval sector, has to date accumulated over 6200 reactor-years of operational experience involving 526 nuclear reactor cores (WNA, 2012). Despite the successful implementation of traditional nuclear reactor options one aspect that escaped the attention of the commercial industry sector is the use of Small Modular Reactor (SMR) technology onboard ocean going vessels.

Following a brief review of existing nuclear marine propulsion options this paper summarises the efforts of an industry led consortium to explore the feasibility of developing a commercially viable concept for a Suezmax Tanker able to carry oil cargoes based on a conventional hull form, but with alternative arrangements accommodating for the 70 MW Gen4Energy SMR propulsion plant. This vessel choice does not underestimate the importance of exploring the feasibility of future application of SMR technology to other ship types or FOIs. Yet, it helps to explore the potential of modern nuclear propulsion against a realistic technical background. The paper reviews past and recent advances, outlines the basics of Gen4Energy SMR technology and describes the rational behind some of the possible concept design choices. A brief discussion on the need for future research and development activities attempts to shed some light on the barriers that the industry will have to overcome over the long term.

2. The potential of nuclear marine propulsion

To realise the importance of considering modern nuclear marine propulsion technology options it is important to appreciate the global impact of anthropogenic emissions induced by the international shipping sector. In recent years, different approaches for estimating the overall global shipping emissions have been presented (e.g. IMO, 2009; Paxian et al., 2010). Walsh and Bows (2012) explain that the availability and range emission factors for shipping are still susceptible to some uncertainty related with the so called Life Cycle Assessment (LCA) and Product Chain Assessment (PCA) concepts. The IMO estimates that today shipping contributes between 2.7% and 3.3% of the global CO_2 emissions annually (IMO, 2009). This number, on its own, would place this industry, in absolute terms, as the sixth in line between countries that are the largest producers of anthropogenic emissions. If no action is taken these emissions could grow significantly and by 2050 they could amount between 12% and 18% of the total allowable CO_2 induced GHG under the International Energy Agency 450 ppm stabilisation scenario (OECD/IEA, 2008). This implies that, in comparison to 2007, anthropogenic emissions from shipping may be expected to range between 6% and 22% (925–1058 Mt of CO_2 emissions) higher in 2020 and between 119% and 204% (1903–2648 Mt of CO_2 emissions) by 2050. Looking into the medium to long term options (see Table 1) it appears that, except for hydrogen which is not ready for shipboard installation (Aspelund et al., 2006), there is currently no solution that eliminates all emissions and none can offer a significant CO_2 reduction. For example, natural gas is a promising medium term solution provided that sufficient port infrastructure is developed (Lloyd's Register, 2012a). On the other hand, renewable energy sources (solar and wind) can offer only limited capacity to the overall power requirements for ocean going ships and hence they would be mostly appropriate for auxiliary propulsion solutions (Hirdaris and Cheng, 2012). Fuel cells are an extremely efficient way of producing energy if hydrogen is used (San and Bradshaw, 2012). However, the lack of availability of hydrogen resources and its low volumetric energy density implies that the solution may take some time to be implemented (Andrews and Shabani, 2012; Hirose, 2012).

With the world's merchant shipping reported to have a total power capacity of about 410 GWt (approximately 1/3 of world nuclear power plants) understanding the potential of implementing nuclear technology options seems conceivable. Apart from the need to mitigate the climate change agenda, the resurgence of interest in nuclear propelled ships that could