CONCEPT DESIGN FOR A SUEZMAX TANKER POWERED BY A 70MW SMALL MODULAR REACTOR

(DOI No: 10.3940/rina.ijme.2014.a1.276)

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SUMMARY

This paper describes a preliminary concept design study for a Suezmax tanker that is based on a conventional hull form with alternative arrangements for accommodating a 70MW Small Modular Reactor (SMR) propulsion plant. Emerging nuclear technology concepts, associated design risks and technical options available are outlined within the context of risk based ship design. It is concluded that the concept is feasible and the adoption of the technology would be compatible with the target application. However, further maturity of nuclear technology solutions and the development and harmonisation of the regulatory framework will be necessary before implementation of the ideas presented would be viable.

NOMENCLATURE

B	Ship beam (m)
BHP	Brake Horse Power
B_4C	Boron Carbide
D	Ship depth (m)
D_R	Reactor diameter (m)
GM_0	Initial metacentric height (m)
GZ	Righting lever arm (m)
HP	High pressure
H_R	Reactor height (m)
LCG	Longitudinal Centre of Gravity
L_{OA}	Ship length overall
L_{PP}	Length between perpendiculars (m)
O_2	Molecular oxygen
P_{ALT}	Alternator power (kW)
P_B	Brake power (kW)
P_R	Reactor power (MW_T)
P_S	Shaft power
P_T	Thermal power (kW_T)
RPM	rev/min
T	Draft (m)
U	Uranium
^{235}U	Uranium fissile isotope = 0.72% U
UN	Uranium Nitride
V	Normal service speed (knots)
W	Ship weight
W_R	Reactor weight (tonnes)
∇	Displacement volume (m^3)
η	Efficiency (%)
θ	Angle of heel (degrees – deg.)
θ_f	Angle of flooding (degrees – deg)

1. INTRODUCTION

The ocean is the principal highway for international trade in raw materials and manufactured goods. About 90% of the total trade is carried by sea. The shipping industry 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. Some decarbonisation solutions may be associated with substitution of renewable energy (e.g. wind, solar) for fuel oil. Other solutions involve alternative energy resources that may be dependent on fossil carbon (e.g. natural gas) or the harvesting of non-fossil carbon resources (e.g. biofuels) [1]. Without underestimating the potential environmental and economic benefits of these, it would be only sensible to add on the nuclear engineering option as a possible alternative with minimal detrimental emissions (CO_2, NOx, SOx). The adoption of a nuclear solution for ship propulsion will, of course, involve a number of ship life cycle emissions that are detrimental (e.g. nuclear waste, radiation etc.). However, taking account of the associated risks and benefits within the context of the broader maritime environmental agenda the option of nuclear propulsion of merchant ships might appear reasonable despite the many challenges involved. This paper explores nuclear propulsion by means of a case study, which sets the issues against realistic technical background.

Nuclear powered ships have been operated by a few navies and in Russian icebreakers for over 60 years. This successful operational history of nuclear power has not, been exploited in commercial shipping, beyond a few experimental projects. The possible use of emerging Small Modular Reactor (SMR) nuclear technology onboard ocean going vessels opens up new opportunities and this technology forms the basis of the study reported.

The 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 for accommodating the 70MW Gen4Energy SMR propulsion plant. The choice of the target ship has been driven by the fact that such assets generally perform loading/unloading operations outside ports and therefore the use of a nuclear powered ship might face less adverse local challenge. The publication reviews some of the recent technical advances, the background of the Gen4Energy SMR technology that has been chosen for the study and describes the risk based ship design rationale behind the concept design choices. The focus of this paper is technological. However, a brief discussion on the need for further research, harmonised standardisation and policy actions is also provided in an attempt to identify the knowledge and experience that the maritime and nuclear industries will have to develop or acquire so as to enable commercial development of nuclear powered shipping in the future.

2. THE NUCLEAR OPTION RATIONALE

When considering modern nuclear technology options for marine propulsion it is important to appreciate aspects of safety and economy in relation to engineering solutions for the maritime environment. Historically, improving safety standards to protect human life and the environment has been one of the prime drivers for the development of engineering technologies. Developing proactive engineering solutions, understanding the effects of adverse incidents with the aim to continuously implement improved regulations has been the key for assuring safety in both maritime and nuclear industries. It is true that over the years, the inevitably strong social and environmental impact of selected nuclear disasters led to strong scepticism on the viability of expanding the capacity and capabilities of the land based nuclear industry [2]. The impact of more recent nuclear incidents has refreshed the level of public and political opposition to expansion of land-based nuclear power projects and it must be anticipated that this will be reflected in any proposals to use nuclear power at sea in commercial applications. However, recent advances in nuclear technology and the continuous development of the nuclear regulatory framework may result in this tide of scepticism turning as pressure to reduce dependence on fossil carbon increases. So although fears about safety have caused political restriction on port access for the few experimental civil nuclear ships in the past the global demands for energy security and the need to reduce the dependence of the world's economy on fossil fuels further support the need to explore the feasibility of modern nuclear technology options for exploitation by the merchant marine sector.

The shipping industry's desire to explore emissions abatement solutions within the context of a global decarbonisation policy deserves special recognition. According to the International Maritime Organisation (IMO), today international shipping contributes between 2.7% and 3.3% of the global CO_2 emissions annually [5]. This contribution, on its own, places the industry, in absolute terms, as the 6th in line in relation to the countries that are the largest producers of CO_2. Without action the contribution of shipping could grow significantly and by 2050 could amount to between 12% – 18% of the total allowable global emissions of CO_2 under the International Energy Agency (IEA) 450 ppm stabilisation scenario [6]. Nuclear propulsion has obvious advantages in terms of reduced CO_2 emissions and could deliver significant benefits provided that appropriate policy and safety measures are well agreed and unified at international level. For example, lifecycle CO_2 emissions from fossil fuels are by far higher than their corresponding nuclear indirect emissions [7]. Also, in contrast to hydrocarbon driven combustion, nuclear fission entails no chemical reactions. Yet, it is important to realise that the overall nuclear fuel cycle has some potentially hazardous emissions associated with the released energy of fission and the energy of neutrons. Additional GHG and other contaminants may be released into the atmosphere during plant construction, uranium mining or milling, reactor fuel manufacture and transportation, auxiliary power generation and plant decommissioning.

3. KEY MARITIME DEVELOPMENTS

Commercial marine nuclear power applications benefit from the demonstration of the effectiveness of naval nuclear technology over a period of more than 60 years. A small number of nuclear powered merchant vessels, employing similar Pressurised Water Reactor (PWR) technology, have also been commissioned. The most famous of all was the 22,000 tonnes USA-built *NS Savannah* that entered service in 1962 Propelled by a 74 MWt reactor. She was a technical success but not economically viable [8]. The 15,000 tonnes German-built *NS Otto Hahn* was a cargo ship and research facility, commissioned in 1972. She sailed some 650,000 nautical miles on 126 voyages over 10 years without any technical problems with a 36MWt reactor delivering 8MW to the propeller. However, it proved too expensive to operate and in 1982 she was converted to diesel propulsion. The 8,000 tonnes Japanese-built *NS Mutsu*, also driven by a reactor of the same specification as *NS Otto Hahn*, was the third civilian vessel. She was put into service in 1970. Research and development activities related to this vessel focused on ship design for safety within the context of deterministic engineering solutions [9] and reactor safety features [10]. Commercial and political issues led to her removal from service in 1995 [11].

Merchant marine applications have been technically and economically useful in the Russian Arctic where operating conditions are beyond the capability of conventionally powered icebreakers [3]. Since the launch of the icebreaker *Lenin* in the 1960's, the Russian *Arktika* class icebreakers have been operating in 'The Northern Passage Route'. The 6th ship in the class of 25,800 displacement tonnes named *NS 50 Let Povedy* propelled by two OK-900A Russian PWR providing electrical power to three shafts was delivered by the Baltic shipyard at St. Petersburg in 2007. With a length of 160m, beam of 30m and a spoon – shaped bow she is designed to break a passage through ice 2.8 m thick. Following on from these developments, in 2009 the joint stock company 'Central Design Bureau Iceberg' completed the concept design of the new 'Universal Nuclear Icebreaker' using a KLT-40S PWR unit [12]. This larger beam, highly automated design allowed for reduction of ship personnel to about half of that on the previous generation of vessels. Engineering capability for operations in both deep and shallow water conditions was achieved through the implementation of a system able to move 9,000 tonnes of ballast water within 4 hours. Based on conclusions from this project, tenders were called for building the first of a new generation LK-60 series of Russian icebreakers in mid 2012. These vessels are of dual-draught configuration (10.5 m with full ballast tanks or 8.55m at 25,540 tonnes), displacing up to 33,530 tonnes. The first ship of the series is to have a length of 173 m and has been designed to break through 3 m thick ice at 2 knots forward speed. The LK-60 will be powered by two of the latest generation Russian PWR RITM-200 of 175 MWt. Together these reactors will deliver 60 MW at the three propellers via twin turbine generators and propulsion motors. At 65% capacity factor, refuelling is estimated to take place every 7 years. The service life is estimated for 40 years under western Arctic operational conditions.

Since 2002 the changing market economics and environmental concerns led marine nuclear propulsion proponents to reconsider the feasibility of traditional technology options. Vergara and McKesson et al [13] developed a design for a large, fast mono-hull ship using two helium cooled nuclear reactors and Sawyer et al [14] presented a simplified economic investigation on the feasibility of a 9,200TEU PWR powered container ship for trans-pacific service. These studies concluded that whereas new building costs would be increased, such nuclear propelled vessels would save on lifetime fuel costs and still provide a margin for cost, weight and size optimization. More recently, Hill et al [15] examined the potential of the thorium cycle driven molten salt reactor for medium sized surface warship propulsion. The authors concluded that risks related with the reactor's thermal and radiological shielding and insulation, the overall plant heat management including drain tank cooling as well as Tritium removal from the salt chain would have to be resolved before seriously considering implementing such technology. In 2009 Lloyd's Register studied the benefits of applying marine nuclear propulsion using proven technology. The study confirmed in principle that a safe and efficient ship, using proven PWR reactors for propulsion, was practicable provided that the political climate, regulatory requirements and market dynamics remained favourable [16]. The longer term research effort presented in this paper, also initiated in 2009, aims to identify realistically the risks and implications of implementing modern SMR nuclear technology [17] in place of the proven PWR technology. This work has been supplemented by research into innovative modular ship concepts [18] and hybrid (diesel/nuclear battery) nuclear options [19].

4. RULES AND REGULATIONS

Lloyd's Register was the first Classification Society to introduce Provisional Rules for the Classification of Nuclear Ships in 1966 [20], in anticipation of an imminent interest in building nuclear powered merchant ships following on from the demonstration of the concept with *NS Savannah.* At the time Lloyd's Register introduced the Nuclear Powered (NP) class notation on the basis of deterministic requirements for the hull, pressure vessels and components, reactor engineering and control, survey and maintenance. These Provisional Rules also considered some complementary requirements outlining the importance of shielding, refuelling, effluent disposal, emergency installations and shock.

During the 1970s, significant work by the IMO led to the adoption of Resolution A.491-XII [21]. The purpose of this code was to provide a technical and regulatory reference for nuclear powered merchant ships and to supplement other applicable International Conventions, codes and recommendations. The Resolution defined specific safety issues and criteria concerned with the protection of people and the environment from possible radiation hazards on the basis of a quality assurance programme spanning the vessel lifecycle. Whereas the quality assurance programme would be the responsibility of a single organisation it would not prohibit transfer of Class. The code also defined requirements concerned with the reactor shielding, core cooling, ship stability, structural integrity, fire and safety features, whilst also defining surveying requirements during construction, sea trials and operation. These issues are specifically addressed in the form of six appendices discussing respectively: sinking velocity, seaway loads, safety assessment, dosage limits and application of single failures. Safety objectives have been implemented through:

- Protection of people and the environment against 'unacceptable' hazards due to intentional or accidental release of radioactive substances and ionizing radiation in both port and at sea;
- Functional safety of the ship system;
- Safety of interaction between the nuclear propulsion plant with the ship, cargo and operating environment.

In 2011 Lloyd's Register withdrew the Provisional Rules, which were still extant, and published a set of provisional goal based guidance notes for the design of nuclear propelled vessels [22]. On the assumption that prescriptive requirements may not be thorough enough for integrating a nuclear plant into a ship these guidance notes attempt to satisfy land based nuclear regulators and give sufficient confidence to Class a vessel. Design goals are underpinned by design principles and corresponding detailed design requirements. The latter provide an illustration of either the only way or one way in which the required design performance can be achieved. The goals identified relate to engineering and safety systems, the ship structure and radiological protection. The overall rationale of the Rule making process assumes that in contrast to the current marine industry practise where the designer/builder typically demonstrates compliance with regulatory requirements, in the future the nuclear regulators will wish to ensure that it is the operator of the nuclear plant that demonstrates safety in operation, in addition to the safety through design and construction.

4. MARINE NUCLEAR TECHNOLOGY

4.1 TECHNOLOGY CLASSIFICATION

A nuclear reactor is a device used to initiate and control a sustained nuclear chain reaction [16] and to produce thermal energy that can be used to, for example, raise steam. Nuclear reactor types can be classified according to the type of nuclear reaction, the moderator material that controls the reaction, the coolant type, the application focus and the technology used. To date, marine nuclear technology has primarily evolved through two system designs namely:

- Generation I early prototypes and first-of-a-kind reactors built in the 1950s and 1960s primarily by USA, USSR and UK; and
- Generation II reactors built from 1960s - 1990s. These utilise low enriched uranium with light water as coolant and moderator and are therefore designated as Light Water Reactors (LWR).

Modern reactor technologies can be classified as:

- Generation III advanced LWR of the PWR or Advanced Boiling Water Reactor (ABWR) type with active safety systems (e.g. General Electric Co. ABWR, Westinghouse Electric Co. AP600) or heavy water reactors (e.g. Atomic Energy of Canada Ltd. CANDU 6);
- Generation III+ reactors that add incremental improvements to proven designs with enhanced levels of safety and security (e.g. Areva/EDF European Pressurised Water Reactor EPR, Westinghouse Electric Co. AP1000);
- Generation IV reactors that mark a more radical departure from current designs including reactors cooled by lead, sodium, molten salt, supercritical water and helium. These advanced reactors use various nuclear fuel types including oxide, nitride, carbide, and metal, and can be based on uranium, plutonium, and thorium.

4.2 SMALL AND MEDIUM SIZE REACTORS

Modern small and medium size reactors came into focus in recent years, due to large initial capital investment requirements for nuclear power plants. In the area of marine applications the technology could offer simpler, standardised and safer modular design by being factory built, cheaper and easier to manufacture [23]. Small and medium size reactors can be classified as:

- Type I LWR designs based on proven and utilised PWR technology. These are thermal reactors that use normal water (as opposed to heavy water) as coolant and neutron moderator;
- Type II Fast Neutron Reactor (FNR) designs for medium to long term deployment in main or remote locations. Those may be of smaller size than Type I designs. They use liquid metals (instead of water) as coolants and allow for fast neutrons of higher energy to create fission in the reactor;
- Type III advanced High Temperature Reactors (HTR) that are cooled either by liquid metal or liquid salt. These designs are expected to be the most difficult to license because there is not much operational experience.

4.3 THE GEN4ENERGY SMR

The Suezmax Tanker design application presented in this paper is based on the Gen4Energy Generation IV, fast neutron SMR developed in association with the Los Alamos National Laboratory. The basic specification of the reactor system and the rationale of some of the key technology selections are presented on Table 1. The reactor comprises the following two systems (see Figure 2):

- The primary system which is a single loop, liquid metal cooled fast reactor using Lead Bismouth Eutectic (LBE) as coolant. The reactor module has been sized to be transportable and is shielded in a containment that can provide protection from external threats. When the module is connected to the primary loop, the liquid metal coolant is pumped through the reactor module to heat exchangers that heat the secondary liquid metal circuit. Additional primary system components include the cover gas system and the oxygen control system;
- The secondary system is a steam generation system and operates as a steam Rankine cycle. The steam generator contains a feed pump, an evaporator and a super-heater. High and low pressure turbines are connected to a common shaft. The condensate system includes a condenser and a condensate pump.

Table 1. Key Gen4Energy SMR technology features

Engineering	Description	Characteristics	Benefits
General Reactor features	Fast Neutron Spectrum	• P_R = 70$MW_{thermal}$; 25$MW_{electrical}$ • W_R < 50 tonnes • D_R = 1.5 m ; H_R = 4 m • Use of full energy potential • Better dynamic performance • Few changes in system with lifetime	• Long core lifetime without refuelling (approx. 10 years) • Small impact of fission products on reactivity • Little isotropic transmutation • Reduced radioactive waste trough transmutation
Core Coolant	Liquid metal LBE (Pb-Bi)	• Lower melting temperature and minimum expansion at melting in comparison to Pb • Lower risk of leaks and subsequent chemical reaction with water or air in comparison to Na	• Compact core design that can produce a 500^{0}C high coolant temperature • Good system efficiency
Nuclear Fuel	UN (stainless clad)	• ^{235}U enrichment = 19.75% • UN pellets contained in tubes made of HT-9 (ASME 12Cr1MoVW) stainless steel	• Good thermal conductivity • High core life • Low fission gas release and fuel swelling • Resistance to irradiation damage over extended time • Factory fuelling
Reactor core	• UN (open lattice) • Improved active and passive safety features	• Reactivity control rod system composed of 6 inner and 12 outer B_4C shutdown rods • Reserve shutdown system consisting of a cavity into which a single B_4C rod may be inserted. • Heat is transferred from the core via circulation of coolants.	• Light design; easy sealing and transportation • 10 year Long life without refuelling • Enhanced system reliability to operational blackouts and shutdown conditions • Improved Safety by active and passive shutdown • Independent and diverse means to remove decay heat under all plant shutdown conditions

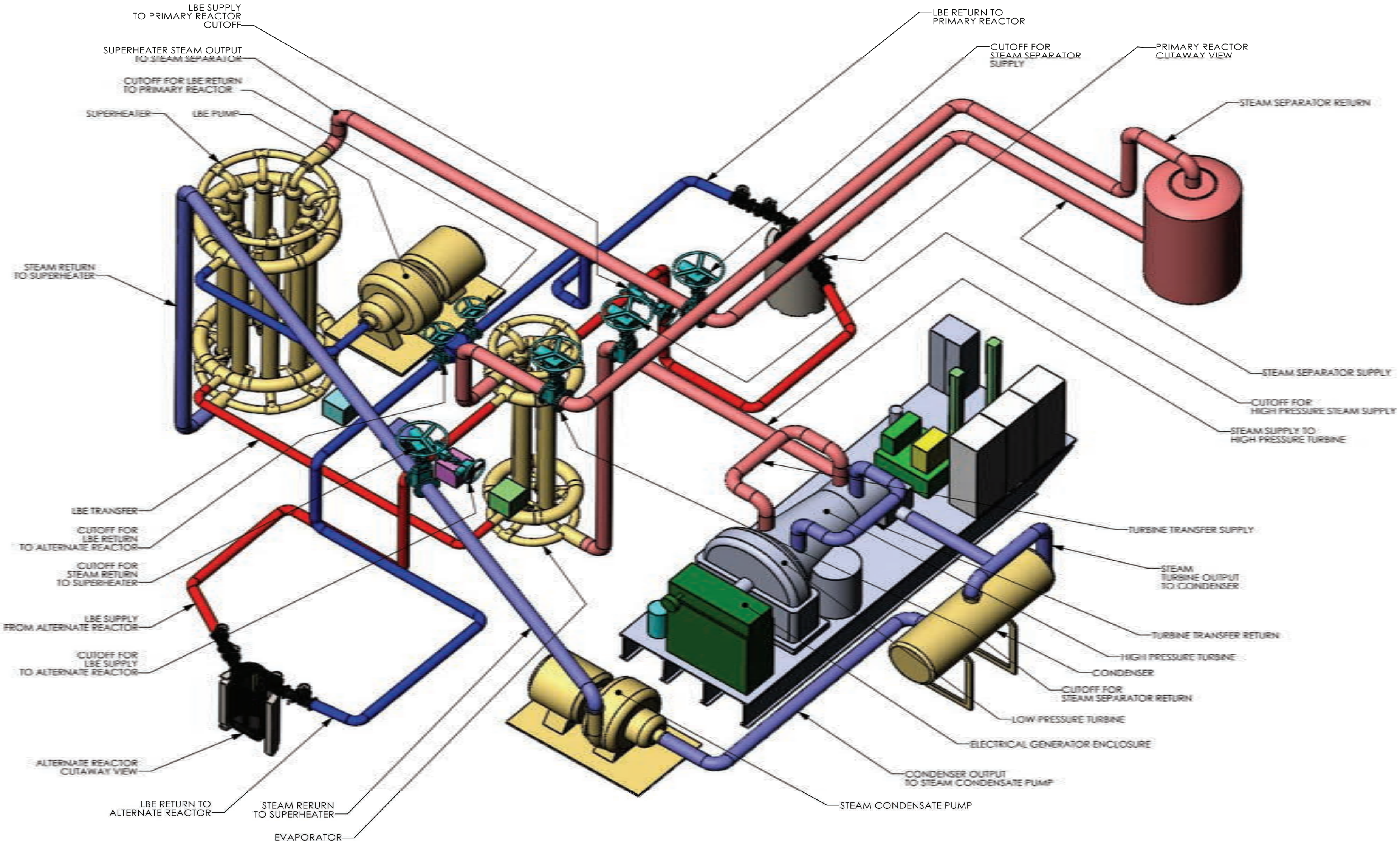


Figure 2. Gen4Energy SMR Power Generation core Module

Table 2. Principal particulars of parent versus SMR tanker designs.

Principal Particulars		Parent Ship	SMR Tanker
L_{OA}	(m)	274.48	304.25
L_{PP}	(m)	264.00	287.03
B (moulded)	(m)	48.00	48.00
D (moulded)	(m)	23.10	23.10
$T_{scantling}$ (moulded)	(m)	17.05	15.84
Summer freeboard	(m)	6.07	7.26
$T_{summer\ load}$ (moulded)	(m)	17.05	15.84
$A_{wetted\ surface}$ (at $T_{scantling}$)	(m^2)	18,814	20,018
Lightship weight	(tonnes)	23,528	29,870
∇	(tonnes)	182,617	185,371
Deadweight	(tonnes)	159,090	155,501
P at 100% Maximum Continuous Rating	(kW)	18,881	23,515
V	(knots)	14	14
%MCR at V		54%	42%

Table. 3 Preliminary engineering design considerations

Reference Suezmax Tanker	SMR Suezmax Tanker
• $L_{cargo\ tanks} = 78\% \times L_{OA}$ • $L_{stern\ section\ to\ fwd\ bulkhead} = 16\% \times L_{OA}$ • $L_{bow\ section\ fwd\ of\ cargo\ tanks} = 6\% \times L_{OA}$ • $A_{wetted\ surface} = 768\ m^2$	• SMR integration may imply change of principal particulars. Suez Canal Authority design restrictions should apply: 1. $B_{max} < 77.5m$ 2. $T_{air\ max} <68m$ 3. $T_{max} < 12.192m$ in way of B_{max} (in ballast) 4. $T_{max} < 20.12$ m if $B_{max} > 50m$ (full load) 5. $A_{wetted\ surface} = 20{,}018\ m^2$ (at $T_{scantling}$) 6. No length extension restrictions
• $LCG_{cargo\ tanks}$ = 5% fwd amidships • $W_{cargo} > W_{lightship}$	• Maintain similar trim to conventional suezmax tanker (hull form and weight should balance around W and $LCG_{cargo\ tanks}$)
• The main cargo tanks longitudinal bulkhead is sub-divided into 6 pairs of main, side and bottom tanks for water ballast. • 2 slop tanks are aft the main cargo area.	Current Suezmax features should be maintained to comply with damage stability standards
• Slow speed diesel engine • Power = 18,881KW at 91 rpm • Direct coupling to a fixed pitch 8.2m diameter propeller	• Modification in the specific choice of propulsion equipment may be necessary • Manoeuvring, propulsion & powering requirements should be maintained
• No redundancy for propulsion, steering and essential systems	• Consider redundancy arrangements
• Cargo handling by centrifugal pumps installed in a pump room co-located foreword of the machinery space. Crew accommodation in a deckhouse above the engine room, separated from the funnel casing to reduce noise & vibration	• Risk mitigation measures associated with both of these features should be considered

5. CONCEPT SHIP DESIGN

The main objective of the ship design exercise has been the development of a basic concept implementing the Gen4Energy SMR technology on a modern Suezmax tanker vessel, based on ships currently operated by Enterprises Shipping and Trading S.A (see Table 2). Table 3 summarises the preliminary naval architecture and marine engineering design considerations. Although there is currently no Classification requirement for propulsion machinery redundancy the consortium took the view that this matter would be essential to ensure that the public perceives future nuclear vessels to be safer than current designs.

5.1 RISK ASSESSMENT

The purpose of the risk assessment process has been to demonstrate that the concept design would present a risk of environmental damage or loss of life due to a nuclear accident or oil spills that is As Low As Reasonably Practicable (ALARP). The study took account of the following top-level objectives:

- Minimisation of the risk of radiation leakage due to engineering, human or environmental factors;
- Minimisation of the risk of small, medium or large oil spills as a result of accidental failures;
- Achievement of a zero fatality and injury rate for tanker operations.

Ship designers, SMR providers and the ship owner interacted in the role of system engineers. Their role has been to:

- Define the capability that the SMR Tanker should have, based on trade-offs between design decisions;
- Create the high-level design, or system architecture, and translate it into the requirements for each element;
- Identify and assess the top level risks associated with functional safety, engineering systems dependability and human factors aspects.

The role of Lloyd's Register has been to facilitate the risk assessment processes, acting as an independent assurer for the safety of the ship as befits a classification society. This included provision to the project team of advisory expertise on the application of the Classification Rules [24], the IMO SOLAS Regulations for Alternative Designs and Arrangements [25] and the IMO MARPOL Annex I damage extend requirements [26]. To ensure that qualitative risk assessment was undertaken consistently, with an appropriate degree of rigour and in a manner consistent with applicable IACS guidelines [23], the consortium addressed top level issues assessing the associated risks and the mitigation, or risk control, options. The risk assessment was carried out in two stages that aimed to cover all reasonably foreseeable hazards, irrespective of whether they may eventually fall within the scope of Classification or Statutory approval. In specific:

- <u>Stage 1</u> assisted with short listing design options and with screening the risk profile of the ship ;
- <u>Stage 2</u> was a comprehensive Hazard Identification Study (HAZID).

Completion of this risk analysis process could be sufficient to lead to *'design approval in principle'* for the concept. This step was not taken as the regulatory position cannot yet be finalised and further development of nuclear engineering concepts would be expected. This position is wholly consistent with the requirements set down in Lloyd's Register's provisional guidance notes for nuclear ships which condition any Classification approval on the successful submission to a Nuclear Inspectorate of the design of the nuclear reactor plant, along with the safety case for a specific vessel application [22].

5.1 (a) Stage 1 Risk Assessment

A number of oil tanker accidents for ships of age up to 30 years as well as available records of 40 submarine accidents have been reviewed [3],[4]. As shown in Figure 3 until 2011 40% of the tanker accidents have been related to structural failure. Despite advances in merchant ship designs and standards, risks due to fire, grounding and collisions are still present. On the other hand the majority of submarine accidents are due to fires or explosions. The following lessons emerging from PWR merchant marine technology demonstrators were also considered:

- In 1970 at the first official run of *NS Mutsu* very high levels of gamma and neutron radiation were measured. It was discovered that neutrons had leaked out through the gap between the reactor and the primary shield hitting the secondary shield structure and producing gamma rays ;
- In 1965, when *NS Lenin* was undergoing repairs and refuelling severe mechanical damage to the fuel assemblies was detected during the removal of the used fuel from reactor number two. It was established that the reactor core had been left without cooling water due to human error;
- In 1967 *NS Lenin*'s piping of the tertiary circuit sprung a leak following the loading of fresh nuclear fuel. Further reactor damage was sustained, when the biological shield of the reactor compartment was opened to locate the leak.

To understand the influence of the choice of the novel SMR technology on reactor safety the design team considered the design features of the SMR technology in comparison with a standard PWR nuclear installation (see Figure 3(d)). It was concluded that an SMR is inherently safe in comparison to a typical PWR design or a more modern LWR. This is because it operates with the primary coolant close to atmospheric pressure (so there is less stored energy to be released in a postulated leak or break accident). Also the reactor is cooled with LBE which has a very high vaporization temperature of 1700 ^{0}C. Hence, it cannot flash to vapour.

Top level risks associated with selecting different locations for the SMR and propulsion systems were considered for both intact and damaged operational modes (see Tables 4,5). Each possible SMR location was assessed for vulnerability to collision damage, fire and explosion, ship motions and vibrations. From the four SMR location options short listed it was concluded that placing the SMR aft of the cargo tanks and below the forward end of the accommodation is the preferred choice, being subject to low or medium levels of risk (Option B). Inevitably, the need to design for a vessel with inherent survivability capabilities [26] led to some complex power train options. The propulsion options considered were as follows:

- Twin screw mechanical drive option: Each screw would be driven by a steam turbine and reduction gear. The two independent propulsion systems would be separated by a longitudinal bulkhead to reduce the risk of common cause failure due, for example, to fire or flooding. Auxiliary steam turbo-generators would be arranged to generate electrical power. In case of a failure of the SMR or steam generation system a diesel generator would provide emergency electrical power and also provide power to shaft motors to retain some propulsion;
- Twin screw electric drive option: Each screw would be driven by an electric motor. The two independent propulsion systems would be separated by a longitudinal bulkhead to reduce the risk of common cause failure due, for example, to fire or flooding. Electrical power would be generated by steam turbo generators fed by the SMR, smaller auxiliary steam turbo generators would be arranged to supply harbour loads. In case of a failure of the SMR or steam generation system a diesel generator would emergency electrical power and also provide power the shaft motors to retain some propulsion;
- Single screw mechanical drive with propeller and electrical podded propulsor: The podded propulsor would run in normal operation in contra-rotating motion to the main propeller shaft to propel and steer the vessel. The propeller would be driven by a steam turbine and reduction gear and the podded propulsor would be driven by a steam turbo generator supplying electrical power. The arrangement would increase propulsive efficiencies over a single propeller installation. In the redundant mode if a failure occurred somewhere in the main drive train, the podded propulsor would provide some propulsive capability;
- Single screw mechanical drive with single shaft line: A single main shaft line driven through a steam turbine with a reduction gear would provide the normal propulsion solution. A shaft motor and a clutch would be installed on the gearbox output that would be used in the event that the main propulsion unit failed.

A well designed mechanical drive option, designed for the correct duty point of the vessel, will take up less space, weigh less and provide better propulsive efficiencies than an electric propulsion option. It was therefore decided to submit the twin and single screw mechanical drive propulsion train arrangements along with option B general arrangement in stage 2 review.

5.1 (b) Hazard Identification Analysis (HAZID)

During the HAZID study four key nodes representing the SMR, the steam generation and turbines, the propulsion system and the redundant power source for propulsion were considered. The process assumed that:

- A diesel driven generator would supply electrical power to shaft motors to provide propulsion redundancy.
- Hazards associated with independent failures of steam generation and turbine systems are well understood.
- Hazards relevant to operation of the SMR should be considered based on fundamental analysis.

Some of the key recommendations emerging from the analysis are outlined on Table 6. The main issue identified for the single shaft line installation was the requirement to ensure that there was sufficient separation of the shaft motor compartment so that the motor would not be affected by flooding if the main engine room was breached. A single screw shaft line arrangement is less vulnerable to any side penetrations and hence would be at lower risk of damage during an accident. Consequently, a single shaft line power train running for 70%-85% of the total installed propulsive power with a rudder or Azipod designed for 15%-30% of the installed power was considered preferable in comparison to the twin screw propulsion arrangement.

The human factors analysis, which formed part of the HAZID assessment, assumed that the nuclear lifecycle licensing standards and processes required for land-based reactors, nuclear facilities and personnel would be applicable for maritime applications. Some of the hazards considered were (a) human errors not necessarily specific to the SMR installation, (b) violations including operator errors or misuse of technology that together with other failures may affect the SMR (e.g. inappropriate post casualty response, operation beyond vessels limits) and (c) malicious acts (e.g. piracy or adverse security actions). It was confirmed during the study that all principal disruptions to the reactor or auxiliary services systems would be covered by safe shut down through engineered failsafe mechanisms enabled by:

- Installation of a fully redundant power supply;
- Provision of uninterruptible power supply to critical emergency electrical systems;
- Automated control of the reactor power that reduces the risk of operator error under emergency conditions;
- The SMR control software.

It was recognised that potential hazards may cause or contribute to the occurrence of failures. However, further understanding of those will be necessary at detailed design stage,

Table 4. SMR location options

Option	SMR Location	Qualitative vulnerability realisations		
		Collision Damage	Cargo Tanks & Fire/Explosion	Motions & vibrations
A	Aft end – Under Funnel	High	Low	Medium
B	Aft of Cargo Tanks	Low	Medium	Medium
C	Amidships	Medium	High	Low
D	Forward of Cargo Tanks	High	Medium	High

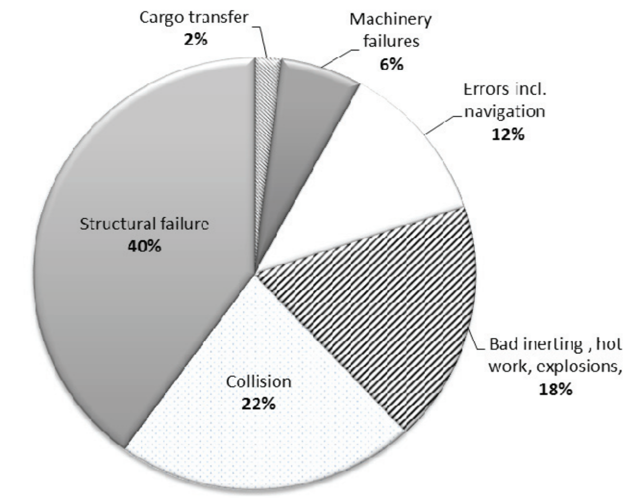
Table 5. SMR power train options

Item	Steam Drive		Electric Drive		Comments
	Option 1 Twin Screw	Option 2 Single Screw	Option 3 Twin Screw	Option 4 Single Screw	
Technology					Marine steam turbine reduction gears are commercially available but may need to be updated for SMR steam conditions.
Efficiency					Single screw would lead to low powering requirements. Steam drive & reverse reduction gear would allow for better underway efficiencies.
Redundancy					Arrangements can be configured to comply with safe return to port and have redundant power.
GA Impact					Twin screw installations may prove more challenging. Electric installations are likely to require greater machinery space volumes than direct steam drive installations.

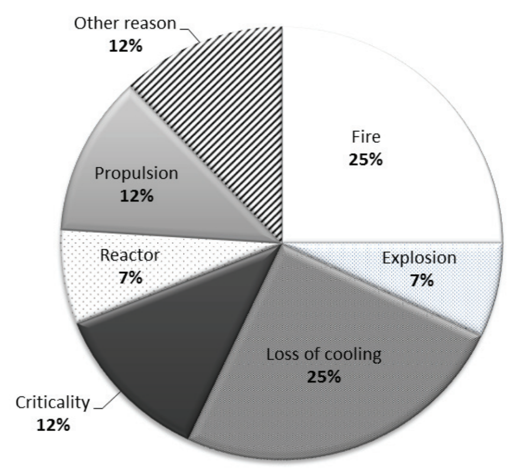
Keys

Better / No Issue
Neutral / Some Issue
Poorer / More Issues

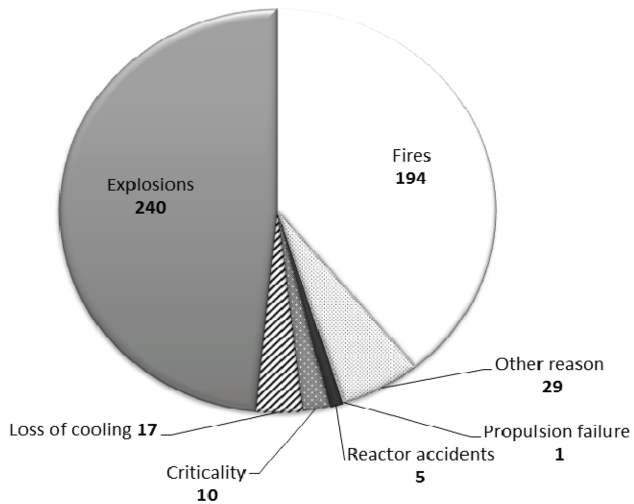
(a) Oil tanker accidents



(b) Indicative % of submarine accidents



(c) Submarine fatalities



(d) PWR technology versus Gen4Energy SMR

Characteristics	PWR	Gen4Energy SMR	Advanced SMR features
Technology	Generation II	Generation IV	Design
Coolant	Water	Pb-Bi	Coolant unlikely to evaporate
Containment	Bulky structure	Well contained structure	Better isolation
Fuel cladding	Zirconium	Stainless steel	Non-reactive with coolant
Decay heat removal	Active safety (electrical)	Passive safety (30 days)	Less susceptible to accidents
Size	Very large	Small	

Figure 3. Key commercial tanker and naval nuclear submarine accidents (NB: 'Propulsion failure' may involve the reactor system although in most cases this seems not to be the case; 'Other reasons' involve collisions and suspected operator error).

Table 6. Key HAZID considerations

Item	Key issues	Considerations
1	Accessibility to high radiation areas	Practical control of 3rd party accessibility
2	Space for a 2nd SMR	SMR positioning
		SMR cooling, access, containment
		Operational requirements
		Regulations; Vessel could be considered to be carrying spent radioactive waste
		Methods for reactor removal
3	Operation of emergency cooling systems	Capacity/design of the reactor passive cooling systems accounting for cooling duration
		Consider grounding conditions where the vessel could tilt
4	Protection of the reactor from accidental loading	Design SMR cooling system to prevent meltdown in the event of ship sinking
		Define operational guidelines on grounding to maintain reactor integrity
		Define fire fighting system requirements and boundary cooling for SMR compartments in case of onboard fires/explosions
		Design for back-up power source setup and positioning to account for reactor shut down due to loss of propulsion
5	Reactor protection against terrorist attacks	Physical protection of the reactor against impact from missiles
		Considerations under Section 4 a,b,c,d apply
6	Reactor/propulsion system emergency stop	Define transient operating conditions for the reactor, steam system, turbine and heat removal

5.2 SHIP CONCEPT DEVELOPMENT

Concept design efforts focused on developing a practical solution for the SMR Tanker by developing a complete general arrangement for the ship, incorporating the proposed main and auxiliary systems (see Figures 4-7). The principal decisions that influenced the resulting concept solution are summarised as follows:

- A mechanical propulsion installation option utilising a shaft driven propeller and a podded drive with Contra Rotating Propellers (CRP). The diesel electric CRP mounted on a steerable pod (i.e. Azipod solution or equivalent), should be the preferred main propulsion option as this improves the propulsive efficiency of the vessel whilst having less impact on overall vessel length. Studies found that this solution would require 30 m (or 11%) increase of the overall vessel length once the design is adjusted to the reference vessel's hydrostatic trim. This comprised 20m aft of the cargo zone to incorporate the new propulsion system and to accommodate redundancy after damage as well as a 10m extension forward of the cargo zone. This is more practical and economic in comparison to the 25m lengthening of the original vessel's engine room (leading to 40-50 m L_{OA} increase) necessary for the implementation of the single screw/shaft motor installation option;
- The CRP Azipod arrangement and the redundant power sources should be located at the stern of the vessel;
- The main steam turbines and associated reduction gearing should be located in the main machinery space along with two auxiliary steam turbine generators and all associated condensers;
- In order to maintain propulsion in the worst case damage condition and to accommodate for the primary spatial constraint on installation of the propulsion systems two transverse bulkheads should be located more than 14.5 m apart separating the main engine room from the Azipod compartment;
- The Azipod and redundant power sources would have to be separated by a compartment containing two fuel tanks, each containing sufficient fuel to propel the vessel for a distance of 2,000 nautical miles from mid Atlantic to a safe refuge assuming that the redundant propulsion system is in operation;
- Emergency propulsion arrangements should provide for service speeds between 6 – 8 knots. These should be arranged to propel the vessel in the event of failure of any component in the main drive train under the worst case conditions. A diesel engine running on marine diesel oil would accommodate this demand;
- The SMR compartment should be located aft of the pump room trunk;
- Two SMR vaults should be installed in the SMR compartment. In principle, this concept choice would allow the option for a spent reactor core to cool down while the vessel is still in operation.

The following issues were considered important for enabling the operation of engineering system components surrounding the SMR:

- Emergency cooling water arrangements: To ensure that in any condition of heel or trim 30 days of decay heat removal could be provided to the reactor core, the machinery arrangement provides for four 100 m^3 tanks;
- Collision and grounding protection: Whilst it has not been the scope of this concept study to propose any detailed structural proposals, the reactors have been located in a compartment that is located on the vessel centre-line well above the double bottom;
- Radiation protection: A 1 m space provision should be made for radiation protection of the reactor compartment, allowing for a combination of 0.15 m lead shielding and 0.8 m polyethylene shielding in way of the 0.05 m steel casing of the reactor;
- Vibration: In principle the inclusion of a steam turbine reduction gear should provide low levels of vibration. The use of a CRP installation further improves matters in the sense that the main shaft line would transmit approximately 70% of the power required by the vessel. At detailed design level it would be necessary to assess anticipated ship borne vibrations and accelerations and ensure that the reactor vault is designed to suit these values.

5.3 NAVAL ARCHITECTURE REVIEW

The naval architecture review process examined weight distributions, trim, stability, powering and reactor life with respect to fuelling and endurance estimates. A preliminary capital expenditures and expenditures creating future benefits (CAPEX) projection estimate was also considered. Two departure loading conditions namely (a) normal ballast and (b) homogeneous full scantling loading, were studied to evaluate the trim of the updated vessel. It was concluded that the SMR Tanker is intended to carry the same cargo as the reference ship with a deadweight increase primarily due to modifications on the lightweight distributions (see Figure 8). To assess the impact of alternative propulsion choices on power resistance a 'Holtrop' resistance prediction was conducted [29] and corrected for the known trials data for the reference vessel (see Figure 9). With regards to stability, since the cargo tank geometry and capacities had not been changed, the free surface correction recorded for the reference vessel was applied to the loading conditions of the SMR powered vessel and the results were found to be within the range of relevant IMO threshold criteria [21],[28] (see Table 7).

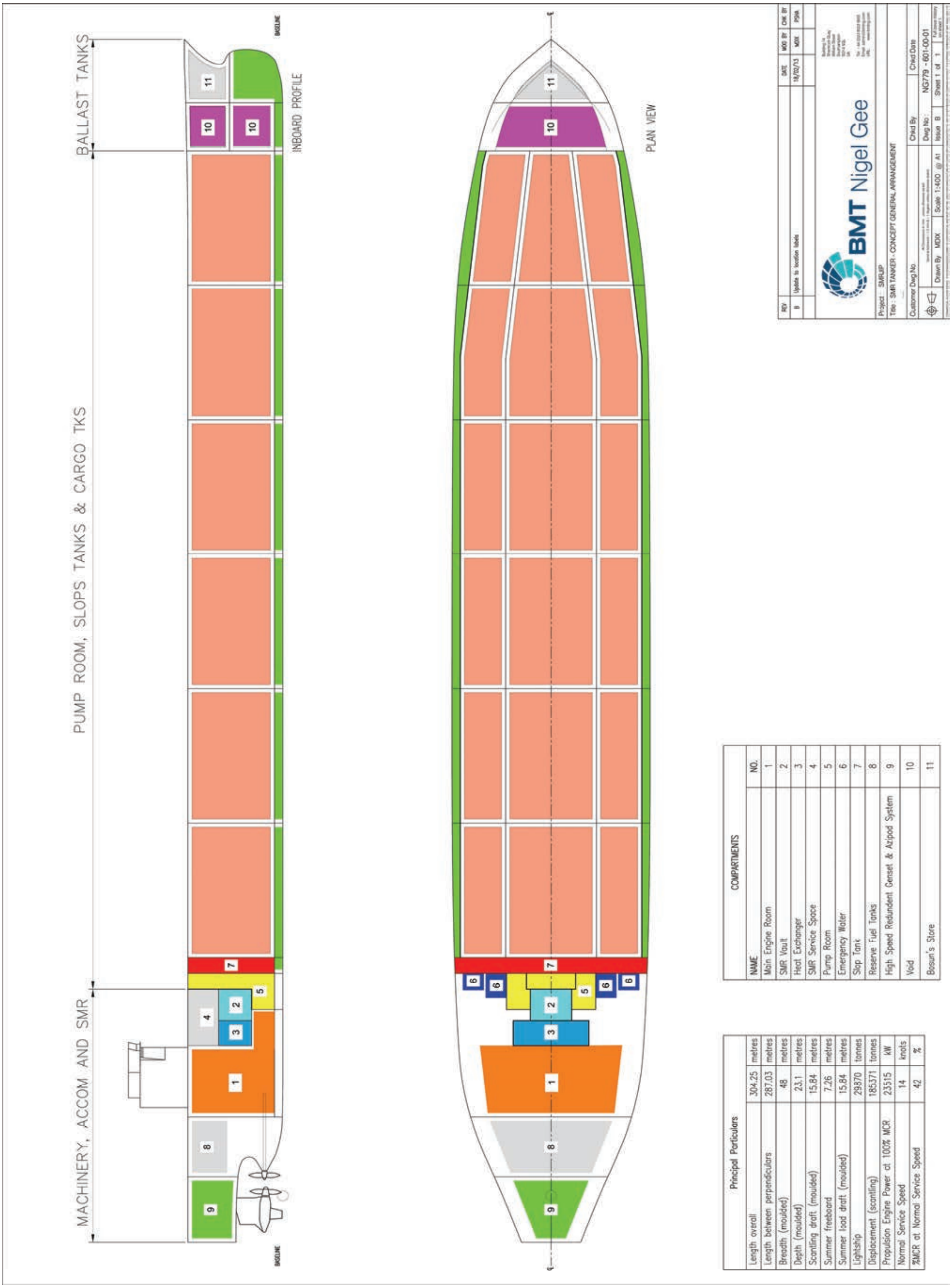


Figure 4. SMR concept vessel General Arrangement.

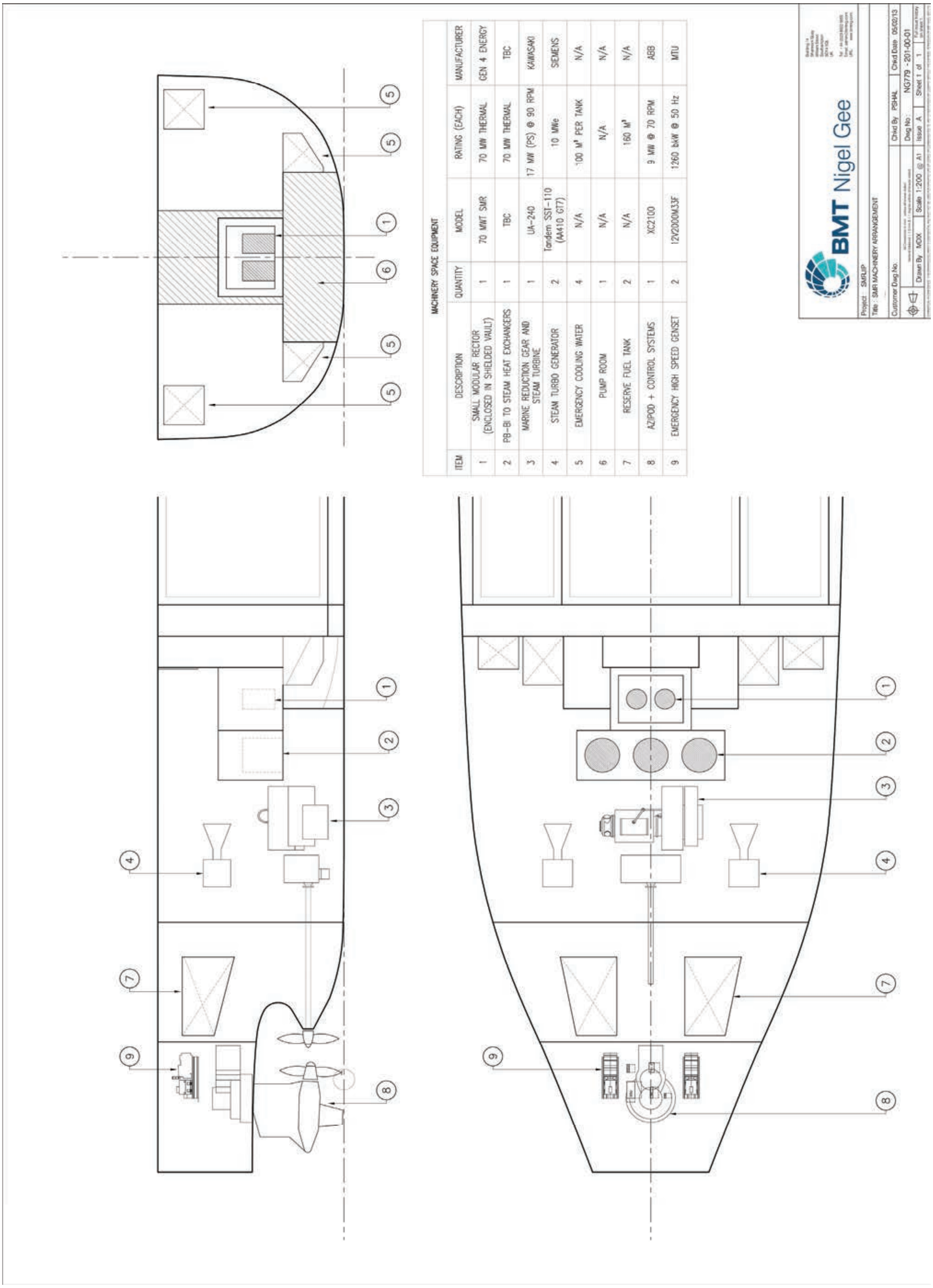
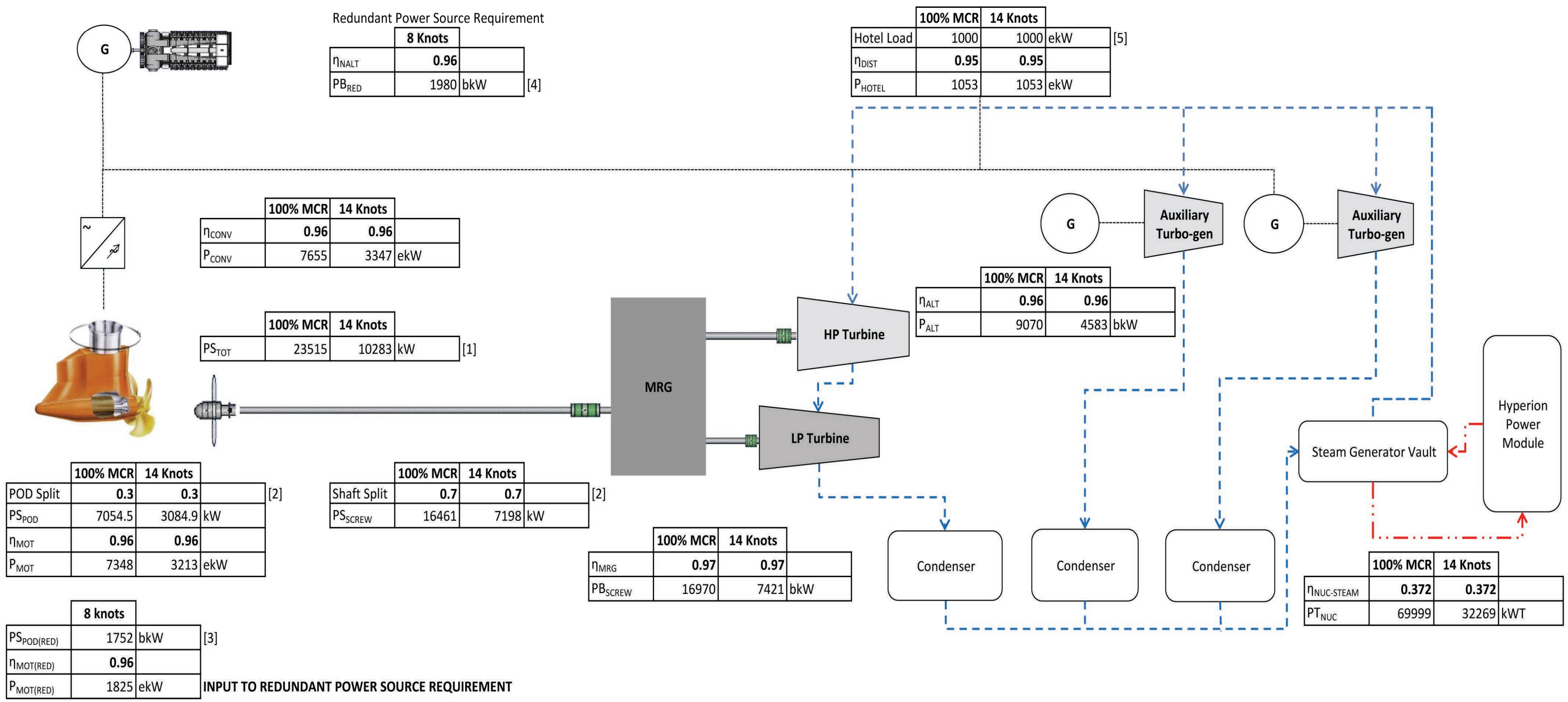


Figure 5. Plan view of SMR concept vessel Machinery Arrangement



Notes

[1] At 100% MCR
[2] Delivered power ratio between azipod / rudder propeller and shaftline.
[3] Achieves 8 knots in redundant propulsion mode. No account made of additional drag of main shaft.
[4] Based on redundant propulsion power requirement only
[5] Assumed sea-going electrical load for the vessel.
[6] Single screw shaft speed @ 100% MCR ~ 91 RPM

Key

- - - - Steam Circuit
.... Electrical Circuit
— · — Second stage Pb-Bi circuit

PS	Shaft Power	G	Generator
PB	Brake Power	MRG	Marine Reduction Gear
PT	Thermal Power	HP	High Pressure
η	Efficiency	LP	Low Pressure

Figure 6. SMR Tanker direct drive steam turbine and Azipod / rudder propeller. Demonstration of efficiencies at 100% Maximum Continuous Rating and 14 kn

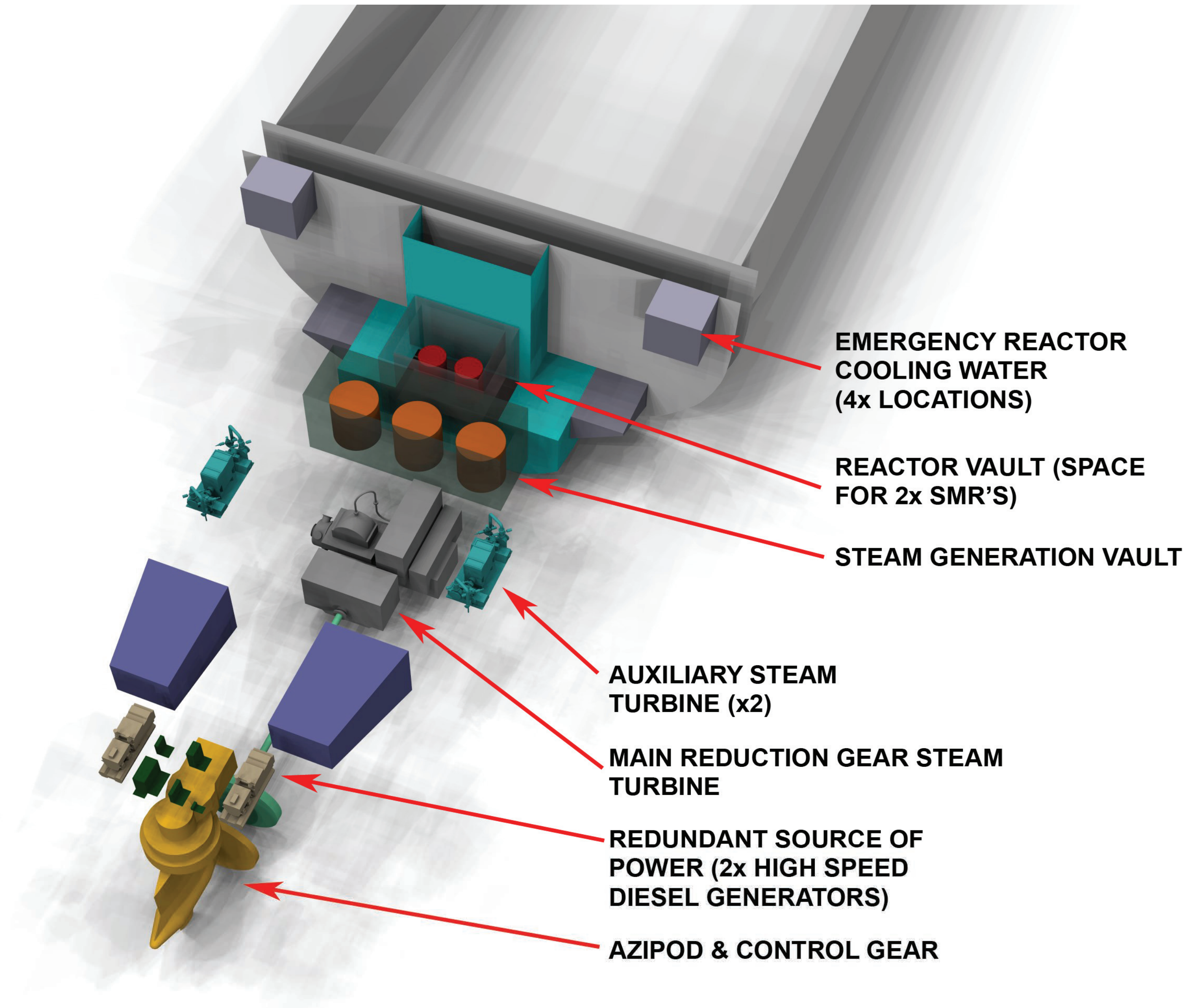
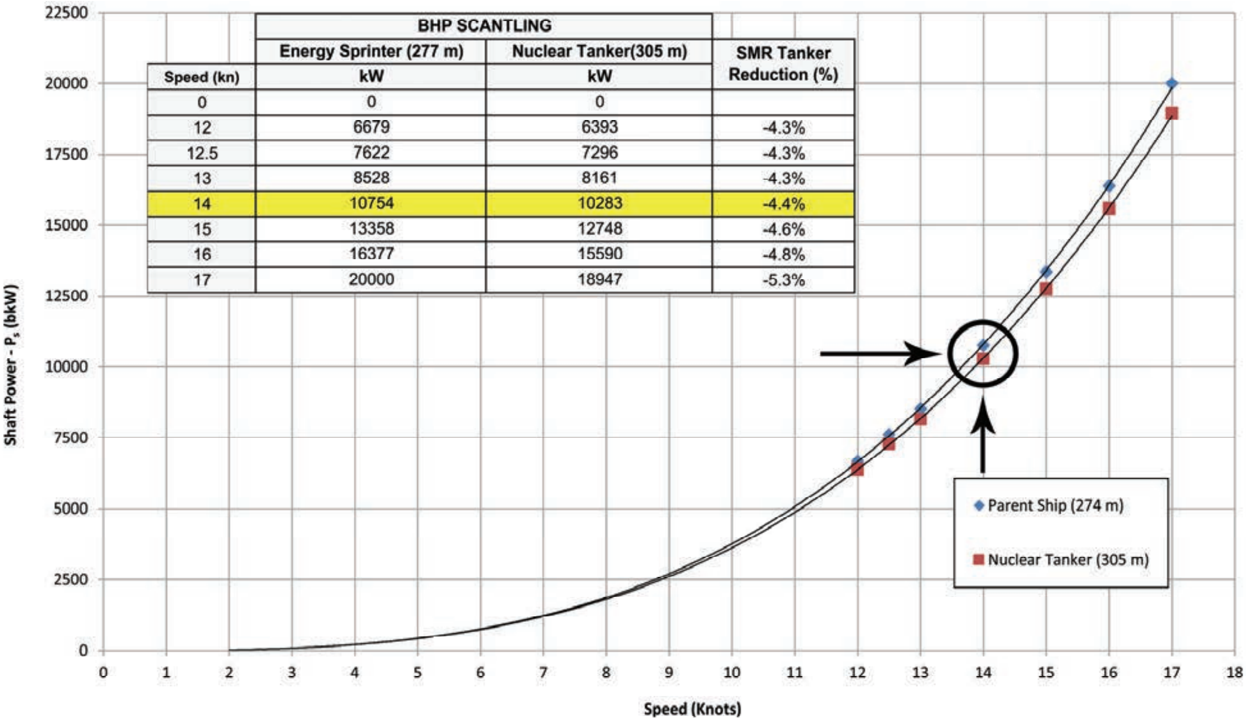


Figure 7. Three - dimensional view of machinery arrangement for SMR Tanker

LIGHTSHIP	Mass (t)	LCG (m)	VCG (m)
Weights ON			
2 x SMR (Small Modular Reactor)	100.00	48.400	9.550
Steam Generation Unit	150.00	41.900	11.550
Propulsion Reduction Gear and Steam Turbines	260.00	30.919	5.270
Azipod and Associated Switchgear	270.71	-1.517	9.750
Azipod Drive	11.00	-1.517	9.750
Auxiliary Turbines	94.26	27.511	15.700
Redundant Power Source Generators	56.00	0.639	19.193
Emergency Cooling Water	423.20	54.006	13.051
Lengthening of vessel	2291.84	142.700	12.886
Lengthening of vessel (Increased scantlings)	45.84	142.700	12.886
SMR Structural Protection	3374.3	48.400	11.550
Intermediate Shaft	29.41	19.264	4.563
Weights OFF			
Main Engine Hyundai – B&W	-555.00	25.200	14.575
Steering Gear	-20.74	1.600	20.000
D/G Engine	-42.90	16.000	14.575
Generator	-15.00	16.000	14.575
Aux. Boiler	-94.00	16.600	20.000
Exh. Gas Economizer	-22.10	19.700	20.000
Atmospheric Condenser	-1.53	24.000	11.550
C.O.P.T. Condenser	-13.05	24.000	11.550
M/E Jacket F.W Preheater	-0.29	24.000	11.550
Total ΔLightship	**6342**	**82.280**	**11.145**
DEADWEIGHT	**Mass (t)**	**LCG (m)**	**VCG (m)**
Weights ON			
Fuel Capacity for Redundant Power Source	274.27	11.269	17.314
Weights OFF			
Bunker Fuel and Tanks	-3862.30	35.798	16.980
Total ΔDeadweight	**-3588**	**37.673**	**16.952**

Figure 8. Lightweight distribution comparisons of SMR Tanker against parent ship



	BHP SCANTLING		
	Energy Sprinter (277 m)	Nuclear Tanker(305 m)	SMR Tanker Reduction (%)
Speed (kn)	kW	kW	
0	0	0	
12	6679	6393	-4.3%
12.5	7622	7296	-4.3%
13	8528	8161	-4.3%
14	10754	10283	-4.4%
15	13358	12748	-4.6%
16	16377	15590	-4.8%
17	20000	18947	-5.3%

Figure 9. Performance prediction estimates for SMR Tanker (homogeneous scantlings departure loading condition)

Table 7. Stability Assessment according to IMO Res. A.749(18) under departure [21],[25]

Intact Stability Criterion		Ballast LC		Homogeneous Scantling LC	
		Parent Ship	SMR Tanker	Parent Ship	SMR Tanker
Area under GZ curve ≤ 30^0	0.055 m·rad	2.426 m·rad	2.494 m·rad	0.706 m·rad	0.786 m·rad
Area under GZ curve ≤ 40^0 or θ_f (whichever is less)[$]	0.09 m·rad	3.978 m·rad	4.031 m·rad	1.070 m·rad	1.225 m·rad
30^0 ≤Area under GZ curve ≤ 40^0 or θ_f (whichever is less) [$]	0.03 m·rad	1.552 m·rad	1.537 m·rad	0.364 m·rad	0.438 m·rad
GZ at angle ≥ 30^0	0.20 m	9.361 m	9.220 m	2.128 m	2.553 m
Angle at which GZ_{max} occurs	25^0	44.10^0	43.2^0	29.70^0	31.8^0
GM_0	0.15 m	17.949 m	19.164 m	5.648 m	5.842 m
[$] $\theta_f \geq 40^0$ so for the case studied 40^0 is adopted					

Table 8. Cruising power consumption comparison (parent versus SMR Tanker designs assuming 14knots constant speed; LC : Loading Condition)

LC	P_S (kW)		%
	Parent Ship	SMR Tanker	
Scantling	10,754	10,283	-4.4%
Design(trial)	10,263	9,812	
Ballast(trial)	7,773	7,431	

Table 9. SMR module Life and CAPEX prediction (Estimated figures are based on operation over 347 days/annum).

SMR	Life	10	EFPY
SMR	P_R	70	MW_T
SMR	Full Life Energy Delivery	2.21×10^{16}	J
SMR Tanker	P_S (average)	9746	kW
SMR Tanker	Reactor loading	30738	kW_T
SMR Tanker	Annual availability	95	%
SMR Tanker	Annual energy consumption	9.22×10^{14}	J
SMR Tanker	Reactor life	24	Years
SMR Tanker CAPEX	SMR[1]	100-125	$ Million
SMR Tanker CAPEX	Fossil fuel[¥]	25.2	$ Million
SMR Tanker CAPEX	Oil[¥]	0.84	$ Million
SMR Tanker CAPEX	Total [¥,2]	126.04 to 151.04	$ Million

[¥]Assumes 50% increase from current price over 24 years
[1]10 years refuel cycle for including the steam plant. Spares and maintenance costs excluded
[2]Manning, training, classification and maintenance costs excluded

Based on discussions with CRP equipment manufacturers the projected propulsive efficiency of the SMR Tanker was increased by 8% in comparison to the reference vessel. Hence, at the scantling draft, the power required to propel the SMR Suezmax at 14 knots was estimated at 10,280 kW, corresponding to a 4.4% decrease from the reference design (see Table 8). On the conservative assumption that the SMR powered vessel would operate with full cargo for 60% of the year and under ballast conditions for the remaining period it was concluded that an average shaft power of the order of 8,860 kW is a realistic propulsion estimate.

Considering that the reactor core design is expected to run for 10 Effective Full Power Years (EFPY) and the full power rating of the reactor is 70 MW_T a single SMR installation was considered as satisfactory for providing sufficient energy to propel the vessel for almost 25 years (see Table 9). Therefore, the requirement for two reactor modules would need to be assessed at the detailed design stage against better defined resistance predictions and the intended design life of the vessel. The CAPEX projection outlined in Table 9 is a very preliminary estimate demonstrating that although marine construction costs would increase the operation of the vessel would probably lead to break even costs over a 24 year period. This projection does not include the influence of any shipping market fluctuations, severe changes in freight rates, fuel prices, insurance implications or manning, training and maintenance costs. These unknowns imply the need to assess the effects on CAPEX within the context of techno-economic analysis in a future investigation.

6. DISCUSSION

The ideas and concepts presented in this paper are the result of a multidisciplinary cross-industry research effort that considered past experience, advances in technology and regulatory trends within the context of risk thinking. Some discussion points emerging from these considerations follow in an attempt to shed some light on the steps that should be taken forward to facilitate the implementation of the concept in the future.

6.1 REGULATORY PROSPECTS

Although the public and political acceptability of nuclear power has changed since the introduction of the IMO code of safety for nuclear merchant ships [21] most of the safety principles remain relevant today. There are also several areas where ship safety assessment requirements have changed due to advances in technology and more sophisticated methods defining the regulatory requirements. For example, it might be preferable to adopt a probabilistic rather than deterministic approach for damage stability assessment at the detailed design stage. Similarly, in the future assessment of accidental or extreme loads, not currently covered by Classification Rules, may need to be assessed using appropriate design assessment procedures and quantitative risk assessment methods.

Whereas for the purpose of this publication it was not necessary to apply such procedures it is evident that integration of the SMR technology onboard ocean going vessels will imply the holistic review of existing prescriptive maritime regulatory requirements. This will ensure that the required engineering capability is achieved, with the mitigation of the risks to life and the environment being demonstrated to be ALARP.

In this new regulatory scenario the Classification Societies might be responsible for providing the assurance that successful integration of reactor modules in the ship has been demonstrated within the context of risk based Life Cycle Assessment (LCA). It would also have to be demonstrated that hazards from and to the ship's nuclear reactor are managed. The land based nuclear regulators would have to be involved in providing assurance that the reactor was satisfactory for the intended duty cycle, since this is where the expertise resides. This approach is consistent with the regulatory framework adopted by most land-based nuclear authorities today and it is sensible that the marine industry would base any future regulatory approach on instruments similar to the Irradiated Nuclear Fuel (INF) code [27]. Lloyd's Register's provisional guidance notes for marine nuclear propulsion [22] would support these efforts as these introduce the concept of a design authority, which represents the organisations involved in design, construction and operation of the ship. Validation of Goal Based Standards, harmonisation of nuclear and marine regulations and introduction of new licensing procedures for SMR technologies are equally important for the pragmatic facilitation of the concept over the long term.

6.2 FUTURE RESEARCH DIRECTIONS

The following research directions could be considered in establishing the knowledge required for developing design options and the future approval tools and methods:

- The top level risk analysis process applied in this paper is thought to be appropriate within the context of the ALARP principle. Further development and application of this process for detailed design and verification as well as a formal systems engineering approach within the context of LCA should be developed [30];
- Modernisation of the nuclear specific maritime regulations would require the development of a database of marine accidents, near misses and failure investigations for use within risk based design according to the IMO FSA guidelines [31],[32];
- Further development of naval architecture and marine engineering concepts using innovative holistic approaches that are applicable to alternative arrangements and operational scenarios should be developed as these would assist with the development of techno-economically efficient risk based solutions spanning throughout the ship's lifecycle [33];
- Development of direct analysis design procedures for the assessment of extreme and accidental loads would be essential for risk mitigation and approval at detailed design stage. The practical complexities associated with undertaking such work could play an important role in capturing the effects of risk peculiar to nuclear ships [34],[35];
- The preliminary human factor considerations identified a number of potential hazards that could cause or contribute to the occurrence of failures. However, further understanding of the implications of those on design and operations will be necessary. For example, there would be additional challenges that relate to the provision of emergency support and the development of the infrastructure supporting the vessel; ship specific competence development and assurance for shore and ship personnel will be required for the reliable operation of a nuclear powered fleet of vessels. This may imply the need for a new model for resourcing that is significantly different to that traditionally employed in the maritime industry.

6.3 SOCIAL & COMMERCIAL ASPECTS

Independent of any research or regulatory efforts it has to be recognised that commercial realisation of nuclear powered merchant shipping depends on the creation of a niche amongst a mix of other propulsion technology options. Convincing stakeholders about the technical and operational, safety, security and commercial issues of the deployment of the asset over its lifecycle may not be straightforward, with many less tangible issues affecting the choice. It could prove difficult to convince multiple national and local authorities to allow port entry to nuclear powered vessels.

To many stakeholders the use of nuclear reactors, whether the SMR used in this study or another technology, will be inescapably linked with accidents such as Fukushima, Three Mile Island and Chernobyl. This reaction in the aftermath of nuclear accidents increases the challenges faced by the nuclear industry. Nuclear ships will be subject to particular attention, during design, construction, operation and decommissioning. Any nuclear accident, on land or at sea, could impact on nuclear merchant shipping and the acceptability might change over time in response to public and societal reactions that may be extreme.

The necessity to provide an effective emergency response capability supported by external agencies would put additional requirements on competence development for all stakeholders. Ship specific competence development and assurance for shore and ship personnel would certainly be required for the reliable operation of nuclear-powered vessels. This may require a new model for resourcing that is significantly different to that traditionally employed in the maritime industry in order to deliver continuity of expertise.

A number of safeguards were identified by the study to mitigate the likelihood and/or consequences of human hazards that may affect the safety of the reactor or the vessel. Other issues to be addressed are the cost of reactor decommissioning, spent nuclear fuel and supply chain management.

7. CONCLUSIONS

This paper presents a feasibility study on the concept development of Suezmax Tanker propelled by the 70MW Gen4Energy SMR. Assessment of the risks associated with different SMR locations and power train systems suggested that an SMR located aft the cargo tanks, below the foreword end of the accommodation would be preferable. A direct shaft line with a CRP Azipod mechanical installation would be the preferred main propulsion option on the basis that it would lead to a modest 11% increase to the overall length compared to the reference design, once the necessary adjustments are made for the changes in hydrostatic trim. Such arrangement combined with a conventional diesel engine would be adequate for propulsive redundancy assuming operations and faults under harbour and ocean going conditions.

The risk assessment process and engineering solutions developed demonstrate that the concept that has been described would be feasible. However, considering that the current style of regulation within the maritime industry is prescriptive and the operational framework of national nuclear administrations is highly segmented, readdressing the needs of the technology, regulators and organisations involved within the context of harmonised performance based standards will be necessary for the pragmatic implementation of the concept presented over the long term.

8. ACKNOWLEDGEMENTS

The views expressed in this paper do not necessarily express the opinion of Lloyd's Register Group Ltd. The authors wish to acknowledge the support from technical colleagues and executive management within their own organisations. Special thanks of appreciation go to Mr. Victor Restis of Enterprises Shipping and Trading S.A.

9. REFERENCES

1. HIRDARIS, S.E. AND CHENG, F., The Role of Technology in Green Ship Design (keynote address). *In Proceedings of the 11th International Marine Design Conference (IMDC),* ***1****:21-40*, Published by the IMDC Secretariat and the University of Strathclyde Glasgow, UK, 2012.
2. HIROSE, K., 2011 Fukushima Daiichi Nuclear Power Plant Accident: Summary of Regional Radioactive Deposition Monitoring Results. *Journal of Environmental Radioactivity*, 111: 13–17, 2012.
3. REISTAD, O., HUSTVEIT, S. AND ROUDAK S., Operational and Accident Survey of Russian Nuclear Submarines for Risk Assessments using Statistical Models for Reliability Growth. *Annals of Nuclear Energy*, 35(11):2126–2135, 2008.
4. WNA, Nuclear Powered Ships Information Letter. *The World Nuclear Association*, INF:34 (http://www.world-nuclear.org/info/inf34.html), 2012.
5. IMO, Prevention of Air Pollution from Ships. *Final Report of the 2nd IMO GHG study*. A Publication of the International Maritime Organisation under MEPC 59/INF.10, 2009.
6. OECD/IEA, Energy Technology Perspectives 2008 Scenarios and Strategies to 2050. *OECD Executive Summary Document in support of the G8 plan of action*, Published by the Organisation for Economic cooperation and Development and the International Energy Agency, 2008.
7. SATHAYE, J., LUCON, O., RAHMAN, A., CHRISTENSEN, J., DENTON, F., FUJINO, J., HEATH, G., KADNER, S., MIRZA, M., RUDNICK, H., SCHLAEPFER, A., SHMAKIN, A., Renewable Energy in the Context of Sustainable Development. *In IPCC*

Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner,T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (Eds)], Cambridge University Press, 2011.

8. CROUCH, H.F., Nuclear Ship Propulsion. *Cornell Maritime Press*. Library of Congress Catalogue Card No: 59-13449, Cambridge Maryland (USA), 1960.
9. HIROSHI ŌI, TANIGAKI, K., The ship design of the First Nuclear Ship in Japan. *Nuclear Engineering and Design*, 10 (2) 211-219,1969.
10. SATO, K. AND EGUSA, T., Reactor Plant Design of the First Nuclear Ship in Japan. *Nuclear Engineering and Design*, 10 (2):187-210, 1969.
11. ISHIDA T., Response to Severe Changes of Load on the Reactor System of Nuclear Ship Mutsu. *Journal of Nuclear Science and Technology*, 30 (2)116, 1993.
12. KHLOPKIN, S.N., KUZNETSOV P.V AND MAKAROV, V.I., Nuclear Energy - Foundation for the Arctic Icebreakers Fleet. *In Proceedings of the International Conference and Exhibition on the Performance of Ships and Structures in Ice (ICETECH)*. Session 2: Ships in Ice and Propulsion, 1:1120-1140, Anchorage, Alaska, USA, 2010.
13. VERGARA, J.A. AND MCKESSON C.B., Nuclear Propulsion in High-Performance Cargo Vessels. *Marine Technology*, 39(1):1-11, 2002.
14. SAWYER, G., SHIRLEY, J., STROUD, J., BARLETT, E. AND MCKESSON, C., Analysis of High Speed Trans-pacific Nuclear Container Ship Service, *In Proceedings of the RINA International Conference on Design and Operation of Container Ships,* ISBN 987-1-905040-48-3, London, UK, 2008.
15. HILL, R. (Sir), HODGE, C.G. and GIBBS, T., The Potential of the Molten Salt Reactor for Warship Propulsion, *In Proceedings of the IMarEst 11th International Naval Eng. Conference and Exhibition*, (INEC) Session G : Ship Design, paper 3, London, UK, 2012.
16. CARLTON, J.S.; SMART, R.; JENKINS, V. The Nuclear Propulsion of Merchant Ships - Aspects of Engineering, Science and Technology. *Proceedings of IMarEst Part A: Journal of Marine Engineering and Technology*, 10(2)47-59, 2010.
17. HIRDARIS, S.E., CHENG, F., JENKINS, V., BONAFOUX, J., SHALLCROSS, P., ANDREW, W., PETERSON, O.P., GOVERS, R., DEAL, J.G., RICH, K., LUCAS, D., Concept design of a Suez-max Tanker propelled by a small modular reactor- some preliminary considerations, *The 1st Global Forum on Structural Longevity*, Orlando (Florida), USA, 2011.
18. GRAVINA, J. BLAKE J.I.R., SHENOI, A., TURNOCK, S.R. AND HIRDARIS, S.E., Concepts for a modular nuclear powered containership, *In Proceedings of the 17th International Conference on Ships and Shipping Research (NAV 2012)*, Napoli, Italy, 2012.
19. DEDES, E., TURNOCK, S.R., HUDSON, D.A. AND HIRDARIS, S.E., Possible power train concepts for nuclear powered merchant ships, *In Proceedings of the 1st International Conference on Technologies, Operations, Logistics and Modelling for Low Carbon Shipping (LCS)*, Glasgow, UK 2011.
20. LLOYD'S REGISTER, Deterministic Provisional Rules for the Classification of Nuclear Ships. *Published by Lloyd's Register of Shipping*, Chapter R(C):101-116, 1966.
21. IMO, Code of Safety for Nuclear Merchant Ships, IMO Resolution A.491 (XII), *Published by the International Maritime Organisation*, 1981.
22. LLOYD'S REGISTER, Provisional Guidance Notes for Marine Nuclear Propulsion. *Published by Lloyd's Register*, 2011.
23. IACS LTD., A Guide to Risk Assessment in Ship Operations. *Published by the International Association of Class Societies*, Unified Recommendation (UR) No. 127, 2012.
24. LLOYD'S REGISTER, Rules for the Classification of Ships, Part 7 Chapter 15 - Engineering Systems of Unconventional Design. *Published by Lloyd's Register*, 2012.
25. SOLAS, Safety of Life At Sea Consolidated Edition 2009, Regulations on Alternative Designs and Arrangements (II-1 Reg 55, II-2 Reg. 17, III – Reg. 38). *Published by the International Maritime Organisation*, 2009.
26. MARPOL,. Marine pollution Prevention Consolidated Edition, Annex I on the Prevention of pollution by Oil, *Published by the International Maritime Organisation*, 2011.
27. INF, International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes on Board Ships under the International Convention for the Safety of Life at Sea of 1 November 1974. *Published by the International Maritime Organisation*, 1974 .
28. IMO RES. A749 (18), Code on Intact Stability for All Types of Ships Covered by IMO Instruments, *Published by the International Maritime Organisation*, 1993.
29. HOLTROP, J. AND MANNEN, G.G., An Approximate Power Prediction Method,

International Shipbuilding Progress, 29:166-171, 1982.

30. POMEROY, R.V., TWOMEY, B. AND SMITH, R., System design and integration. *Lloyd's Register Technology day proceedings* (available online under http://www.lr.org), 2010.
31. CAI, W., KONOVESSIS, D. AND VASSALOS, D., A Methodology of Marine Accident Investigation for Risk Based Design. *In Proceedings of the 11th International Marine Design Conference (IMDC)*, **1**:263-280. Published by the IMDC Secretariat and the University of Strathclyde Glasgow, UK, 2012.
32. ELIOPOULOU, E., PAPANIKOLAOU, A., DIAMANTIS, P. AND HAMMAN, R., Analysis of Tanker Casualties after the Oil Pollution Act (USA, 1990). *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 226(4):301-312, 2012.
33. PAPANIKOLAOU, A., Holistic Ship Design Optimisation. *Computer Aided Design*, 42:1028-1044, 2010.
34. PAIK J K; THAYAMBALLI A K; YANG S H., Residual Strength Assessment of Ships After Collision and Grounding. *Marine Technology*, 35:38–54, 1998.
35. TEMAREL, P. AND HIRDARIS, S.E. (EDS.), Proceedings of the 5th International Conference on Hydroelasticity in Marine Technology. *A Publication of the University of Southampton*, ISBN: 9780854329045, Southampton, UK (2009).