

# CONCEPTS FOR A MODULAR NUCLEAR POWERED CONTAINERSHIP

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## ABSTRACT

With the amendments to the MARPOL Annex VI regulations to control NO<sub>x</sub> and SO<sub>x</sub> emissions, fuel prices will increase considerably by 2020. Coupled with depleting fossil fuel reserves and owners' perceptions on their environmental impact, fossil fuel alternatives are being actively sought. The IMarEST reports that nuclear power is the only emissions free energy which can replace fossil fuels entirely (Jenkins, 2011).

Two critical drawbacks for a nuclear powered ship are route restrictions and accidents. The goal of the research underway is to ensure that a concept nuclear containership can sustain an accident without catastrophic consequences as well as operate freely at sea without intervention from port states due to the mode of propulsion.

The paper will present the work to date on the concept analysis and how the issue with route restrictions is being addressed by designing a modular vessel consisting of a propulsion module and a cargo module which can decouple outside of territorial waters. A service factor analysis with hydroelasticity models will provide the long term bending moments and the modular coupling concept assessment in open waters for unrestricted service. Accidents will be addressed using risk based design focussing on grounding and collisions in restricted waters using probabilistic models.

## 1. INTRODUCTION

The shipping industry is being faced with pressure due its carbon dioxide (CO<sub>2</sub>) emissions as well as those from other pollutants. The probable introduction of market based measures, the rising price of fuel, depleting fossil fuels and owners' perceptions on their environmental impact is causing interest towards fossil fuel alternatives. Currently nuclear power is the only emissions free energy (at point of use) which can replace fossil fuels entirely (Jenkins, 2011).

Several issues arise with regard to the transit of nuclear powered ships in territorial waters of different port states for example the New Zealand Nuclear Free Zone, Disarmament, and Arms Control Act 1987, The South Pacific Nuclear-Free Zone Treaty (Treaty of Rarotonga) and Article 22 and 23 of UNCLOS. Even when the requirements of the International Maritime Organisation (IMO) Code of Safety for Nuclear Merchant Ships, Resolution A.491(XII) and the internationally recognised and approved manual for safety provisions for nuclear powered ships are met it is still difficult to get permission to enter territorial waters and ports. The procedure involves getting a licence based on bilateral agreements which is time consuming and expensive (Khlopkin and Zotov, 1997). A study by Haven Bedrijf Rotterdam concluded that a permit for a route from Rotterdam to the Far East for the vessel *Sevmorupt* would cost €522,000 excluding political aversion and forming of policies for a visit (Jacobs, 2007).

These problems can be avoided if the nuclear plant does not enter territorial waters. This can be achieved through a modular ship consisting of a propulsion module (containing the nuclear plant) which never enters territorial waters and a cargo module (carrying the payload) which has no route restrictions. The modules will be independent of one another with the ability to connect/disconnect through a coupling mechanism. The idea lends itself from tug/barge systems which operate in a 'drop and swap' method keeping the tug in constant operation while the barge is loaded/unloaded. The modules will remain coupled in international waters and will

decouple outside of territorial waters so that the cargo module can proceed into port using a secondary propulsion system (stored battery power charged by the nuclear plant when coupled).

The consequences of a nuclear accident can be catastrophic, so safety is imperative for a nuclear powered ship. Traditionally safety regulations by the IMO have been driven by individual incidents rather than a pro-active and holistic approach. Every catastrophic maritime accident has led to new safety regulations and subsequent design measures in the form of prescriptive rules imposed by the IMO and classification societies (Papanikolaou et al., 2009). This approach is unacceptable for a nuclear powered ship. Goal based rules, as opposed to the conventional prescriptive rules, would be the basis for any nuclear ship design with safety and integrity of the reactor being the key aspect. In designing a nuclear ship it must be proven that in the event of any accident the reactor compartment and containment will remain intact.

To avoid any serious consequences from an accident the structure in way of the reactor compartment must be strengthened to resist penetration of the nuclear plant. An energy absorption based analysis is required for the structural design in way of the engine room. This way during an impact the energy will be dissipated through the hull and away from the reactor compartment by an elasto-plastic collapse. In the vessel *Otto Hahn* this was achieved through cutting decks which would cut any object colliding into it thus reducing impact penetration (Jacobs, 2007). Another option is provided by sandwich material consisting of 'Y' shaped frames which has proven energy absorption due to its plastic collapse (Pedersen et al., 2006).

In this paper five different concepts for a modular nuclear containership are explored and the best design is selected using a subjective method. The new emissions regulations together with their consequences are discussed. A brief description of the approaches, technology and powering alternatives to reduce/eliminate the emissions are given. The nuclear power option is presented including its advantages/disadvantages and details of the new commercially available small modular reactors (SMR). The most suited concept for the modular ship is discussed including a review of tug/barge systems. Finally the further work to be carried out is outlined.

## 2. BACKGROUND

### 2.1 Emissions and Regulations

The shipping industry is an efficient mode of transport and is responsible for 90% of world trade, however in doing so contributed 2.7% of global CO<sub>2</sub> emissions in 2007. The shipping industry is expected to keep growing and without control measures for greenhouse gas emissions, by 2050, CO<sub>2</sub> emissions are estimated to be 2.4 to 3 times their current value (McCarthy, 2009). Restrictions on ships' emissions are being put into place and talks are underway regarding a carbon tax. Although the cost penalties have not been decided, estimates put their value anywhere between \$5 to \$50 per tonne of CO<sub>2</sub> (Nika, 2010).

Other environmental concerns are the emissions of sulphur oxides (SO<sub>x</sub>), nitrous oxides (NO<sub>x</sub>) and particulate matter. Shipping is responsible for 4-9% and 15% of the global SO<sub>x</sub> and NO<sub>x</sub> emissions respectively (Eyring et al., 2010). These are regulated by Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) which was first adopted in 1997. Due to the shortcomings of the regulations, Annex VI was revised by the IMO to significantly strengthen emissions standards. Emission Control Areas (ECAs) were introduced in the Baltic Sea, North Sea, North America, Puerto Rico and US Virgin Islands. Ships operating in these waters must comply with extremely strict emissions standards by using ECA compliant fuel oil which is much cleaner than conventional heavy fuel oil. The sulphur limits will change from 4.5% currently to 3.5% in 2012 and to 0.5% by 2020. The new NO<sub>x</sub> emissions regulations have set 'Tier' limits for different engines. 'Tier I' applies to all engines installed from January 1990, 'Tier II' to those installed after January 2011 and 'Tier III' to those installed on ships operating in ECAs after January 2016. 'Tier II' and 'Tier III' NO<sub>x</sub> limits are estimated to cut emissions by 16-22% and 80% relative to those of 'Tier I' (AirClim, 2010).

The impacts of the new regulations are that by 2020 the estimated cost of marine fuel will further increase by 45-80% with an average of 75% leading to probable sea transport cost increases of 30-50% (Castanius, 2010). The increase in bunker prices between 2004-2009 are about 300% (ICS, 2009). Carnival Shipbuilding Corporation saw a decrease in income of 13% during the first quarter of 2011 due to increased fuel prices (Mackay, 2011). The restrictions on

ships' emissions and the consequent anticipated additional costs are only going to make the situation worse. Since fuel costs are the most considerable proportion of operational costs, it is in the owners' interests to reduce consumption or to reconsider the use of heavy fuel oil and use alternative technologies.

## 2.2 Emission Control & Alternative Marine Propulsion

An alternative to using low sulphur distillate fuel rather than heavy fuel oil to achieve the equivalent levels of SO<sub>x</sub> and particulate matter emissions, is the use of exhaust gas cleaning systems (Scrubbers). These remove the pollutant before being discharged as exhaust however are costly, large installations that take up a considerable amount of engine room space.

NO<sub>x</sub> reductions are achieved through combustion process optimization and/or expensive NO<sub>x</sub> control technologies like exhaust gas recirculation systems and selective catalytic reduction.

If ships continue to rely on fossil fuels emissions reductions can be achieved through technological and operational developments together with the implementation of the IMO Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP). Hull and propeller design improvements as well as hybrid propulsion could reduce fuel consumption (Dedes et al., 2012). With these efforts it is anticipated that CO<sub>2</sub> reductions of 15-20% may be achieved by 2020, however this will be extremely challenging (ICS, 2009).

Natural gas is an alternative which reduces emissions considerably (see LNG in Table 1). This naturally has disadvantages including limited availability due to land based demand and its lower volumetric energy density. Natural gas requires liquefaction for storage and would require four times the amount of storage space than that of conventional fuel oil.

Renewable energy from wind power and solar power is available in many different systems. However their contribution to the power required for propulsion is small and depends heavily on weather conditions. They can therefore only offer a reduction in fuel consumption with the option of providing auxiliary power. Marine diesel engines will still need to be the main mode of power generation for propulsion.

Fuel cells are an extremely efficient way of producing energy if hydrogen is used. Hydrogen as a fuel for marine power generation is unlikely in the short term due to its lack of availability and even lower volumetric energy density than natural gas. Presently a fuel cell would require conventional fuel oil or natural gas which would be converted into hydrogen at a much lower efficiency. This makes the plant much larger and more complex and does not solve the emissions problem. Currently fuel cells are not a viable solution but may be in the long term.

Table 1 shows a list of the available technologies which offer emissions reduction. It is clear that there is no solution that eliminates all emissions and none can offer a significant CO<sub>2</sub> reduction (except for hydrogen, however this is not ready for shipboard installation). Nuclear power can replace these emissions entirely and for this reason it is being considered as a viable option and several feasibility studies and basic designs are being developed (Carlton et al., 2010b).

Table 1. Reduction performance percentages of mitigating technologies (Naval Architect, 2012).

Category	Technology/Measure	NO <sub>x</sub>	SO <sub>x</sub>	CO <sub>2</sub>	PM
Pre Combustion	Humid Air Motor	70	0	0	0
	Exhaust Gas Recirculation	35	0	0	0
	Water in Fuel (Max 20%)	20	0	0	40
	Low Sulphur Fuel (2.7-0.5%)	80	0	0	20
	LNG	60	90	25	72
	Hydrogen	20	100	100	0
During Combustion	Direct Water Injection	50	0	0	50
	Basic Engine Modification	20	0	0	0
	Advanced Engine Modification	30	0	0	0
Post Combustion	Selective Catalytic Reduction	90	0	0	0
	Plasma Assisted Catalytic Reduction	90	0	0	0
	Seawater Scrubber	0	75	0	25

Regulations on emissions, increasing oil prices and decreasing resources of fossil fuels can make nuclear power an attractive, economically viable alternative. Nuclear powered ships have been in operation for over 50 years and since the first nuclear submarine, about 700 nuclear reactors have operated at sea on various vessels (primarily military). Today there are around 200 nuclear reactors still in use (Carlton, 2011). A history of nuclear powered ships is given in (Carlton et al., 2010a).

### 2.3 Nuclear Power Advantages & Disadvantages

In addition to no emissions nuclear power also has the following advantages:

1. The price of nuclear fuel is steady and predictable, unlike the price variations of fossil fuels.
2. It may be possible to increase the speed of vessels so that a smaller fleet of ships would transport the same amount of cargo in a given time. Sawyer et al. (2008) found that if fuel oil costs were higher than \$89 USD/barrel it was economical to run three 9200 TEU containerships at 35 knots than four conventional ships running at 25 knots.
3. Nuclear power can provide a considerable engine room space saving due to the compact power source (Babcock, 2012). Storage for thousands of tonnes of heavy fuel oil will not be required; consequently these vessels will weigh less and have a larger carrying capacity.
4. Nuclear ships could be designed to have a longer lifespan since the power plant will not be subjected to the wear and tear of fossil-fuels.
5. The reliability of nuclear reactors is very high. Based on naval experience, the reliability of the power plant including refuelling operations is greater than 95% (Carlton et al., 2011).
6. Nuclear power is a proven marine propulsion technology which has had about 700 nuclear plants that served at sea with no serious accidents.

Some of the disadvantages of nuclear power in addition to route restrictions and accidents are:

1. Nuclear ships will have high capital and scrapping costs as opposed to costs being spread over the ships' lifetime. Investment will require a financial review over the entire life of the vessel. This causes the shipping business case to appear as a utility investment requiring an entirely different approach which may detract typical shipowners (Penfold, 2011).
2. If several nuclear powered ships are to enter into service an infrastructure of dedicated specialised facilities will be required (dry docking, repair, maintenance and refuelling).
3. Numerous issues arise due to the disposal of radioactive fuel and decommissioning of the reactor with regard to the significant costs, the ownership of contaminated waste and the requirement of specialized facilities to carry out the decommissioning.
4. Significant changes in ship design will be required. Conventional ships are designed using prescriptive rules defined by the IMO and classification societies. Design of nuclear ships will require a goal based approach. Each design goal will have a set of design principles that must be satisfied, which in turn have design details that are the only way or one way of meeting the design principles and hence goals (Jenkins, 2011). The design process will be driven by a safety case involving the integration of nuclear, mechanical, electrical and naval architectural aspects. The safety and integrity of the nuclear reactor will take precedence over all other design aspects (Carlton, 2011).
5. A lack of education has led to negative public perception (Carlton et al., 2010a).
6. Licensing a reactor will be a serious issue since there are 35 different nuclear regulatory bodies worldwide. The enhanced risk of nuclear ships will most definitely raise insurance costs. Increase in liability limits and claims period will also cause insurance challenges.
7. Nuclear ships will require a higher level of manning and training with nuclear engineers on board which will increase manning costs.

#### 2.3.1 Small Modular Reactors (SMR)

Up until now most maritime reactors have been PWR (Pressurised Water Reactors) due to the proven technology. SMRs provide improvements in safety, construction, operational flexibility and economics. The improvement in safety is achieved through lower fuel inventory, greater use of passive safety features and eliminating design features which are susceptible to possible accidents (Ingersoll, 2009) and since the SMR is built modularly, the proliferation risk is considerably reduced (Mackay, 2011). Operational flexibility is achieved since they are compact and can fit in a twenty-foot container allowing the SMR to act as a plug-in nuclear battery which can be easily removed and replaced when the core is burnt-up. Upon licensing SMRs are expected to have economy of mass production, reduced siting costs and majority of construction and assembly to be completed at the factory thus reducing capital cost and construction time hence reducing financial risk (Hirdaris and Cheng, 2012).

Hyperion offers a liquid metal cooled, fast reactor with a thermal power of 70MW<sub>T</sub>. The efficiency of the transfer heat system using helium can be up to 40%. The size of the sealed unit is only 1.5m in diameter and 2.5m high with a cost of \$50 million USD (Dabrowska et al., 2012). Some other properties of the reactor are given in Table 2 (HIRDARIS et al., 2011).

Table 2. Hyperion SMR characteristics

Electrical output	25MW <sub>E</sub>
Lifetime	8-10 years
Weight	Less than 50 tons including pressure vessel, fuel and primary coolant
Structural material	Stainless steel
Coolant	Lead-Bismuth
Fuel	Stainless clad, uranium nitride
Enrichment	Less than 20% U-235

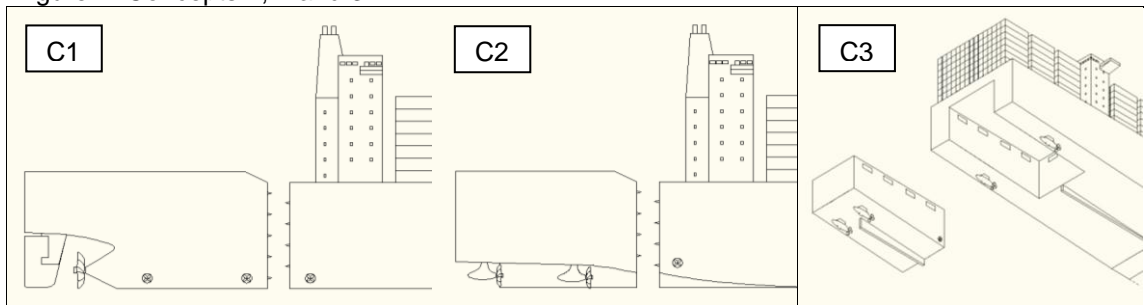
### 3. MODULAR CONCEPTS

Five preliminary concepts were developed for a modular containership with illustrations as shown in Figure 1 and Figure 2. Detailed descriptions are presented in Gravina (2011) and summarised as follows: Concept 1 involved taking a conventional containership and separating it into two parts while keeping the same hullform. The aft end of the vessel becomes the propulsion module and the rest of the ship is the cargo module. The modules are coupled by hydraulic arms which extend into slots and rotate to form a rigid connection. When decoupled, the propulsion module of this concept would inevitably have trim problems due to the very fine form towards the propeller. It may also be excessively long to fit all the machinery in.

Consequently Concept 2 was developed to solve these problems by changing the hullform to one using podded propulsors which would have a much fuller form and higher block coefficient. The same coupling mechanism as that for Concept 1 is used. The loads (shear forces, bending and torsional moments) on the couplings for Concept 1 and 2 were anticipated to be significantly large which could cause structural integrity issues.

Subsequently Concept 3 was designed to alleviate these loads. Concept 3 has a propulsion module which submerges (using similar principles to that of a submarine) and slots into a space in the aft end of the cargo module and is coupled by hydraulic arms from the sides, roof and front of the propulsion module.

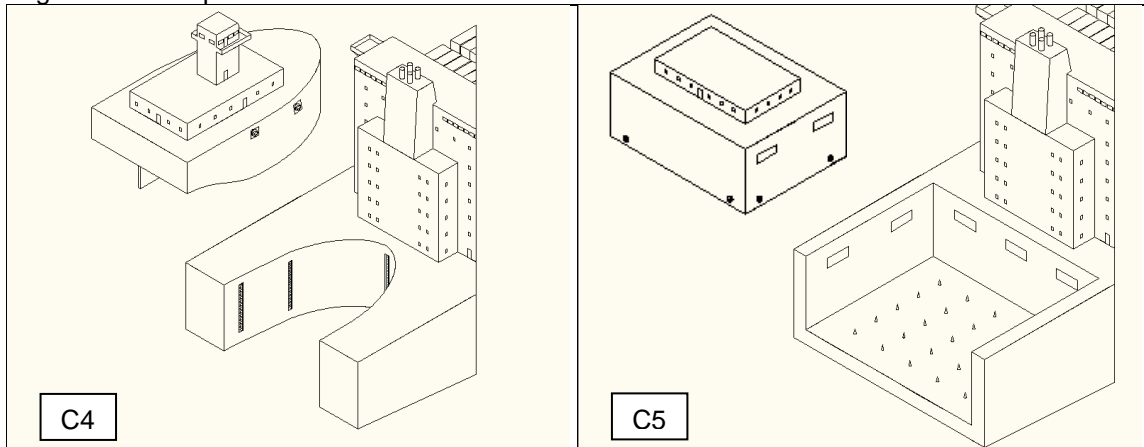
Figure 1. Concepts 1, 2 and 3



Although Concept 3 would have better structural integrity than Concept 1 and 2 the coupling mechanism is very complicated involving ballasting and de-ballasting of the propulsion module as well as tight manoeuvring into the cargo module slot which will be problematic in rough weather. Concept 4 is similar to Concept 3 however eliminates the need to submerge by using the model of a tug/barge system with a mechanically rigid connection. The pusher (tug) is the propulsion module while the barge is the cargo module. The tug can connect in the front as well as sides of the slot at the aft end of the barge using hydraulic arms. Using a multi-step tooth engagement system as used on pusher-barge systems designed by Taisei Engineering (Taisei, 2010c), the helmets of the hydraulic arms can fit into teeth at various locations on the barge allowing various draughts.

In all the previous designs there will be unavoidably large loads on the couplings. Concept 5 attempted to eliminate these coupling loads entirely. This was achieved using a float-on/float-off model with a cargo module that can change its draught sufficiently for the propulsion module to float onto the docking station at the aft end. This way the propulsion module simply becomes a large load on the stern of the cargo module. The stern will simply require increased scantlings over a conventional ship to support the additional load of the propulsion module. The issue with this design is whether it is possible to ballast the cargo module sufficiently for the propulsion module (which will inevitably have a large draught due to high machinery mass) to float on.

Figure 2. Concepts 4 and 5



A decision matrix was used to select the best performing concept. A set of fundamental criteria were established each with differing importance. For each concept a subjective score between 1 and 5 was assigned for each criterion (1 negative or challenging, 5 positive or practicable). A description of the criteria is as follows:

1. Module design is an overall score of the propulsion module hullform, trim, machinery space, manoeuvrability and ballasting requirements.
2. Propulsion refers to the propulsive performance of the coupled vessel as well as the propulsive machinery on board.
3. Coupling system refers to the actual connections between the modules.
4. Coupling forces refers to the anticipated load magnitude (a low score implies high loads).
5. Coupling mechanism refers to the ease of the coupling/decoupling procedure.
6. Application to different vessels is dependent on whether the concept is able to be applied to vessels which have a large range of operational draughts.
7. Cable power connection refers to how easy it will be to form a power connection between the modules required to charge the batteries on board the cargo module.

The results are as in Table 3. Concept 4, a tug/barge system was the best performing and was therefore selected for further development.

Table 3. Concept decision matrix

Concept Criteria	Importance	Alternative Concepts				
		C 1	C 2	C 3	C 4	C 5
Module Design	17.5	1	1	2	4	3
Propulsion	10	5	4	3	3	4
Coupling system	20	1	1	4	4	5
Coupling forces	20	2	2	4	4	5
Coupling mechanism	20	1	1	2	5	4
Application to different vessels	10	2	2	2	5	1
Cable power connection	2.5	5	5	3	2	5
<b>Total</b>	<b>100</b>	<b>1.8</b>	<b>1.7</b>	<b>2.93</b>	<b>4.15</b>	<b>3.95</b>

#### 4. TUG/BARGE SYSTEMS

Concept 4 which used the model of a tug/barge system scored the highest in the subjective analysis. More detail of tug/barge systems and their application to a modular nuclear containership is discussed hereafter.

##### 4.1 History

Tug/barge systems have been used for many years on short routes in inland waterways and rivers where speed and fuel cost are of smaller importance than in long voyages. Their main advantage is the ability to operate in a 'drop and swap' method thus keeping the tug in constant operation while the barge is loaded/unloaded leading to cost savings of up to 30% (van-Leeuwen, 1992).

Initially barges were rope towed or pushed using rope connections. Towing led to high wave making resistance due to the high speed/length ratio and skegs required for course-keeping

resulted in low service speeds. The resistance of a pusher-barge on the other hand is much lower since the wave-making resistance is a function of the combined length of the pusher-barge and the tug operates in the wake of the barge (van-Leeuwen, 1992). The degree of safety of a pusher-barge is also much higher since the system is shorter, the tug/barge can stop using its own power, has a higher degree of manoeuvrability and better course-keeping capability.

Pusher-barges originally used cable connections and were restricted to operation in calm water. Operation in open waters and more severe sea states meant that the tug would have to revert to towing. Consequently mechanically connected pusher-barges were developed in the early 1970s which satisfied the desire for unrestricted service. Mechanical connections also had other advantages; the rigid connection improved running stability and manoeuvrability. Coupling/decoupling became much quicker and achieved electronically rather than manually.

A description of the different types of mechanical connection systems in operation are given in van-Leeuwen (1992) and Wright (2000). The most effective designs are those using a two-point or three-point connection. Coupling occurs through hydraulically operated arms mounted on the tug which have a helmet that fits into a tooth on the barge when extended. The barge has a multi-step tooth engagement arrangement allowing the pusher to connect at any barge draught.

#### **4.2 Two-Point and Three Point Mechanical Connections**

A study was carried out at the David Taylor Naval Ship R&D Center to investigate the differences between two-point and three-point connected tug/barge systems: "Experimental Research Relative to Improving the Hydrodynamic Performance of Ocean Going Tug/Barge Systems". The work included resistance and propulsion, and seaworthiness (including loads and motions) experiments on three different concepts; Concept I was a tug/barge system using a three-point connection and Concept II and III used a two-point connection (one single-screw and the other twin-screw). The two-point connection allows relative pitching while the three-point connection is rigid.

The results of the barge alone (a Series 60 hull) and those of Concept I were similar (Day, 1974). The resistance of Concept II and III was 15% and 21% greater than that of Concept I respectively (Day, 1974). The reason for the difference is that a two-point connection requires a greater clearance between the hulls to avoid impact between the pusher stem and the barge stern. This extra clearance causes large eddies which increase resistance significantly. For a three-point connection the clearance between the hulls of the pusher and barge can be minimized to lower the eddy resistance allowing a much higher propulsive performance. Although eddy resistance is still present, with optimized hullforms speed differences of only about 0.3 knots from conventional ships may be achieved (Taisei, 2010b).

The wave excited loads on the couplings depend on their position and the number of connections. In relation to the coupling position, the vertical load component increases and the longitudinal load component decreases as the coupling position moves towards amidships of the pusher for both types of connections (Taisei, 2010c). In general the magnitude of the wave excited loads on the couplings are lower for the two-point connection due to the relative pitching of the pusher to the barge. The results in Rossignol (1974) showed that the longitudinal accelerations and pin force for Concept II were greater than that of Concept I, however the vertical pin force was lower. For a two-point connection the pitching angle increases when the coupling position approaches the centre of gravity. More detailed results of loads and motions for a two-point connected tug/barge are given in Mumford (1993).

#### **4.3 Application to a Modular Nuclear Containership**

The first era of nuclear powered containerships will be best demonstrated for the largest vessels (around 10,000 TEU or 350m+) to take full advantage of the high power of a nuclear reactor with minimal operational fuel costs. The vessels will also require service speeds equal or higher than their conventional counterparts (around 25 knots). It will also apply to long trans-oceanic shipping routes so that the amount of coupling/decoupling of the modules can be minimized.

These requirements do not suit a two-point connected tug/barge system which has lower speed than conventional ships of the same power and deadweight. Two-point connected tug/barges are more suitable for short routes where speed and fuel cost are of smaller importance than in long voyages. A three-point rigid connection on the other hand can fit this operational envelope so is much more applicable for the nuclear powered containership.

Taisei Engineering has used their three-point connection system 'Trifix' on several vessels. The largest of which are a fleet of 205m and 30,000 DWT barges powered by a 48m pusher developing 6.6MW with a maximum speed of 16 knots (Taisei, 2010a). It is clear that there is a significant gap between these vessels and the nuclear powered containership to be designed. The service speed will have to be around 10 knots faster and the size of the tug/barge system over 100m longer. There is also the further requirement for coupling/decoupling to take place in high seas since these manoeuvres will take place outside of territorial waters (as opposed to calm waters in port for current tug/barges). The above requirements pose a large challenge which will need to be investigated to assess the viability of a modular nuclear containership.

#### **4.4 Theoretical and Experimental Work**

The work described below serves as a starting point to investigate the loads and motions for the modular nuclear containership. The theory will be extended to account for the increased size, service speed and undocking manoeuvres of the vessel to be examined.

In Rossignol (1974) linear theory was used to predict the loads and motion responses of Concept II (mentioned in Section 4.2). The program evaluated the hydrodynamic and hydrostatic forces with the only coupling being the pin vertical forces and corresponding moments. The predictions and experimental results were in good agreement.

In Bougis and Vallier (1981) a 3D hydrodynamic method was proposed to calculate the forces and moments in the connections of a rigid tug/barge system in waves. A calculation program DYNAPLOUS 81 was developed to solve the diffraction-radiation problem with running speed. The results were compared to the experimental results in Rossignol (1974) and good agreement was achieved for the first order motions, accelerations and forces at the couplings.

In Mumford (1993) a method for calculating the vertical force on the couplings of a two-point connected pusher-barge was presented. Experimental tests were carried out to evaluate the accuracy of the theory which is solved using a numerically-fast 3D solution method using unified slender body theory. The results under predicted the motions.

Rossignol and Woo (1975) carried out experiments on the undocking manoeuvres for Concept III. An important finding was that decoupling of the tug was only ideal when "the pins were retracted at a point of minimum motion and force, followed by prompt backing of the tug before considerable motion could develop" (Rossignol and Woo, 1975) demonstrating that coupling/decoupling is possible in a moderate sea state but not recommended for higher sea states (Robinson, 1976).

### **5. FURTHER WORK**

The next stage of the research will include a definition of the vessel particulars. The nuclear modular ship will be much larger and have a higher service speed than the tug/barge systems currently in operation, consequently an analysis on the coupling loads must be carried out. The methods and work described in Section 4.4 will be extended and applied to the selected vessel. Wave motion based theory will be used to obtain the global loads using a hydroelastic model. The local loads on the couplings will then be inspected by making a 3D model and applying nonlinear impulses at different locations to simulate stern slamming. Different locations of the couplings will be investigated so as to select the best position for minimum stresses.

Rossignol and Woo (1975) provided a method to estimate the loads for undocking manoeuvres. This will be applied to the nuclear ship to estimate the safe operational envelope of sea states for coupling and decoupling manoeuvres outside of territorial waters.

Structural protection of the SMR to withstand an accident is also required. This will include design of a novel structure such as cutting decks or metallic matrices/honeycomb/sandwich structures so as to absorb the energy of an impact. High impact load modelling and non-linear structural dynamics software will be used to carry out the analysis.

### **6. CONCLUDING REMARKS**

The shipping industry is having a significant impact on world emissions of CO<sub>2</sub>, NO<sub>x</sub> and SO<sub>x</sub>. If global emissions of CO<sub>2</sub> are to be stabilised to a level consistent with a 2<sup>o</sup>C rise in temperature by 2050 it is clear that drastic measures must be taken otherwise shipping will account for 12-



18% of global CO<sub>2</sub> emissions (Dedes et al., 2011). The amendments to MARPOL Annex VI will change fuel prices considerably by 2020. These facts indicate that a move away from conventional power sources is crucial. Although many options are available to reduce emissions none come close to those offered by nuclear power. Even though nuclear power has its drawbacks, there is a large driving force towards it as nuclear powered ships will offer longevity and reliability with no emissions and independent operation on fluctuating fuel costs.

Route restrictions were identified to be a serious issue for nuclear powered vessels. This paper outlined the solution to avoid the problems associated with route restrictions by having a modular vessel. Five concepts were introduced and a subjective method was used to select the best design. The concept based on a tug/barge system scored the highest overall. This concept is also supported by the proven technology of tug/barge systems and the numerous vessels that are in operation as well as those designed for unrestricted service. It may be argued that this analysis was not sufficient to select the best performing concept since each concept has its own associated risk assigned to each criterion which must be quantified. A high level risk assessment including functional requirements, societal impacts and safety may be required where a systematic committee of experts will rate each concept to confirm the decision taken or select an alternate concept.

The most successful tug/barge systems are those with a two-point connection or three-point connection. As the nuclear powered ship will be used for long trans-oceanic voyages a three-point connection was selected for the concept since the resistance is much lower than that of a two-point connected tug/barge system and also comparable to that of conventional ships. This will result in higher wave excited loadings on the coupling which will require a more complex coupling system able to withstand the loads. Although this will cost more to construct, the vessel will have a higher service speed and a long term fuel saving.

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