DISCUSSION

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

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COMMENT

Dr Gao Yongjun, COSCO, People's Republic of China

The authors are to be congratulated on a well-researched and timely technical paper. I am pleased to express my personal opinion on the subject.

COSCO was intending to initiate a study in December 2009 on nuclear powered ship design in order to reduce GHG emissions from shipping. However, this plan was aborted three years after, following the catastrophic accident at the Fukushima nuclear power station in Japan during March 2011. This intensified political and public opposition to nuclear power to the extent that Germany has since adopted plans to decommission its entire nuclear infrastructure. However, confidence is beginning to re-emerge - confidence which I share. With increasing attention being given to GHG emissions arising from burning fossil fuels for global aviation and marine transport, together with the excellent safety record of nuclear power in the marine environment and the development of the new generation of SMRs, it is quite conceivable that renewed attention will be given to the application of nuclear power in merchant ship propulsion.

In producing this paper, the authors have made a significant contribution in the field of innovative ship design development. They have demonstrated the feasibility of applying the latest generation of nuclear reactor to commercial ship propulsion. Whereas nuclear power has been widely used in vessels of a number of navies and icebreakers, it has yet to be adopted for commercial ships other than a small number of research projects. This paper has provided good rationale for accommodating nuclear power in merchant shipping including speed and range requirements, required specific volume on board, environmental considerations etc. The study has also considered the risks associated with design and the arrangement of nuclear systems including location of the SMR, type of propulsion options and other safety-critical issues, not least the radiological risk to persons on board, involved in maintenance and in port.

Because of its high power density and the elimination of the need for large fuel bunkers, a nuclear propulsion plant allows more space for cargo payload. It also allows a vessel to operate at higher speeds for years without refuelling. This improves the speed and efficiency of ocean-going commerce.

Military vessels, such as submarines and aircraft carriers, can travel at high speeds over vast distances. This is limited only by the endurance of their crews and the availability of food and other consumables. Arctic vessels can operate for months independent of fuel supplies. The greatest barrier to change will be in convincing politicians and changing public opinion sufficient to create a positive legislative requirement to permit operation of nuclear-powered merchant ships. Often, it is the business case which compels such change and in closing, it is suggested that a preliminary cost and benefit analysis of this innovative design could be carried out with an assumption of a few designated trading routes in the future study. Owners would be particularly interested to see the real tangible benefits in terms of operational cost and return on investment in addition to the compliance of the environmental regulatory regime and the acceptance of the overall safety case.

Dr C Park, Marine Research Institute, Samsung Heavy Industries, South Korea

Gen4Energy SMR is one of the promising SMR candidates. Unlike other SMRs (e.g. Nuscale, B&W m-Power, 4S, etc.), it uses Lead-Bismuth Eutectic (LBE) as a primary coolant. Clearly, this type of reactor has many advantages in terms of inherent passive safety, thermal efficiency, a long fuel cycle and proliferation resistance. However, it may be prone to some critical problems during operation. Below I try to explain some of the key issues that may have to be considered.

- In general, the biggest problem in operating LBE reactor is "Polomium-210 (Po-210)". Bismuth-209 (Bi-209) in LBE coolant undergoes neutron capture (Bi-210) and subsequent beta decay and finally becomes Po-210 which is highly radioactive and dangerous material emitting alpha radiation. In my view the HAZID considerations outlined under Table 6 of this publication should have addressed the Po-210 protection method on the basis of possible accident scenarios.
- Under section of 5.1 (a), the authors state that the tanker accidents have been related to structural failure. How is it possible to prevent or mitigate corrosion induced by LBE coolant flow? The melting point of LBE is about 123~150 ℃. It means that the primary LBE coolant may be solidified when the reactor is operated at lower temperatures (reactor trip). Although LBE has a negligible change in volume (e.g. Lead may expand while Bismuth

may shrink). When LBE is solidified inside the coolant pipes it blocks the main coolant flow so that the emergency core cooling material cannot remove the residual or decay heat from reactor. Is it possible to solve the low melting point problem of LBE under abnormal conditions?

- You quoted that high levels of neutron radiation were measured at the run of Japanese Nuclear Ship, Mutsu. In general, the irradiation effect of fast neutron on the Gen4Energy reactor vessel or the pipes is greater than that of thermal neutron used in the convectional PWR. It is known that the expected lifetime of LBE reactor is 10 and more years. However, if we don't solve the problems mentioned above, the lifetime of nuclear ship with LBE reactor could not be guaranteed. I would like to know your views on whether future research should consider the "material" problems induced by LBE and fast neutrons.
- The operating pressure of the primary system is about atmospheric pressure. However, that of the secondary system is much higher since the secondary system uses light water as a feed-water (second cooling water). When MSLB (Main Steam Line Break) or SGTR (Steam Generator Tube Rupture) occurs, the secondary feed-water would flow to the primary circuit reversely, which leads to damage of reactor core. It would be useful to know your opinion on this matter.
- Land-based reactors have two or more shut-down systems such as control rods and Boron (Chemical and Volume Control Systems - CVCS). Are there redundancy shut-down systems in the nuclear ship you proposed?
- One of the biggest differences between a marine reactor and a land-based reactor is the influence by ship motions such as heaving, pitching, rolling, etc. How do you assure the exact (precise) control rod drive mechanism under ship motions?

Professor Paul Howarth, Managing Director, National Nuclear Laboratory, UK

In my view more detail and assessment from nuclear perspective is needed. This however may come later in a follow on paper. This paper probably needs to set out the operating parameters for reactor system as a power source, but clearly factor in the nuclear issues in the HAZID, and then different reactor systems can be assessed over ability to meet the operating parameters.

Dr Nicolas Catsaros, Institute of Nuclear, Radiological Sciences and Technology- Demokritos, Greece

With increasing attention paid to GHG emissions arising from fossil fuels used for air and marine transport along with the excellent safety record of nuclear-powered ships, it is quite conceivable that renewed attention will be given to marine nuclear propulsion. Furthermore, the changing economic conditions of the world market lead international ocean transporters to consider the nuclear propulsion option for merchant vessels and the present work is a valuable contribution to this process. As far as the proposed reactor is concerned and in order to render their approach more complete, the authors may find useful to address the following issues:

- The LBE which is used as coolant has a relatively high melting point of 123.5^{o}C (pure lead melts at 327°C). Consequently, an additional independent heating system (superheated steam? other?) should exist to prevent solidification of the coolant in case the reactor is operating at temperatures lower than 123.5^{o}C or is shutdown. Otherwise, the integrity of the fuel assemblies and the capacity to restart the reactor could be compromised. This was the reason that triggered the Project 705, 705 K (Lira) Soviet nuclear submarines (NATO Classification: Alfa) [36] to be put out of service much earlier than expected. It should be noted that in Alfa submarines the external heating was proved to be unsatisfactory. Consequently, the submarines had to be constantly manned and their reactors had to be kept running even at harbour.
- Under intense neutron irradiation in the reactor core, the Bismouth (Bi) contained in the coolant alloy transmutes to Polonium 210, a nuclide with extremely high radiotoxicity [37]. The presence of Polonium (Po-210) is a cause of great concern during reactor dismantling/decommissioning or in case of an accidental release. Thus, licensing is expected to raise issues that may considerably delay the authorization to operate PbBi-cooled reactors

Dr Il Guk, Woo, Daewoo Shipbuilding and Marine Engineering (DSME), South Korea

- It would be useful to address matters related with the implementation of new materials that would be used for the haul, decks, etc.
- In Figure 2, the steam separator is located between the super-heater and the evaporator. I would like to know the purpose of the steam separator & the direction of the steam after being separated.
- I am not confident that the installation of two reactors is economically advantageous. I would like to recommend a diesel generator instead of one auxiliary reactor.
- In Figure 3(c), what's the meaning of "criticality"?
- The reactor weight was described as 100 tons (see Figure 8). I think that it's too light weight compared to other reactors. What is your view on this point?

Apostolos Sigouras, CEO NAFSOLP S.A., Greece

The authors are to be congratulated on a well-researched paper of technological focus. Some of the general remarks I would like to make relate mostly with future work and are as follows:

- The types of ships and the marketing aspects required could be further analysed. For example, people working in Ports and Ship Crew should be "trained" and "educated" for the nuclear energy use, its side effects, etc.
- The additional safety requirements and standards necessary for the operation of a nuclear reactor in a ship should in further be investigated.
- The "testing" and "roll out" procedures should be designed and adequately recorded. This includes the non-conformity reporting procedures subject to apply.
- Simulation procedures must precede any real test scenarios, in order to increase safety precautions and technical disabilities in general.
- It is more than certain that shipyards and ship repair facilities would have to adjust to the new requirements raised, in terms of safety, materials, etc. For this reason infrastructure for new builds and ship maintenance/repairs will be useful to be examined.
- It would be useful to address matters related with the implementation of new materials that would be used for the haul, decks, etc.

Dr Baogang San, Shell Shipping and Maritime Technology, London, UK

Sustainable and efficient provision of shipboard energy is an obvious challenge for the merchant marine industry. Over the last few years various technology initiatives have tested engineering solutions that could in theory partly or entirely replace the combustion engine. Accordingly, nuclear propulsion has been widely advertised as an efficient and environmental friendly solution of such kind. This paper presented a conceptual design using a 70MW SMR propulsion plant onboard a Suezmax tanker. The target ship and Generation IV fast neutron SMR are carefully chosen. The rationale behind the design selections is logical and is well-presented. The naval architecture review and marine engineering review of the conceptual design are well in place.

However, the later discussion on the techno-economic analysis forecasted 24 years of payback period. It is noted the design life for commercial oil tanker is around 25 years. Not to mention also the additional operational cost such reactor registration, qualified crew for nuclear ship, nuclear fuel supply chain management, and limitation on port access. These issues raise some commercial challenges. In industry the trading off between absolute ALARP and economic model could be a very difficult decision and may hinder the application of the technology in commercial shipping.

Professor Paul Wrobel (FRINA), University College London, UK

This is a most interesting paper. It sets out to address the issues that determine when nuclear powered shipping will be a viable alternative to more conventional means of propulsion. The key issues are rightly identified as Safety and Economic. From a technical perspective the authors cite the use of nuclear propulsion in selective military vessels and ice breakers. These are both instances where there is a step change in capabilities over non-nuclear propulsion and where the cost of risk is borne by National Governments and hence not fully explicitly priced. There are however regulatory requirements that can be read across into the genuinely commercial shipping sector.

I have a question for the authors concerning the "marinising" of the proposed SMR. Experience from other technologies (including nuclear power) shows that the particular requirements of the marine environment and the confines of a taut ship design incur appreciable additional cost when compared to a static land plant that afford to be relatively dispersed. To what extent has this process been applied to the land based SMR design?

The analysis of hazards is interesting. A nuclear ship will still be subject to the same sort of external hazards such as errors in navigation and collision. In addition there are the hazards from within the ship, both directly as a result of failure in the nuclear plant and indirectly from incidents in the ship whilst at sea. The analysis of design options and application of the ALARP principles is to be applauded, however my impression is that the regulator would take the view that the design proposed is not yet as safe as it is reasonably practicable to be e.g. :

- a single longitudinal bulkhead separating the propulsion elements should be increased with significant separation;
- whilst it is good to see independent propulsors they are vulnerable to a single collision in this region.

However these are readily addressed and wouldn't greatly detract from the economic case for which my real concern is the items that have been identified in the text but omitted from the financial case in Table 9. The authors correctly identify these as insurance and to a lesser degree trained on-board manpower. As noted the nuclear powered vessels in service today are implicitly insured by National Governments. Commercial ships need to be insured by the market and this needs to include piracy. To be a serious proposition it will be necessary to compare the full cost of designing, building, owning, operating & disposing of nuclear powered ships with the other options available to reduce emissions from commercial shipping. These will include synthetic fuel from land based nuclear plants with the benefits of scale i.e. approximately ten land based nuclear plants compared to 1,000 nuclear powered ships. The sector is busy identifying all of the current and emerging options and putting together all the elements to allow the various players in the shipping sector to make the right investment decisions. These will change looking further ahead as the cost of emissions becomes increasingly expensive or restrictive by regulation. Somewhere down that road nuclear propulsion will become economically attractive but only by an objective comparison will the sector know when and under what circumstances. This paper makes a start down that road and I would now like to see the other parts of the jigsaw put in place and the comparisons made.

Professor Chris McKesson, University of New Orleans, School of Naval Architecture and Marine Engineering

I appreciate being given the opportunity to discuss this paper. The conversation about nuclear power for merchant ships is one that is overdue. Nuclear power is a viable and practical alternative, and to summarily dismiss it from consideration without rigour is simply bad decision-making. I am glad to see the authors engaging in good decision-making, by providing realistic engineering data on the impact of nuclear power upon the ship design. It may be amusing to note that all ships are already nuclear powered, even row boats and sailing craft. It is just that in this case the nuclear fusion reactor has been safely located 93 million miles distant, and the power is beamed to earth as sunlight, where it is stored in plant and animal tissues, and sometimes concentrated by geological processes.

The question that concerns us at present is whether it is viable to place the reactor somewhat closer to home, and use the power somewhat more directly. Note that recently in the Journal of Energy Policy Dr. Julio Vergara et al. [38] calculated the important role that nuclear power can play in mankind's attempt to stabilize climate change. Today's paper is the collaborative product of a reactor designer and a ship designer, and it is presented in a journal of marine engineering. It is thus appropriate that its focus be technological. However, as the authors themselves state, the barriers to adoption of nuclear power are mostly not technological. I therefore suggest that what is interesting in these studies is to determine the extent to which we technologists can use our technological tools to remove or circumvent the non-technological barriers.

The SuezMax study presents an interesting case study in this, which I explain as follows:

A large part of the objection to nuclear power boils down to "not in my backyard", or NIMBY. This attitude has effectively stopped the deployment of fixed site nuclear power stations. The use of nuclear power on a mobile basis provides a means for circumventing this, by ensuring that the plant is "not OFTEN in my back yard." Indeed, the project cited by the authors as Reference 14 assumed that the nuclear plant would only be used for high seas propulsion, and that near shore and harbor propulsion would be accomplished by diesel engines. This is an intriguing philosophical approach, and we can even imagine an extreme or asymptotic version, wherein the nuclear-powered ship stays in the high seas for her entire 50-year life, transshipping cargo to shuttle tankers for delivery to and from her ports, such transshipment taking place outside any nation's EEZ. (Note that I am not seriously proposing such an employment, merely using it to model the "NEVER in my back yard" asymptote.)

This philosophical approach depends upon the assumption that the high seas are seen as "not my back yard." This, I believe, will depend upon the inherent safety of the plant. In other words, a moderate risk "way out there" may be viewed as acceptable. But replace that with a huge risk, and the world's reaction will be "this is a small planet that we all must share. Every piece of it is my back yard." Where lies the line that differentiates between these two attitudes? I don't know[1]. But an important step toward finding it is the completion of risk-quantification studies such as the present one. As a result of this study we now know some of the costs and engineering impacts of nuclear power upon a ship of this type. The question of whether these risks are acceptable depends upon a subjective evaluation of the benefits we get by accepting them. For decades the planet accepted the risk of global thermonuclear war, because that was felt to be the only course that provided the benefit of an armed peace. In the case of a nuclear tanker the quotient will be "how much risk are you willing to accept, in order to reduce the delivery cost of oil?" As for myself, I wonder if this risk will be acceptable to a majority of people any time before oil becomes the price of diamonds, or if by contrast we are already past the threshold, and using nuclear power to save a penny at the pump is already an easy sell. Again, I don't know – the answer to this question lies outside the realm of marine engineering.

Similarly, building on my NIMBY model, I do wonder if a Suez route is an appropriate route for a ship like this. The Suez route passes through many nations' back yards, and some of the more tumultuous waters of the world. Would a CapeSize ship be a better application of the NIMBY philosophy? Remember that the increased stage length of sailing around Africa would not result in

[1] A test is to ask yourself how far your nation is from Fukushima, and the degree to which your countrymen believed the Fukushima accident to have happened in your back yard. I know some Seattle-ites who felt it was much too close to home.

any increased fuel burn, only a cost increase attributable to wage rates and ship amortization. Finally, returning to the marine engineering of the paper, the authors note that the plant emergency cooling water arrangements are configured to ensure that in any condition of heel or trim 30 days of decay heat removal could be provided to the reactor core. By "any condition" do they include a Costa Concordia attitude? Again, let us recall that this is the picture that is in the minds of our landside countrymen.

I am very pleased with this paper. I think that nuclear power belongs at sea, and I think that our naval and nuclear industries have the tools to make that a safe proposition. But the safe operation of nuclear naval ships has come about as a result of rigorous assessments of risk and benefit, and nuclear merchant shipping will require the same rigor. The present paper is an excellent contribution to that dialogue. We now see what professionals in the industry are able to do. Let us take the next step and find out what our customers are willing to accept, and then jointly move forward for the betterment of all mankind. I thank the authors for the opportunity to discuss this excellent paper, and I applaud the Institution for publishing it.

Sir Robert Hill (KBE, FREng, Hon FIMarEst, FIMechE), UK

Based on a recent publication by the Royal Academy of Engineering [39] I would like to raise the following points:

- It is useful for nuclear powered merchant ship designs to be undertaken from time to time and this concept design shows how one type of small modular reactor could be used and such a design is clearly feasible. The question is whether nuclear powered merchant vessels will ever be regarded as acceptable.
- The RAEng study accepts that Small Modular marinised Reactors have the advantage of possibly attenuating "many of the difficulties with nuclear propulsion". It summarises the situation with the words "The conventional methods of design, planning, building and operation of merchant ships would, however, need a complete overhaul since the process would be driven by a safety case and systems engineering approach. Issues would also need to be addressed in terms of international regulation, public perception and acceptability, financing the initial capital cost, training and retention of crews, setting up and maintenance of a global infrastructure support system, insurance and nuclear emergency response for ports." The paper touches on some of these issues, but it is clear that investment in nuclear powered merchant shipping will not take place until these issues, which by-and-large are not design-specific, are resolved and there would have to be very serious objection to diesel powering before international efforts are taken to make nuclear powered merchant ships acceptable.
- The submarine accident statistics should not be taken as typical. Worldwide, the largest number of nuclear submarines has been operated by the US Navy and the stringent and demanding standards of design, quality assurance, testing, operator selection, training and inspection introduced by Admiral Rickover and maintained by his successors have ensured considerably higher safety and avoidance of accidents than implied by these figures. Such high standards would need to be applied for merchant ships, notwithstanding the costs.
- It would have been helpful for an understanding of the risks if the numbers (not just the %) of oil tanker (and indeed other large merchant vessel) accidents had been provided. Foundering and sinking should be included also. Arguably, these represent the merchant ship hazard equivalence of a tsunami hitting a shore based power station!
- Risk analysis should also include piracy. It is not hard to imagine the headlines that would result from the capture of a nuclear powered merchant vessel. Potential threats to the operators, to the locality (when in harbour) and to the environment both ashore and at sea would need to be evaluated. Paragraph 6.3 rightly touches on these issues, saying "Convincing stakeholders ……… may not be straightforward, …." and "It could prove difficult to convince multiple national and local authorities to allow port entry …"

Nevertheless, as a study of how one type of small modular reactor could be used, it is an interesting and useful exercise.

Professor Apostolos Papanikolaou (FRINA), Ship Design Laboratory, National Technical University of Athens, Greece

The authors should be commended for a thought provoking paper, addressing critical issues of future energy sources for the propulsion of ships and their impact on the marine and aerial environment. The present discusser believes that on the long run, the use of nuclear energy for the powering of several types of ships will be inevitable, thus the timely development of relevant technology, which to a great extent exists, is a must. Of course, the environmental risks of nuclear powered merchant ships, next to the economy of shipbuilding and of operation in a life cycle approach, need to be carefully addressed and convincingly documented, before we come closer to practical applications. The focus of this paper is however mainly technological, while touching the risks of a SMR powered tanker, thus my discussion will be mainly focusing on these two issues. The authors may kindly comment on the following points:

- The justification for the selection of a tanker as a candidate for the demonstration/fitting of an SMR appears not very convincing because: (a) the actual energy demand of tankers, compared to other ship types, is relatively low to the extent that even a small 70MW reactor appears large for a SUEZMAX tanker (b) based on statistics (e.g. see Reference [32] of the main paper), the risk of fire and explosion accidents on tankers is high and may have serious consequences (c) the risk of oil pollution in case of tanker accidents will have a magnification effect on the likely impact of an accident of an SMR powered tanker, thus societal acceptance level will be very low; if this is combined with a SMR accident the impact on the marine environment appears beyond present thinking in terms of consequences and acceptance.
- The shown statistics of tanker accidents (as shown in Figure 3a) attributing 40% of the accidents to structural failures (Non-Accidental Structural Failures?!) greatly deviates from other known statistics (e.g. see [32] of the main paper and [40] below), show much lower percentages. As the breakdown of the shown statistics is unique with respect to the indicated hazards (partly mixing causal issues with consequences, while omitting groundings, contacts, etc.), some reference to the source of the data or the reasoning behind this breakdown would be appreciated.
- A risk assessment, in which typical hazards of tanker operation along with those of the operation of an SMR onboard a ship are analysed, is still pending. The due cost benefit analysis should not only compare alternative Risk Control Options for mitigating the consequences of accidents, but also make comparison to traditional tanker design on the basis of both economy and safety, including the environmental impact.
- It would be helpful to have a better documentation of the exact changes of ship's characteristics in terms of ship's displacement, wetted surface, LCB etc., in order to be able to better assess the validity of required powering. The rational behind this inquiry is based on the following thoughts: (a) for the Froude number range of interest, the most significant part of ship's total resistance (may be around 80%) is the frictional part, which is directly proportional to ship's wetted surface (assumed herein to have increased, proportionally to ship's length increase), (b) The viscous pressure part of the total resistance, which may be for the SMR ship with an increased length, to a certain degree lower, cannot counterbalance the increase in the frictional part, (c) Taking different propulsive efficiencies, when comparing the SMR option with the original design is not fair, as this has nothing to do with the inherent SMR design features, which are simply associated with an increased length, displacement and wetted surface, for the same payload capacity. Thus, the total resistance or the effective power is the proper criterion to use in the assessment of the two design options.
- The CAPEX estimates listed in Table 9 are valuable, though very crude for a serious assessment. One interesting point that the authors may like to comment is the fact that the SMR cost should be actually considered as part of ship's shipbuilding cost, whereas a conventional ship's fuel cost part of ship's operational cost that is partly carried by the charterers. Is there any financing concept of SMR powered ships in sight?!

AUTHORS RESPONSE

We would like to thank all discussers for their valuable comments. Clearly, the purpose of this publication has not been to resolve all issues related with SMR merchant marine propulsion. We do hope, however, that in light also of the RAEng study on future fuel options [39] the technological focus of our paper will steer in further the interests of academics, engineering practitioners and regulators. Clearly realising the benefits and drawbacks of nuclear merchant marine propulsion is a long term, yet meaningful debate. In the future nuclear propulsion may become economically attractive and in this sense further studies and objective comparisons can only assist with innovation, technology development and future implementation.

We would like to thank **Dr Gao** for his useful and encouraging comments. We also hope that - as the tide of scepticism against nuclear propulsion turns, technology develops, regulations mature and harmonise - policy makers, regulators, academics and commercial industry stakeholders will get more interested in the subject. For sure costs and business benefits will have to be counterbalanced against technical risks. In this sense we fully agree that justifying the business case which compels the transition toward nuclear propulsion is perhaps an immediate important exercise.

Dr Park raises a number of valuable technical questions to which we would like to respond as follows:

- When the reactor system is closed there is no exposure to Po-210 and hence there is no hazard to be considered as part of the HAZID study. Po-210 cannot penetrate the steel piping. During maintenance, good industrial controls such as protective clothing or respiratory protection are considered sufficient to manage Po-210 exposure. At decommissioning stage, Po-210 has half-life of 138 days and decays to negligible levels in about 2 years.

- To date, significant amount of international research has been conducted on the subject of mitigating corrosion induced by LBE coolant flow. In general, corrosion of piping by LBE is controlled by (a) material selection, (b) oxygen content of the LBE and (c) flow velocity in the piping. For further details we suggest that you refer to the open literature (e.g. [41], [42]).
- We agree that enabling for safe operation at a low melting point of LBE under abnormal conditions is important. At engineering stage the Gen4Energy team will explore whether such feature could be enabled by introducing a melting system available to prevent solidification during short shutdowns. For example, this system could be electrical heating powered by diesel generation.
- The issue of material degradation from fast neutron irradiation has been studied by leading researchers for many years (e.g. [43], [44]). On the case of Gen4Energy SMR, the reactor vessel and internals are only used for 10 full-power years which is a rather short lifetime requirement.
- The aspect of pressure balancing between primary and secondary systems and the possibility of damage of the reactor core in those cases that the secondary feed water flows to the primary circuit reversely is an important one. Yet, we would like to mention that this scenario has been modelled with computer simulation and it has been determined that the secondary water / steam would not reach the reactor core.
- On the matter of the number of shut down systems we would like to respond that in the SMR installation presented in this paper we assume two independent shutdown systems.
- Regarding the need to assure the exact precise control drive mechanism under ship motions we would like to mention that methods for precise control have been well developed over the years and are widely published in the open literature (e.g. [45],[46])

Our reply to the detailed technical comments raised by **Dr Woo** is as follows:

- In Figure 2 of the paper we demonstrate that a steam generator is located between the super-heater and the evaporator. This is a generic design that has been used in another fast reactor and operational experience has proven that it worked effectively. We feel that explaining the operating details on this matter is beyond the scope of the work presented here.
- It would be useful if the economic advantage of the system with reference to maritime operations is studied in further in the future. However, in our view it is not necessary to install a diesel generator instead of one auxiliary reactor. In the design presented in this paper the second reactor is installed so that the ship can have 20 full-power years of operation without major power system overhaul. The two reactors are not to be available by the same time so, in this respect, there is no issue with regards to the economy of the propulsion solution suggested.
- The term criticality under Figure 3(c) implies the ability of the reactor system to sustain nuclear reaction. It is a term that implies that there is an equivalent balance between the neutrons used and produced.
- We do not believe that the reactor is too lightweight compared to other reactors. The weight of 100 tons is considered as rather appropriate at this stage of the design.

We respect the comments by **Professor Howarth**. Currently, more detailed engineering work is carried out as part of the Gen4Energy development programme. We feel that within the context of preliminary design this paper sets well the top level risks and associated requirements for ship safety. Future publications could discuss such matters within the context of ship life cycle assurance and associated Nuclear Industry requirements.

We would like to thank **Dr Catsaros** for his technical comments. Our reply is as follows:

- The concept for maintaining the LBE as a liquid is electrical heating. The electrical circuit would be powered by a diesel generator. Details on the total load required are worked out at present as part of a broader engineering study and it is very likely that they shall not be unmanageable.
- Po-210 has a half-life of 138 days so in about 2 years it decays to negligible levels and can be easily managed for decommissioning. During operations it would be a concern only if there was a reactor system leak.
- The comment on management of Po-210 contact, also raised by Dr Park, is handled the same as other industrial hazards including protective clothing and respiratory protection. We note that this solution would only be required when the system is open for maintenance or if there were a leak.

Both **Mr Sigouras** of NAFSLOP and **Dr San** of STASCO express opinions representing the pragmatic interests of the shipping commercial sector. We fully agree with Mr Sigouras that the maritime industry practise (training, certification, regulation etc.) will be significantly different should nuclear merchant marine propulsion becomes a reality. Regarding the key issue of payback period and the need to balance ALARP against asset economic viability over a 25 year return period raised by Dr San we should like to mention that there is nothing to suggest that over the long term the industry standards would not allow for new construction of longer life-time merchant marine assets.

It is probable that the survey regime of SMR propelled vessels will be significantly different. In this sense cost and design for safety should be well balanced not simply for new construction but also throughout the life time of the asset. A working group comprising of leading shipyards, insurers, industry regulators and academics could help to bring all these matters in perspective.

We would like to thank **Professor Wrobel** for his valuable comments. We agree that marinisation of the technology used on a land based reactor will most probably increase the costs. However we have not conducted this analysis at this time.

On the matter of “design options” and the possible objections of a regulator on matters of safety our reply is as follows:

- The vessel was designed to maintain a “safe return to a safe haven” capability whilst applying the current MARPOL Annex I damage extent scenarios. Whilst both propulsors are located on the centerline, there is adequate longitudinal separation within the vessel to ensure that a maximum MARPOL damage condition would not result in both propulsors being out of action. So propulsion redundancy is achieved by longitudinal separation and additional transverse bulkheads.
- The twin screw configuration was considered, but was noted to have significant impact on hull form (and therefore powering) and principal vessel characteristics. A HAZID study was conducted in the concept study comparing a twin and single screw installation and in principle the redundancy of the single screw configuration was considered to be acceptable. Whilst a single screw with both propellers close together could be susceptible to damage extending to centreline, the damage would have to extend to centreline, which is above the damage extent that needs to be considered in accordance with MARPOL Annex I requirements.
- In principle the target was to develop a nuclear powered concept that improves the safety over a current Suezmax tanker design, which it does, especially considering the ability to propel the vessel when the maximum MARPOL Annex I damage extent has been inflicted.
- Regarding the economic case. On Table 9 we address only top level issues. Indeed in the future it will be necessary to compare the full cost of SMR nuclear propelled merchant vessel Such study would definitely require significant involvement from a shipyard.

We would like to thank **Professor McKesson** for his encouraging and valuable comments. For sure recognizing the barriers to the implementation of nuclear technology will help counter balance the extent to which technologists can be used to remove the circumvent of non-technological issues. However, we should not undermine that education, licencing, policy and regulatory issues are key enablers of implementing advanced nuclear technology onboard ocean going vessels. Regarding the comment on the vessel type and routing choices. For sure operational matters and vessel choices should be discussed in the future. The study presented in this publication had no intention to prohibit the industry from developing designs for other ship types and we would be delighted to read more papers by others on this subject in the future.

The consortium is honoured to receive comments by **Sir Robert Hill**. We recognise the impact of the recently published study by the Royal Academy of Engineering and we are delighted that we have been able to demonstrate our interest on the subject through this publication. For sure, international perception, acceptability, financing, global infrastructure, regulation, insurance are some of the important issues that should be thought of carefully and consist the main core of a future study. If SMR propelled ships were to become a reality there would have to be a step change in the style of implementing and developing maritime performance based standards. Harmonisation between nuclear and merchant maritime regulations suitable use of data and development of risk profiles would also be important. With regards to the later and based on the comments on the risk statistics presented we would like to mention that:

- We are in full agreement that some of the key submarine accident statistics presented in this publication cannot be taken as necessarily typical but should be carefully considered as some of their effects may be critical. The same holds for piracy attacks.
- Further background on the risk related with the oil Tankers fleet can be found in the work by Papanikolaou and Eliopoulou (see reference [32] of the main paper).
- In any case there is a clear need to research more the nuclear accident statistics by exploring ex-Soviet Union databases, harmonise the risk profiles available from different existing maritime databases and conclude on risk profiles also on the basis of lack of key or extreme accidents by using, possibly advanced probabilistic models (e.g. see [47]).

In conclusion, good balancing between commercial, political and technological issues is important. We hope that the technology focus and question-marks raised by our publication contribute at least to this front and in this sense we sincerely hope that we did not simply conduct a study that led to “one more paper” on nuclear propulsion.

We would like to thank **Professor Papanikolaou** for his rather valuable comments. We fully agree that environmental risks next to the economy of shipbuilding and operation will need to be carefully addressed. To the technical comments raised our reply is as follows:

- In our view the selection of a tanker as a candidate for the demonstration/fitting of an SMR is rational based on 2010 market trends, owner experience, expectations and shipyards interests. Notwithstanding the SMR technology has inherent features of functional safety that make it by far superior to older generations of nuclear reactors and some of those have been highlighted in this paper. In our view the debate is not "which ship type" but which "direction" on the front of performance based assessment and design development we should follow to assure safety. In plain terms it has not been the purpose of this publication to suggest that Suezmax Tankers are the only or the most preferable ship segment for the application of SMR technology. We would welcome further design, technology and techno-economic studies.
- The shown statistics of tanker accidents are based on the Centre for Tank Ship Excellence database (www.c4tx.org) which includes latest available statistics from oil majors and other highly respected operators. The breakdown of the shown statistics appears to be "unique" as it is driven by operational and business driven experience. For sure the work outlined by reference [32] of the main publication and the IMO tanker FSA risk profile of tanker vessels is broadly acceptable. Perhaps, it does not highlight some of the factors we inevitably had to consider during the classification of risks for this design. There is probably very little point in initiating a political debate on this matter. Instead it would be useful to make use of this opportunity to highlight once again that the expansion, harmonisation and unification of databases for the broad benefit of the maritime industry is a tremendous "big data" exercise that needs to initiate the soonest. This exercise should also consider the meaningful use of probabilistic data for those cases where accident databases are not available (e.g. [47]).
- On the question of clarifying the rationale behind the powering choices we would like to respond that the purpose of this part of the study was to sort list feasible options and investigate their envisaged implications. As part of incorporating nuclear propulsion into the vessel it was concluded that redundancy was required. The single screw installation (with azipod) was selected for numerous technical, architectural and general arrangement based reasons as explained in the paper. Therefore the modified vessel, by nature of the selected propulsion system has some inherent efficiency improvements that should be considered in terms of propulsive demands and reactor life. We are not comparing options here, merely assessing the implications of the change. Our base analysis was conducted by examining the parent vessel and adjusting the resistance estimates to the new characteristics of the SMR tanker. The block coefficient has remained constant due to changes in hull form at the stern and bow, not just parallel mid-body lengthening of the original vessel. The bare hull resistance did increase in comparison to the parent vessel, in the region of about 4% compared to the parent vessel. You will note that whilst length has increased by 30 metres, the displacement has only increased by 2700 tonnes. It is well understood that the application of a Contra Rotating Propeller (CRP) installation improves propulsive efficiencies by quite a margin. On higher speed vessels this is estimated to be in the region of 15%. After initial discussions with ABB, it was agreed that an estimated 8% efficiency improvement was a sensible estimate at this stage for the target vessel. This 8% efficiency improvement clearly negates the 4% increase and therefore results in a lower power demand on the SMR vessel (with a CRP installation).

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