NUCLEAR PROPULSION OF MERCHANT SHIPS – ASPECTS OF RISK AND REGULATION

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SUMMARY

Following its exploitation in submarines and aircraft carriers, nuclear propulsion was introduced into merchant ships in the 1960s. These developments were for the most part successful in their technical achievement, but commercially less so. Notwithstanding this early scenario, there has been a steady, although low level, development of nuclear propulsion in the intervening years, which has mostly centred on icebreakers but has also included some other merchant ship types.

Current concerns over CO_2 emissions and other air pollutants have awakened interest within the marine industry in nuclear propulsion. This paper considers some of the aspects of Lloyd's Register's research and development studies relating to the nuclear propulsion of merchant ships. After establishing the background to nuclear power at sea, the paper discusses the subject of the safety, risk and regulation aspects that the wider marine industry may have questions about with regard to nuclear propulsion. A companion paper will address the science, technology and engineering aspects in the near future.

1. INTRODUCTION

In keeping with many other industries, both within the transport and other sectors, the marine industry is seeking ways to reduce carbon and other emissions from ships. MARPOL Annex VI and the moves towards a Carbon Index bear testament to these initiatives. While much valuable research is being undertaken in different areas of two and four-stroke diesel engine technology, together with parallel work in the context of fuel cells and wind propulsion power augmentation [1], it is pertinent to pose the question of whether nuclear propulsion has some potential for merchant ship propulsion [2]. If so, then carbon, NO_X, SO_X, HC and particulate emissions could be reduced to zero, certainly as far as ship operation is concerned. Moreover, the complementary developments for naval ships and submarines have demonstrated an enviable safety record, and land based installations have, apart from two major isolated incidents, been safely generating electric power for many years.

This paper addresses the safety, risk and regulatory aspects of nuclear propulsion, while a companion paper [3] considers the science, technology and engineering aspects of nuclear power within the marine industry.

2. HISTORY

It is about 55 years since the first nuclear reactor was brought to power on the submarine *USS Nautilus*. This boat used a single pressurised water reactor (PWR) and this development led to the *Skate Class* submarines and the aircraft carrier *USS Enterprise* in 1960. This latter ship was powered by eight reactors and is still in service.

The 20,000 dwt *Lenin*, which entered service in 1959 and remained in service for 30 years until her hull deteriorated to a point beyond economic repair, was the world's first nuclear powered icebreaker. She was finally powered by two 171 MWt OK-900 reactors which delivered 34 MW at the propellers.

The *USS Long Beach* followed in 1961 and one year later the US Navy had a fleet of 26 nuclear powered submarines in service with some 30 under construction. *HMS Dreadnaught*, the Royal Navy's first nuclear powered submarine, completed sea trials in 1962. This boat used American nuclear propulsion technology and, while the US technology was shared with the United Kingdom, the Chinese, French and Russian developments of marine nuclear propulsion technology proceeded separately.

In the case of merchant ships, during the 1950s the development of designs for nuclear propelled ships commenced and in 1962 the first merchant ship, the *NS Savannah*, was commissioned. This ship had an installed power of 21,000 shp and was capable of 21 knots; although she performed well technically, she was not economically viable at the time and was decommissioned some eight years after entering service. The *Otto Hahn*, which was both a cargo ship and research facility, followed *Savannah* into service and also experienced little in the way of technical difficulties over her ten year life span as a nuclear propelled ship but, again, she also proved too expensive to operate commercially. Subsequently, the *Otto Hahn* was converted to diesel propulsion. A third ship, the *Mutsu* was less fortuitous and suffered a number of technical and political problems. All three of these pioneering merchant ships used reactors with low-enriched uranium fuel having 3.7 to 4.4% ^{235}U.

The success of the *Lenin* led to the *Arktika Class* of ice breakers in 1975. The propulsion systems of these ships were capable of delivering 54 MW at the propeller from two OK-900 reactors having a capability of 171 MWt each. As such, the ships were capable of operating in deep Arctic waters: indeed, *Arktica* was the first ship to reach the North Pole in 1977. Of this class, the *Rossija*, *Sovetskiy Soyuz* and *Yamel* were still in service towards the end of 2008 with the *Yamal* offering passenger cruises towards the North Pole. More recently the NS *50 Let Povbedy* (Figure 1) was commissioned in 2007. This icebreaker is an upgrade of the *Arktika Class*, having a displacement of 25840 tonnes, and is designed to break through ice up to 2.8 metres thick. The installed power is 75,000 shp and is powered by two nuclear reactors. The ship, whose speed in open water is 21.4 knots, doubles as an icebreaker and arctic passenger cruise ship, having 64 cabins.

In 1988, the *Sevmorput*, a fourth nuclear merchant ship, was commissioned in Russia (Figure 2). It is a lash barge carrier and container ship, 260 metres in length and fitted with an ice breaking bow. It has operated successfully on the Northern Sea route serving the Siberian ports and is powered by a KLT-40 135 MWt reactor similar to that used in the larger ice breakers. This propulsion system delivers 32.5 MW at the propeller and has required refuelling only once up to 2003.

Figure 1: NS 50 Let Povbedy (50 Years of Victory).

As a precursor to the *Sevmorput* and other icebreaker developments, the Russians developed both PWR and lead-bismuth cooled reactor designs. The PWR designs became the predominant type of reactor and four generations of designs were developed with the last entering service in 1995 in the *Severodvinsk Class* of submarine. Nevertheless, the largest Russian boats were the *Typhoon Class* which were powered by twin 190 MWt PWR reactors; however, these were superseded by the *Oscar II Class* using the same power plant.

Continuing this development, two *Taymyr Class* shallow draught icebreakers of 18,260 dwt were launched in 1989 for use in estuarial waters. Looking to the future, a Russian 110 MW icebreaker is planned together with further dual-draught vessels delivering 60 MW at the propellers.

Figure 2: N.S. Sevmorput.

In response to the early developments in nuclear propulsion for merchant ships, Lloyd's Register produced *Provisional Rules for the Classification of Nuclear Ships* [4] in 1966. These Rules embraced requirements for the hull, pressure vessels and components, reactor engineering and control in addition to requirements for complementary installations and survey and maintenance. These Rules, although maintained during their existence, were withdrawn in 1976 due to the lack of widespread application of the technology in merchant ships. However, currently there are some 600 nuclear reactors in operation, of which nearly one third are used in the marine environment.

Set against this background, some three years ago Lloyd's Register began to consider whether the concept of nuclear propulsion for merchant ships had potential merit, given the design and operational experience accrued in the naval and power generation sectors over the last half century. The concept study initially examined the technical design issues surrounding a number of ship types, including container ships, cruise ships, tankers and bulk carriers. In addition, the relationship of these ships to existing international conventions and codes was considered, as were the risk issues surrounding a nuclear installation on board a trading merchant ship.

3. ENVIRONMENTAL CONCERNS AND DRIVERS

It is highly probable that any use of nuclear powered merchant vessels will be inextricably linked to the environment. Such an environmental linkage will be either through simply wanting to be visibly green, with little or no emissions from the ships stacks, or as a result of carbon tax and the simple economics of operating nuclear powered vessels. The British government has recently produced a memorandum detailing options for decarbonising Britain by 2050. This is not a complete removal of carbon production from the UK, but an expected 30 to 50% reduction depending on how the accounting is done. The memorandum was undertaken under the leadership of Prof. David J C MacKay FRS, via the Commons select committee environmental audit. The full document can be viewed at the government's parliamentary web site [5] under parliamentary business. The last and most relevant paragraph reads as follows:

"5.10. International shipping
International shipping is quite an efficient user of fossil fuels, but perhaps we should plan to defossilize it too. (In 2002, Britain's share of international shipping used a power of 10 GW; that corresponds to a significant fraction of the UK's carbon budget for 2050.) In plan C, Britain restarts President Dwight D. Eisenhower's "Atoms for Peace" initiative, building and maintaining a new fleet of nuclear-powered container ships and passenger ships."

It is highly likely that other governments are also considering similar options to reduce their own CO_2 production. Indeed, testament to this is the current level of interest that is being shown by owners and builders around the world in nuclear propulsion.

4. HEALTH IMPLICATIONS

It is known that large doses of ionising radiation can cause increased incidences of cancer and leukaemia in the population over time. Furthermore, evidence from experiments on animals and plants suggests that smaller doses of ionising radiation may also cause genetic mutations to occur; however, there has been no evidence of this in humans. While embryos are sensitive to radiation damage, the amount of damage caused by radiation will depend on many factors, typically:

1. the actual dose received
2. the dosage rate
3. the type of radiation experienced
4. the age of the person
5. the state of health of the individual
6. the part of the body which suffers exposure.

For most people, the principal exposure to radiation is from naturally occurring background sources. These levels are typically in the range of 1.5 to 3.5 mSv/year but in certain geographical areas they can rise to in excess of 50 mSv/year. As such, the doses received by members of the public during their lifetime can reach several Sv. Figure 3, as an example of the sources of radiation, defines typical exposure in the United States of America. While it might be plausible that a very small dose of radiation may pose a risk to human health, as with natural sources of exposure, there is no scientific evidence that short term doses of up to between 50 and 100 mSv/yr pose a threat. Indeed, at dose rates of up to about 10 mSv/yr, there is some evidence to suggest that beneficial effects may arise.

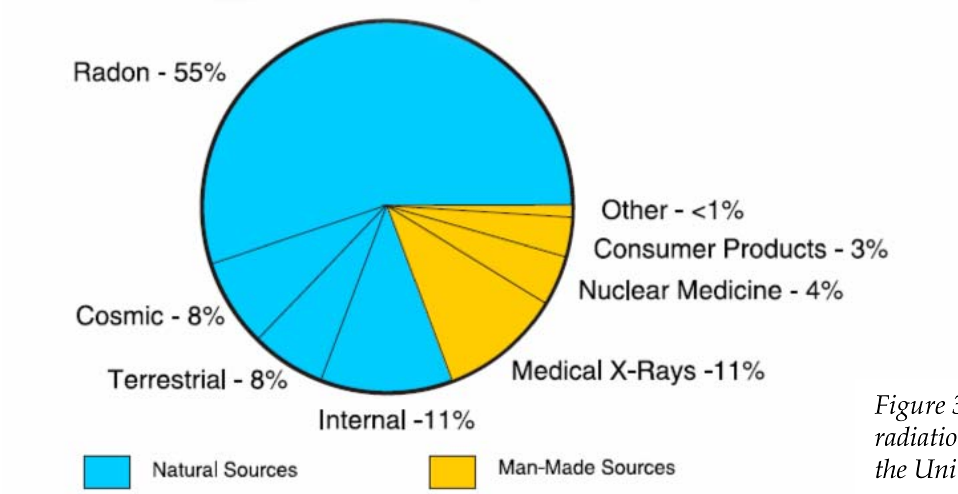

Figure 3: Sources of radiation exposure in the United States [6].

Dosage	Comment
50mSv/yr	This is the dose rate which naturally occurs in some places on the Earth; for example Iran.
100 mSv/yr	This is the lowest level at which any increase in cancer becomes evident; above this level the probability of a cancer occurrence increases with dose level.
1,000 mSv/cumulative	If encountered in a short term dose, this is around the threshold for inducing immediate but temporary radiation sickness in an average person, but would be unlikely to cause death. The estimated risk of a fatal cancer developing at some time in the future at this level of radiation is of the order of 5 in every 100 people exposed.
Single dose greater than 1,000 mSv	Immediate effects would be temporary nausea and decreased white blood cell count. Between 2,000 and 10,000 mSv, when encountered in a short term dose, severe radiation sickness would result, with an increasing likelihood that this would be fatal.
A single dose of 5,000 mSv	Radiation at this level would kill about half those receiving the dose within a month.
A single dose of 10,000 mSv	If experienced as a short-term and whole body dose, this would cause immediate nausea and decreased white blood cell count as well as death within a few weeks.

Table 1: Likely health consequences of radiation exposure.

In the case of higher radiation dosages, some guidance can be derived from Table 1, which endeavours to correlate health effects with dosage parameters. Clearly, some variation in the anticipated effects can be expected depending upon the specific physiological characteristics of the person involved.

There will naturally be concern from the marine industry with regard to exposure to radiation. Within naval nuclear practice, each crewman wears a dosimeter, a device that measures levels of exposure to radiation at all times. Each man's dosimeter is checked periodically to enable the navy to monitor how much radiation each man has been exposed to in relation to strict controls that are in-place to minimise exposure.

5. NUCLEAR POWER RISK – BOTH REAL AND PERCIEVED

Is the public right to be concerned about nuclear power? Perhaps. It certainly is an industry which, if the facilities are incorrectly designed, operated and maintained, has very significant incident consequences for any population in its vicinity. The same is true of the chemical industry, or a few other high hazard industries, in as much as the consequences of an incident are significant.

There is a huge amount of effort put into ensuring the design, operation and maintenance standards of modern reactors are second to none and that the probabilities of an incident are remote. What is certain is that all energy production systems carry risks. There are two key differences, however, in terms of how the public perceives the nuclear industry, when compared to other industries:

1) The unseen killer

The first is that is it very easy to see and understand the implications of what might be called conventional or traditional hazards; for example, an explosion or fire. While such consequences are hugely destructive, people have generally had some degree of personal experience of such consequences in their life and how to manage them. The public believes the effects of conventional industries are understood, visible and tangible and people know what to do in escaping their effects. By contrast radiation is the unseen killer. If the dose is below 1000mSv, you are completely unaware that you are being exposed to radiation; it does not hurt and there is no sensation when you are exposed to it. The effects are generally not immediate, unless you are exposed to very significant doses: even then it is hours or days rather than seconds or minutes. The effects are typically revealed in later life as cancers. Radioactive contamination can lay unseen, or be airborne, and no one would know it is present without the right measuring equipment. It is insidious. Life typically does not equip the individual with the ability to identify, understand and take action to protect themselves from radiation.

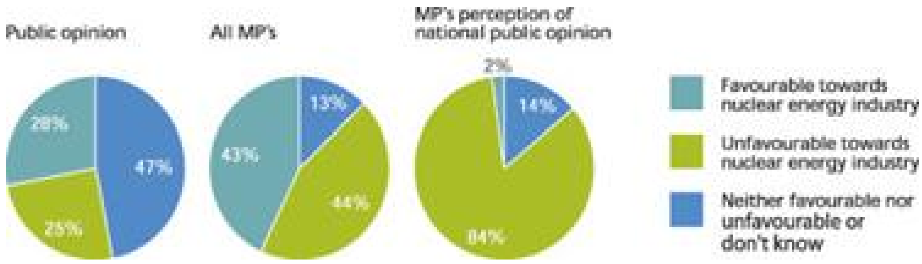

Figure 4: Comparison of perceptions of the public and MPs.

2) A nuclear bomb

The public generally has little appreciation of the difference between a nuclear weapon and a nuclear power plant. Lack of education by the industry and society has resulted in the public generally equating the worse case incident at a nuclear power station to that of a nuclear explosion. This could not be further from the truth. It is impossible to have a nuclear explosion in the core of a civil nuclear power station. One of the perception issues is surely related to comparison with other forms of energy. For instance, people know that petrol will explode if handled incorrectly, but its energy release is controlled in a car engine. The public knows petrol can be useful but also destructive. The same assumption is not true of a nuclear weapon and power plant. Civil nuclear power plant fuel, the core, can not generate a nuclear weapon explosion. The complexity of nuclear power technology has its draw backs when trying to convey it to the general public. Most people's appreciation of the scale of nuclear weapons is based on images from World War II, the Hiroshima and Nagasaki bombs, and the scale of devastation. The principal destructive force, however, of nuclear weapons is not radiation, as the public perceive; it is the pressure or thermal wave, and flying debris. Radiation is only present as a by product of splitting the atom.

At what point the public has come to the view above is hard to discern. Nuclear incidents such as Three Mile Island in the US, which had no effect on the population at all, through to Chernobyl in the former USSR, which had a huge effect on the local population and has contaminated large tracts of land, have certainly influenced the public. How the media has chosen to portray the nuclear industry has also had a significant impact on shaping the public view. It is interesting to look at the findings of a study conducted by the Nuclear Industries Association in Figure 4.

Clench [7] when conducting a limited survey of people's attitudes to nuclear power as a suitable alternative for ship propulsion in general, recorded that 57.4% of his sample of 64 members of the public agreed with the proposition. As such, this tends to support the findings shown in Figure 4. Perhaps the fallibility of humans and confidence levels in complex engineered systems is also a contributor to how the public perceives nuclear power.

The marine industry is now at the very earliest stages of looking again at nuclear power in merchant ships. How will the public and the marine industry view this? What are the issues or hazards, perceived or factual, which will need to be addressed and managed? While the real and perceived issues will be many, a high level view can be gained from looking at the substantive differences in culture, design, operation, maintenance, decommissioning and the costs of nuclear and conventionally powered ships.

Culture

- ***Safety culture***
  A similarly exacting safety culture that is present in the civil and military nuclear power world would be required. While the marine industry has achieved different safety cultures and standards, for example in the transport of LNG, the culture required for a nuclear powered ship clearly extends beyond those staff operating the plant. It would have to pervade the whole operating, owning and regulating structure. The initial capital costs to invest and develop the technology would typically only attract those owners who have a longer term, strategic and typically high safety culture. Various models could be envisaged for the supply and qualification of ships' staff; however, it is without doubt that the companies supporting both the civil and military nuclear power sectors would be key to the development of the required culture.

- ***Training regime***
  Quite different regimes have been achieved in the merchant sector, as seen in LNG operation. The industry would have to look towards the civil and military nuclear industry for support in this area. Clearly, engineers would have to become nuclear experienced and qualified. The deck staff would also have to have an appreciation of the technology. Given the differences between seagoing merchant and naval engineering training, the present merchant training would require significant modification. In the case of naval engineers and artificers, they receive specialised courses of instruction in nuclear engineering. A solution to the merchant marine problem might be obtained in a number of ways, each of which would need detailed exploration. One option might be to train merchant marine engineering officers in a similar way to naval engineering staff, recognising that a merchant officer generally comprises an amalgam of the naval officer and artificer models. An alternative solution could be to split the engineering staff into nuclear and general engineering staffs where the chief engineer would clearly need to be nuclear-trained. Yet a third alternative may be to encourage manufacturers of nuclear propulsion plant to offer an engineering solution whereby, in addition to supplying the plant, they also provide though-life operator and service support to a shipowner. Such a model is consistent with the discussion on the regulatory environment.

- ***Employment regime***
  The current short term contract regime of the merchant world would undermine developing and maintaining the very high safety culture required to support a nuclear merchant marine. There would clearly need to be a longer term commitment by the owner or operator to the employee, and accordingly the owner or operator would want to ensure that the significant money invested in training and competence was not in vain.

- ***Health physics capability and responsibility***
  The health and safety aspects associated with nuclear power, for example nuclear medicine, would also have to be developed both shore side and on the ship. International guidance is established through the International Atomic Energy Authority (IAEA) and each country has its own implementation of the IAEA guidance. Health physicists have deep expertise, just as in any technical or medical discipline. The person on board ship would not need to be a health physicist: rather, a person who is dual trained to the degree necessary, much like someone who is first aid trained.

Design and build

One view is that, at a high level, the nuclear plant could be dropped into the prime mover's place in the engine room. While this may be overly simplistic, there are not so many differences or implications for the technology: the principal areas being reactor shielding, primary and secondary circuits and considerable robustness of the control and instrumentation systems. The majority of the design build aspects are discussed in [3].

Maintenance

How merchant ships are maintained has changed significantly over the last 20 to 30 years. There are a number of reasons for this, with system complexity and the degree of specialist knowledge required being key. Ships' maintenance is now typically undertaken by suppliers, such as engine or control systems manufacturers. Nuclear plant has always been complex, but unlike other sectors, the use of PC systems for control is held at a relatively low level due to the predictability of failure modes. The use of spares not from the original manufacturer is a source of concern for many industries, including the marine industry. The integrity of spares and components for nuclear plant must be unquestionable and, again, is further discussed in [3]. It is highly probable that the original supplier of the nuclear plant would provide through-life maintenance and support for the plant, ensuring the integrity of the components and quality of maintenance.

Operation

- ***Health physics monitoring***.
  This would be a new discipline required on board ship and within the company. The ship board role would cover two aspects: normal day to day monitoring of the dose burden, and the care of people after any unplanned exposure. Depending on the company size and number of nuclear ships, there may be a requirement for a full time health physicist shore side.

- ***Manning***
Twenty four hour watch keeping of nuclear plant is the norm. The rationale for this is the ability to respond quickly by operators that are fully awake; as opposed to those who have just been dragged from deep sleep and have to make their way to the engine control room and make potentially critical decisions on plant safety. At the present time, all reactor plants are attended by watch-keepers at all times: this is true whether the plant be land or sea-based. Typically, in a land based power station there may be 100 watch-keepers assigned to a plant; however, it must be remembered their watch-keeping rota is very different to that encountered on a naval ship where the normal sea watch regime of 1 in 3 is in place. This permits a considerably lower number of qualified staff to be required at sea. The question naturally arises as to whether the unmanned machinery spaces concept would be valid for a nuclear powered merchant ship. In the short, or indeed medium, term this is thought to be unlikely. This is because, although nuclear plant control systems are becoming considerably more sophisticated as witnessed by the new third generation reactor designs [3], there is still some considerable experience to be gained with these control systems before such a move could be confidently made. Undoubtedly, however, this experience will first be gained with land-based installations and then, to some extent, transferred to marine practice. It must also be remembered that marine systems are considerably smaller than their land-based counterparts and, therefore, the response of the marine system is potentially likely to be faster.

- ***Radiation Shielding***
The shielding of people from ionizing radiation from a core is achieved by lead and polythene within the ship. Water is a very good moderator and shield from radiation. If a reactor compartment is in contact with the ship's side, below the water line, no additional physical shield is provided. Accessing, or close proximity to, the underside of a ship would then have to be restricted in normal operation, for example when the vessel is in port. If the reactor was shut down while in port, the dose burden through the hull would be minimal and associated with decay heat. If the reactor was operational for cargo operations, or hotel loads, then the dose burden, through the hull, would be considerable. This may have implications for any diving operations associated with surveys.

- ***Dry dock and refuelling facilities***
The dry docking of nuclear powered ships would include items not normally seen in the merchant marine. The largest issue is most probably the timescales involved in dealing with the reactors' decay heat: the spent fuel remains hot and needs to be cooled continuously. In this sense, decay heat is rather like a kettle after is has boiled. Unlike a kettle, however, where the heat dissipates in minutes, a reactor core will continue producing heat for hours or days depending on how used the core is. This amount of heat is considerable and has to be removed, with the ultimate heat sink, via cooling systems, being the sea. Hence, docking a vessel has to be a much more controlled evolution and one which would take longer than a conventionally powered vessel. Nuclear refuelling happens far less often than bunkering and while bunkering has its hazards, nuclear refuelling requires even more design and process rigor. New fuel is relatively easy to move about from a radiological perspective. Spent fuel, however, has significant radiological and health physics issues. Typically, this involves shielding and the transfer of the spent fuel within a controlled water bath from the ship to the storage facility. Hence, the dry dock would need to have considerable additional features to cope with refuelling. The time period involved in refuelling could, however, most probably tie into the five-year survey period; detailed reactor design would dictate this.

- ***Ports and local population***
Public opinion is a hugely powerful force in a democracy. Cold ironing, the supply of shore side electrical power while in port, was pioneered in Alaska, at least from a merchant marine perspective. The drive was from the local population who could see the visible exhaust gas emissions. The same has happened in San Francisco and other Californian ports, where increased pockets of cancers appear around ports, particularly container terminals. Cold ironing is being discussed and imposed by the ports on the ship operators. The local councils, who issue the port operating licences, have responded to public pressure and concern over hot spots of cancer. The ports from which nuclear ships operate will be exposed to public concern, be it from real or perceived issues.

While robust approaches to understanding the risks of nuclear powered ships entering a specific port will have to be undertaken, such as that undertaken for LNG terminals in populated areas, remote port locations for nuclear ships are likely to be much more politically acceptable.

- ***Public perception***
  The acceptability of nuclear powered vessels in a country's sovereign waters, from both the regulator's and public's perspective, is an area that has been mentioned several times. If we ignore the fact that nuclear powered vessels have traded globally in the past, so clearly precedence has been established several decades ago, there is a case for acceptability of nuclear powered merchant vessels today. The *NS 50 Years of Victory*, a Russian-registered icebreaker, is currently marketed by several companies which offer adventure cruises to the Artic. The vessel carries up to 128 fare paying passengers and sails from Murmansk in Russia during the Northern Hemisphere's summer period. This illustrates that at least one flag state today is happy with nuclear powered vessels entering its territorial waters, and that there are members of the public who are happy to be on such a vessel. The companies selling the adventure cruises are very open about the vessel's source of power, as can be seen from their marketing literature which contains detailed information about the ship and its propulsion systems.

- ***Terrorist threat***
  This will be a real issue as far as the public are concerned. The fact is that it may be more one of perception. But nevertheless, a terrorist could use the perceived risk as a real threat. In the current environment piracy is such an example. The public perception of the leverage Somali pirates, for example, could achieve for the capture of a nuclear powered vessel would be immense. There would be some factual concerns about nuclear safety: was the plant shut down properly? There would also be a concern about the use of the reactor fuel in weapons: either nuclear weapons or dirty bombs. Removing nuclear fuel from a reactor is not the same as siphoning fuel out of a car's fuel tank. It is much more complicated, involving significant engineering capabilities. Even if the fuel were removed, to create a nuclear weapon requires industrial equipment that only a few countries in the world posses. It is highly improbable that any merchant marine core design would hold sufficient fissile material to make a nuclear weapon. A dirty bomb is not a nuclear weapon; conventional explosives are used to propel contaminated material, typically highly radioactive material, into the atmosphere. In the case of a dirty bomb, the raw fuel material from a nuclear powered ship could be used. The vessel could possibly also be used as a target by a missile, the objective being to create panic from many sources. Alternatively, blocking a sea lane with a nuclear propelled ship might be seen as a propaganda coup, with the target being impact on trade, finance and stock markets, as well as panic to the local population from a perception of contaminated water and the like. The facts however are quite different. A reactor pressure vessel is a hefty thing, capable of withstanding the pressure of immense depth and it typically would be water filled, hence incompressible. The majority of the energy of a missile would be expended in penetrating the ship's side, with little harm being done to the reactor itself due to its construction. Experience from armour piercing shells used against tanks is that the war head, after penetrating the tank, simply rattles around the inside of the tank – killing the occupants but doing little damage otherwise.

Decommissioning

The decommissioning of a nuclear facility is very different to the scrapping of a ship. Decommissioning would have several implications for the marine industry:

- The cost of decommissioning.
- The ownership of contaminated waste after decommissioning.
- Facilities to physically undertake decommissioning.

One view is that the merchant marine hardly thinks about ship scrapping; the vessel is sold, and then it is effectively forgotten. The purchaser takes liability for everything, with the majority of the steel being recycled and other components sourced for spares or raw materials. While the majority of a nuclear powered vessel could, in broad terms, be treated the same way, this is only after removing the parts of the vessel which pose an ionizing radiation risk, typically referred to as contaminated waste. At the end of a nuclear facility's life, the plant has accumulated a considerable amount of activated material, along with the depleted core, which has to be treated appropriately. Varying degrees of radioactive waste are created:

- High level waste is the by-product of fission in the core and what has happened to the nuclear fuel after it is 'spent'. This represents about 1% of contaminated material. This percentage equates to the UK nuclear industry producing an amount of high-level waste equivalent in volume to a taxi each year.

- Intermediate-level waste is far less radioactive than high-level waste. Intermediate-level waste is made up of such things as fuel cladding material and sludge that come from the nuclear reprocessing treatment processes. Intermediate waste accounts for around 19% of contaminated waste.

- Low-level wastes are components of the reactor circuit which have become radioactive from exposure to neutron radiation from reactor operation. This waste is also generated from exposure, generally within a nuclear facility, and includes items such as shoe covers and clothing, wiping rags, mops, filters, reactor water treatment residues, equipment, tools and luminous dials. Similar low-level waste is generated in medical treatment and research, such as medical tubes, swabs, injection needles, syringes, and laboratory animal carcasses and tissues. Worldwide, low-level waste comprises 90% of the volume of total nuclear waste, but only 1% of the total radioactivity.

Waste has to be stored appropriately until it becomes safe or is subjected to reprocessing, as discussed in relation to the nuclear fuel cycle [3]. How it becomes safe is by natural decay, where the waste material effectively loses its radioactive energy. An analogy of radioactive decay would be a car battery, losing its power when it is not used for several months. Nothing happens to the physical state of the battery; it simple loses its electrical charge. The same is true of radioactive waste, but the time period for it to become safe takes much longer. The waste, however, remains to all intents and purposes, physically intact. While the waste loses its energy, it needs to be shielded, so waste depositories tend to be quite large places with small amounts of contaminated material surrounded by large voluminous structures to absorb the harmful ionizing radiation.

There are significant costs associated with decommissioning. While the volume of contaminated waste is small, there is a cost to the process and the ongoing storage of waste. The ownership of waste is also an issue that requires addressing.

There are typically three ways of undertaking decommissioning:

- **Immediate dismantlement:** soon after the nuclear facility closes, equipment, structures, and portions of the facility containing radioactive contaminants are removed or decontaminated to a level that permits release of the property, such that it can be treated as any other ship.
- **Safe Storage:** often considered delayed dismantling. The ship would be stored and monitored in a condition that allows the radioactivity to decay; afterwards, it is dismantled.
- **Entombed:** the radioactive contaminants of land based plant are permanently encased on site in a structurally sound material such as concrete and appropriately maintained and monitored until the radioactivity decays to a level permitting restricted re-use of the property. From a ship perspective this could take a number of different routes, from deep dispersal at sea to removal of certain ship sections and encasement.

There may be some mixing of the first two methods, which would limit the cost of decommissioning. While the cost of decommissioning would appear to be expensive, the total life cycle costs have to be considered. The large quantity of CO_2 produced by ships' engines throughout their life also has to be considered.

There are a number of examples from nature which would seem to suggest that containment of radioactive materials for very long periods of time is possible [3].

Through-lifecycle costs

For a conventionally powered merchant ship, the costs are spread throughout its life, while for a nuclear powered vessel the costs are much more biased towards the initial purchase cost. Noting present day fuel costs, nuclear power is only comparable when considering through-life total costs. However, with the potential move to distillate fuels and the imposition of carbon taxation, nuclear power becomes significantly more attractive.

The differences in costing model for a nuclear ship would, therefore, imply that the philosophy associated with chartering rates would need to be re-evaluated.

6. THE REGULATORY ENVIRONMENT

One of the major stakeholders in this arena will be the relevant governments, which may only be a few, if fixed trade routes are considered. If a wider deployment of marine nuclear power is established, as for example in cruise ships or yachts, then significantly more countries will need to be involved. This political influence may be visibly limited to the technical aspects of safety; those which are environmental, operation and so on. However, the approach and methodology could vary significantly and be influenced by electoral and business interest. The two fundamental regulatory regimes could be either prescriptive or a goal-based safety case.

During the 1970s, significant work was undertaken within the IMO which resulted in the adoption on November 19, 1981, of IMO Resolution A.491(XII) *Code of Safety for Nuclear Merchant Ships*. The purpose of the Code was to provide a technical and regulatory reference for nuclear merchant ships and supplement other applicable international conventions, codes and recommendations. The Code is still relevant today, even if some of the standards have been superseded. It defines specific safety issues which should be addressed, together with criteria to protect people and the environment from radiological hazards throughout all phases of a ship's lifecycle: design, construction, commissioning, operation and decommissioning (scrapping). One of the most significant differences between this Code and most other IMO regulatory requirements is the concept of a Quality Assurance Programme (QAP) which would embrace the whole ship's lifecycle. The QAP would be the responsibility of a single organisation; however, it should not prohibit transfer between bodies – transfer of class.

The Safety section looks at a single failure criteria impacting on the safety of the nuclear power plant which can be addressed through redundancy, independence, segregation or diversity. Risk assessment is based on the principle of likelihood (frequency) against the consequence (impact), including decommissioning and loss, and recovery following loss of the ship.

Within the Design Criteria and Conditions section of the Code there are three main aspects which have to be addressed for defined systems: shielding, heat removal and cooling the core. The Code defines each of the necessary safety functions for all plant process conditions.

The section design aspects are primarily influenced by the radiation hazard to the space or the consequence from the design. The Ship's Structure section deals with the nuclear plant, its effect on the structure locally and globally, while most other aspects supplement existing regulatory requirements: that is, stability (two compartment standard), fire and safety, navigation and so forth. Other sections of the Code cover nuclear steam supply, machinery and electrical installations, radiation safety, operation and surveying. The surveying requirements clearly define what is required during construction, trials, operation and decommissioning to the extent of defining the standards for pressure testing and the scope of non-destructive examination.

The six appendices of IMO Resolution A.491(XII) discuss, respectively: sinking velocity, seaway loads, safety assessment, dosage limits, quality assurance programme and application of a single failure. They expand significantly on how these aspects should be undertaken when referenced in the main body.

Even though the nuclear environment has changed since the writing of the Code, most of the safety principles are pertinent today. However, there are a number of areas where ship safety has changed; for example it might be pertinent to use a probabilistic rather than deterministic approach for damage stability.

It may not be appropriate, as with previous examples in the development of new ship types and radical engineering solutions, that standards are prescriptively developed. It might be more appropriate to ensure engineering capability is achieved while the risks to life and the environment, as far as practicable, are mitigated in an appropriately transparent manner: the methodology stated in IMO Resolution A.491(XII). This approach is consistent with the regulation of most land-based nuclear industries. Within this context, the marine industry could base its approach on IMO Resolution A.491(XII) and, in particular circumstances, the INF Code.

7. CONCLUDING REMARKS

From the risk and regulatory aspects of nuclear propelled merchant ships the following has been concluded:

1) The current international concerns relating to global warming and, in particular, the adverse situation concerning CO_2, may provide an environmental driver for the promotion of nuclear based ship propulsion. This is because a nuclear propulsion system emits no CO_2 during its operation.

2) Governments are presently discussing methods to address the CO_2 issue, with some specifically mentioning that serious consideration should be given to the nuclear propulsion of ships. Governmental interest in nuclear power is being paralleled in a number of areas within the marine industry.

3) Nuclear power is a proven marine propulsion technology, both in the military and merchant services. In the case of the merchant ships, following an initial flurry of activity in the 1960s there has been a steady, but low-level, activity continuing up to the present time. Notwithstanding this, approximately one third of the 600 or so nuclear reactors in operation today are serving at sea.

4) There exist today at least two nuclear propelled ships which undertake passenger cruising duties during the summer and ice breaking functions in the winter. The newest of these ships was commissioned in 2007 and there is an ongoing build programme .

5) To date, most marine experience has been derived from PWR systems.

6) There are a number of public perception issues which will need to be addressed. While dealing with these issues will not be easy, it is believed that they will not be insurmountable.

7) Port and flag state responses will be significant in the future development of nuclear propulsion. However, it is apparent that some countries, and by implication port states, are prepared to admit nuclear propeller ships into their ports.

8) There are, however, specific issues with nuclear propulsion which need to be addressed. Nevertheless, models for this exist. Specific issues include:

    a. training and culture of ships' crews and shore based staff
    b. recovery of irradiated fuel and decommissioning
    c. spares and maintenance.

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