The Nuclear Propulsion of Merchant Ships: Aspects of Engineering, Science and Technology

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Abstract

This is the second in a trilogy of papers addressing the findings of Lloyd’s Register’s studies on the nuclear propulsion of merchant ships: the first being presented at Lloyd’s Register’s Technology Days 2010. This paper first considers the underlying physics of nuclear propulsion and then explores the application of that science to the propulsion of merchant ships. In achieving this aim the paper examines the options for the exploitation of nuclear technology and considers some of the engineering implications of deploying the technology.

Introduction

In many parts of the world today consideration is being given to a renaissance of nuclear propulsion. Set against that background some 600 or so nuclear reactors are operating in the world today and of those approximately one third are serving at sea. Moreover, since the first application of the technology, under the guidance of Admiral Rickover in the United States of America, some 700 marine nuclear reactors have operated at sea. Most of these reactors have been of the pressurised water type and, consequently, the majority of the maritime experience has been accumulated with these types of reactor.

In the first paper of this trilogy various aspects of the associated risks and regulatory requirements of adopting nuclear propulsion within merchant ship operation were explored. In this second paper the underlying science of nuclear propulsion is first considered in outline terms, sufficient for the understanding of the application of the technology to merchant ships. Given that a fission technique will be deployed in the first applications, since the greatest marine experience resides with pressurised water reactor applications of that technology, the paper then considers the technical measures necessary for the successful introduction of nuclear propulsion should the industry or some parts of it decide to move in that direction. Notwithstanding this historically driven concept, consideration is given to the developing technologies that may provide additional alternatives for future

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applications of nuclear propulsion. Throughout the discussion the marine engineering and naval architectural implications of employing nuclear propulsion are introduced.

THE UNDERLYING PHYSICS

In its macro scale the atom comprises a nucleus with a number of electrons, having negative charges, orbiting the nucleus in their various shells. Indeed, sometimes an atom is compared to a mini-solar system in order to convey its structure. While such a visualisation has some merit, the analogy has to be treated with caution since in relative terms the atom is some 100 times emptier than the solar system. The space between the nucleus and the electrons orbiting it comprises extremely strong electric and magnetic force fields and within the atomic nucleus the forces are considerably stronger. Indeed, it is the force fields external to the nucleus that give solidity to the matter. In dimensional terms an atom might be of the order of $10^{-10}$ m in size while the nucleus could be expected to have dimensions of about $10^{-14}$ to $10^{-15}$ m.

The nucleus of an atom has as its principal components neutrons, neutrally charged, and protons which are positively charged. Within the atomic structure of a pure element the electrical charge of the electrons and protons can be expected to balance such that the element has a zero net charge. The number of protons in the nucleus defines the element and, for zero net charge, clearly also defines the number of electrons orbiting the nucleus. However, recognising that like charges repel when placed at finite distances apart, it is only the Strong Force when the charges are at very close proximity that overcomes the electrical repulsion and, thereby, maintains the equilibrium of the nucleus. Notwithstanding this, there is a limit to the number of protons that can be accommodated in the nucleus in close proximity. This defines why there is a heaviest naturally occurring element, uranium, which comprises 92 protons within the nucleus. If further protons were accommodated then the nucleus would not survive because the electrical disruptions become too significant. As such, beyond uranium there are unstable elements, such as plutonium, which are highly radioactive.

If the neutron and proton are magnified further it will be seen that they also comprise a complex internal structure. This structure is made up of smaller particles, termed quarks, which are the fundamental particles of matter as they are currently known today: Figure 1.
The nuclear isotope of an element has a reconfigured nucleus, while essentially retaining the basic characteristics of the parent element. This reconfiguration takes the form of retaining the same number of protons as the original element but with a different number of neutrons.

Nuclear fission is induced when a free thermal neutron is absorbed in a large atom such as $^{235}$U, $^{239}$Pu or $^{233}$U. Absorption of this type can set up vibrations within the nucleus which cause it to become distended to the point where it splits apart under mutual electrostatic repulsion of the parts. If this happens the atom splits into fragments and energy is released. In the case of $^{235}$U if a free neutron is absorbed into an atom, the $^{235}$U is converted into $^{236}$U which is highly unstable because of the neutron to proton ratio. Fissionable nuclei break up in a number of different ways:

Indeed the $^{235}$U nucleus may break up in some 40 or so different ways when it absorbs a thermal neutron. Typically, this might be to split into two fragments, $^{140}$Xe and $^{94}$Sr as well as emitting two neutrons. Alternatively, the split may take the form of $^{147}$La and $^{87}$Br fragments plus two neutrons. The energy spectrum of neutrons from the fission $^{235}$U ranges from a few keV to upwards of 10MeV within which the average is around 2MeV. All of the fission fragments are initially radioactive and the majority then undergo a decay process to stable daughter elements. For example, the $^{140}$Xe and $^{94}$Sr fragments are unstable when formed and, therefore, undergo beta decay. During this decay process the fragments emit an electron each after which they both become stable.

The key elements of the reactor are the fuel, the control rods and the moderator. Nuclear fission defines the chain reaction within the fuel which in a simplified form may be described as following the splitting of the $^{235}$U into two fragments and the emission of neutrons, the average being 2.5 per fission event, which are then absorbed into two new $^{235}$U atoms. As such, it can be seen that under these conditions the process starts again and continues until some intervention into this sequence of reactions is undertaken.

This intervention is in the form of control rods, Figure 2, which are manufactured from materials which have large thermal neutron-absorption cross sections and are used in the context of controllable poisons to adjust the level of reactivity. Commonly used materials are cadmium and boron. Control rods have three principal purposes:
To achieve intended changes in the reactor operating conditions including shut-down and start-up;

To adjust the reactor for changes in its operating conditions such as changes in the fissile and poison content of the fuel;

To execute an emergency shut-down if required.

The control rods adjust the multiplication of neutrons and this is done by the insertion of rods into the fuel bundle. By varying the positions of the rods, with respect to the fuel, the effective neutron multiplication factor can be made to vary over the required range. Moreover, in order to shut the reactor down the control rods need to be inserted to an extent where they absorb the additional neutrons generated in the fission process. When this is done the system loses neutrons faster than they are formed by fission and the effective multiplication factor reduces below unity and the chain reaction dies out. The effective multiplication factor $k_{\text{eff}}$ is defined as:

$$k_{\text{eff}} = \frac{N_{i+1}}{N_i}$$

where $N_i$ is the number of neutrons in the system and $N_{i+1}$ is the number of the next generation thermal neutrons after a fission event.

Neutrons are classified according to their energies and at the low end of the spectrum are the thermal neutrons which are in approximate thermal equilibrium with their surroundings. As such, their energies are distributed in accordance with the Maxwell-Boltzmann relationship. Because neutrons are uncharged they can travel considerable distances in matter without interacting; moreover, their interaction potential with electrons is negligible. In order to maximise the probability of the capture of a neutron by a nucleus it is necessary to slow the neutron down to thermal energies where it will move around randomly by the
process of elastic scattering until it is absorbed by a nucleus. This slowing down process is termed neutron moderation and in the reactor, therefore, a moderator through which the neutrons pass is required. The most effective moderators are those with a relatively low atomic mass number which precludes uranium from being its own moderator. Instead, water (H\(_2\)O), deuterium in heavy water (D\(_2\)O) or carbon in graphite (C) are the normally the preferred media for use as moderators. A good moderator, therefore, is a material which reduces the speed of fast neutrons in a small number of collisions and will not absorb neutrons to any great extent.

The energy released from the fusion of \(^{235}\text{U}\) comprises a number of components and these energies derive from:

- The kinetic energy of the charged fragments of fission;
- The fission neutrons;
- Fission gamma rays;
- Subsequent beta and gamma decay;
- Neutrinos.

The sum of these energies is about 195 MeV of which the kinetic energy of the charged fission fragments is by far the greatest, around 83%.

It is important to distinguish between the fission and fusion processes. Although both create usable energy as a by-product of their reactions, it is the former process which is of primary interest for marine propulsion purposes. The fusion process is where multiple atoms combine and during the process release or absorb energy. Typical of such a process is when Deuterium and Tritium combine and during the process they produce helium, a neutron and energy which is contained in the neutron. The corresponding fusion equation is:

\[
\text{D} + \text{T} \rightarrow \text{^{5He}} \rightarrow \text{^{4He} + n}
\]

Unlike fission, nuclear fusion cannot create a chain reaction.

**FUELS**

The nuclear fuel cycle, Figure 3, commences with the mining of uranium and then passes through conversion and enrichment processes to the fuel fabrication and then to its use in the reactor. From there the cycle continues to storage of the used fuel and then to either reprocessing or disposal. Indeed, the reprocessing option for nuclear energy permits the nuclear fuel cycle to be a true cycle.

Following the mining process, which typically might be open cast, underground or in-situ leaching, the ore containing the uranium is then milled to produce uranium oxide concentrate. The uranium concentrate is not able to be used directly in most nuclear reactors: indeed, less than 1% of natural uranium is fissile. Consequently, the fissile uranium isotope needs to be increased by the process of enrichment.
Within the enrichment process the uranium oxide concentrate is first refined to uranium dioxide and then converted into uranium hexafluoride which is a gas at relatively low temperatures. The enrichment process then separates the uranium hexafluoride into two streams: one being enriched to the appropriate level and known as low-enriched uranium while the other is progressively depleted in $^{235}\text{U}$. Following the enrichment process the reactor fuel is then made. This is generally in the form of ceramic pellets which are formed from pressed uranium oxide which has been sintered at temperatures above 1400 deg.C. The pellets are then enclosed in metal tubes to form the fuel rods which are configured into an assembly for insertion into the reactor. The dimensions of the fuel pellets and fuel rod assembly are subject to rigorous quality control to yield a consistent fuel characteristic.

Once inside the reactor the nuclei of the $^{235}\text{U}$ atoms are split in the fission process, thereby, releasing energy. During this process the $^{238}\text{U}$ does not contribute directly to the fission process but does so indirectly by the formation, as a by-product, of fissile isotopes of plutonium in the reactor core.

During the operation of the reactor the concentration of fission fragments and heavy metals increase to a level where the fuel has to be replaced. When the fuel is removed from the reactor it emits radiation from the fission fragments and heat. Following this the fuel may, in the case of land based installations, be held in ponds for several months or years prior to reprocessing or disposal. During reprocessing uranium or plutonium is recovered and returned to either the conversion or fuel fabrication stages of the cycle respectively. In some instances used fuel may also be retained in central storage facilities.

**Uranium (U)**

Uranium is the basic fuel for a nuclear reactor. It is a slightly radioactive metal which occurs relatively widely throughout the earth’s crust in many rocks and even in seawater: typically it is about as common as tin. In terms of concentration, it occurs in concentrations of around 4 ppm in granite which comprises about 60% of the Earth’s crust. Australia has about 25% of the world’s total but Canada is at...
present the leading producer. Other countries with known significant reserves are
the United States of America, South Africa, Namibia, Brazil, Kazakhstan and
probably China.

Uranium is the heaviest of all of the naturally occurring elements. It has a specific
gravity of 18.7 and has a number of differing isotopes. Natural uranium is found
within the Earth’s crust as a mixture of three isotopes: $^{238}\text{U}$, $^{235}\text{U}$ and $^{234}\text{U}$
accounting respectively for 99.275%, 0.720% and 0.005%. Of these isotopes
uranium $^{235}\text{U}$ is particularly important because under certain conditions it can
readily be split, releasing significant amounts of energy in the process. Indeed, it
is the only naturally occurring material that can sustain a fission chain reaction.

**Plutonium (Pu)**

Plutonium in former times occurred naturally in the Earth’s crust but only trace
quantities are found today. By contrast several tonnes of plutonium may be found
in the Earth’s biosphere which is due to the atmospheric testing of nuclear
weapons in the 1950s and 1960s.

While the uranium $^{235}\text{U}$ atom is fissile, the $^{238}\text{U}$ atom has the useful property that it
can capture one of the neutrons which are scattering around in the reactor core and
therefore, indirectly, becomes plutonium $^{239}\text{Pu}$. This element, which is similar to
$^{239}\text{U}$, fissions when hit by a slow neutron and in the process yields a significant
amount of energy. Indeed, because the major component of uranium in the reactor
core is $^{235}\text{U}$ these reactions occur frequently and some one third of the energy
derives from burning $^{239}\text{Pu}$. Typically, the reactor grade plutonium that is
recovered from reprocessing used power reactor fuel has about one third non-
fissile isotopes in it: these mainly comprise $^{240}\text{Pu}$.

In keeping with all other heavy elements, plutonium has a number of isotopes
which differ from each other by the number of neutrons in the nucleus. All 15 of
these isotopes are unstable and, therefore, are radioactive. Consequently, when
they decay they emit particles and some gamma radiation. All of these isotopes
are fissionable with fast neutrons but only two are fissile with slow neutrons. Of
these two, only $^{239}\text{Pu}$, which is the most common formed in a nuclear reactor, has a
major role in conventional light water power reactors.

In essence there are two kinds of plutonium: reactor grade and weapons grade.
The difference being that reactor grade plutonium is a by-product from a nuclear
reactor fuel having been irradiated for around three or more years while weapons
grade is irradiated for between two to three months in plutonium production
reactor. While the two kinds of plutonium differ in their isotopic composition,
both need to be considered in terms of a proliferation risk and managed
accordingly.

International arrangements which are applied to safeguard uranium trading are
extended to the plutonium arising from it which demands constant audits of even
reactor grade plutonium. This, therefore, addresses some of the uncertainty as to
the explosive potential of reactor grade plutonium and its weapons proliferation
potential.
Thorium (Th)

Thorium is a naturally occurring and slightly radioactive metal which is found in small concentrations in most rocks and soils: indeed, soil commonly contains on average 6ppm of thorium. It is about three times more abundant than uranium.

Thorium can be used as a nuclear fuel and while not fissile in itself, $^{232}$Th will absorb slow neutrons to produce $^{233}$U. The process by which uranium $^{233}$U is produced is that the neutron absorption of $^{232}$Th produces $^{233}$Th which has a half life of around 22 minutes. This then undergoes beta decay to form protactinium, $^{233}$Pa, which has a half life of 27 days, and most of which forms $^{233}$U by further beta decay. Some 11% of the $^{233}$U is then converted by further neutron absorption to $^{235}$U which is the fissile isotope of uranium.

A thorium based fuel cycle despite having a number of attractive features has also had a number of problems associated with it. To overcome these problems significantly more development work is required before it can become commercialised. Indeed, the abundance of uranium seems also to work against significant resources being devoted in this area of technology. Nevertheless, the thorium fuel cycle, with its potential for breeding fuel without the need for fast neutron reactors, holds potential for the long term.

MOX Fuel

While the used fuel in a nuclear reactor will mostly comprise $^{238}$U it will also contain about 1% of $^{235}$U in a slightly higher concentration than would occur naturally, a further 1% of plutonium and around 3% of highly radioactive fission products together with some transuranic elements formed in the reactor. The reprocessing function permits the recycling of the uranium into a fresh fuel and, thereby, produces significantly less waste material. The plutonium can be made into a mixed oxide fuel (MOX), which is UO$_2$+PuO$_2$ and constitutes about 2% of the new nuclear fuel used today. This fuel is widely used in Europe in concentrations of about one third of the core but some reactors will accept up to 50%. The use of concentrations up to this level will not change the operating characteristics of the reactor although some adaptation is necessary. One advantage of using MOX fuel is that the fissile concentration can easily be increased by adding more plutonium whereas the enrichment of uranium is relatively more expensive. Indeed, MOX fuel comprising around 7% plutonium when mixed with depleted uranium is broadly equivalent to uranium oxide fuel enriched to about 4.5% of $^{235}$U. Furthermore, the separation of plutonium in reprocessing for recycling as MOX becomes more attractive as uranium prices rise.

PBMR Fuel

Fuel for the Pebble Bed Modular Reactor (PBMR), being developed in South Africa, is based on a German fuel design comprising low enriched uranium triple coated isotropic (LEU-TRISO) particles contained in a moulded graphite sphere. The uranium in the pebble bed modular reactor fuel is enriched to about 10% in $^{235}$U so as to sustain a chain reaction. Each fuel pebble contains about 9g of uranium inside a pebble weighing 210g.
MARINE NUCLEAR PROPULSION PLANTS

Since USN Nautilus, the first US nuclear powered submarine, the majority of marine based reactors have been of the pressurised water type (PWR). The general arrangement of most of these power plants have been similar in that the heat derived from the water cooled reactor in its primary circuit is transferred, through a heat exchanger, to produce steam which drives a turbine within the secondary circuit. Consequently, this system represents a well proven technology within the naval environment. Figure 4 shows in diagrammatic form the general layout of a pressurised water propulsion system.

**FIG.4 - OUTLINE DIAGRAM OF A PWR MARINE PROPULSION PLANT**

Naval technology, as represented by the Russian, United Kingdom and United States of America practices, has largely centred on the use of highly enriched uranium fuelled reactors. Such a practice permits long intervals between refuelling of the reactor, if indeed this is needed within the design life of the vehicle. Nevertheless, when considering an extension to the merchant environment the use of highly enriched uranium introduces an enhanced threat in easing the path of terrorist procurement. Consequently, a low-enriched uranium fuel becomes a more attractive option from this perspective.

In view of the considerable experience that has been built up with marine pressurised water reactors fuelled by uranium, it is considered that for contemporary merchant marine purposes the first reactors are likely to be uranium based and, perhaps, together with its processes MOX form. However, with low-enriched fuels, in order to promote reactor core longevity, the fuel should contain approximately the same amount of $^{235}$U but with the addition of enough $^{238}$U to dilute the $^{235}$U. This has the effect, if the longevity constraint were preserved, of increasing the core volume and, as such, the weight and size of the pressure vessel; the size of the reactor compartment and ultimately the displacement and operating costs of the ship. While such considerations of size are significant for submarines, this may not necessarily be so acute in the case of large merchant ships.

For operational purposes a reactor needs to be constructed in such a way that it is appreciably greater than its critical size. This is because by having a
A multiplication factor greater than unity provides the only feasible means of increasing the number of neutrons, and hence the fission rate, to a level where the required power level can be obtained. As such, when the multiplication factor is exactly equal to, or slightly greater than unity a chain reaction is possible. Consequently, once the required power level is reached in the reactor then the effective multiplication factor must be reduced to unity where the reactor will then remain in a steady state. In this state the neutrons produced just balances the rate of leakage and capture.

A number of nuclear based propulsion alternatives present themselves for consideration in the context of merchant ship propulsion. These are, in addition to the pressurised water reactors; high temperature reactors with a closed cycle helium gas turbine; or a high temperature reactor with an open cycle gas turbine. Other options include boiling water reactors and, in time, nuclear batteries.

The closed cycle helium gas turbine system is not dissimilar in principle to the PWR system except that helium is used as the working fluid and, like the PWR system, gives rise to no external emissions. This system, however, was studied in the NEREUS project and was found to be too expensive and complicated to pursue further. In contrast, the open cycle system uses a standard open cycle gas turbine which drives the propulsor or electric motor together with any auxiliaries. The air from the compressor is passed through a recuperator and an intermediate heat exchanger before entering the turbines. In these systems the heat exchanger potentially receives its thermal energy from a pebble bed or other form of high temperature reactor using a helium primary circuit. In this way the turbines are driven by heated air and the only emissions to the atmosphere are warm air. Notwithstanding the potential attractiveness of this arrangement the pebble bed reactor is still under development and high temperature reactor experience is limited in marine applications.

GENERAL ENGINEERING CONSIDERATIONS

Reliability and Experience

Experience with naval reactors of the pressurised water reactor type has shown that the reliability of these systems is high provided that proper attention has been paid to the engineering and control systems. Indeed, reliability of the power plant, including the refuelling operations, is generally considered to be in excess of 95% when based on naval experience. This premise is also born out by the experience gained in the early days of merchant nuclear propulsion from the Savannah and Otto-Hahn.

Most of the experience to date in the maritime arena has been with PWR reactor systems and, consequently, there is a significant body of information available upon which to draw for merchant ship applications. Notwithstanding that the technology for high temperature gas turbine systems can trace its lineage back to the UKAEA site at Winfrith in the United Kingdom; however there is little, if any, experience with these systems in maritime applications. Moreover, gas based systems using helium and sodium, while not precluded, will need additional consideration since they are in the vicinity of sea water.
**Location in Ship**

The location of the reactor, at a high level of consideration, becomes a compromise between the safety of the crew and passengers and the preservation of the integrity of the reactor pressure vessel and its containment structure. In the case of the crew and passengers it might be argued that a location remote from the accommodation areas might be the most satisfactory. However, in a ship such areas, typically at the bow and stern of the ship, are frequently subject to the greatest levels of motion in a seaway. Moreover, they probably have the highest risk of damage in a collision or other accidental damage. Notwithstanding that modern reactor design of the second and third generation have improved reliability, if a reactor unit is subjected to significant ship motions or impact loadings this may increase the probability of a malfunction or damage. For example, weak or damaged fuel elements may become opened up; control rod drives may be more likely to develop faults or leaks could be induced in pumps, pipelines and valves. Furthermore, control system instrumentation, sensitive to neutron fluxes, temperature, flow rates, and radiation may suffer deviations in calibration. As such, faults and control system deviations of this type may enhance the probability of an accident to the reactor system and consequently the risk of these happening should be minimised. Therefore, the ideal location for a reactor plant in a surface ship should be at a location where the ship motions are minimised: typically in the region of the centres of longitudinal floatation and gravity of the ship. Indeed, from studies made of the general arrangements of the early nuclear propeller merchant ships such considerations may have influenced the location of their reactor compartments.

Such a central location in the ship should not impose too much of a penalty on the naval architectural considerations of the continuity of ship strength along the hull. This would apply to tankers, bulk carriers, container ships and cruise ships. Indeed, in the case of large tankers the distribution of longitudinal bulkheads would significantly aid the protection of the reactor plant.

With regard to the location of the nuclear reactor in the ship it is best if the plant is placed low down in the ship. This certainly would need to be the case if the ship were propelled by a purely mechanical system comprising a reactor steam raising plant driving a steam turbine coupled by a double reduction gearbox to a propeller. However, due to the weight of a PWR reactor plant together with its shielding then this is likely also to be the case even if a turbo-electric propulsion system were selected. Moreover, with the PWR designs additional secondary shielding can be gained from a lower location in the ship because of the presence of the normal ballast, water and sewerage tank arrangements since advantage can then be taken of the ability of water to absorb radiation. Indeed, cargo holds also have some potential in this respect.

In terms of weight, this is likely to be for a nuclear-gas turbine system around 15kgf/kWe while for the more conventional PWR-steam turbine propulsion system this may rise to about 54kgf/kWe \(^2\).

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Reactor Protection

The deployment of crumple zones or related structural features within the ship structure ahead and astern of the reactor compartment is desirable to protect the reactor pressure vessel in the event of a collision. The importance of such considerations in a merchant ship is witnessed by the damaged encountered by the USS San Francisco following a collision with an underwater obstruction while travelling at 30 knots as seen in Figure 5. Indeed, such considerations are reflected in Lloyd’s Register’s former Provisional Rules \(^3\), where it is seen that accelerations of 3g were specified in order to withstand shock loading.

In this context and in terms of ship-ship collisions, allowance has to be made for hull penetration and the former Provisional Rules considered that the reactor containment shell should be at a distance B/5 from the side shell of the ship. Since that time piracy has featured, although in reality it has always been a risk, and weapons have become more penetrating and powerful. However, if a missile, depending on the type, penetrates the hull it is likely to expend a considerable amount of its energy and may therefore not be able to penetrate the containment shell of the reactor: indeed, experience with tank warfare penetrations tend to bear this premise out. Moreover, reactor containment structures are particularly robust. The distance between the side shell and the reactor containment might be increased, perhaps to B/4, however, the B/5 dimension has a long standing history in IMO Rules. A better solution might be found in strengthening to resist attack. Such constraints would be consistent with the sizes of modern PWRs and ship breadth, however, this aspect needs further careful exploration.

![FIG.5 - USS SAN FRANCISCO FOLLOWING A COLLISION AT 30 KNOTS](image)

Modern land based power stations have a requirement for the reactor pressure vessel to withstand direct impact from an aircraft and such incidents need to be carefully considered in the ship context. However, there is one significant

\(^3\) Rules and Regulations for the Construction and Classification of Steel Ships. Lloyd’s Register, London. 1996 through 1976.
difference between the two situations in that land based structures have nominally rigid foundations while ships operate in a medium which cannot withstand shear.

**Pressure Vessel and Primary Plant Design**

When considering nuclear propelled options for merchant ships the integrity of the propulsion system, particularly with regard to the primary circuit and containment systems, has to be of a high order. In this context the ASME III nuclear pressure vessel standard contains a significant body of information which will most likely have been used by the manufacturers for plant design purposes and would also be available for design appraisal. The ASME Code, or similar standards, dictates that the components forming this part of the propulsion plant as well as the other associated systems need considerable quality control associated with their manufacture and installation. Such considerations, furthermore, dictate that strict control over the supply of replacement components is observed and pirate parts cannot be tolerated within the nuclear part of the propulsion system. This, in turn, suggests that some benefit might accrue if manufacturers of the plant provided a through-life maintenance service to the shipowner after the manner of the naval model. Alternatively, this model might well be extended to the aviation model applied to civil aircraft engines.

**Effect of Irradiation on Ship Structural Steel**

Neutrons can degrade materials since the bombardment of materials with neutrons creates collision cascades that can produce point defects and dislocations in the materials. This can lead to embrittlement of metals and other materials as well as swelling of some of them. This poses a problem for nuclear reactor vessels and significantly limits their lifetime. However, their life can be somewhat prolonged by controlled annealing of the vessel which reducing the number of the built-up dislocations.

In general, irradiating steel increases both its yield stress and tensile strength, Figure 6, while decreasing its rate of work hardening.

![FIG.6 - THE EFFECT OF IRRADIATION ON MATERIAL PROPERTIES](image_url)
Similarly, with the material fracture toughness which increases the risk of intergranular brittle fracture. The ductile to brittle transition will shift to higher temperatures and decrease the upper shelf toughness.

![Graph of impact energy versus temperature curves for ASTM 203 Grade D steel](image)

A. Unirradiated  
B. Irradiated to a fluence of 3.5 x 10^{19} n.cm^{-2}  
C. Irradiated to a fluence of 5 x 10^{18} n.cm^{-2}  
D. Annealed at 300 °C for 15 days after irradiation to a fluence of 3.5 x 10^{19} n.cm^{-2}

**FIG.7 - IMPACT ENERGY VERSUS TEMPERATURE CURVES FOR ASTM 203 GRADE D STEEL**

Considering the implications of Figure 7, structural steel materials in danger of irradiation should be made from the higher toughness grades to allow for degradation of properties during the lifetime of the vessel.

**Reactor Control**

The fission multiplication factor $k$, introduced earlier, may be considered as the fundamental defining parameter of a nuclear fuel and its neutron moderator for a self-sustaining fission reaction. The reaction is a self-sustaining fuel system when $k = 1$ and is termed critical. However, to sustain a reaction beyond its initial state, due to losses, the value of $k$ must be greater than 1. To achieve this state where $k > 1$, termed an excess $k$, the fission multiplication factor is derived from two other $k$ values: one termed $k_e$ which assumes that the fission multiplying region is of infinite size and the other $k_{eff}$ which takes account of the leakage of neutrons from the multiplying region.

With regard to $k_e$, this can be expressed in terms of the thermal utilisation factor $f$ and the resonance escape probability $p$ as follows:

$$ k_e = \eta \varepsilon f p $$

In this expression the thermal utilisation factor defines the fractional absorption of the $\eta$ neutrons in the fuel when the losses in the moderator and reactor core have been taken into account. The resonance escape probability ($p$) accounts for the resonance peaks in the $^{235}$U portion of the fuel when the neutrons are slowing
down from fission to thermal energies. These resonance peaks capture the neutrons and, therefore, prevent them from fissioning with the \(^{235}\text{U}\) fuel component. Additionally, in the above equation \(\varepsilon\) is the fast fission factor and \(\eta\) is a preliminary index of fuel efficiency based on the level of its enrichment. Typically the functional relationship of the \(\eta\) and \(\varepsilon\) characteristics with the fuel to moderator ratio of the reactor is outlined in Figure 8.

\[K_{\text{eff}} = k_{\infty} \Phi_f \Phi_t\]

where, from the Fermi-Age theory for an unreflected reactor, \(\Phi_f = e^{-T B^2}\) in which \(T\) is the Fermi age of the neutrons, which is a measure of the distance that the neutrons travel from fission energy to thermal energy, and \(B^2\) is a buckling factor dependent on the reactor geometry. As a second approximation diffusion theory suggests that \(\Phi_t\) for a bare reactor is given by \(\Phi_t = 1/(1 + B^2 L^2)\). In this relationship the term \(L^2\) is the composite thermal diffusion length of neutrons in the moderating, fuel and poison regions. Combining these relationships it is seen that

\[K_{\text{eff}} = k_{\infty}(e^{-T B^2})(1 + B^2 L^2)..........................(1)\]

and this must equal unity for criticality. The effect of the leakage terms is to reduce \(k_{\infty}\), consequently if \(k_{\infty}\) is not greater than unity then criticality is unlikely to be attained. Considering the terms in the above equation, \(k_{\infty}\) is a property of the fuel; \(T\) and \(L^2\) are properties of the moderator and \(B^2\) is a property of the core geometry.

In terms of reactor control the temperature coefficient is the most important parameter because it governs the direction and magnitude of changes in the fission multiplication of the core for changes in temperature. As such, the temperature

\[\text{FIG.8 - COMPETITIVE FUEL FRACTIONS}\]
A coefficient characterises the behaviour of $k_{eff}$: if positive then $k_{eff}$ will increase with temperature and if negative $k_{eff}$ will decrease and the reactor will shut itself down. The temperature coefficient is defined as the fractional rate of change of $k_{eff}$ with incremental changes in temperature; that is $1/k_{eff}(dk_{eff}/dT)$. If this expression is applied to equation (1) an expression for the temperature coefficient can be derived.

Ship and submarine based reactors, when compared to their land based power generation counterparts, can be considered to be small reactors. As such, due to their time constant the marine reactor responds faster to non-steady power generation conditions and the control system design must be capable of accommodating this aspect of the operating spectrum. Notwithstanding this consideration, the reactor based propulsion system can be perfectly adequately designed to accommodate the manoeuvring requirements for berthing or restricted seaway navigation. Indeed, it is considered normal for a nuclear propelled submarine to navigate and manoeuvre itself close to the berth with only a tug standing by to give assistance in the final stages of the docking process.

With regard to transient modes of operation a blackout when operating at full load is unlikely to be an issue for primary systems of the propulsion plant due to the control philosophies employed and responsiveness of the system. However, this could be a problem for secondary systems in terms of trying to dump the heat load quickly. This aspect needs careful consideration at the design stage of the ship’s propulsion plant. An alternative case is that of an excess steam demand accident. Such a situation will have implications for the primary system, however, a PWR’s protection systems are designed to cope with this eventuality.

The thermal management of the engineering system when the ship is in port may need consideration. Some concern might be expressed that the heat dumped into the harbour by a nuclear propulsion system when the ship is in port may lead to a significant change in the aquaculture in the port: the analogous argument being that of land based power stations. Such a situation is improbable: first, because previous experience with conventional steam powered ships did not show evidence of this happening and, secondly, unlike a land based power station a ship’s energy requirement will be considerably reduced to a largely hotel or cargo handling load when in port and, therefore, a reduction in heat developed from the reactor will be governed by the control system. A further option might be that the ship is able to supply the shore with an environmentally clean source of power. Furthermore, for conventionally powered ships the practice of shut-down in port (cold ironing) is likely to become more widespread, however, irrespective of the shore energy supply option this may not be necessary for nuclear ships as no harmful exhaust emissions will be produced.

An operational issue which relates to the fuel specification for the reactor is the fuel burn-up rate. This parameter defines the energy per unit mass of the fuel and is consequently proportional to the enrichment level required in the fuel and is also clearly related to the time between re-fuelling. Moreover, the energy that is produced from a fuel rod assembly varies with the type of reactor and the reactor operator’s policy.

**Main Propulsion Machinery**

Given that, in the first instance, a conventional PWR reactor would be the most likely option for use in a merchant ship; this suggests that either a propulsion
system involving a steam turbine or, alternatively, a steam or gas to air heat exchanger which provides thermal energy for gas turbo-generator would be the most likely propulsion system. Clearly, in this latter case the air temperature the turbine would need to be sufficiently high in order to maximise the output energy and system efficiency and this may require a high temperature reactor to fully realise this potential. In the case of steam turbine propulsion this could either be used directly to drive the main propulsion system through a locked train, double reduction gearbox together with suitable steam bleed-offs to drive turbo-generator sets or, alternatively, the main steam turbine could be deployed as a turbo-generator set after the manner of a land based power station for an electrically propelled ship. Such an option might be attractive where the hotel or non-propulsion electrical load of the ship is high.

In keeping with marine practice it may be for purely mechanical transmission systems that a simple cycle steam turbine may form the basis of the mechanical system. While more complex steam based cycles, commonly used in land based applications, involving reheat offer the potential for enhanced efficiency, they have not found favour in marine practice due to the need for direct drive marine steam plants having a requirement to go astern. When this happens there is no steam flow through the reheater and means are required to protect the reheater from overheating of the reheater tubes. A similar situation exists during port operation. Notwithstanding this reheated marine boilers have been produced which have separately fired, water cooled reheater furnaces following the main generating bank. If, however, instead of a conventional steam turbine-gear shaft drive chain a turbo-electric propulsion arrangement were deployed then the need for reversing the turbine is nullified since the electrical power control will take care of preparing the power supply for astern running. The deployment of podded propulsors or conventional electric propulsion would equally well satisfy this requirement.

With regard to gearboxes suitable for deployment in a steam turbine driven system these generally are of the double reduction type and with the demise of steam as a favoured mode of propulsion, experience of construction, operation, maintenance, helix correction and alignment of these components is now vested in only a few locations in the world. This may, in the short to medium term, provide a restriction on the availability of servicing and repair capabilities.

**Auxiliary Propulsion Machinery**

Consideration will need to be given to the provision of an auxiliary power source should an emergency situation arise where the main reactor plant had a failure necessitating a shut down.

**Vibration**

The majority of marine experience has been gained with naval vehicles, mostly with submarines. In these applications the levels of shipboard vibration is generally low and this is true of the reactor compartments. As such, naval reactors have operated in a largely benign vibration environment and it is reasonable to anticipate that the reliability of the nuclear plant is to some extent a function of this environment. Given that ships of the merchant service do not always live up to these vibration standards, consequently, for merchant applications of nuclear power it would be prudent to pay attention to the vibration characteristics of the machinery spaces. Indeed, given that the prime movers will be either gas or steam
rotating machinery which produces little in the way of vibration signature, if correctly installed and maintained, there may be a case for resilient mounting of the reactor plant and primary circuit to isolate it from other propeller and seaway induced vibration response. Some experience in this context, however, exists in relation to the deployment of nuclear reactors in aircraft carriers.

**Refuelling**

For a merchant ship, unlike a submarine because of the higher levels of enrichment of the fuel permitted in these boats, refuelling should be contemplated on about a five to seven year cycle depending on the level of fuel enrichment. Based on experience, the refuelling process may take something of the order of 30 days and clearly this down time requires to be factored into the economic model for the ship. Nevertheless, a five year refuelling cycle fits well with current survey requirements.

The design of the ship has to be such as to be able to retrieve the spent fuel from the ship unless the design philosophy is to retain the spent fuel within the reactor compartment in the ship throughout it life. In this latter case the ship will have both active fuel and nuclear waste stored on board which will have an impact on the classification and regulatory regime. The de-fuelling process or the storage of waste fuel presents the area of highest risk. This situation derives from the unstable isotopes and gamma radiation that is present in the irradiated fuel: in contrast fuelling presents little radiation hazard since it can be readily handled. To illustrate this point Figure 9 shows the activity of a selection of radionuclides with respect to time for wastes after removal from a PWR.

![Image of radionuclides activity](FIG.9 - ACTIVITY OF RADIONUCLIDES AS A FUNCTION OF TIME)

Given the radiation risks and thermal emissions from spent fuel a study of the arrangements for the **Savannah** and **Otto Hahn** shows that the reactor compartment was able to be accessed from the main deck level, thereby, giving a direct pathway

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for extraction of spent fuel. Nevertheless, the use of cranes in the de-fuelling process does present a further hazard since this introduces an additional source of accident. An alternative is to use dedicated transverse passageways accessed through side shell doors. Indeed, this would be in keeping with modern naval architectural practice for a number of ship types and consequently constitutes a well understood means of access to ships. Moreover, such an arrangement, given that the conventionally located engine room spaces are predominantly used, would not encroach on the cargo space as significantly as that observed for the Savannah and Otto Hahn. This represents an economic advantage for the ship.

In order to extract the spent fuel a suitable shielding system will need to be provided together with suitably sized water baths for cooling purposes. Alternatively, if the spent fuel is stored on-board then a dedicated storage tank water cooling system will need to be provided together with suitable redundancy. The shore based reception of this type of nuclear waste would need to be done at dedicated establishments sited at strategic locations around the world close to trade routes. In this context it would not be unreasonable to consider the possibility of using existing naval facilities for this purpose. Moreover, if this were the case the cost of refuelling per unit ship should fall for both merchant and naval vessels.

Radiation Hazard Zones

Notwithstanding that the location of the reactor compartment is dictated so as to minimise the effects of the dynamics of the ship, there is a need to identify zones within the ship defining the radiation hazard: analogous to the normal fire zones and watertight compartments. Typically, three such zones might be identified within the ship, these being:

- Zone 1 - Area of limited access. This would be defined by the area enclosed by the reactor containment shell which includes the reactor and the control rods, flux sensing equipment and the primary piping loops and pumps;

- Zone 2 - Areas of intermittent access. These would typically include the purifiers, ion exchangers, waste collection and after-cooling systems and the secondary side of the heat exchangers;

- Zone 3 - This would include all other spaces within the ship.

With respect to these zones, Zones 1 and 2 should only be accessible when the ship is at sea in order to undertake essential maintenance. This implies that access doors will be necessary but subject to necessary warning signs and security systems including the implications of health physics.

APPLICATION TO DIFFERENT SHIP TYPES

Considering the range of small reactors that are either currently offered or under development, there are a broad range of power outputs available. In the case of PWR reactors these range from around 27 MWe to 300 MWe, recognising that the thermal rating of the power plant, particularly with PWR technology, will be some three to four times the electrical power rating.
Lloyd’s register has undertaken a series of economic and technical concept analyses for three ship types: the economic and operational aspects will form the third of this trilogy of papers. The study embraced full form tankers and bulk carriers as well as container and cruise ships. For each ship type two sizes were studied: one having generally large proportions, but within current practice, while the second was either an extrapolation of current practice or at the limit of current endeavour.

**TANKERS AND FULL FORM SHIPS**

In the case of a tanker or bulk carrier the reactor should be sited close to the midship region of the ship so as to minimise the effects of ship motions and vibration on the reactor plant. Moreover, such a position gives protection from collision in the bow region and also from propeller induced vibration in the stern. Such an arrangement would imply that the superstructure could also be located in this region so as not to unnecessarily restrict the cargo volume: indeed such arrangements are not dissimilar to these types of ship in an earlier age. Port loading and discharge constraints may, however, dictate a more contemporary location for the superstructure. The principal concern, however, is the continuity of longitudinal strength of the hull. With regard to the location of the reactor, a tanker hull is particularly well suited by virtue of the central and wing tank arrangements. Indeed, the central tank region would be the obvious location for the reactor since the central longitudinal bulkheads will give a large measure of collision protection with the wing tanks at this station housing other secondary plant machinery.

**300,000 DWT Tanker**

For this size and type of ship the maximum power capacity installed, excluding the emergency generator capability is 29.7 MW. To achieve this power requirement using a nuclear PWR reactor will require a reactor capacity of the order of 120 MWt if a conventional marine steam turbine plant is deployed. Such a capacity is well within the capability of the class of small reactors and could be supplied from a single reactor since the requirement for 29.7 MWe is towards the lower end of the small reactor units currently envisaged. Moreover, single shaft-propeller transmission systems have been shown to work satisfactorily for this type of ship and there is little reason to change this on propulsion grounds provided that the ship speed remains in line with current practice. Consequently, one propulsion option for a VLCC of this type, operating at 16 knots, would be to deploy a 120 MWt capacity PWR reactor, operating on 3.5 to 4.7% $^{235}$U enriched fuel or, alternatively, a combination of uranium and MOX fuel. This would supply steam to a steam turbine, having high and low pressure stages, driving a double reduction gearbox directly coupled to a single screw fixed pitch propeller. Alternatively, a turbo-electric capability might be considered to either obviate the need for reduction gearing or, if a greater degree of redundancy were required, to support a twin screw propulsion train in association with twin rudders. In addition to the single reactor nuclear main propulsion plant, because there is no redundancy, a diesel generator would be required for emergency propulsion power in the event of a main power plant failure. This diesel generator would be required to supply power to a shaft mounted motor in order to permit the ship to navigate at around 6 knots in calm water.
Clearly, a higher level of redundancy could also be achieved by deploying two nuclear steam generation plants of 60MWt each. If this were the case then the need for an auxiliary diesel generator to provide emergency propulsion power would be reduced.

**1,000,000 DWT Ship**

Such a ship was extensively studied at the time of the rapid increase in tanker sizes during the 1970s by Emerson et al.\[^5\] It was concluded at that time that in order to obtain the required levels of efficiency, propeller thrust loading and power density that a triple screw arrangement was likely to be the most beneficial. The prime movers, as was the custom at the time, were steam turbines. The power requirement predictions were for a ship speed of 16 knots with the two wing screws each absorbing 21MW while the centre propeller would have a power absorption of 29 MW. These propulsion powers together with the auxiliary power required would lead to an installed power of the order of 78 MW. This would prescribe a PWR capability of 290 MWt; again operating on 3.5 to 4.7% \(^{235}\)U enriched fuel or a combination of uranium and MOX fuel.

As with the previous smaller VLCC either a direct drive steam plant or a turbo electric propulsion system located in the midship region of the vessel would suffice: the latter being particularly advantageous, as in the former case, if shaft lines through the after cargo tanks are to be avoided. For this ship in order to promote the concept of redundancy a two or three PWR system would be envisaged. Recognising, however, that with increasing numbers of reactors the individual power requirement for each unit moves closer to the lower end of the range of existing small reactors offered and, conversely, the installation costs will increase as will the crewing cost. Assuming that two PWR units would be selected then two 145 MWt/39MWe units would satisfy the requirement.

**CONTAINER SHIPS**

A recent paper \[^6\] has studied the application of nuclear power to a 9200 teu container ship. From this study it was concluded that such a ship is technically feasible using proven and currently available PWR technology which is in service today. Moreover, the authors considered the situation in which the ship speed was considerably increased over that to which contemporary ships are designed. In that concept study the speed was increased to 35 knots to permit three ships to undertake the same level of service as a conventional four ship, 25 knot service on a Trans-Pacific route. To achieve the speeds upon which the study was based, a PWR reactor with a capability of 1000 MWt was selected. In that case, given the assumptions employed, the break-even fuel cost in order to give nuclear propulsion the advantage was estimated to be 89 US$ per barrel.


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**7450 teu Container Ship**

In the context of a modern medium sized container ship, such a ship would require an installed power of 40 MW when operating at a ship speed of 23 knots. To achieve this, the nuclear power requirement would be in the region of 150 MWt which is readily available from small PWR reactor installations, albeit at the lower end of the systems currently offered. For such a ship a central location for the machinery space would be advantageous, as with the full form ships, and would be broadly in keeping with design of these types of ship today. Similarly, it is envisaged that such a ship would be single screw and have a fixed pitch propeller.

Recognising that such a power requirement is relatively modest in comparison to the small units on offer, it is likely that a single PWR plant operating on 3.5 to 4.7% 235U enriched fuel or a combination of uranium and MOX fuel would be the propulsion basis. Given this scenario, an auxiliary diesel generator with the potential to drive a shaft mounted electric motor would be required. The drive train could either be based on direct drive steam turbine through reduction gearing or, alternatively, turbo-electric in which case the auxiliary power source could feed the normal propulsion motor if required.

**12500 teu Ship**

In this case the basic ship design that was considered was the ultra-large container ship propulsion study undertaken by Lloyd’s Register [7]. The parent ship had a design speed of 25 knots and required a total installed power of 77 MW to achieve this speed requirement together with the hotel and cargo load. The ship was propelled by means of a single fixed pitch propeller.

To substitute the slow speed diesel propulsion with a nuclear power plant would require a PWR having a capacity of about 285 MWt: this could be supplied by either a single or twin reactor system. In the latter case redundancy is inherent while in the former an auxiliary diesel generator of sufficient capacity to maintain steerage way and limited propulsion, in the event of a reactor failure, would be required. As with the case of the smaller container ship, the propulsion drive train could be either direct steam turbine through reduction gearing or turbo-electric.

Again, the positioning of the reactor plant is entirely consistent with the general arrangement layout of the vessel as proposed in [8] and such an arrangement also has certain ship structural advantages: particularly in relation to the torsional vibration response of the ship’s hull structure.

**CRUISE SHIPS**

**1500 Passenger Ship**

Such a ship represents a medium sized cruise ship. The subject ship had a propulsion requirement of 2x14.7 MW when operating at 21 knots while the installed power is 52 MW in order to accommodate the variable hotel load. Such a

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requirement could be provided by PWR reactor(s) giving a thermal power in the region of 200 MWt. As with the previous examples either direct drive steam turbine systems with bleed-off supplies of steam for electrical power generation or turbo-electric machinery can be used to satisfy both propulsion and hotel loads. While the former case would satisfy the propulsion solution of conventional shaft driven propulsion, if, however, podded propulsion were used to enhance manoeuvrability then the turbo-electric option would be the system of choice. The fuel would either be 3.5 to 4.7% $^{235}$U enriched uranium or a combination of uranium and MOX fuel.

For cruise ships the new safe return to port requirements may place a requirement for two reactors of 100 MWt capacity each to be installed in the ship so that redundancy can be assured given a one compartment flooding or fire occurs. Alternatively, it may be sufficient to deploy a single reactor having a capacity of 200 MWt and then use a diesel generator, located separately as the auxiliary source of power to maintain the reduced navigational requirements to return the ship safely to port in the event of an emergency. Clearly, the conventional machinery systems would require to be dealt with in the normal segregated way.

**5400 Passenger Ship**

Much the same analysis applies to this larger version of the cruise ship operating at 22 knots. Such a ship would most likely be equipped with three podded propulsors and an installed power of 105 MWe to account for the propulsion and hotel loading. Such a power requirement could be satisfied with PRW reactors having a capacity of 390 MWt. This requirement can easily be accommodated within the range of small reactors in either a single or twin reactor installation.

**General Considerations**

For all of the ship types considered refuelling would need to be undertaken at about five to seven year intervals and would need to be accomplished at a dedicated facility over a period of around 30 days. The removal of spent fuel and the re-fuelling would be undertaken through dedicated, largely transverse passageways, by means of side shell doors.

In the context of fuel usage it is of interest to note that in the case of the 12500 teu container ship when undertaking a voyage of 3500 nm at 25 knots the weight of residual fuel used is of the order of 1540 tonnes together with the production of some 4850 tonnes of CO$_2$. If the ship were powered by uranium a mass of 3.4 kg of $^{235}$U would be consumed, assuming no allowances are made for the plutonium generated from the $^{238}$U in the reactor. Moreover no CO$_2$ emissions would occur.

**CONCLUDING REMARKS**

It is concluded that pressurised water reactor technology has had the greatest application at sea. Furthermore, it has demonstrated a high level of reliability throughout the 55 years or so of operation in maritime service. Clearly, other nuclear technologies are progressing in terms of potential application at sea. Of these high temperature and pebble bed reactors with their potential for application to the expansion of hot air through turbines may be a source of future application. Similarly the application of nuclear batteries may find future application in the marine area.
To accommodate nuclear technology the general arrangement of the ship should alter in order to provide the reactor with the best possible operating environment. Typically in this respect is the positioning of the nuclear reactor and the collision and vibration protection necessary is a prime consideration.

Having considered the applications of pressurised water reactors to a range of merchant ships, it is not foreseen that there are any technological based reasons why a nuclear propelled merchant ship should not be built and satisfactorily operated.

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