The nuclear propulsion of merchant ships: Aspects of engineering, science and technology

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This paper first considers the underlying nuclear physics and then explores the potential application of that science to the propulsion of merchant ships. It then examines the options for the exploitation of nuclear technology and considers some of the engineering implications of deploying the technology. Consideration is then given to the application of nuclear propulsion to a series of ship types, including tankers, container ships and cruise vessels. In each case two sizes of ship are chosen, one of fairly conventional size and the other much larger.

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INTRODUCTION

In many parts of the world today consideration is being given to a renaissance of nuclear propulsion. It is now over half a century 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 34MW at the propellers.

The USS *Long Beach*, a guided missile cruiser, followed in 1961. 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 UK, the Chinese, French and Russian developments of marine nuclear propulsion 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 combined passenger and cargo ship had a power of 21 000shp and was capable of 21 knots. Although she performed well technically, she was never intended to be a commercial proposition as she was built as a technology demonstrator under President Eisenhower's Atoms for Peace Programme. Having achieved her aim she 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 as a nuclear propelled ship. Subsequently, the *Otto Hahn* was converted to diesel propulsion. A third ship, the *Mutsu* was less fortunate and suffered a number of technical and political problems. All three of these pioneering merchant ships used reactors operating on low-enriched uranium fuel having 3.7 to 4.4% enrichment.

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 54MW 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. More recently the NS *50 Let Povbedy* was commissioned in 2007. This icebreaker is an upgrade of the Arktika-class, having a displacement of 25 840t, and is designed to break through ice up to 2.8m thick. The installed power is 75 000shp from two nuclear reactors. The ship doubles as an icebreaker and an arctic passenger cruise ship having 64 cabins.

In 1988, the *Sevmorput*, a fourth nuclear merchant ship, was commissioned in Russia. It is a lash barge carrier and container ship, 260m long and fitted with an ice breaking bow. It 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 32.5MW at the propeller and required refuelling only once up to 2003.

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 260dwt were launched in 1989 for use in estuarial waters.

Looking to the future, a Russian 110MW icebreaker is planned, together with further dual-draught vessels delivering 6 MW at the propellers.

Set against this background some 600 or so nuclear reactors are operating in the world today and of those approximately one third are currently serving at sea. Moreover, since the first application of the technology some 700 marine nuclear reactors have operated at sea. Most of these have been of the pressurised water type and, consequently, the majority of the maritime experience has been accumulated with this type of reactor.

In an earlier paper[1] various aspects of the associated risks and regulatory requirements of adopting nuclear propulsion within merchant ship operation were explored. In this 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, the paper then explores 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. 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 it 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 tendency to 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.

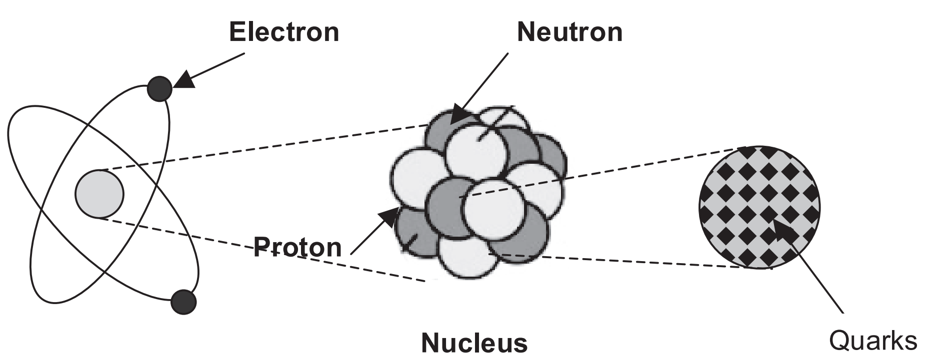

Fig 1: The structure of the nucleus

This structure is made up of smaller particles, termed quarks, which are the fundamental particles of matter as they are currently known today (Fig 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 occurs 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 of ^{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. 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.

The key elements of the reactor are the fuel, the control rods and the moderator. The control rods (Fig 2) facilitate the chain reaction intervention process and are manufactured from materials which have a large thermal neutron-absorption cross section. They are used in the context of controllable poisons to adjust the level of reactivity. Commonly the materials used are cadmium and boron. Control rods have three principal purposes:

1. To achieve intended changes in the reactor operating conditions including shut-down and start-up.
2. To adjust the reactor for changes in its operating conditions such as changes in the fissile and poison content of the fuel.
3. 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

Fig 2: Simulated control rods from a marine pressurised water reactor

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_{eff} is defined as:

$$k_{eff} = N_i + 1/N_i$$

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_2O), deuterium in heavy water (D_2O) or carbon in graphite are 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 fission of ^{235}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, depending upon the condition of the reactor and the time since refuelling, 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:

$$D + T \rightarrow 5He \rightarrow 4He + n$$

Unlike fission, nuclear fusion cannot create a chain reaction.

FUELS

The nuclear fuel cycle is outlined in Appendix 1 by way of background to the discussion. With regard to the possible fuels consideration should be given at this stage to four principal types: uranium, plutonium, thorium and MOX fuel.

Uranium (U)

Uranium is the basic and most widely used 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. In terms of concentration it occurs at around 4 ppm in granite and this comprises approximately 60% of the Earth's crust. Australia has about 25% of the world's total but Canada is the leading producer at present. Other countries with known significant reserves are the USA, 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 18.97 and has a number of isotopes. Natural uranium is found as a mixture of three isotopes: ^{238}U, ^{235}U and ^{234}U accounting respectively for 99.275%, 0.720% and 0.005%. Of these isotopes uranium 235U 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}U atom is fissile, the ^{238}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}Pu. This element, which is similar to ^{235}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 ^{238}U these reactions occur frequently and some one third of the energy derives from burning ^{239}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}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. Moreover, these isotopes are fissionable with fast neutrons but only two are fissile with slow neutrons. Of these two, only ^{239}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 and this 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 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, may hold 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.

MARINE NUCLEAR PLANTS

The general arrangement of a PWR power plant is shown in Fig 3. Given that the purpose of the reactor is to generate steam, the heat derived from the water-cooled reactor in its primary circuit is transferred, through a heat exchanger, to produce steam which drives a broadly conventional power plant. Consequently, this latter part of the propulsion system represents a well proven technology within the marine environment.

Naval technology, as represented by the Russian, UK and USA practices, has largely centred on the use of highly enriched uranium fuelled reactors having a compact design. Such a practice permits long intervals between refuelling of the reactor, if indeed this is needed within the design life of the vehicle. However, when considering an extension of reactor technology to the merchant environment there are limitations on the level of enrichment for civil applications. Therefore, refuelling during the design life of the ship must be a consideration.

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 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 balance the rate of leakage and capture.

A number of nuclear-based propulsion alternatives present themselves for consideration in the context of merchant ship propulsion for the future. 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 potentially include boiling water reactors and, in time, nuclear batteries if these become marinised.

Reactor control

In terms of reactor control the temperature coefficient is the most important parameter because it governs the direction

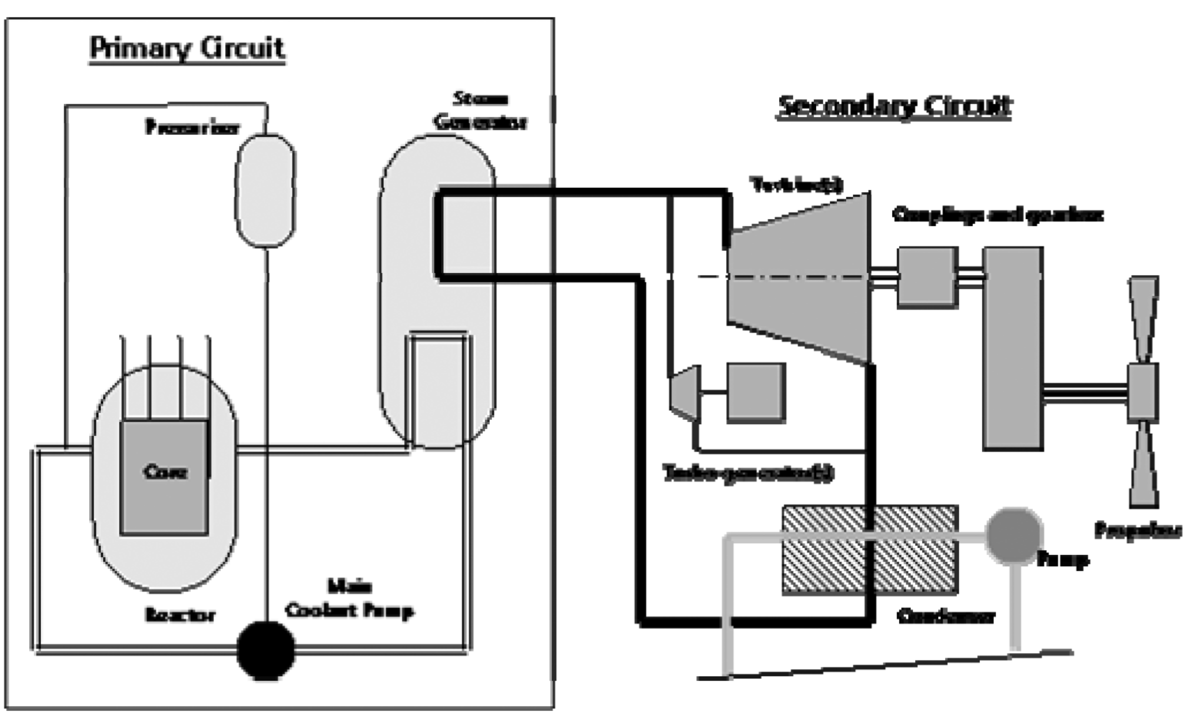

Fig 3: Outline of a PWR marine mechanically-driven propulsion plant

and magnitude of changes in the fission multiplication in the core for changes in temperature. As such, the temperature coefficient characterises the behaviour of the effective fission multiplication factor: if the temperature coefficient is 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 $1/k_{eff}.(dk_{eff}/dT)$.

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, a 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 the general responsiveness of the system. However, this may 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 plant's primary system, however, PWR protection systems are designed to cope with this eventuality.

It should be noted that even when an operational reactor is shut down it will still produce heat energy and, consequently, there is a requirement for continuous cooling to be maintained within the mechanical and control systems. In this and related contexts 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 unlikely: 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, small reactor cooling or cargo handling load when in port.

An alternative option might be that the ship is able to supply the shore with an environmentally clean source of power: the reverse, in some cases, of the situation adopted in some ports today. Indeed, the practice for conventionally powered ships to shut-down in port (cold ironing) is likely to become more wide-spread, 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. It 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.

ENGINEERING CONSIDERATIONS

From an engineering perspective there is little that is problematic to be overcome in developing a nuclear propulsion plant for a merchant ship, given that previous design experience is utilised. The design process will need to be based on a safety case principle involving the integration of the nuclear, mechanical, electrical and naval architectural aspects. Within this process the safety of the nuclear plant must take precedence over the other aspects of the design.

To achieve the correct balance in the design the implications of failure in any of the ship's systems or a sub-component of the nuclear plant has to be carefully evaluated at an early stage in the design process. This is because, while the reactor can have an effect on the ship outside of a defined nuclear plant boundary, so also can the ship influence the performance of the reactor plant. Typical of such a situation might be an excess steam demand from the turbines. As such, to effectively achieve a soundly based design the ship should be broken down into a number of components and these analysed for any interactive influences on the nuclear plant: either directly or through each other. From such an analysis the full implications of each component's design can be appreciated.

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 the technology for high temperature gas turbine systems can trace its lineage back to the UKAEA site at Winfrith in the UK; 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 seawater.

Location in ship

The location of the reactor, at a high level of consideration, is directed towards 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. Although 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 scenarios happening should be minimised. Therefore, the ideal location for a reactor plant in a surface ship should be 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 propelled 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 conventional distribution of longitudinal bulkheads would significantly aid the protection of the reactor plant.

It is also best if the reactor plant is placed low down in the ship. This certainly would need to be the case if the ship were propelled by a mechanical system comprising a reactor steam raising plant driving a steam turbine and 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 a PWR, 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.

With regard to 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]

Reactor protection

Fig 4 shows a collision scenario between two merchant ships. In such cases the protection of the reactor compartment which comprises the radiation barriers, the reactor containment pressure vessel, reactor pressure vessel and primary steam raising plant is essential.

To achieve the required performance of the ship's structure an energy absorption based analysis for the structural design of the ship would be required such that the energy dissipation of

Fig4: Ship collision scenario

the impact can be accommodated though an elasto-plastic collapse of the structure. As such, this is analogous to the crumple zones deployed in automotive and other designs. Indeed, such considerations are reflected, in part, but in a more elementary way, consistent with the technology of the time, in Lloyd's Register's former Provisional Rules.[3] Extending these ideas further, these structural energy absorption considerations would also need to be applied to the defence against terrorist action in terms of missile or other impact attack.

The structural design of the reactor compartment requires special attention such that its integrity is not compromised by the ship seaway dynamics, slamming, whipping and vibration. Consequently, the continuity of strain flux and its relaxation through consecutive structural arrangements is of considerable importance from a fatigue and brittle fracture perspective.

Modern land-based power stations have a requirement for the reactor pressure vessel to withstand direct impact from an aircraft and analogous incidents need to be carefully considered in the ship context. However, there is a significant difference between the two situations in that land-based structures have foundations built into the ground while ships operate in a medium which cannot withstand shear. Clearly, in this latter situation the intact and damage stability characteristics of the ship are important.

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 order to meet the requirements of the safety cases. 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 a similar standard, dictates that the components forming this part of the propulsion plant as well as the other associated systems need rigorous 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, therefore, 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 be extended to the aviation model applied to civil aircraft engines in which the shipowner would lease from the manufacturer the nuclear plant. Such an arrangement might have further benefits in easing the burden of the discharge of the owner's responsibilities as duty holder for the nuclear propelled ship.

Effect of irradiation on ship structural steel

The bombardment of materials with neutrons creates collision cascades that can produce point defects and dislocations in the materials. These can then degrade the materials and lead to embrittlement of metals and other materials as well as the 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 reduces the number of the built-up dislocations.

In general, irradiating steel increases both its yield stress and tensile strength (Fig 5) while decreasing its rate of work hardening; 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. From Fig 6 it is indicated that at greater levels of irradiation the ductile to brittle transition region moves to higher temperatures. Furthermore, if annealing occurs then the transition region can be returned towards the unirradiated state of the material. Considering the implications of Fig 6; structural steel

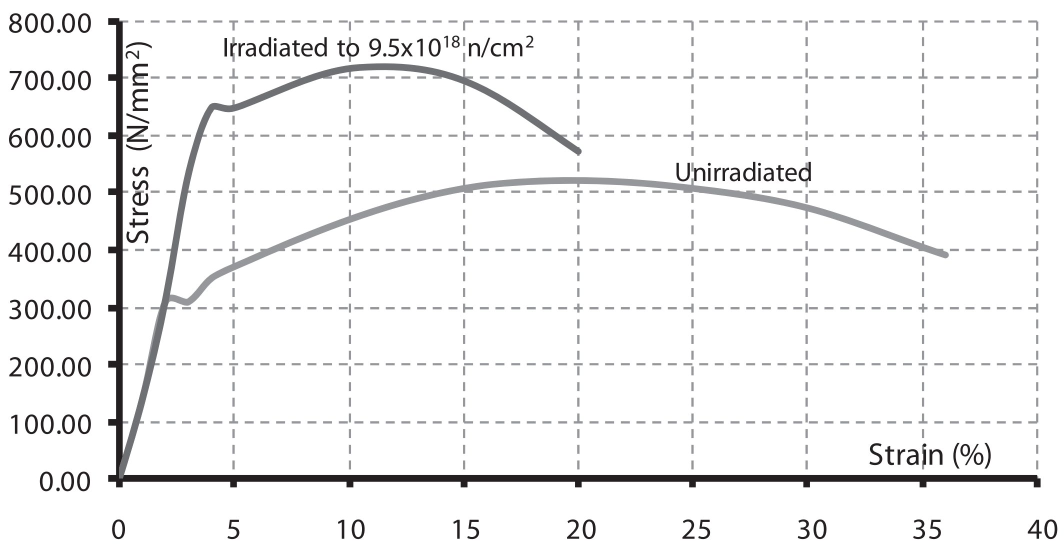

Fig 5: The effect of irradiation on material properties

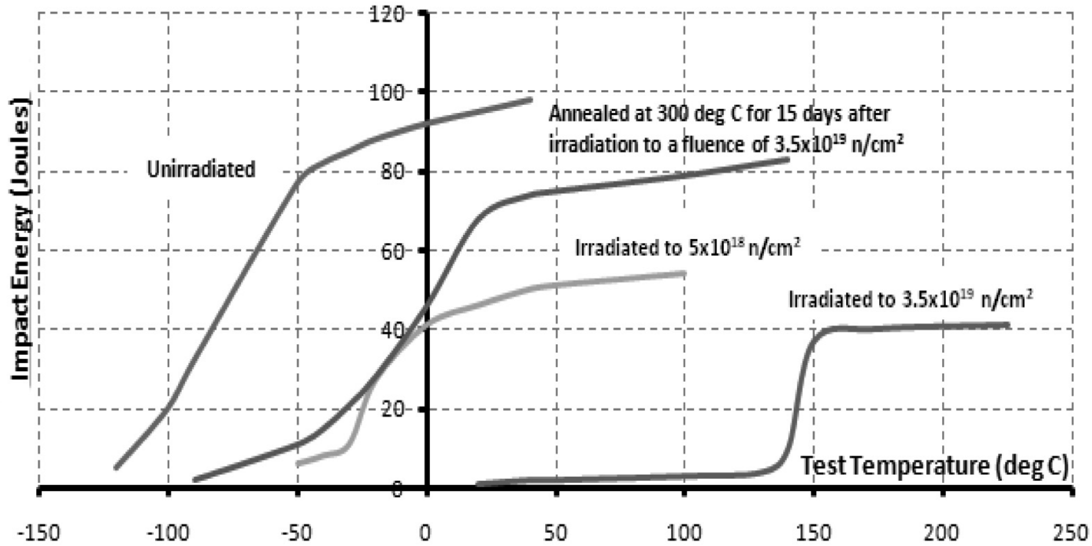

Fig 6: Impact energy versus temperature curves for ASTM 203 grade D steel

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.

Main propulsion machinery

Given that in the first instance a conventional PWR reactor would be the most likely choice for use in a merchant ship; a propulsion system involving a steam turbine would be the most likely option. In this case it could 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. Alternatively, the main steam turbine could be deployed as a turbo-generator set for an electrically propelled and managed ship. Indeed, such an option might be attractive where the hotel or non-propulsion electrical load of the ship is high.

In keeping with traditional marine practice it may be, for mechanical transmission systems, that a simple cycle steam turbine might form the basis of the mechanical system. While more complex steam-based cycles involving reheat, as commonly used in land-based applications, offer the potential for enhanced efficiency, they have not generally found favour in marine practice due to the marine steam plant having a requirement to go astern. When this happens there is no steam flow through the reheater and means are, therefore, required to protect the reheater tubes from the overheating. A similar situation also exists during port operation. Notwithstanding these constraints reheat marine boilers have been produced which have separately fired, water-cooled reheat furnaces following the main generating bank. With regard to gearbox arrangements suitable for deployment in a merchant ship direct drive steam turbine systems, these are generally of the double reduction type. However, 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 relatively few locations in the world. This may, in the short to medium term, provide a restriction on the availability of servicing and repair capabilities.

If, however, instead of a conventional steam turbine-geared shaft drive train a turbo-electric propulsion arrangement were deployed, then the need for reversing the turbine is nullified. In such a case the electrical power control will take care of preparing the power supply for astern running. Indeed, this may then support the deployment of podded propulsors or conventional electric propulsion.

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. The level and type of the requirement will depend upon the number of independent reactor units fitted.

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 these nuclear plants has, to some extent, been a function of this environment.

Given that ships of the merchant service do not always live up to these vibration standards, for merchant ship 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 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 them 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 and other surface ships.

Refuelling

For a merchant ship, unlike a submarine because of the higher levels of fuel enrichment permitted, refuelling should be contemplated on about a five to seven year cycle depending on the actual level of enrichment deployed and the duty cycle of the ship. Based on the experience to date, the refuelling process may take something of the order of 30 days and clearly this downtime requires to be factored into the economic model for the ship. Nevertheless, a five-year refuelling cycle would fit well with current classification survey requirements.

The design of the ship has to be such that it is possible to retrieve the spent fuel from the ship unless the design philosophy is to retain the spent fuel within the reactor compartment of the ship throughout its life. In this latter case the ship will have both active fuel and nuclear waste stored on board and this will have an impact on the classification and regulatory regime that will need to be applied.

The de-fuelling process or the storage of waste fuel presents the area of highest risk. This risk derives from the unstable isotopes and gamma radiation that are present in the irradiated fuel. In contrast fuelling presents little radiation hazard since it can be readily handled.

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 providing a direct pathway for the 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 general access to a number of ship types and, therefore, constitutes a well understood means of gaining entrance to ships for all sorts of reasons. Moreover, such methods of gaining access, if chosen advisedly, are unlikely to encroach on the cargo spaces 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. The shore-based reception for this type of nuclear waste must 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.

Alternatively, if it were contemplated that the spent fuel was to be stored onboard then a dedicated storage tank water cooling system will need to be provided together with suitable redundancy.

Radiation hazard zones

Recognising that the location of the reactor compartment is dictated so as to minimise the effects of the ship dynamics, 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

Within 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 typically range from around 27 MWe up to 300 MWe. It should, however, be noted that the thermal rating of the power plant, particularly with PWR technology, will be some three to four times the electrical power rating.

A series of basic concept analyses for three ship types has been undertaken. This 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 medium to 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 was sited close to the mid-ship region of the ship to minimise the effects of ship motions and vibration on the reactor plant: in particular, from propeller induced vibration in the stern. Moreover, this location gives protection from collision in the bow region. Such an arrangement might also imply that the superstructure could be located in this region so as not to unnecessarily restrict the cargo volume: indeed, such arrangements are not dissimilar to those used for these types of ship in an earlier age. Cargo handling constraints may, however, dictate some reappraisal of the superstructure location.

The principal concern is the continuity of the longitudinal strength of the hull. When considering 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 an 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 the other secondary system plant machinery.

300 000 dwt tanker

For this size and type of ship the maximum power capacity installed, excluding the emergency generator capability, was taken to be 29.7 MW. To achieve this power requirement using a PWR reactor will require a reactor capacity of the order of 120 MWt if a conventional marine steam turbine plant is to be deployed. Such a capacity is well within the capability of the class of small reactors and could be supplied from a single reactor. Indeed, the requirement of 29.7 MWe is towards the lower end of the small reactor units currently envisaged.

Single screw 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 fuel enriched to 3.5 to 4.7% or, alternatively, a combination of uranium and MOX fuel. The reactor unit 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. Clearly, if a higher ship speed were chosen then it may be necessary to increase the number of propellers.

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 nuclear reactor main propulsion plant, because there is no redundancy, a diesel generator would be required for emergency propulsion power in the event of a requirement to shut-down the main power plant. This diesel generator would be required to supply power to a shaft mounted motor to permit the ship to navigate at a speed of around 6 knots.

Clearly, a higher level of redundancy could also be achieved by deploying two nuclear steam generation plants, if available, of 60MWt each. If this were the case then the need for an auxiliary diesel generator to provide emergency propulsion power would be reduced.

1000 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*.[4] It was concluded at that time that 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 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 require a PWR capability of 290 MWt; again operating on fuel enriched to between 3.5 to 4.7% or a combination of uranium and MOX fuel.

As with the previous 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 option would be particularly advantageous if in the former case the shaft lines passing 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. It should be noted, 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 currently 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[5] 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 of that paper considered the situation in which the ship speed was considerably increased over that to which contemporary ships are designed. In that 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.

7450TEU container ship

In the context of a modern medium sized container ship, such a ship would require an installed power of approximately 40MW 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, again, 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 having 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% enriched fuel or a combination of uranium and MOX fuel would form 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 in this case could either be based on steam turbines driving through reduction gearing or, alternatively, turbo-electric in which case the auxiliary power source could directly feed the normal propulsion motor.

12 500TEU container ship

In this case the basic ship design was that considered in the ultra-large container ship propulsion study undertaken by Lloyd's Register.[6] The parent ship had a design speed of 25 knots and required a total installed power of 77MW 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 conventional 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 and limited propulsion, in the event of a reactor failure, would be required. As in the case of the smaller container ship, the propulsion drive train could be either direct steam turbine driving through reduction gearing or turbo-electric.

The positioning of the reactor plant is entirely consistent with the general arrangement layout of the vessel as proposed by Tozer & Penfold.[7] Moreover, such an arrangement also has certain ship structural advantages, particularly in relation to the torsional 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 52MW to accommodate the variable hotel load. Such a requirement could be provided by PWR reactor(s) giving a total thermal power in the region of 200 MWt. As with the previous examples, either direct drive steam turbine systems 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. As with the previous examples, fuel enriched to either be 3.5 or 4.7%, or a combination of uranium and MOX fuel, would form the basis of the propulsion system.

For cruise ships the 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 and life support requirements to safely return the ship to port in the event of an emergency. Additionally, 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 cruise ship, in this case operating at 22 knots. Such a ship would most likely be equipped with three podded propulsors and an installed power of 105MWe to accommodate the propulsion and hotel loading. Such a power requirement could be satisfied with PRW reactors having a capacity totalling 390 MWt. Again, this requirement can easily be accommodated within the range of small reactors in either a single or twin reactor configuration.

General considerations

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

Within the context of fuel usage, it is of interest to note that in the case of the 12 500TEU container ship when undertaking a voyage of 3500 nmile at 25 knots the weight of residual fuel used is of the order of 1540t together with the production of some 4850t of CO_2. However, if the ship were powered by uranium fuel, a mass of about 2.2kg enriched to 3.5% would be consumed. Moreover no CO_2 emissions would occur during operation.

CONCLUDING REMARKS

It is concluded that pressurised water reactor technology has had the greatest application at sea. It has demonstrated a high level of reliability throughout the 55 years or so of operation in maritime service. Clearly, other nuclear based technologies are progressing in terms of their potential application to marine transport.

To accommodate nuclear technology the general arrangement of the ship should, for the most part, alter from that commonly seen today in order to provide the reactor with the best possible operating environment. A prime consideration in this respect is the positioning of the nuclear reactor and the collision and vibration protection necessary. With regard to collision protection the structure will have to be designed so as to absorb and distribute the energy of impact.

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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APPENDIX 1
THE NUCLEAR FUEL CYCLE

The nuclear fuel cycle (Fig A-1) 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. However, 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 at this stage in the process is known as low-enriched uranium while the other is progressively depleted in ^{235}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

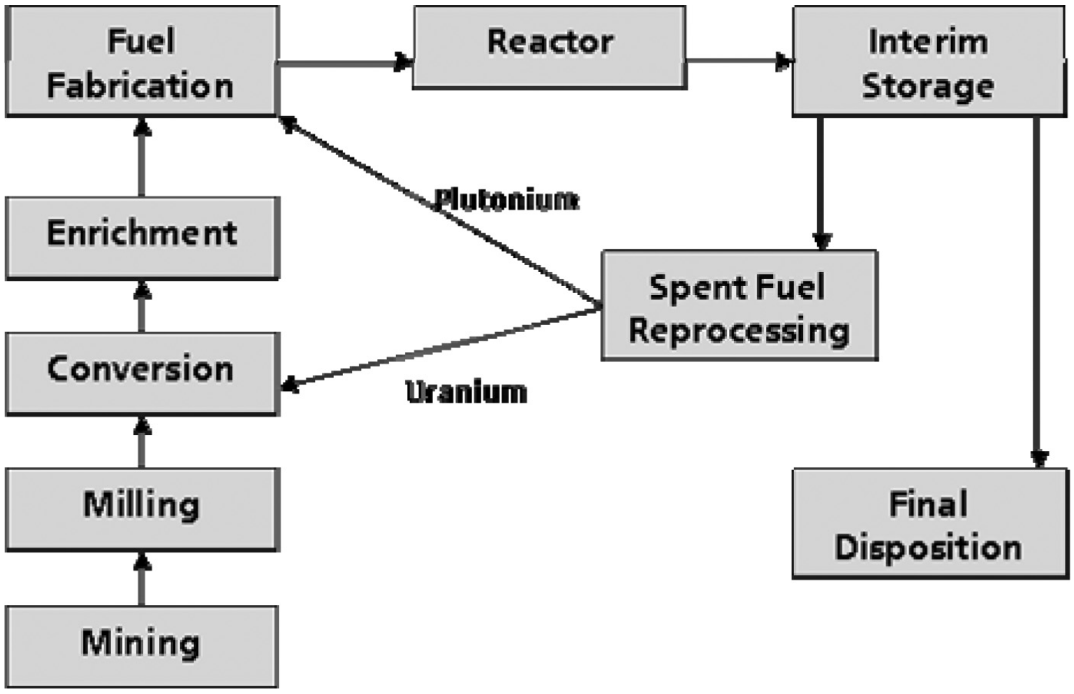

Fig A-1: The nuclear fuel cycle

uranium oxide which has been sintered at temperatures above 1400°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 resulting rods are manufactured to a high tolerance specification after which the dimensions of the fuel pellets and fuel rod assemblies are subject to rigorous quality control to yield a consistent fuel characteristic.

Once inside the reactor the nuclei of the ^{235}U atoms are split in the fission process, thereby, releasing energy. During this process the ^{238}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 eventually the fuel has to be replaced. The exception to this requirement is the case of the highly enriched fuels used by some naval ships and submarines. When the fuel is removed from the reactor it emits radiation from the fission fragments and significant quantities of 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.