Nuclear Propulsion for Submarines and Surface Vessels

A Review

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NUCLEAR PROPULSION

Today more than three hundred ships are propelled by nuclear plants. They all use pressurised water reactors, and are either:
- Naval Surface Ships
- or Submarines

The first vessel of any kind to use nuclear power was a submarine, the USN Nautilus. At the time of her launch, she was the world's largest submarine. Almost exactly one year later she flashed an historic message from Long Island Sound, a stretch of water off the eastern coast of the USA: "Under way on nuclear power". In the years that followed, Nautilus and her successors rapidly demonstrated the tremendous advantages that nuclear power gives a submarine. Forty years later more than five hundred reactors are in service around the world on board three hundred and fifty American, British, Russian, Chinese and French vessels.

NUCLEAR PROPULSION FOR SURFACE SHIPS

In the sixties it looked that nuclear propulsion could also apply to merchant ships. The 10,000 tonne freighter Savannah in the US, and a German ore ship the Otto Hahn of equivalent capacity were commissioned in 1962 and 1968 respectively. Drawings for their successors have since been kept in their filing cabinets. Their main problem was obtaining free access to harbours in a number of countries but there were others, such as flags of convenience.

A nuclear propulsion assembly is voluminous and dense, partly on account of the heavy radiological protection. On board a submarine, this is acceptable because it is a very compact vessel not designed to carry any commercial freight. Its weight, submerged, is equal to the lifting force with a density of 1, which is about the same for the nuclear reactor assembly proper. The weight and width of the reactor determine the submarine's overall size and the diameter of the hull.

It is far different for a surface ship with a density three to five times less than when unladen. Her size has therefore to take into consideration the extra weight of the nuclear reactor and its heavy metal shielding in order to make the ship commercially economical.

Designed as the first frigate with nuclear propulsion, the USS Longbeach was eventually commissioned as a cruiser. Since then all surface ships in the US Navy, excluding
aircraft carriers, are above 9,000 tonnes. This impact of weight on size is reduced as the size of the ship increases. This is the case for aircraft carriers.

The cost of a conventional submarine is approximately A$250,000/m³. The cost of a frigate with conventional propulsion is at least three times less. The cost of the nuclear plant alone is also A$250,000/m³, and therefore makes the cost of a nuclear plant a heavy burden on surface ships.

Another factor increasing costs is the high quality of parts and sophisticated fabrication procedures of all components of the nuclear installation required to ensure adequate safety. Costs are not so different for a submarine because high technology components are necessary throughout anyway. A merchant ship is of much simpler design.

Finally the maintenance and logistic support required for a nuclear merchant ship are out of proportion when compared with the support required for a conventional one.

Where Navy ships are concerned, cost is not always the dominant factor, especially not when a country has the means to afford them. Nuclear propulsion ensures a greater mobility and endurance and this particularly applies to an aircraft carrier and her escort which often have to operate at high speed when planes are taking off or landing. These are more decisive factors than costs.

An often useful advantage of nuclear propulsion for aircraft carriers or cruisers is that it eliminates the need for funnels that induce air turbulence, which in turn affects the operation of aeroplanes and helicopters.

A surface ship is, of course, more exposed to missiles than a submarine. Nuclear propulsion greatly improves speed and mobility for an aircraft carrier and her escort but it does not eliminate vulnerability, far from it. Above a certain size a surface ship has to be designed and constructed to take blows and survive. This requires very heavy protection of the nuclear plant not only for major conflicts but also for intervention in any areas likely to be hostile.

The US Navy has made a choice which few other countries can afford. Its aircraft carriers are the largest by far and most expensive because they were designed to carry aeroplanes of all types and aptitudes whatever the flying condition. The cost of nuclear propulsion is only one item among many others of an extraordinarily high budget.

Aircraft carriers are deployed with escorts well equipped with anti-aircraft, anti-surface and anti-submarine warfare weaponry and also with detection devices, which make hostile aggression unlikely to succeed. There remain the problems of defence against ballistic missiles with or without nuclear warheads. Carriers are sometimes criticised in the USA because of their price and their key importance which makes them prime targets for hostile fleets.

In northern Russia, with its exceptional winter conditions, nuclear propulsion looks successful for ice-breakers which, thanks to nuclear power, can survive isolated from the rest of the world for long times. The costs are then irrelevant. The Russians are also designing cargo ships for use in ice fields. Spending a winter in the Arctic certainly justifies different considerations. As for their navy the Russians envisage surface ships with a relatively small reactor for cruising and supplying power on board, and additional oil burners to boost the steam pressure for higher speed.

A Japanese project to build a nuclear powered commercial vessel about twenty years ago had to be abandoned because of strong anti-nuclear public opinion. Nevertheless the Japanese still maintain a research and development programme for the use of nuclear propulsion for surface ships.
NUCLEAR SUBMARINES

Nuclear Submarines are in service in the navies of the USA, the UK, Russia, China and France, while India has one under construction. There are two types of nuclear submarines: the attack vessel known as SSN (Submarine Ship Nuclear) (Fig. 1) and the missile-carrying submarine or SSBN (Submarine Ship Ballistic Nuclear) (Fig. 2). The former is designed to attack and destroy other submarines and enemy vessels. The SSBN is a frightening weapon, its role being to serve as a platform for nuclear missiles, which is hidden in the depths of the ocean. The world's SSBN forces threaten retaliation to any country that makes first use of nuclear weapons, a threat designed to prevent the outbreak of war. Threat of nuclear retaliation very likely has prevented nuclear war for half a century.

Whenever a submarine is to operate far from base and has to cover a vast patrol zone for periods of months or longer, the nuclear submarine is the only capable weapon. It has almost total independence far away from base, which is not the case for a conventional submarine. No alternative means of propulsion can compete against nuclear propulsion for oceanic submarines. Chemical, air independent propulsion (AIP) fuel systems, e.g. using hydrogen gas, could be the means to improving the acoustic discretion of coastal patrol submarines which do not require great mobility. However, this cannot apply to oceanic patrols, because of constraints imposed by the storage requirements of the hydrogen or other chemical fuels on board.

In 1958 Nautilus passed across the North Pole, sailing deep beneath the extremely thick ice cap in that hostile region, so demonstrating that there was no ocean in the world a nuclear submarine could not command.

Operating nuclear submarines is claimed to be excessively costly, particularly by detractors. The investment is indeed substantial but nuclear energy allows the production of much larger, highly versatile and very fast vessels. The cost is a consequence of high performance requirements, and not exclusively due to the cost of nuclear propulsion. Performance levels possible with a nuclear plant cannot be achieved by any other method. No one can win the Grand Prix without a Formula 1 design.

If a country has already invested in a nuclear industry or received assistance from a friendly country, it becomes possible to develop a submarine fleet at an acceptable cost. Whatever the choice, cost and efficiency have to be compared over the whole life of submarines. From this viewpoint, it is definitely in favour of nuclear power because a conventional submarine equipped with sophisticated weapon systems will never have the mobility and invulnerability matching such an investment. This means that the choice of nuclear propulsion for oceanic missions cannot be contested, provided of course that the country concerned can afford it.

Nuclear propulsion is the only technology allowing a submarine to remain submerged and silent for a long time. Conventional submarines run on batteries which have to be recharged using noisy diesel engines. At a speed of 2 or 3 knots they can operate for several days prior to recharging but at 20 knots batteries will not last more than one hour. A nuclear submarine can run at more than 25 knots for the whole mission. Some American or Russian submarines are capable of a submerged speed of more than 50 knots at depths down to 600m.

Up to 1995, nuclear powered naval ships had covered more than 100 million nautical miles accumulating more than 4,600 reactor years of operation and have never experienced a reactor accident or any problem...
involving a reactor which has resulted in the release of radioactivity. Since World War II the US Navy has only lost two submarines: one struck an underwater mountain, while a mechanical malfunction caused the second submarine to plunge into the ocean depths where the enormous pressure crushed its hull. The Russian Navy has lost 12 submarines due to problems with the reactors, including outright failure. It is careless about the environmental aspects of its nuclear programme and, according to its experts, it faces enormous costs to restore the programme’s health and safety margins.

**Discretion - Silence**

In order to perform any mission it is not enough to be discreet, i.e. remain silent to avoid trouble. It is also necessary to be able to detect any potential aggressor.

The only efficient means known today for discovering the position of a submarine navigating beneath the surface of the ocean is the acoustic method commonly known as sonar. The electronic ears of a sonar system analyse the frequencies of the sound waves transmitted through the water and identify their origin.

Once below the surface the crucial imperative for any submarine is to possess the acoustic advantage over its potential aggressor. Specifically this means having a quieter propulsion system than the enemy vessel so as to detect its position before it detects yours. There are three main causes for the noise produced by submarines: the turbulence of the water along the hull, the noise produced by the propulsion system and the noise produced by the operation of various types of equipment such as motors, pumps, fans, valves and so on. Submarines are equipped with a total of 75,000 parts connected by 300 km of cables and 50 km of pipes. Every piece of equipment has to be fully independent from the hull and installed on flexible mountings or cradles isolated from the hull.

As for the reactor (Fig. 3), it produces pressurised steam and the same type of reactor is used in all American and European submarines. These reactors are characterised by the position of the steam generation system which is located directly above the reactor vessel. Water in the primary circuit is driven by convection between the reactor vessel and the steam generator unit, requiring no pumps under a wide range of operating conditions. The advantage of this design is the low level of noise as compared to noise generated from pump driven systems (Fig. 4).

The steam turbines drive two alternators: 1) the propulsion alternator produces the necessary electricity for the main electric engine which drives the propeller directly without an intervening noisy reduction gearbox; 2) the power alternator provides the electricity necessary to the ship’s services. Instead of propellers, large submarines are now using pump jets but details of the mechanisms are jealously guarded military secrets.

For a speed greater than 10 to 12 knots, noise from both nuclear and conventional submarines is mostly of hydrodynamic origin. For speeds less than 10 to 12 knots most noise comes from the reduction gear, the reactor primary cooling pump (unless a convection system is used) and the propeller. A conventional submarine is silent when patrolling at 3 knots unless the batteries are being re-charged by noisy diesel generators.

Nuclear propulsion offers such a range of operational possibilities that it is difficult to imagine how submarines of the future could be anything but nuclear, except for those operating in small seas such as the Baltic or those designed for coastal duties, in which other AIP systems could be considered, such as fuel cells, although they would then face the difficulties of oxygen storage on board.
The French Navy is developing a small 2 megawatt reactor which could be used as an AIP propulsion system for 3000 tonne submarines enabling them to cruise at 8 knots indefinitely.

Conventional diesel-electric submarines have become increasingly vulnerable to airborne and shipborne advanced radar capable of detecting, at very long range, the snorkel mast and periscope when they are raised above the surface, and the wake created by them. Detection by these methods may cause the submarine to be lost even before reaching its patrol area.

The submarine batteries supplying the propulsion motors have to be charged regularly. Modern conventional submarines will spend 20% of their time at a snort station for a speed of advance (SOA) of 10 knots, 15% for an SOA of 8 knots, and 7% for an SOA of 5 knots. In the case of an Australian submarine this indiscretion ratio is actually more constraining than may appear because long distances have to be cruised at 8 or 10 knots before reaching the assigned patrol area. The journey from Sydney to the Strait of Lombok, for instance, lasts 20 days, of which 3 to 5 days are spent snorting. Nuclear propulsion would permit the same trip to be made in 8 days, with no snorkel indiscretion at all, the submarine remaining permanently submerged.

A conventional submarine on patrol at 3 to 4 knots would be snorting 2 hours a day, 2 hours that may prove extremely hazardous when a hostile aircraft has been ordered to clear the area for the benefit of an incoming task force, 2 hours that would be better spent quietly submerged and undetectable, searching for targets.

Mobility - Speed

Mobility in terms of submarine warfare means that a pre-determined speed be sustained for hours or days. When *HMS Conqueror* was despatched by the British Navy to the Falklands, she sailed 8000 nautical miles at more than 20 knots, submerged all the way, and could thus lock the Argentinian fleet in its harbour before it could take any action.

A modern submarine is equipped with acoustic sensors that permit it to detect, classify and track targets up to 100 km away. But the torpedoes and other weapons carried by the submarine have a strike range of no more than 30-40 km, In many instances the vessel has to get even closer to identify a selected target. The submarine captain is for most of the time in the position of a hunter who has to manoeuvre quickly in order to get into a firing position on a fast moving target, whereas a vessel equipped with diesel-electric propulsion might not be able to catch up.

If engaged in modern warfare, a diesel-electric submarine would soon be forced to a standstill by the limited capacity of its batteries, rather than be able to act as an aggressive hunter. In this context, the greatest advantage of nuclear propulsion is clearly evident: a nuclear submarine could track a fast running target for hours and days at a time—whether the quarry be either surface combatant or submarine — retaining the capability of firing at selected times on selected ships. A conventional submarine will have the opportunity to act once, and once only. The limitation imposed by its battery capacity will prevent it from keeping up with surface warships or merchant vessels, and thus it cannot act as an escort. Furthermore its range is limited by its fuel capacity.

The comparison of nuclear and conventional propulsion in terms of mobility and speed, is definitely in favour of nuclear propulsion. The validity of this assertion can be put in a few words: the conventional submarine can travel at a maximum speed of 20 knots for one hour only, approximately the distance between Garden Island and Palm
Beach, followed by several hours snorting versus unlimited sustained speed in submerged conditions for the nuclear submarine. In other words, the greater the speed the higher the chances for survival.

During World War II acoustic sensors and radar capable of detecting submarines at very long range were far from being as efficient as they are today and satellites did not exist. Nevertheless, 781 out of 842 or 93% of diesel-electric U-boats that saw action at the time were lost. Of the 38,000 German submariners 28,000 died and 5,000 were taken prisoners, i.e. there were 85% casualties. Towards the end of the war only two out of every ten U-boats that set out could expect to return. Would any come back today?

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Nuclear</th>
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</thead>
<tbody>
<tr>
<td>Tonnage, Submerged</td>
<td>3000 tonnes</td>
<td>3000 tonnes</td>
</tr>
<tr>
<td>Maximum Speed</td>
<td>22 knots (one hour only)</td>
<td>&gt; 25 knots (unlimited time)</td>
</tr>
<tr>
<td>Construction Cost</td>
<td>1</td>
<td>1.3</td>
</tr>
<tr>
<td>Annual Maintenance</td>
<td>1</td>
<td>1.35</td>
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**Patrol 3600 mile from Base:**

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Nuclear</th>
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</thead>
<tbody>
<tr>
<td>Transit Speed</td>
<td>10 knots</td>
<td>18 knots</td>
</tr>
<tr>
<td>Indiscretion Ratio</td>
<td>22% (snorting)</td>
<td>0%</td>
</tr>
<tr>
<td>Transit Time</td>
<td>15 days x 2</td>
<td>8.5 days x 2</td>
</tr>
<tr>
<td>Patrolling Time</td>
<td>40 days</td>
<td>53 days</td>
</tr>
<tr>
<td>Patrolling Speed</td>
<td>3.5 knots</td>
<td>10 knots</td>
</tr>
<tr>
<td>Indiscretion Ratio</td>
<td>5% (snorting)</td>
<td>0%</td>
</tr>
</tbody>
</table>

To permanently maintain 2 submarines over the patrolling area, including maintenance and transit time:

| Required Number of Submarines | 8 | 5 |
| Purchase Price               | 8 | 6.5 |
| Maintenance cost per annum   | 8 | 6.75 |

Advantage is in favour of nuclear propulsion. The price difference will more than cover the cost of the infrastructure required for supporting the nuclear fleet, which is estimated at approximately 75% of the total price of one unit.

Table 1
Comparing Costs of Nuclear and Conventional Submarines

Comparison is valid if both submarines are of similar capacity, with similar weapon systems and the same number of torpedoes and missiles.

In this situation the price of one nuclear propelled submarine is 30% higher than for a conventional submarine, and its maintenance costs 35% more, but the vessel is capable of far superior performance, so much so that the price comparison should not be restricted to the number of units per fleet.

As an example, in order to permanently maintain two submarines patrolling over a distant area, the respective requirements are set out in Table 2:

<table>
<thead>
<tr>
<th></th>
<th>Cost</th>
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<tr>
<td>8 Conventional</td>
<td>8 x 1</td>
</tr>
<tr>
<td></td>
<td>= 8</td>
</tr>
<tr>
<td>5 Nuclear submarines</td>
<td>5 x 1.3</td>
</tr>
<tr>
<td></td>
<td>= 6.5</td>
</tr>
</tbody>
</table>

These figures apply to 2 equivalent 3000 tonne dived submarines with the following salient features.

A nuclear submarine has a much higher transit speed, not having to charge batteries for 20% of the time at sea with noisy diesel-generators broadcasting its position. Furthermore, it will cruise at 10 to 15 knots over the patrolling area instead of only 3 to 4 knots for the diesel electric unit.

The area covered by the nuclear vessel is 3 to 4 times greater for the same number of days at sea, with zero indiscretion ratio (Fig. 7). Thanks to its faster transit speed a nuclear submarine will spend 53 days permanently submerged over the area concerned, whereas a conventional vessel can only remain 40 days, occasionally snorking. Diesel submarines are warships of position, whereas nuclear submarines are fast vehicles of manoeuvre.

All advantages are on the side of nuclear propulsion. The significantly lower operating costs of nuclear submarines, as stated in the table, will more than cover the cost of the infrastructure required for supporting the nuclear fleet, which is estimated at approximately 75% of the total price of one unit. It is also relevant that while a 3000 tonne conventional submarine will require 25,000 tonnes of fuel during its operational life, not forgetting handling problems, only one tonne of nuclear fuel would be used over the same period.

In a nation where 96% of our imports and exports depend on ships, conventional submarines could not escort and protect any of them. The use of conventional technology would condemn our young sailors to overwhelming inferiority should an emergency occur. Would anyone like to be a sailor on board what the German U-boat Commander Herbert Werner called ‘iron coffins’, in the event of a conflict in the Indian Ocean?

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The powertrain
The energy generated in the reactor creates steam which turns a series of turbines. These are connected to the propellers by drive shafts and gears. Great effort is spent to make the submarine run as quietly as possible to avoid detection by enemy ships.

The SSBN

Missiles
At the centre of the submarine, to the rear of the fin, is a raised section of the hull that holds two lines of vertically-mounted missile launch tubes. The size of an SSBN is dictated by the size and number of the missiles it is designed to carry.

The Fin or Sail
The fin or sail acts as a bridge when the sub has surfaced and contains the submarine’s aerials, sonar, periscopes and other equipment. Hydroplanes attached to the side help keep the sub stable when submerged.

Living Quarters
Beneath the fin are the crew’s quarters, officers’ wardrooms, staterooms, galleys and the operations and communications centre of the sub. With crews of up to 140 men, great care is taken to provide recreation and comfort for long voyages.

Hull and bows
A submarine has an inner and outer hull. Between the two are ballast tanks which are filled with water when the submarine dives. In order to withstand high water pressures when submerged, the hull is made of extra-strong steel alloys, and special welding techniques are used in construction. The bow contains torpedoes launch tubes, used to defend the boat should it come under attack by an enemy submarine. This is also where the main sonar detection equipment is housed.

SS Le Redoutable
The SS Le Redoutable, shown here, launched in 1967, was France’s first SSBN. It has all the basic equipment typically found in missile-carrying submarines. Attack submarines are smaller, and do not have missile launch tubes. In attack subs, torpedoes can be positioned at the front, rear and middle of the hull.

Nuclear reactor
The nuclear reactor is fuelled by a small piece of uranium. This gives off harmful radiation, so the reactor has a thick lead shield to protect the crew. The reactor also needs a constant cooling, to stop it overheating. As well as powering the boat, the reactor is the source of all the electricity used on board the sub.
Fig. 3 (left). Nuclear boiler.

Fig. 4 (below). Propulsion: nuclear fuels 1 contained in reactor vessel 2 boils the primary water 3. This water circulates by natural convection into steam generator 4 and causes the evaporation of the secondary water 5 to feed the turbines 6. The secondary water is cooled in the condenser 7 before being returned to the steam generator. Each turbine drives two alternators 8 and 9. The propulsion alternator 9 produces the necessary electricity for the main electric motor 10 that drives the propeller 11. Power alternator 8 provides the necessary electricity for the ship's services.

Fig. 5. Area covered during patrol.

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