NUCLEAR SUBMARINES

by
Dr David Maddison

On April 26th this year, the Australian Government announced the $50 billion purchase of the next generation of 12 submarines, with the firm decision being made against the use of nuclear propulsion. Despite this decision, we now take a detailed look at nuclear submarines and their significant advantages compared to diesel-electric counterparts.

Before discussing nuclear submarines, we will briefly look at the history of submarines and the different methods of propulsion which have been used.

The idea of a submersible vessel such as a diving bell has been around for a very long time but the first vessels considered to be submarines were powered by hand-operated cranks driving propellers. A famous example was the Turtle, which was said to be used in 1776 in the US War of Independence to attempt to destroy an enemy ship, the HMS Eagle.

Arguably, there may have been no such attempt as there is no British record of the incident. However, it was the first submarine to be associated with a military use. The Turtle was not viable, though, as the operator quickly ran out of breathable air.

Then in 1863, the French Navy built the Plongeur which was powered by compressed air but this submarine was highly impractical and unmanageable.

A replica of the Turtle at the Submarine Force Library and Museum in Connecticut, USA, the first submarine associated with military use.

The next type of propulsion system was developed for the Spanish Navy by Narcis Monturiol in 1867. His "Ictineo II" used steam power on the surface and "air-independent" propulsion under water. The latter propulsion system used hydrogen peroxide which was decomposed, in contact with a catalyst, to generate oxygen and steam. This steam powered the propeller and the oxygen was breathed by the crew – a practical and ingenious approach.

With the development of the Whitehead torpedo in 1866 (mentioned in the September 2015 SILICON CHIP article on "Autonomous Underwater Vehicles"), the submarine also became a useful weapon.

(For more information on hydrogen peroxide as a fuel, see "Personal Flight Vehicles" in SILICON CHIP, August 2016.)

Next came the development of the British Resurgam in 1879. This was powered by a closed-cycle steam engine while on the surface. This engine could generate sufficient superheated steam while the vessel was on the surface to allow it to remain submerged and manoeuvre for up to four hours.

Before diving, the furnace was extinguished to avoid using the oxygen inside the submarine. But this submarine was not practical nor useful as the steam engine produced intense heat inside the vessel, as well as leaking fumes.

While the Resurgam was not a success, it did lead to the development of the series of Nordenfelt submarines, named after the Swedish industrialist who supported their development.

Like the Resurgam, they produced a reserve of pressurised steam on the surface which was later used for underwater propulsion. The Nordenfelt II (1886), III (1886) and IV (1887) each carried torpedoes.

The next major development was electric propulsion which required the development of suitable batteries. The first electric submarine was the Nautilus, built in 1886. Designed by Polish-Russian engineer Stefan Drzewiecki, it was 18m long, had a 9.7kW engine and 52 batteries but its development was discontinued after it became stuck in mud; a somewhat ignominious end.

This was followed by the Porpoise, designed in 1886 or 1887 by James Franklin Waddington in the UK. It had a battery of 45 2V 660Ah cells. This could power the vessel underwater for eight hours at seven knots (13km/h).

The Porpoise was equipped with two externally-mounted torpedoes and even though it performed well, Waddington was unable to get the Royal Navy interested in his futuristic craft and it sat anchored for two years. It was eventually broken up and Waddington went bankrupt.

Battery charging

A problem with purely electric submarines was that they needed to recharge the batteries without having to return to home port. The idea of recharging the battery on the surface via a petrol, kerosene or diesel powered engine came about around the beginning of the 20th century. This became the dominant form of submarine propulsion and this has been continuously developed ever since.

Initially, these submarines had to regularly resurface to charge their batteries and that made them vulnerable. The Dutch are credited with the invention of the snorkel between the two world wars to enable submarines to ingest air for their motor(s) to recharge their batteries while the bulk of the submarine remains submerged. With the use of radar for the detection of German U-boats at sea, the German navy retro-fitted snorkels to their submarines in order to avoid detection.

The Royal Navy tested snorkels but did not adopt the idea until *after* WWII.

Nuclear submarines

The next great development was nuclear propulsion, with the launching of the USS Nautilus in 1955. Nuclear propulsion offered the possibility of unlimited range, restricted only by the on-board food supply, maintenance requirements, atmosphere control and the mental ability of the crew to remain isolated, with no contact with the outside world.

Reactors on nuclear submarines generally do not need refuelling throughout their expected service life of 25 years or more. As an example, the US Virginia-class nuclear attack submarine does not need refuelling for 33 years.

Because of the high levels of power available on a nuclear submarine, they have very high top speeds and no restrictions on the "hotel" power loads which provide crew comfort such as unlimited hot showers, very clean air and so on.

The high speed and great range of nuclear submarines also mean they can escort naval convoys; conventional submarines are not fast enough to do this (at least, not when submerged).

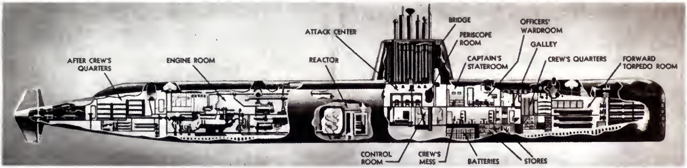
In contrast to the almost unlimited endurance of nuclear submarines, typical diesel-electric submarines might have submerged endurances of a few hours at top speed or a few days at slow speed. With air-independent propulsion or AIP (see panel), the submerged endurance of a non-nuclear submarine might extend, at slow speed, to as much as two weeks or a little more.

Nuclear submarine development

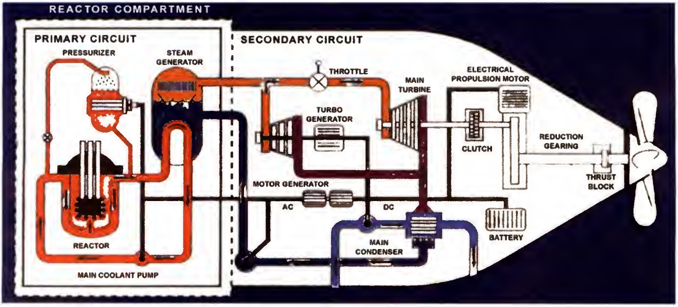
The idea of a nuclear submarine was proposed by the US Naval Research Laboratory and championed by Admiral Hyman Rickover. The US Government gave approval in 1951 and the first submarine was named USS Nautilus (SSN-571), after the submarine of the same name in the Jules Verne novel, "*Twenty Thousand Leagues Under the Sea*", written in 1870.

Nautilus took only 19 months to build from the time its keel was laid. It was powered by a purpose-built Westinghouse S2W pressurised water reactor which produced 10MW of power to propel the vessel.

On its maiden voyage, the Nautilus travelled 2,200km in less than 90 hours (faster than 13 knots or 24km/h), breaking the record of that time for the greatest distance



Internal view of USS Nautilus (SSN-571), the first nuclear-powered submarine, commissioned in 1954.



Typical reactor layout for nuclear submarine. This particular layout is based on UK designs. Note the direct drive from the main turbine via gearing. There is also an electric drive motor which is used in emergency situations which can use power from a battery if needed.

travelled underwater and the highest sustained speed of a submerged submarine.

Nautilus had a displacement of 3533 tonnes surfaced and 4092 tonnes submerged. It had a top speed of 23 knots (43km/h), was 98m long, had six torpedo tubes and a crew complement of 105.

By comparison, Australia's current Collins-class submarines have a displacement of 3100 tonnes surfaced and 3407 tonnes submerged, a maximum speed of 20 knots (37km/h) submerged, a length of 77m, six torpedo tubes and a crew complement of 58.

Because of the great sustained speed and endurance of the Nautilus, all existing techniques of anti-submarine warfare at the time were rendered obsolete. Nautilus was also the first vessel to travel to the geographic North Pole under the polar ice cap in 1958. This involved a difficult navigational problem because compasses don't work at those latitudes and the boat could not surface to take navigational measurements from the sun and stars.

The navigational problem was solved with the use of a modified inertial guidance system from a cruise missile. The main purpose of the mission to the Pole, apart from setting the record, was President Eisenhower's desire to demonstrate to the Soviets the capability to launch ballistic missiles from close to their territory.

The fascinating details of this journey and other material can be seen in the video link on the Nautilus.

Nuclear reactors in submarines

Submarine nuclear reactors fall into the category of small nuclear reactors, which by definition have a power output of less than about 300MW. The topic of small nuclear reactors was discussed in the June 2016 issue of SILICON CHIP.

The US Virginia-class nuclear attack submarine (displacement 7800 tonnes, 115m long) has a reactor that can deliver 30MW of power to the main propulsor (which is effectively

Operation Ivy Bells

Operation Ivy Bells involved the use of a nuclear-powered submarine and a nuclear-powered eavesdropping device to tap into Soviet Navy communications that were carried on an undersea cable.

In the 1970s, the USA became aware of a submarine cable connecting a Soviet Navy base to the Soviet Pacific Fleet headquarters in Vladivostok. This cable ran through what the Soviets claimed as their territorial waters.

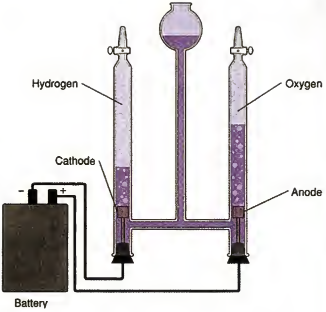
The US desired information running through this cable and so deployed the USS Halibut and deep sea divers working from the submarine in 120m of water to attach a recording device to the cable.

The device had no galvanic connection to the cable but could detect information running on the cable via inductive coupling. The listening device itself was nuclear-powered and was 7m long and weighed six tonnes. In the event that the Soviets ever pulled the cable up for repair, the device was designed to fall off so the Soviets would not find it.

The device recorded data on tape and every month, divers would return to change the tape. The Soviets did not suspect anything and had perfect confidence in the security of the cable as evidenced by the fact that communications were not encrypted.

This listening technique was so successful that many other such taps were installed at different Soviet cable locations and more advanced devices were developed that could store one year's worth of communications.

Eventually, the operation was compromised by an American agent with financial problems who sold the secret to the Soviets in 1980. Some time after that, US Navy divers returned to the site and discovered that the listening device had been removed.



(Above): basic "electrolysis" scheme by which electricity is used to separate and collect oxygen and hydrogen from water.

(Right): the Treadwell Corporation Low Pressure Electrolyser as used on some US Navy submarines to generate oxygen by the electrolysis of fresh water. Hydrogen that is also produced by the unit is discarded overboard or reacted in another process.

a ducted propeller). The largest nuclear submarine class ever built, the Soviet Typhoon class, had two 37MW steam turbines driving its propulsors, delivered from two 190MW (thermal) output reactors.

In contrast, the highly advanced air-independent propulsion system on non-nuclear submarines such as the German 212-class (displacement 1830 tonnes submerged, length 57m) has a main motor of 1700kW (ie, 1.7MW), a marine diesel engine with a power rating of 2150kW (2.15MW) and a type U32 fuel cell bank which can provide 240kW (0.24MW).

While the two types of submarine are not comparable in size or function, these figures show the huge difference in power. For example, when operating in AIP mode, the 212-class submarine uses the 240kW output of its fuel cells while the US Virginia class has up to 30,000kW available; 125 times more power for just over four times the displacement.

Reactors used in submarines have special requirements compared with land-based reactors. They must be corrosion-resistant against sea water, must have minimal vibration when operating, must be resistant to shock waves from explosions and they must not rely on gravity to drop control rods as the submarine may not be in an exactly vertical position.

Air Independent Propulsion

The possibility of air-independent propulsion (AIP) is often used to argue against the necessity for nuclear submarines, even though the range is still limited.

A conventional submarine has to surface regularly to run its (typically) diesel engine to recharge its batteries. Air-independent propulsion has been used as a method to get around this problem and enable a submarine to remain submerged for extended periods of time, giving it the advantage of some extra range, although nothing like that of a nuclear submarine. AIP has the possibility of being retrofitted into existing hulls.

AIP can be achieved by using liquid oxygen to provide oxygen to a closed-cycle diesel engine or alternatively, hydrogen peroxide which decomposes to yield oxygen and water. Both of these approaches have significant safety concerns.

Another type of AIP involves a closed-cycle steam turbine that burns ethanol and pressurised oxygen (at 60 atmospheres). This particular system is offered by a French company and can be retrofitted into some models of existing French submarines by, in one case, inserting an 8m long, 305-tonne "plug" or section to the hull of a submarine. This system gives an endurance of 21 days underwater.

AIP is also available by the use of a Stirling cycle engine using diesel and liquid oxygen, as fuel and oxidiser. In the Swedish Gotland-class submarines, a 75kW engine is used to run a generator to recharge batteries, giving a 14-day endurance at 9.3kph submerged.

Fuel cells have also been used for AIP with the use of ethanol and liquid oxygen. Siemens have a range of fuel cells from 30 to 120kW that have been used in some German submarines.

The Japanese Soryu-class submarine uses AIP with a Stirling engine and liquid oxygen but it has been suggested that later models may use lithium batteries instead, giving about the same range and much quieter operation.

The ultimate form of AIP is, of course, nuclear power.

Furthermore, as well as being compact and needing easy access to maintainable parts, due to limited space they must have a high power output per unit of volume and weight, and must be able to work when the submarine is accelerating, decelerating or turning.

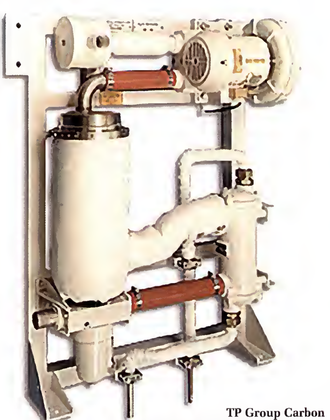
Also, they must be able to vary their output power rapidly or shut down altogether. Finally, of course, they must be ultra-safe.

Due to the high level of power and required long fuel life, submarine reactors use uranium with a much higher enrichment level than used in civilian power reactors. So while a civilian power reactor typically has fuel with U235 content of around 3 to 5%, a typical military nuclear reactor's fuel has an enrichment level of 50 to 90%; the US Navy goes higher still and uses 96% U235 in its submarines.

The reactor is used to heat a fluid in its primary circuit, typically water under pressure, to a temperature of 250-300°C and this is used to heat water in another circuit, the secondary, via a heat exchanger. Two circuits are used so that radioactive byproducts which may leak from the fuel do not leave the reactor compartment.

American nuclear submarines use the secondary steam to drive a turbine which drives the propulsion system plus secondary equipment such as electrical generators. By contrast, in French and Chinese nuclear submarines, the steam turbine drives an alternator to produce power for the main electric drive motor.

Nuclear submarines usually have a battery bank for emergency use, a diesel engine to recharge it and an electric motor in the drive train so that the submarine can still move in the unlikely event of a reactor shut down. Because the battery bank is only for emergency use, it can be much smaller and lighter than in a conventional submarine.



TP Group Carbon Monoxide and Hydrogen Eliminator.

Desalination on a nuclear submarine

Sea water is desalinated on a nuclear submarine and the fresh water produced is used for feed water for the steam generators, water for cooling equipment, drinking, cooking and personal hygiene and for electrolysis to generate oxygen for breathing.

Two processes can be used for desalination, reverse osmosis or vacuum evaporation/distillation. The latter is commonly used on nuclear submarines and the partial vacuum enables water to boil at a much lower temperature than is normal. The vacuum is produced by the main steam turbine's condenser and waste steam from the turbine is used as the heat source.

Atmospheric control

The main requirements for controlling the atmosphere in a nuclear submarine are oxygen generation, CO_2 removal (along with other contaminants) and maintenance of the correct humidity level to prevent condensation and for crew comfort.

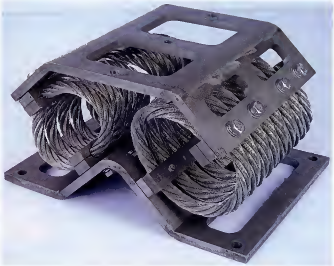
We have touched on oxygen production and there are several electrolysis methods, all of which produce oxygen and hydrogen. In most cases, the hydrogen is pumped outside the hull but it can also be reacted with CO_2 from the scrubber to produce a liquid.

Carbon dioxide (CO_2) is removed from the submarine atmosphere by a process called scrubbing. The most common process involves passing the CO_2 through an aqueous solution of a strong organic base, known as MEA (monoethanol amine, $NH_2C_2H_4OH$). The MEA is then heated to drive off the solution which is compressed and pumped outside the hull.

Other gases that need to be controlled are carbon monoxide, which might originate from an accidental fire, frying

Oxygen generators – a sealed can containing sodium chlorate to produce oxygen by chemical decomposition.

An example of tiles that have become detached from a nuclear submarine due to improper attachment. When attached correctly they are extremely difficult to remove.



A wire rope vibration isolator of the type used on a submarine. One side is bolted to the submarine hull and the other to equipment. This model is a GGG Series of anti-vibration mount by Wuxi Hongyuan Devflex Co., Ltd.

or combustion of engine emissions; and hydrogen, which may come from the emergency battery bank. These gases can be passed over a special catalyst to oxidise them to CO_2 and water, respectively.

Other undesirable gases can be eliminated with other types of catalytic reactor than that discussed above and also filtration through activated charcoal.

Noise and vibration

Modern submarines, no matter what their type, use rubber anechoic tiles on their hulls to reduce their acoustic signature, both reducing noise emanating from inside the submarine and also that reflected from incoming sonar signals.

Specific details of the tiles are a closely guarded secret so no pictures showing the construction of current tiles in use are available but there are many photos available which show what German tiles from WWII looked like.

The ideal tile would be perfectly lossy, work across all frequencies, work at all power levels and work at all operational depths of the submarine.

Tiles are typically made of rubber and are around 25mm thick which makes for a significant extra weight and they typically have a series of holes in them to establish a state of destructive interference to absorb sound waves.

New tile technology work has been published by a group led by Valentin Leroy at the Université Paris Diderot in France. They have produced a silicone tile just 0.23mm thick with internal cylinder-shaped cavities which are 0.013mm high and 0.024mm wide, separated by 0.050mm. Experiments in water showed that this material absorbed 97% of incident sound.

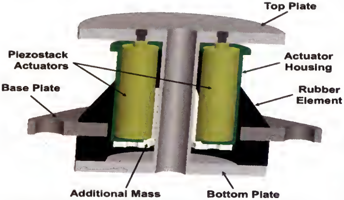
For this material to be useful for the sonar frequencies used to detect submarines, the material would need 2mm bubbles in a 4mm thick tile which in theory would attenuate incident sound waves by 10,000 times, 100 times better than previously thought possible.

Another proposed (or possibly used) method to reduce the acoustic signatures of submarines involves the use of sound cancelling technology to transmit a sound wave of opposite phase of the sound to be cancelled – as in noise cancelling earphones.

Another proposed process is the use of a "phononic crystal" coating theorised by Baile Zhang Nanyang Technological University in Singapore, in which incoming waves bounce off the coating, are curved around and re-enter the crystal, bouncing over and over until they eventually leave the hull in a direction away from the source.

Vibration isolation

Vibration isolation is even more important on a nuclear submarine since cooling pumps for the reactor normally



Exploded view (left) and photo (right) of a mount with piezoelectric active vibration control run continuously. However all submarines need to run air circulation and equipment cooling fans and anything that rotates or makes a noise needs to be silenced.

The specific details of vibration isolation in submarines are not usually published but the general techniques can be classified as either passive or active.

In passive systems, vibration is mitigated by either rubber pads or mechanical springs. In active systems, an electronic actuator, vibration sensors and a feedback circuit work together to cancel out vibrations by sending out-of-phase motion to generate destructive interference to cancel the vibrational mode detected, again, similar to the technique used in noise-cancelling headphones.

Active vibration control can also be used to reduce noise emanating from both the propeller and hull of either type of submarine.

A surprisingly simple but very effective passive vibration isolation system involves two plates connected by lengths of wire rope. This system can be used on the small scale such as with small cameras mounted on drones or on the large scale where it can be seen in videos of nuclear submarines.

For a practical demonstration of just how effective the wire rope can be, you can see an amateur application as used in a drone camera in the video: https://youtu.be/cajoxGhFQck

Note that while reactor cooling pumps normally run all the time, even when the reactor is idle, at times where maximum stealth is required, some reactors can have their coolant pumps shut down. They then rely on convection to circulate cooling water.

However this may only be possible for a limited time and even with the pumps shut down, the reactor may not be totally silent due to gas generation (bubbling) and so on. So any techniques which can prevent sound from the reactor core being heard outside the submarine are worthwhile.

Nuclear submarine types

Today there are two main types of nuclear submarines, attack and ballistic. Attack submarines have a similar purpose to conventional submarines and their functions include fending off enemy vessels which are trying to attack escorted vessels (aircraft carriers, troop transports, etc), attacking enemy vessels with torpedoes, attacking enemy land targets with cruise missiles, espionage operations including direct observation via periscope, listening into communications or sabotage operations with the insertion of commandos into enemy territory. An example of a nuclear attack submarine is the US Virginia class.

By contrast, the ballistic missile submarine is not designed to conduct combat operations but to act as an undetectable platform for the launch of submarine-launched ballistic missiles (SLBMs), which are typically (but not always) fitted with nuclear warheads.

There are also ballistic missile submarines which carry cruise missiles with conventional or nuclear warheads, or possibly a mix of both ballistic and cruise missiles.

In the case of US ballistic missile submarines, their location is so secret that not even the US Navy headquarters knows where they are at any given time. An example of a nuclear ballistic missile submarine is the US Ohio class. Submarines that carry SLBMs are used only by the major powers: US, Russia, UK, France and China.

Ohio-class ballistic missile submarine

Ohio-class submarines are designed to launch SLBMs and remain hidden for the duration of their missions. They displace 16,764 tonnes surfaced, 18,750 tonnes submerged and are 170m long. They are powered by an S8G reactor

Nuclear powered submarines versus conventional or AIP submarines

There are some fundamental operational differences between nuclear submarines and others with relation to their stealthiness and in particular their thermal and audio signatures.

Firstly, it has been said that nuclear submarines leave a thermal wake due to the need to continuously cool the reactor, which can, in theory, be used to detect them. However, in well over half a century of operation, no nuclear submarines are known to have been detected by this method, as at the depth they normally travel, the warm water would be quite dispersed by the time it reaches the surface.

Secondly, conventional submarines are reputed to be quieter and therefore harder to detect than nuclear submarines. The reason is that a nuclear submarine normally has cooling pumps running which make noise as well as steam noise when compared to a conventional submarine.

Of course, conventional submarines are only quiet when submerged; when they are surfaced or snorkelling they are running their diesel engines to recharge the batteries. Nuclear submarines are no noisier when surfaced than when submerged.

It is known with certainty that diesel submarines can be very quiet when submerged, as Australian submarines have been able to score "kills" on major US ships such as aircraft carriers during war games with the US Navy. What is not publicly known however is the true quietness of nuclear submarines. Given the success of nuclear submarines to date, it seems that the theoretical stealth advantage that conventional submarines might have over nuclear (when submerged) is unimportant in practice and has been dealt with by various noise suppression technologies.

In fact, in 2012, a Russian nuclear submarine sailed in international waters in the Gulf of Mexico, close to the USA, where it went undetected for several weeks despite expected US surveillance for submarines in the area so close to its shores.

Russia is now building nuclear submarines which are even more silent than those involved in this incident. See: www.siliconchip.com.au/l/aaaa

However, American nuclear submarines have been traditionally quieter than Soviet or Russian ones.

Also, the stealth advantages of conventional submarines would not apply when certain types of AIP are in use since it requires the running of a Stirling engine while submerged.

The real issue seems to be not that nuclear submarines are noisier than regular submarines but that all submarines are hard to find. In the marine environment finding a submarine is extremely difficult because of the huge number of noise sources, both natural and artificial.

Finding submarines very much comes down to the skill of sonar operators. It has been said that finding a submarine is like listening for a single car engine in a major city.

Also, passive sonar is normally used to search for submarines by other submarines. Active sonar, where "pings" are sent out, might be more effective but is not normally used because it discloses the position of the vessel emitting it.


Artist's concept of Cruise missile-converted Ohio class submarine launching Tomahawk missiles.

powering two turbines, each producing 45MW of propulsion power.

They are reported to be capable of 25 knots (46km/h) submerged and have an official test depth of 240m.

The main armament on the later version of the Ohio class is 24 Trident II D5 missiles, each of which can carry up to eight nuclear warheads with a 300-475 kiloton yield and with a range of 11,300km, along with a number of torpedoes.

After the end of the Cold War, four of these submarines were converted to launch a variety of different payloads apart from SLBMs. Examples of possible payloads include 154 Tomahawk cruise missiles, other supersonic or hypersonic cruise missiles, unmanned aerial vehicles (UAVs) and various intelligence-gathering sensors.

US Virginia-class submarine

The Virginia class are among the most advanced nuclear attack submarines in the Western world. They are designed for operation in shallow as well as deep water. They are expected to remain in service until as late as 2070.

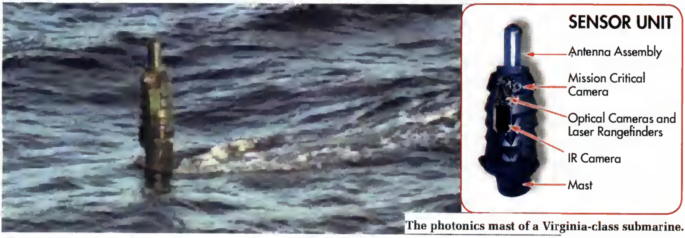
These subs displace 7900 tonnes, are 115m long, have 30MW of propulsive power and have an official top speed of 25 knots although some sources say they can travel at up to 28 knots (52km/h) when submerged, or possibly higher.

They have a test depth of 240m, a crew of 135 and depending on the version, can carry a combined 38 torpedoes and Tomahawk cruise missiles.

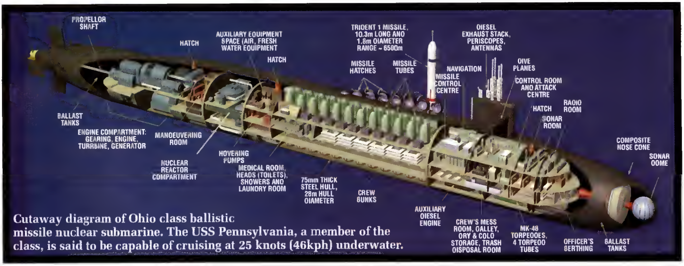
The Virginia class does not use a traditional periscope but has a number of masts for communications, radar, electronic warfare, snorkelling and photonics (ie, visual observation).

Unlike a traditional periscope that penetrates the hull and dictates the interior arrangement of the submarine, the photonics masts contain a variety of optical sensors and are connected with wires and optical fibres to the control room rather than a mechanical tube, enabling great flexibility in design as well as the rapid acquisition of data.

Because of the enormous power of a nuclear submarine, very careful attention has to be paid to the design of the propulsion system to avoid cavitation and the noise that it creates. Cavitation occurs when a propeller goes beyond a certain speed and bubbles (water vapour) form and cause noise when they collapse. The Virginia class uses pump jet



The photonics mast of a Virginia-class submarine.



Cutaway diagram of Ohio class ballistic missile nuclear submarine. The USS Pennsylvania, a member of the class, is said to be capable of cruising at 25 knots (46kph) underwater.

propulsion which is a type of ducted propeller, to minimise cavitation and other noise. No specific details are published but a picture is available of the pump jet propulsor of a US Seawolf-class submarine, which was cancelled before production due to excessive cost (See www.bluebird-electric.net/submarines/submarine_pictures/USS-SeaWolf_fast_attack_submarine_stern_CAD_drawing.jpg).

Later versions of the Virginia class have replaced 12 cruise missile launch tubes with two multi-purpose vertical Virginia Payload Tubes (VPTs) which can carry a variety of items such as Tomahawk cruise missiles, unmanned undersea vehicles (UUVs) or other types of weapons or equipment for specific missions.

From 2019, an additional section will be added to submarines under construction, adding a whole new 21m-long section with an additional four VPTs which will be the same diameter but taller than the other two.

Conclusion

So, as you may gather from the above, both nuclear-powered and conventional-powered submarines have distinct advantages. But it's the nuclear-powered types which have the distinct advantage on range, submerged speed, carrying capacity, power availability and various other parameters which arguably makes them the ultimate sea-based covert military platform. SC

Links, books and videos

"Questions asked of Australia's rejection of nuclear submarines" http://siliconchip.com.au/l/aaab

"The First Nuclear Submarine in The World" (About the USS Nautilus.) https://youtu.be/FeVwEtmwOqg

"The Untold Story of American Submarine Espionage: A Story of Heroes and Spies (1998)" https://youtu.be/yIG4H3QOvH4

"Blind Man's Bluff: The Untold Story Of American Submarine Espionage", Book by Sherry Sontag and Christopher Drew, 1998

"USS Virginia - The Virginia-class fast attack Submarine Fleet answering the Call of Duty to 2060" https://youtu.be/_4mhcE2vPns

"USS Pennsylvania Nuclear Submarine-HD Documentary" (About a ballistic missile submarine.) https://youtu.be/TQLFMRAbOiU

"The Largest Submarine in The U.S. Navy" (About a ballistic missile submarine.) https://youtu.be/UxB11eAl-YE

"Nuclear Depth Charge: Operation Wigwam Nuclear Test 1955 DOE, USAF Lookout Mountain" https://youtu.be/7vR5n_arLwo

AUTHOR'S NOTE: All information in this article was obtained from freely available public sources.

Two views of the Virginia class Ship Control Panel from where the boat is manouevered. The usual four crew positions of helmsman, planesman, chief of the watch and diving officer were combined so that two crew could perform all those roles from two workstations. These crew are called the pilot and co-pilot.