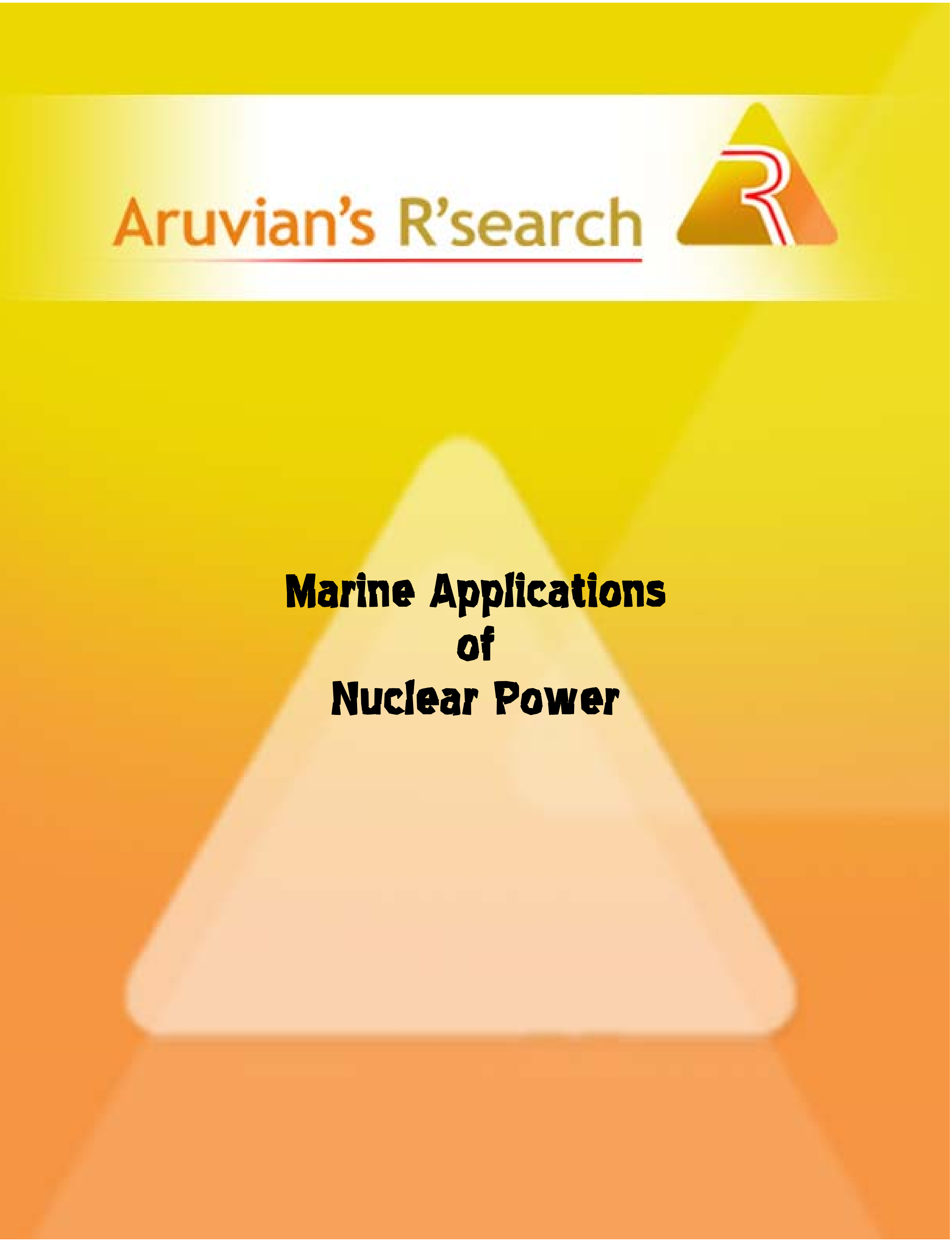

Aruvian's R'search

Marine Applications of Nuclear Power

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A. Executive Summary

The advent of modern civilization has powered the ever expanding human footprint on earth which is now present all across land, air and sea. In a historical perspective of the world, some of society's earliest expansion objectives were met through the sea itself. Thereby, the role played by the oceans and human activity across them has been vital politically as well as in commerce. Today, the modern society also does a sizeable chunk of commerce and holds active political interests in the oceans. It has become an established fact that major industrial commerce takes place by the sea route itself as compared to the air route. In defense terms, the major nations of the world have actively developed their naval strengths as defenders, force projectors, front openers as well as defense backbones. Thus, the role of an exceptional naval fleet in any nation's defense and commerce policy is undeniably critical to the country's geo political success. Today, there are naval forces which are as huge as entire cities on water as they are purpose built for global power presence. Undoubtedly, this entire activity has equally huge energy consumption needs.

In land and air based systems energy needs can be met by transport for land as well as base support or midair support for air needs, the jigsaw comes to fore at sea wherein energy may actually decide the outcome. The operational dynamics of providing energy support at sea are challenging as vessels may not even dock for long periods at go and the support provider itself cannot afford to be marooned in the middle of nowhere. Initially, some nations answered this challenge by powering their naval assets on fossil fuel systems. These worked fine for some time but a growing realization soon dawned upon them that constant replenishment, maintenance, limitation of storage and safety were dampening factors.

The scientific community of developed nations took up the challenge by identifying the two basic needs of energy support at sea. Firstly, the resource had to be long lasting and provide enough energy to meet a multitude of operational requirements in action as well as at peace. Secondly, the resource should have longer replenishment cycles thereby allowing longer range, independence of operation and more uptime to the naval asset at sea. The only resource which has succeeded in meeting all such conditions as also displayed ease of scaling up from built up capabilities is the nuclear energy option.

The adaptation of nuclear energy to power global naval assets has revolutionized the thought process behind this crucial industry. Aruvian's R'search's report on Marine Applications of Nuclear Power focuses on this crucial industry which is a sterling example of technology pushing the physical boundaries of business and defense. The report develops a comprehensive understanding of this subject as under:

a) A clear and comprehensive understanding of nuclear marine propulsion, particularly in terms of military and civilian use; including the various types of marine-type nuclear reactors.

b) The various applications of a nuclear navy. This includes an in-depth analysis of nuclear-powered aircraft carriers, nuclear-powered submarines, and other nuclear-powered vessels.

c) An analysis of the benefits and challenges facing the development of marine applications of nuclear power.

d) Development over the years of the many types of naval nuclear reactors. These include the analysis of the S1W pressurized water reactor design, the large ship reactors, SIR/ S1G intermediate flux beryllium sodium cooled reactor, and many others.

e) An analysis of the naval reactors in the United States, including the designation system for reactors, and the various naval reactors and power plants. Nuclear reactors analyzed include the A1B reactor, A1W rector, C1W reactor, and many others. The analysis also includes an analysis of various types of nuclear-powered submarines owned by the United States.

f) Economic viability of a nuclear navy for the United States

g) A complete analysis of commercial nuclear ships and their reactor designs.

h) Analysis of the nuclear navies around the world.

i) The emerging technologies of All-Electric Propulsion and the various stealth technologies in use are also analyzed. This includes an analysis of anti-submarine warfare as well as the use of free electron laser and the electromagnetic rail gun.

j) An in-depth analysis of nuclear-powered ships used for both civil and naval purposes.

k) A section is dedicated to the analysis of the nuclear-powered surface ships in the United States, including a comparison between conventional and nuclear power usage for ships. The US Navy's Nuclear Propulsion Program is also analyzed, along with an analysis of the current Navy nuclear-powered ships. Cost factor impacting the development of these types of ships are also analyzed.

l) Moving on to an analysis of nuclear-powered icebreakers. The section analyzes the Russian expertise in this industry along with the many rector types that are used in the icebreaks. An analysis of some nuclear-powered icebreakers such as the Lenin Nuclear Icebreaker, the Sevmorput, NS 50 Let Pobedy, etc., completed the section. Use of the nuclear-powered icebreakers for tourism purposes is also touched upon.

m) Nuclear submarines are perhaps the most important application of nuclear power in the marine industry. We analyze the technical features in a nuclear-powered submarine, along with the submarine force of various countries, including China, India, France, Russia, the UK, and the US. Submarines under development are also analyzed, including any new technical developments. The upcoming developments in Argentina, Brazil, and South Korea are also analyzed.

n) An analysis of the nuclear submarines worldwide sums up the in-depth analysis of nuclear-powered submarines.

o) Any report on nuclear-powered marine applications is incomplete without an analysis of Russia's nuclear-powered naval fleet. We carry out a comprehensive coverage of Russia's nuclear-powered naval fleet starting with the military and civilian vessel classes and generations. The section is divided into an analysis of the civilian marine nuclear reactors in Russia and the military marine nuclear reactors in Russia. A well-covered industry forecast concludes this section.

p) The emergence of China and India as forces to reckon with in terms of their Nuclear Navy is looked upon in this report in an analysis of China's Submarine Force and India's Nuclear Navy.

Overall, the research report Marine Applications of Nuclear Power from Aruvian's R'search builds a complete understanding of both civilian and military uses of nuclear power in the marine industry.

Section 1: Understanding Nuclear Power

B. Basics of the Nuclear Industry

Nuclear power is the controlled use of nuclear reactions to release energy for work including propulsion, heat, and the generation of electricity. Human use of nuclear power to do significant useful work is currently limited to nuclear fission and radioactive decay. Nuclear energy is produced when a fissile material, such as uranium-235 (235U), is concentrated such that nuclear fission takes place in a controlled chain reaction and creates heat - which is used to boil water, produce steam, and drive a steam turbine. The turbine can be used for mechanical work and also to generate electricity. Nuclear power is used to power most military submarines and aircraft carriers and provides seven percent of the world's energy and 15.7% of the world's electricity.

History of Nuclear Power

The first successful experiment with nuclear fission was conducted in 1938 in Berlin by the German physicists Otto Hahn, Lise Meitner and Fritz Strassmann.

During the Second World War, a number of nations embarked on crash programs to develop nuclear energy, focusing first on the development of nuclear reactors. The first self-sustaining nuclear chain reaction was obtained at the University of Chicago by Enrico Fermi on December 2, 1942, and reactors based on his research were used to produce the plutonium necessary for the "Fat Man" weapon dropped on Nagasaki, Japan. Several nations began their own construction of nuclear reactors at this point, primarily for weapons use, though research was also being conducted into their use for civilian electricity generation.

Electricity was generated for the first time by a nuclear reactor on December 20, 1951 at the EBR-I experimental fast breeder station near Arco, Idaho, which initially produced about 100 kW.

In 1952 a report by the Paley Commission (The President's Materials Policy Commission) for President Harry Truman made a "relatively pessimistic" assessment of nuclear power, and called for "aggressive research in the whole field of solar energy".

A December 1953 speech by President Dwight Eisenhower, "Atoms for Peace", set the U.S. on a course of strong government support for the international use of nuclear power.

On June 27, 1954, the world's first nuclear power plant to generate electricity for a power grid started operations at Obninsk, USSR. The reactor was graphite moderated; water cooled and had a capacity of five megawatts (MW). The world's first commercial nuclear power station, Calder Hall in Sellafield, England was opened in 1956, a gas-cooled Magnox reactor with an initial capacity of 50 MW (later 200 MW). The Shippingport Reactor (Pennsylvania, 1957), a pressurized water reactor, was the first commercial nuclear generator to become operational in the United States.

In 1954, the chairman of the United States Atomic Energy Commission (forerunner of the U.S. Nuclear Regulatory Commission) talked about electricity being "too cheap to meter" in the future, often misreported as a concrete statement about nuclear power, and foresaw 1000 nuclear plants on line in the U.S. by the year 2000.

In 1955 the United Nations' "First Geneva Conference", then the world's largest gathering of scientists and engineers, met to explore the technology. In 1957, EURATOM was launched alongside the European Economic Community (the latter is now the European Union). The same year also saw the launch of the International Atomic Energy Agency (IAEA).

Installed nuclear capacity initially rose relatively quickly, rising from less than 1 gigawatt (GW) in 1960 to 100 GW in the late 1970s, and 300 GW in the late 1980s. Since the late 1980s capacity has risen much more slowly, reaching 366 GW in 2005, primarily due to Chinese expansion of nuclear power. Between around 1970 and 1990, more than 50 GW of capacity was under construction (peaking at over 150 GW in the late 70s and early 80s). More than two-thirds of all nuclear plants ordered after January 1970 were eventually cancelled.

During the 1970s and 1980s rising economic costs (related to vastly extended construction times largely due to regulatory changes and pressure-group litigation) and falling fossil fuel prices made nuclear power plants then under construction less attractive. In the 1980s (U.S.) and 1990s (Europe), flat load growth and electricity liberalization also made the addition of large new baseload capacity unattractive.

A general movement against nuclear power arose during the last third of the 20th century, based on the fear of a possible nuclear accident and on fears of radiation, and on the opposition to nuclear waste production, transport and final storage. Perceived risks on the citizens' health and safety, the 1979 accident at Three Mile Island and the 1986 Chernobyl disaster played a key part in stopping new plant construction in many countries. Austria (1978), Sweden (1980) and Italy (1987) voted in referendums to oppose or phase out nuclear power, while opposition in Ireland prevented a nuclear program there. However, the Brookings Institution suggests that new nuclear units have not been ordered in the U.S. primarily for economic reasons rather than fears of accidents.

Types of Nuclear Reactors

Fission Reactor

The nuclear fission reactor produces heat through a controlled nuclear chain reaction in a critical mass of fissile material. All current nuclear power plants are critical fission reactors, which are the focus of this article. The output of fission reactors is controllable. There are several subtypes of critical fission reactors, which can be classified as Generation I, Generation II and Generation III. All reactors will be compared to the Pressurized Water Reactor (PWR), as that is the standard modern reactor design. The difference between fast-spectrum and thermal-spectrum reactors will be covered later. In general, fast-spectrum reactors will produce less waste, and the waste they do produce will have a vastly shorter half-life, but they are more difficult to build, and more expensive to operate. Fast reactors can also be breeders, whereas thermal reactors generally cannot.

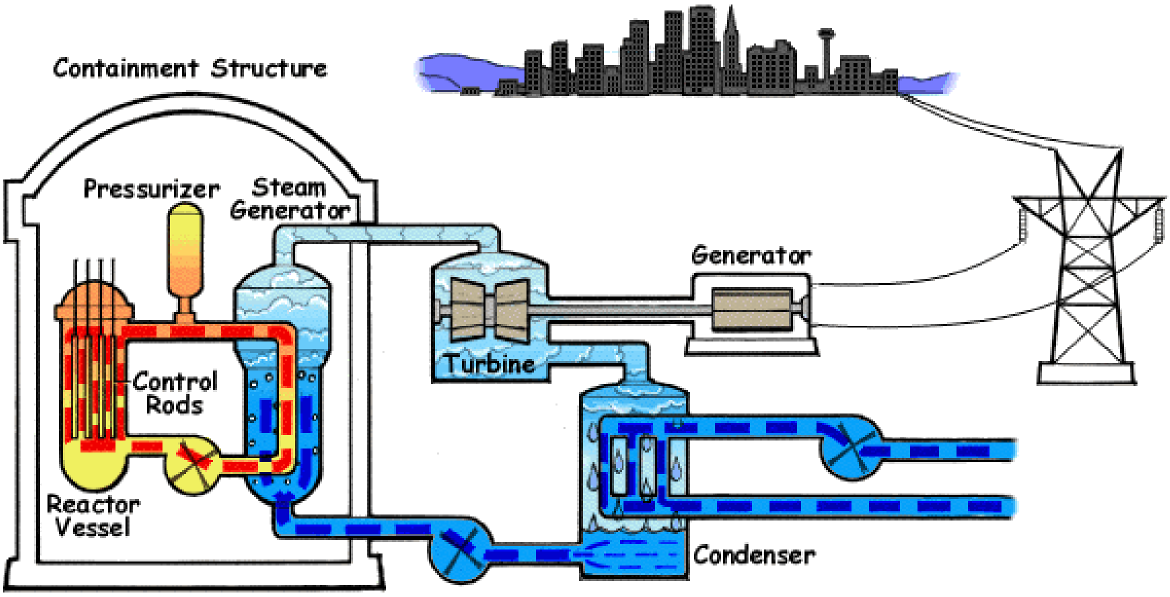
Pressurized Water Reactors

Pressurized water reactors (PWRs) (also VVER) are generation II nuclear power reactors that use water under high pressure as coolant and neutron moderator. The primary coolant loop is kept under high pressure to prevent the water from boiling, hence the name. PWRs are one of the most common types of reactors and are widely used all over the world. More than 230 of them are in use to generate electric power, and several hundred more for naval propulsion. They were originally designed by the Bettis Atomic Power Laboratory as a nuclear submarine power plant. Heat from small PWRs has also been used for heating in Polar Regions.

A PWR works because the nuclear fuel in the reactor vessel is engaged in a chain reaction, which produces heat as the main goal of the entire setup. That heats the water in the primary coolant loop by thermal conduction through the fuel cladding. (The primary coolant loop is shown in the schematic as a red dashed line.) The hot water is pumped into a certain type of heat exchanger called steam generator, which allows the primary coolant to heat up the secondary coolant (shown as the loop steam generator → turbine → condenser). The transfer of heat is accomplished without mixing the two fluids since the primary coolant is necessarily radioactive, but it is desirable to avoid this for the secondary coolant.

The steam formed in the steam generator is allowed to flow through a steam turbine, and the energy extracted by the turbine is used to drive an electric generator. In nuclear submarines the electricity is fed to an electric engine used for propulsion, whereas in a nuclear power station the generator is connected to the electric grid for distribution, as shown above. After passing through the turbine the secondary coolant is cooled down in a condenser before being fed into the steam generator again. This reduces the pressure at the turbine outlet, which helps improve thermal efficiency.

Figure 1: Pressurized Water Reactor



Two things are characteristic for the pressurized water reactor (PWR) when compared with other reactor types:

- In a PWR, there are two separate coolant loops (primary and secondary), which are both filled with ordinary water (also called light water). A boiling water reactor, by contrast, has only one coolant loop, while more exotic designs such as breeder reactors use substances other than water for the task.
- The pressure in the primary coolant loop is at typically 16 Megapascal, notably higher than in other nuclear reactors. As an effect of this, the gas laws guarantee that the primary coolant loop's water will never boil during the normal operation of the reactor. By contrast, in a boiling water reactor the primary coolant is allowed to boil and is in some designs fed directly to the turbine without the use of a secondary loop.

PWR Reactor Design

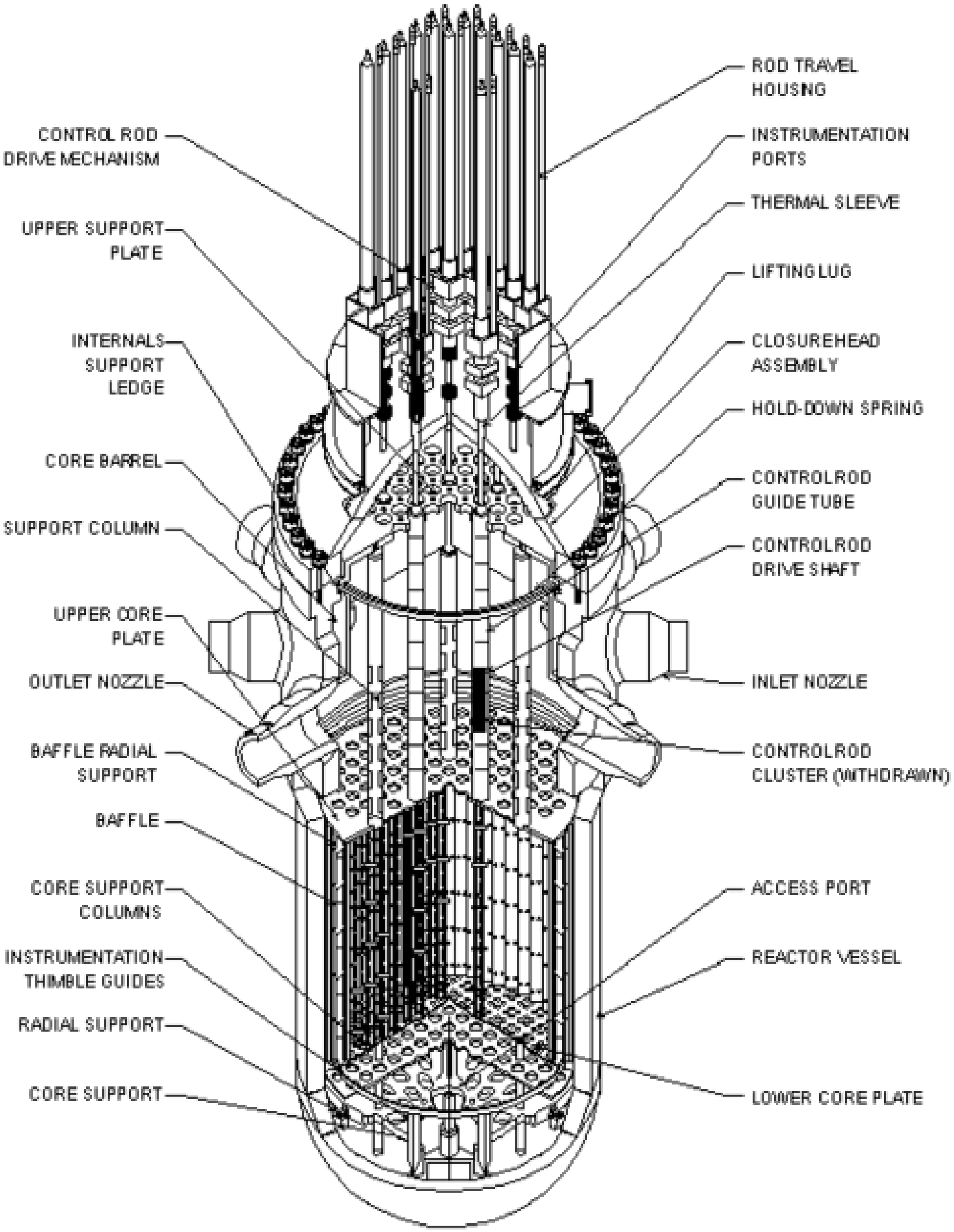
Coolant: Ordinary water is used as primary coolant in a PWR and flows through the reactor at a temperature of roughly 315°C (600°F). The water remains liquid despite the high temperature due to the high pressure in the primary coolant loop (usually around 2200 psig [15 MPa, 150 atm]). The primary coolant loop is used to heat water in a secondary circuit that becomes saturated steam (in most designs 900 psia [6.2 MPa, 60 atm], 275 °C [530 °F]) for use in the steam turbine. Although coolant flow rate in commercial PWRs is constant, it is not in nuclear reactors used on U.S. Navy ships.

Moderator: Pressurized water reactors, like thermal reactor designs, require the fast fission neutrons in the reactor to be slowed down (a process called moderation) in order to sustain its chain reaction. Since the mass of a water molecule is very similar to the size of a neutron, the water molecules cause the neutrons to undergo multiple collisions, which slows the neutrons down. This "moderating" of neutrons will happen more often when the water is denser (more collisions will occur). In PWRs the coolant water is used as a moderator by letting the neutrons scatter off light hydrogen atoms in the coolant, losing speed in the process. The use of water as a moderator is an important safety feature of PWR reactors, as any increase in temperature causes the water to expand and become less dense; thereby reducing the extent to which neutrons are slowed down and hence reducing the reactivity in the reactor. Therefore, if reactor activity increases beyond normal, the reduced moderation of neutrons will cause the chain reaction to slow down, producing less heat. This makes PWR reactors very stable. In contrast, the RBMK reactor design used at Chernobyl (using graphite instead of water as the moderator) greatly increases heat generation when coolant water temperatures increase, making them very unstable. This flaw in the RBMK reactor design is generally seen as one of several causes of the Chernobyl accident.

Fuel: The uranium used in PWR fuel is usually enriched several percent in 235U. After enrichment the uranium dioxide (UO2) powder is fired in a high-temperature, sintering furnace to create hard, ceramic pellets of enriched uranium dioxide. The cylindrical pellets are then put into tubes of a corrosion-resistant zirconium metal alloy (Zircoloy) which are backfilled with helium to aid heat conduction. The finished fuel rods are grouped in fuel assemblies, called fuel bundles that are then used to build the core of the reactor. As a safety measure PWR designs do not contain enough fissile uranium to sustain a prompt critical chain reaction. Avoiding prompt criticality is important as a prompt critical chain reaction could very rapidly produce enough energy to damage or even melt the reactor (as is suspected to have occurred during the accident at the Chernobyl plant). A typical PWR has fuel assemblies of 200 to 300 rods each, and a large reactor would have about 150-250 such assemblies with 80-100 tons of uranium in all. Generally, the fuel bundles consist of fuel rods bundled 14x14 to 17x17. A PWR produces on the order of 900 to 1500 MWe. PWR fuel bundles are about 4 meters in length.

Control: Reactor power in most commercial and military PWR's is normally controlled by varying the concentration of boric acid in the primary reactor coolant. The boron readily absorbs neutrons and increasing or decreasing its concentration in the reactor will therefore affect the neutron activity correspondingly. An entire control system involving high pressure pumps (usually called the charging and letdown system) is required to remove water from the high pressure primary loop and re-inject the water back in with differing concentrations of boric acid. The reactor control rods, inserted through the top directly into the fuel bundle, are normally only used for startup and shut down operations. In contrast, BWR's have no boron in the reactor coolant and control reactor power by adjusting the reactor coolant flow rate. This is an advantage for the BWR design because boric acid is very corrosive and the complex charging and letdown system is not required. However, as a backup to control-blade insertion, most commercial BWRs do have an emergency shutdown system which involves injecting a highly concentrated boric acid solution into the primary coolant circuit. CANDU reactors also inject boron as a backup means to shut down the nuclear chain reaction. Power in most naval nuclear reactors is regulated by the height of the control rods.

Figure 2: Pressurized Water Reactor Vessel



Advantages of PWR Reactors

- PWR reactors are very stable due to their tendency to produce less power as temperatures increase, this helps reduce the chance of losing control of the chain reaction;

- PWR reactors can be operated with a core containing less fissile material than is required for them to go prompt critical. This significantly reduces the chance that the reactor will run out of control and makes PWR designs very safe;

- Because PWR reactors use enriched uranium as fuel they can use ordinary water as a moderator rather than the much more expensive heavy water;

- PWR has two coolant loops, so the water in the secondary loop is not contaminated by radioactive materials.

Disadvantages of PWR Reactors

- The coolant water must be heavily pressurized to remain liquid at high temperatures. This puts strong requirements on the piping and pressure vessel and hence increases construction costs;

- Most pressurized water reactors cannot be refueled while operating. This limits the efficiency of the reactor and also means it has to go offline for comparably long periods of time;

- The very hot water coolant with boric acid dissolved in it is corrosive to steel, causing radioactive corrosion products to circulate the primary coolant loop. This not only limits the lifetime of the reactor, but the systems that filter out the corrosion products add significantly to the overall cost of the reactor;

- Water absorbs neutrons making it necessary to enrich the uranium fuel, which increases the costs of fuel production. If heavy water is used it is possible to operate the reactor with natural uranium, but production of heavy water requires large amounts of energy and is hence expensive;

- Because water acts as a neutron moderator it is not possible to build a fast neutron reactor with a PWR design. For this reason it is not possible to build a fast breeder reactor with water coolant. It is however possible to build a thermal breeder reactor using heavy water coolant;

- Because the reactor produces energy more slowly at higher temperatures, a sudden cooling of the reactor coolant could increase power production until safety systems shut down the reactor.

Boiling Water Reactors

A boiling water reactor (BWR) is a type of light-water nuclear reactor developed by the General Electric Company in the mid-1950s. It is characterized by two-phase fluid flow (water and steam) in the upper part of the reactor core. Light water (i.e., common distilled water) is the working fluid used to conduct heat away from the nuclear fuel. The water around the fuel elements also "thermalizes" neutrons, i.e., reduces their kinetic energy, which is necessary to improve the probability of fission of fissile fuel. Fissile fuel material, such as the U-235 and Pl-239 isotopes, have large capture cross sections for thermal neutrons.

Light water is ordinary water. In comparison, some other water-cooled reactor types use heavy water. In heavy water, the deuterium isotope of hydrogen replaces the common hydrogen atoms in the water molecules (D2O instead of H2O, atomic weight 20 instead of 18).

The Pressurized Water Reactor (PWR) was the first type of light-water reactor developed because of its application to submarine propulsion. The BWR cannot be used for submarine or other maritime applications, and thus the motivation for the BWR is reducing costs for commercial applications through design simplification and lower pressure components.

In contrast to the pressurized water reactor (PWR), in a BWR the steam going to the turbine that powers the electrical generator is produced in the reactor core rather than in steam generators or heat exchangers. There is a single circuit in a BWR in which the water is at lower pressure (about 75 times atmospheric pressure) compared to a PWR so that it boils in the core at about 285°C. The reactor is designed to operate with steam comprising 12–15% of the volume of the two-phase coolant flow (the "void fraction") in the top part of the core, resulting in less moderation, lower neutron efficiency and lower power density than in the bottom part of the core. In comparison, there is no significant boiling allowed in a PWR because of the high pressure maintained in its primary loop (about 158 times atmospheric pressure).

Inside of a BWR reactor pressure vessel (RPV), feed water enters through nozzles high on the vessel, well above the top of the nuclear fuel assemblies (these nuclear fuel assemblies constitute the "core") but below the water level. The feed water is pumped into the RPV from the condensers located underneath the low pressure turbines and after going through feed water heaters that raise its temperature using extraction steam from various turbine stages.

The feed water enters into the downcomer region and combines with water exiting the water separators. The feed water subcools the saturated water from the steam separators. This water now flows down the downcomer region, which is separated from the core by a tall shroud. The water then goes through either jet pumps or internal recirculation pumps that provide additional pumping power (hydraulic head). The water now makes a 180 degree turn and moves up through the lower core plate into the nuclear core where the fuel elements heat the water. When the flow moves out of the core through the upper core plate, about 12 to 15% of the flow by volume is saturated steam.

The heating from the core creates a thermal head that assists the recirculation pumps in recirculating the water inside of the RPV. A BWR can be designed with no recirculation pumps and rely entirely on the thermal head to recirculate the water inside of the RPV. The forced recirculation head from the recirculation pumps is very useful in controlling power, however. The thermal power level is easily varied by simply increasing or decreasing the speed of the recirculation pumps.

The two phase fluid (water and steam) above the core enters the riser area, which is the upper region contained inside of the shroud. The height of this region may be increased to increase the thermal natural recirculation pumping head. At the top of the riser area is the water separator. By swirling the two phase flow in cyclone separators, the steam is separated and rises upwards towards the steam dryer while the water remains behind and flows horizontally out into the downcomer region. In the downcomer region, it combines with the feed water flow and the cycle repeats.

The saturated steam that rises above the separator is dried by a chevron dryer structure. The steam then exits the RPV through four main steam lines and goes to the turbine.

Reactor power is controlled via two methods: by inserting or withdrawing control rods and by changing the water flow through the reactor core.

Positioning (withdrawing or inserting) control rods is the normal method for controlling power when starting up a BWR. As control rods are withdrawn, neutron absorption decreases in the control material and increases in the fuel, so reactor power increases. As control rods are inserted, neutron absorption increases in the control material and decreases in the fuel, so reactor power decreases. Some early BWRs and the proposed ESBWR designs use only natural circulation with control rod positioning to control power from zero to 100% because they do not have reactor recirculation systems.

Changing (increasing or decreasing) the flow of water through the core is the normal and convenient method for controlling power. When operating on the so-called "100% rod line," power may be varied from approximately 70% to 100% of rated power by changing the reactor recirculation system flow by varying the speed of the recirculation pumps. As flow of water through the core is increased, steam bubbles ("voids") are more quickly removed from the core, the amount of liquid water in the core increases, neutron moderation increases, more neutrons are slowed down to be absorbed by the fuel, and reactor power increases. As flow of water through the core is decreased, steam voids remain longer in the core, the amount of liquid water in the core decreases, neutron moderation decreases, fewer neutrons are slowed down to be absorbed by the fuel, and reactor power decreases.

Steam produced in the reactor core passes through steam separators and dryer plates above the core and then directly to the turbine, which is part of the reactor circuit. Because the water around the core of a reactor is always contaminated with traces of radionuclides, the turbine must be shielded during normal operation, and radiological protection must be provided during maintenance. The increased cost related to operation and maintenance of a BWR tends to balance the savings due to the simpler design and greater thermal efficiency of a BWR when compared with a PWR. Most of the radioactivity in the water is very short-lived (mostly N-16, with a 7 second half life), so the turbine hall can be entered soon after the reactor is shut down.

Like the pressurized water reactor, the BWR reactor core continues to produce heat from radioactive decay after the fission reactions have stopped, making nuclear meltdown possible in the event that all safety systems have failed and the core does not receive coolant. Also like the pressurized water reactor, a boiling-water reactor has a negative void coefficient, that is, the thermal output decreases as the proportion of steam to liquid water increases inside the reactor.

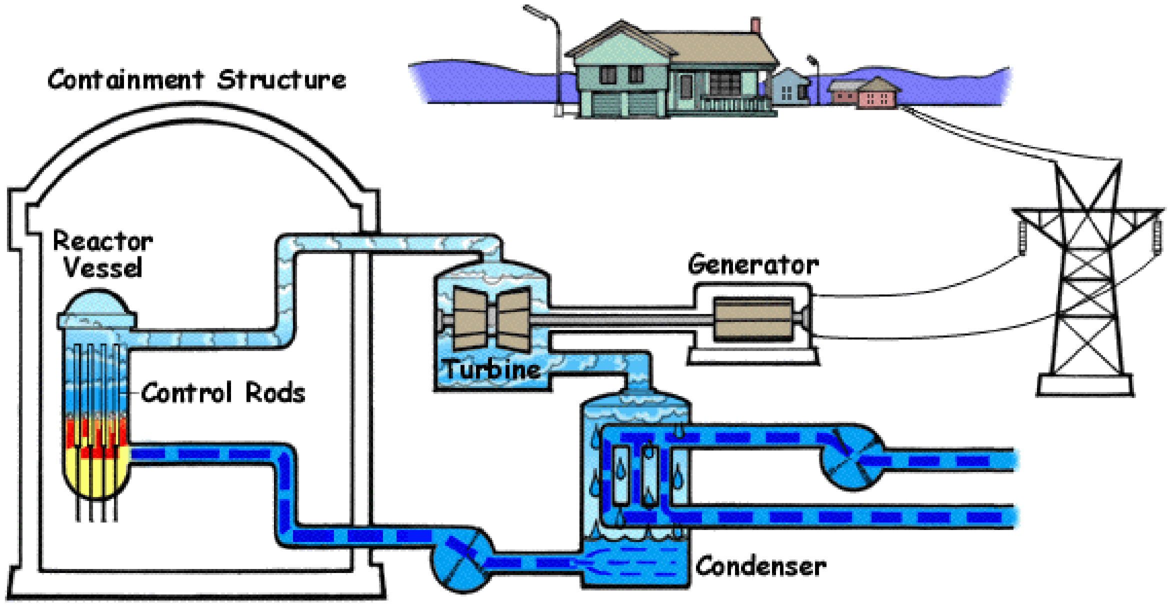
However, unlike a pressurized water reactor which contains no steam in the reactor core, a sudden increase in BWR steam pressure (caused, for example, by a blockage of steam flow from the reactor) will result in a sudden decrease in the proportion of steam to liquid water inside the reactor. The increased ratio of water to steam will lead to increased neutron moderation, which in turn will cause an increase in the power output of the reactor. Because of this effect in BWRs, operating components and safety systems are designed to ensure that no credible, postulated failure can cause a pressure and power increase that exceeds the safety systems' capability to quickly shutdown the reactor before damage to the fuel or to components containing the reactor coolant can occur.

In the event of an emergency that disables all of the safety systems, each reactor is surrounded by a containment building designed to seal off the reactor from the environment.

A modern BWR fuel assembly comprises 74 to 100 fuel rods, and there are up to approximately 800 assemblies in a reactor core, holding up to approximately 140 tons of uranium. The number of fuel assemblies in a specific reactor is based on considerations of desired reactor power output, reactor core size and reactor power density.

The current generation of BWRs, in operation in Japan, are called Advanced Boiling Water Reactors (ABWR).

Figure 3: Boiling Water Reactor



Advantages of BWR

- The reactor vessel and associated components operate at a substantially lower pressure (about 75 times atmospheric pressure) compared to a PWR (about 158 times atmospheric pressure);

- Pressure vessel is subject to significantly less irradiation compared to a PWR, and so does not become as brittle with age;

- Operates at a lower nuclear fuel temperature;

- Fewer components due to no steam generators and no pressurizer vessel. (Older BWRs have external recirculation loops, but even this piping is eliminated in modern BWRs, such as the ABWR.);

- Lower risk (probability) of a rupture causing loss of coolant compared to a PWR, and lower risk of a severe accident should such a rupture occur. This is due to fewer pipes, fewer large diameter pipes, fewer welds and no steam generator tubes;

- Measuring the water level in the pressure vessel is the same for both normal and emergency operations, which results in easy and intuitive assessment of emergency conditions;

- Can operate at lower core power density levels using natural circulation without forced flow;

- A BWR may be designed to operate using only natural circulation so that recirculation pumps are eliminated entirely. (The new ESBWR design uses natural circulation only.).

Disadvantages of BWR

- Complex operational calculations for managing the utilization of the nuclear fuel in the fuel elements during power production due to "two phase fluid flow" (water and steam) in the upper part of the core (less of a factor with modern computers). More incore nuclear instrumentation is required;

- Much larger pressure vessel than for a PWR of similar power, with correspondingly higher cost. (However, the overall cost is reduced because a modern BWR has no main steam generators and associated piping.);

- Contamination of the turbine by fission products;

- Shielding and access control around the steam turbine are required during normal operations due to the radiation levels arising from the steam entering directly from the reactor core. Additional precautions are required during turbine maintenance activities compared to a PWR;

- Control rods are inserted from below for current BWR designs. There are two available hydraulic power sources that can drive the control rods into the core for a BWR under emergency conditions. There is a dedicated high pressure hydraulic accumulator and also the pressure inside of the reactor pressure vessel available to each control rod. Either the dedicated accumulator (one per rod) or reactor pressure is capable of fully inserting each rod. Most other reactor types use top entry control rods that are held up in the withdrawn position by electromagnets, causing them to fall into the reactor by gravity if power is lost.

Advanced Boiling Water Reactor

The Advanced Boiling Water Reactor (ABWR) is a Generation III reactor based on the boiling water reactor. The ABWR was designed by General Electric. The standard ABWR plant design has a net output of about 1350 megawatts electrical.

Internal recirculation pumps inside of the reactor pressure vessel (RPV) are a major improvement over previous GE reactor plant designs (BWR/6 and prior). These pumps are powered by wet-rotor motors with the housings connected to the bottom of the RPV and eliminating large diameter external recirculation pipes that are possible leakage paths. Construction costs are also reduced. The 10 internal recirculation pumps are located at the bottom of the downcomer region (i.e., between the core shroud and the inside surface of the RPV).

Even though BWRs can operate using only the available natural recirculation thermal pumping head without forced recirculation flow, forced flow is desirable in order to increase the available output from the reactor and as a convenient method to change the reactor output by changing the flow.

Prior to the ABWR, all large commercial nuclear steam supply systems provided by GE from the BWR/3 through the BWR/6 designs used jet pump recirculation systems. These systems have two large recirculation pumps (each up to 9000 Hp) located outside of the reactor pressure vessel (RPV). Each pump takes a suction from the bottom of the downcomer region through a large diameter nozzle and discharges through multiple jet pumps inside of the RPV in the downcomer region. There is one nozzle per jet pump for the discharge back into the RPV and the external headers supplying these nozzles. Valves are required to isolate this piping in the event of a failure.

Consequently, internal recirculation pumps eliminate all of the jet pumps (typically 10), all of the external piping, the isolation valves and the large diameter nozzles that penetrated the RPV and needed to suction water from and return it to the RPV.

The first reactors to use internal recirculation pumps were designed by ASEA-Atom (now Westinghouse Electric Sweden by way of mergers and buyouts, which is owned by Toshiba) and built in Sweden. These plants have operated very successfully for many years.

The internal pumps reduce the required pumping power for the same flow to about half that required with the jet pump system with external recirculation loops. Thus, in addition to the safety and cost improvements due to eliminating the piping, the overall plant thermal efficiency is increased. Eliminating the external recirculation piping also reduces occupational radiation exposure to personnel during maintenance.

A nice operational feature in the ABWR design is electric fine motion control rod drives. Older BWRs use a hydraulic system to move the control rods in six-inch increments.

The ABWR is fully automated in response to a loss of coolant accident (LOCA), and operator action is not required for 3 days. These and other improvements make the plant significantly safer than previous reactors.

Advanced Liquid Metal Reactor (ALMR)

The acronym ALMR stands for Advanced Liquid Metal Reactor. Substantial work has been done by General Electric, with the help of Argonne National Laboratory, in designing a reactor of this type. Their design is called the PRISM. PRISM stands for Power Reactor Innovative Small Module. The ALMR (or PRISM) is a fast reactor but, unlike most fast reactors, it is not designed to breed significant amounts of Plutonium (though the core could be modified to optimize this).

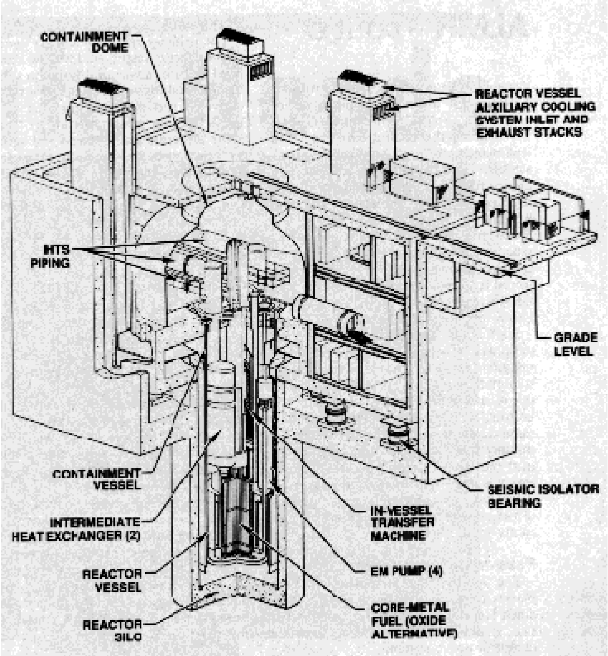
Each plant site contains three power blocks. A power block consists of three of these modular reactors, thus the use of the word Module in PRISM. Therefore, each reactor site contains nine reactors. Each reactor produces 160 MWe of power. A reactor producing this amount of power is considered to be small thus, the use of the word Small in PRISM. Each power block produces 480 MWe of power. The steam generated by the three reactors in a power block passes to a common steam turbine to generate electricity. Thus, the total plant produces 1440 MWe of power from three steam turbines.

A utility can choose to have less than three power blocks on a plant site or they can start with one and add-on power blocks as their demand increases. Even more significant to the economics of the utility is the fact that each reactor is licensed separately and that reactors on a power block can start producing electric power before the other reactors are even built.

The last PRISM innovation is the idea of the reactor components being built in a factory and shipped to the plant site; even the large reactor vessel. Currently, components are constructed at the plant site but, with this new approach, factory standards can be assured before the components are shipped.

At the present time, funding on the PRISM reactor has been discontinued, with no definite plan to resume research in the near future.

Figure 4: Advanced Liquid Metal Reactor



Pressurized Heavy Water Reactor

A pressurized heavy water reactor (PHWR) is a nuclear power reactor that uses unenriched natural uranium as its fuel and heavy water as a moderator (deuterium oxide D2O). The heavy water is kept under pressure in order to raise its boiling point, allowing it to be heated to higher temperatures and thereby carry more heat out of the reactor core. While heavy water is expensive, the reactor can operate without expensive fuel enrichment facilities thus balancing the costs.

The original commercial PHWRs are the CANDUs, a Canadian design built by AECL. Marketed world-wide, some 29 are in use, or under refurbishment. The Nuclear Power Corporation of India Limited (NPCIL) has built and operates 11 PHWR units. Initially these indigenously built reactors were reverse-engineered from the CANDU design, but later models have diverged significantly.

The current installed examples of pressurized heavy water reactors are to be superseded by more advanced designs in the future such as The Advanced Heavy Water Reactor (AHWR) being researched at BARC in India and by the Advanced CANDU Reactor under development by AECL in Canada.

Operation

In the CANDU-based design, heavy water is contained in a large tank called a calandria. Several hundred horizontal or vertical pressure tubes form channels for the fuel penetrate the calandria, which contain the nuclear fuel and are a part of the primary heat transport loop. The heat transport fluid flowing through the pressure tubes (usually heavy water, but also light water or oil in the past) and the heavy water in the calandria are separate and do not mix. As in the pressurized light water reactor, the primary coolant generates steam in a secondary circuit to drive the turbines. The pressure tubes containing the fuel rods can be individually opened, and the fuel rods changed without taking the reactor out of service. This reactor has the least down-time of any known type.

Purpose of Using Heavy Water

The key to maintaining a nuclear reaction within a nuclear reactor is to use the neutrons being released during fission to stimulate fission in other nuclei. With careful control over the geometry and reaction rates, this can lead to a self-sustaining chain reaction, a state known as "criticality".

Natural uranium consists of a mixture of various isotopes, primarily 238U and a much smaller amount (about 0.72% by weight) of 235U. 238U can only be fissioned by neutrons that are fairly energetic, about 1 MeV or above. No amount of 238U can be made "critical", however, since it will tend to parasitically absorb more neutrons than it releases by the fission process. 235U, on the other hand, can support a self-sustained chain reaction, but due to the low natural abundance of 235U, natural uranium cannot achieve criticality by itself.

The "trick" to making a working reactor is to slow some of the neutrons to the point where their probability of causing nuclear fission in 235U increases to a level that permits a sustained chain reaction in the uranium as a whole. This requires the use of a neutron moderator, which absorbs some of the neutrons' kinetic energy, slowing them down to an energy comparable to the thermal energy of the moderator nuclei themselves (leading to the terminology of "thermal neutrons" and "thermal reactors"). During this slowing-down process it is beneficial to physically separate the neutrons from the uranium, since 238U nuclei have an enormous parasitic affinity for neutrons in this intermediate energy range (a reaction known as "resonance" absorption). This is a fundamental reason for designing reactors with discrete solid fuel separated by moderator, rather than employing a more homogeneous mixture of the two materials.

Water makes an excellent moderator; the hydrogen atoms in the water molecules are very close in mass to a single neutron, and thus have a potential for high energy transfer, similar conceptually to the collision of two billiard balls. However, in addition to being a good moderator, water is also fairly effective at absorbing neutrons. Using water as a moderator will absorb enough neutrons that there will be too few left over to react with the small amount of 235U in the fuel, again precluding criticality in natural uranium. Instead, light water reactors first enhance the amount of 235U in the uranium, producing enriched uranium, which generally contains between three percent and five percent 235U by weight (the waste from this process is known as depleted uranium, consisting primarily of 238U). In this enriched form there is enough 235U to react with the water-moderated neutrons to maintain criticality.

One complication of this approach is the requirement to build an uranium enrichment facility, which are generally expensive to build and operate. They also present a nuclear proliferation concern; the same systems used to enrich the 235U can also be used to produce much more "pure" weapons-grade material (90% or more 235U), suitable for producing a nuclear bomb. This is not a trivial exercise, by any means, but simple enough that enrichment facilities present a significant nuclear proliferation risk.

An alternative solution to the problem is to use a moderator that does not absorb neutrons as readily as water. In this case potentially all of the neutrons being released can be moderated and used in reactions with the 235U, in which case there is enough 235U in natural uranium to sustain criticality. One such moderator is heavy water, or deuterium-oxide. Although it reacts dynamically with the neutrons in a similar fashion to light water (albeit with less energy transfer on average, given that heavy hydrogen, or deuterium, is about twice the mass of hydrogen), it already has the extra neutron that light water would normally tend to absorb.

The use of heavy water moderator is the key to the PHWR system, enabling the use of natural uranium as fuel (in the form of ceramic UO2), which means that it can be operated without expensive uranium enrichment facilities. Additionally, the mechanical arrangement of the PHWR, which places most of the moderator at lower temperatures, is particularly efficient because the resulting thermal neutrons are "more thermal" than in traditional designs, where the moderator normally runs hot. This means that the CANDU is not only able to "burn" natural uranium and other fuels, but tends to do so more effectively as well.

RBMK

RBMK is an acronym for the Russian Reaktor Bolshoy Moshchnosti Kanalniy, which means "reactor of high power of the channel type", and describes a now obsolete class of graphite-moderated nuclear power reactor which was built only in the Soviet Union. The RBMK reactor was the type involved in the Chernobyl accident. In 2004, several were still operating, but there were no plans to build any more and there is international pressure to close those that remain.

The RBMK was the culmination of the Soviet program to produce a water-cooled power reactor based on their graphite-moderated plutonium production military reactors. The first of these, AM-1 (Atom Mirny) produced 5 MW electric (30 MW thermal) and delivered power to Obninsk from 1954 until 1959.

Using light water for cooling and graphite for moderation, it is possible to use natural uranium for fuel. Thus, a large power reactor (RBMK reactors at the Ignalina Nuclear Power Plant in Lithuania were rated at 1500 MWe each, a very large size for the time and even for today) can be built that requires no separated isotopes, such as enriched uranium or heavy water. Unfortunately, such a configuration is also unstable.

Design

An RBMK employs long (7 meter) vertical pressure tubes running through a graphite moderator and cooled by water, which is allowed to boil in the core at 290 °C, much as in a boiling water reactor. Fuel is low-enriched uranium oxide made up into fuel assemblies 3.5 meters long. With moderation largely due to the fixed graphite, excess boiling simply reduces the cooling and neutron absorption without inhibiting the fission reaction, so the reactor can have a large positive void coefficient, and a positive feedback problem can arise, such as at Chernobyl, which was an RBMK reactor.

Because the water used to remove heat from the core in a light-water reactor absorbs some of the free neutrons normally generated during operation of the reactor, the concentration of the naturally fissionable U-235 isotope in uranium used to fuel light-water reactors must be increased above the level of natural uranium to assist in sustaining the nuclear chain reaction in the reactor core: the remainder of the uranium in the fuel is U-238. Increasing the concentration of U-235 in nuclear fuel uranium above the level that occurs in natural uranium is accomplished through the process of enrichment.

The fuel core for a light water reactor can have up to 3,000 fuel assemblies. An assembly consists of a group of sealed fuel rods, each filled with uranium oxide (UO2) pellets, held in place by end plates and supported by metal spacer-grids to brace the rods and maintain the proper distances between them. The fuel core can be thought of as a reservoir from which heat energy can be extracted through the nuclear chain reaction process. During the operation of the reactor, the concentration of U-235 in the fuel is decreased as those atoms undergo nuclear fission which creates heat energy. Some U-238 atoms are converted to atoms of fissile Pu-239, some of which will, in turn, undergo fission and produce energy. The products created by the nuclear fission reactions are retained within the fuel pellets and these become neutron-absorbing products, also called nuclear poisons that act to slow the rate of nuclear fission and heat production. As the reactor operation is continued, a point is reached at which the declining concentration of fissile nuclei in the fuel and the increasing concentration of poisons result in lower than optimal heat energy generation. The RBMK has a refueling machine that can change the fuel on-load, while the reactor is still producing power.

High Positive Void Coefficient

Water acts as both a neutron moderator, and hindrance to reaction. In this reactor design, pressurized water is the coolant, causing problems when changing phase to steam. Steam in the coolant water is a void, a bubble that neither moderates the reactor, nor hinders its speed. A reactor's tendency to reduce the effectiveness of its coolant with power output is measured as a void coefficient. A high void coefficient does not automatically make a reactor unsafe. The RBMK design included computer-driven control rods that controlled the reaction speed and, if necessary, stopped the reaction completely.

After the Chernobyl disaster, all RBMKs in operation underwent significant changes, lowering their void coefficients to +0.7 b. This new number precludes the possibility of a low-coolant meltdown.

Containment

The RBMK design includes several kinds of containment needed for normal operation. There is a sealed metal containment structure filled with inert gases surrounding the reactor to keep oxygen away from the graphite (which is normally at about 700 degrees Celsius). There is also a large amount of shielding to absorb radiation from the reactor core. This includes a concrete slab on the bottom, sand and concrete around the sides, and a large concrete slab on top of the reactor. Much of the reactor's internal machinery is attached to this top slab, including the water pipes.

Initially, the RBMK design focused solely on accident prevention and mitigation, not on containment of severe accidents. However, since the Three Mile Island incident, RBMK design also includes a partial containment structure (not a full containment building) for dealing with emergencies. The pipes underneath the reactor are sealed inside leak-tight boxes filled with a large amount of water. If these pipes leak or burst, the radioactive material is trapped by the water inside these boxes. However, RBMK reactors were designed to allow fuel rods to be changed without shutting down (as in the pressurized heavy water Candu reactor), both for refueling and for plutonium production (for nuclear weapons). This required large cranes above the core. As the RBMK reactor is very tall (about 70 meters), the cost and difficulty of building a heavy containment structure prevented building of additional emergency containment structure for pipes on top of the reactor. Unfortunately, in the Chernobyl accident, the pressure rose to levels high enough to blow the top off of the reactor, breaking open these pipes in the process.

Improvements since the Chernobyl Accident

Since the Chernobyl accident, all remaining RBMKs have been retrofitted with a number of updates for safety. The largest of these updates fixes the RBMK control rod design. Previously the control rods were designed with graphite tips, which when initially inserted into the reactor sped up the reaction, instead of slowing or stopping it. This design flaw caused the first explosion of the Chernobyl accident, when the emergency button was pressed to stop the reactor. The updates are:

- An increase in fuel enrichment from 2% to 2.4%. This difference improves neutron absorption, reducing the reliance on cooling water for reactor control;
- Manual control rod count increased from 30 to 45;
- About 80 additional absorbers inhibit operation at low power, where the RBMK design is most dangerous;
- SCRAM (rapid shut down) sequence reduced from 18 to 12 seconds;
- Precautions against unauthorized access to emergency safety systems.

Closures

Of the 13 RBMKs built (and one is still under construction at Kursk), all three surviving reactors at the Chernobyl plant have now been closed and both the reactors at Ignalina in Lithuania have been shut down as of 2010.

Gas Cooled Reactor & Advanced Gas Cooled Reactor

These are generally graphite moderated and CO2 cooled. They have a high thermal efficiency compared with PWRs and an excellent safety record. There are a number of operating reactors of this design, mostly in the United Kingdom. Older designs (i.e. Magnox stations) are either shut down or will be in the near future. However, the AGCRs have an anticipated life of a further 10 to 20 years. This is a thermal neutron reactor design.

An Advanced Gas Cooled Reactor (AGR) is a type of nuclear reactor. These are the second generation of British gas-cooled reactors, using graphite as the neutron moderator and carbon dioxide as coolant. The AGR was developed from the Magnox reactor, operating at a higher gas temperature for improved efficiency, and using enriched uranium fuel so requiring less frequent refueling.

All AGR power stations are configured with two reactors, each reactor with a power output of between 555 MWe and 625 MWe.

The design of the AGR was such that the final steam conditions at the boiler stop valve were identical to that of conventional power stations. Thus the same design of turbo-generator plant could be used. In order to obtain high temperatures, yet ensure useful graphite core life (graphite oxidizes readily in CO2 at high temperature) re-entrant flow is utilized, ensuring that the graphite core temperatures do not vary too much from those seen in a Magnox station.

The fuel is uranium dioxide pellets, enriched to 2.5-3.5%, in stainless steel tubes. The original design concept of the AGR was to use a beryllium based cladding. When this proved unsuitable, the enrichment level of the fuel was raised to allow for the higher neutron capture losses of stainless steel cladding. This significantly increased the cost of the power produced by an AGR. The carbon dioxide coolant circulates through the core, reaching 640°C and a pressure of around 40 bar, and then passes through boiler (steam generator) assemblies outside the core but still within the steel lined, reinforced concrete pressure vessel. Control rods penetrate the graphite moderator and a secondary shutdown system involves injecting nitrogen into the coolant or releasing boron ball shutdown devices.

The AGR has a good thermal efficiency (electricity generated/heat generated ratio) of about 41%, which is better than modern pressurized water reactors which have a typical thermal efficiency of 34%. This is largely due to the higher coolant outlet temperature of about 640°C practical with gas cooling, compared to about 325°C for PWRs. However the reactor core has to be larger for the same power output, and the fuel burnup ratio at discharge is lower so the fuel is used less efficiently, countering the thermal efficiency advantage.

Like the Magnox, CANDU and RBMK reactors, and in contrast to the light water reactors, AGRs are designed to be refueled without being shut down first. However fuel assembly vibration problems arose during on-load refueling at full power, so in 1988 full power refueling was suspended until the mid-1990s, when further trials lead to a fuel rod becoming stuck in a reactor core. Only refueling at part load or when shut down is now undertaken at AGRs.

The prototype AGR at the Sellafield (Windscale) site is in the process of being decommissioned. This project is also a study of what is required to decommission a nuclear reactor safely.

Currently there are seven nuclear generating stations each with two operating AGRs in the United Kingdom. They are all owned and operated by British Energy. These are located at Dungeness B, Hartlepool, Heysham 1, Heysham 2, Hinkley Point B, Hunterston B and Torness.

In 2006, AGRs made the news when documents were obtained under the Freedom of Information Act 2000 by The Guardian who claimed that British Energy were unaware of the extent of the cracking of graphite bricks in the cores of their reactors. It was also claimed that British Energy did not know why the cracking had occurred and that they were unable to monitor the cores without first shutting down the reactors. British Energy later issued a statement confirming that cracking of graphite bricks is a known symptom of extensive neutron bombardment and that they were working on a solution to the monitoring problem. Also, they stated that the reactors were examined every three years as part of "statutory outages".

Super Critical Water Cooled Reactor

The Supercritical water reactor (SCWR) is a Generation IV reactor concept that uses supercritical water as the working fluid. SCWRs are basically LWRs operating at higher pressure and temperatures with a direct, once-through cycle. As most commonly envisioned, it would operate on a direct cycle, much like a BWR, but since it uses supercritical water (not to be confused with critical mass) as the working fluid, would have only one phase present, like the PWR. It could operate at much higher temperatures than both current PWRs and BWRs.

Supercritical water-cooled reactors (SCWRs) are promising advanced nuclear systems because of their high thermal efficiency (i.e., about 45% vs. about 33% efficiency for current light water reactors (LWR) and considerable plant simplification.

The main mission of the SCWR is generation of low-cost electricity. It is built upon two proven technologies, LWRs, which are the most commonly deployed power generating reactors in the world, and supercritical fossil fuel fired boilers, a large number of which are also in use around the world. The SCWR concept is being investigated by 32 organizations in 13 countries.

Design

Moderator: The SCWR uses water as a neutron moderator. Moderation comes primarily from the high density subcritical water. This high-density water is either introduced from cooling tubes inserted into the core or as a reflector or moderated-part of the core.

Fuel: The fuel is traditional LWR fuel. However, it is likely the SCWR will use "canned" fuel elements like the BWR to reduce the chance of hotspots causing local variations in core properties.

Coolant: The coolant will be supercritical water. Operation above the critical pressure eliminates coolant boiling, so the coolant remains single-phase throughout the system. When under extreme pressure, water does not boil and turn to steam when heated - a condition known as supercritical. That means more of the heat produced via fission can be converted into electricity in reactors cooled with supercritical water. In addition, the elements that handle water's phase change from liquid to gas in conventional light water reactors can be cut from the design. Thus, the need for recirculation and jet pumps, pressurizers, steam generators, and steam separators and dryers in current LWRs is eliminated reducing construction costs.

Control: SCWRs would likely have control rods inserted through the top, as is done in PWRs.

Liquid Metal Fast Breeder Reactor

This is a reactor design that is cooled by liquid metal, totally unmoderated, and produces more fuel than it consumes. These reactors can function much like a PWR in terms of efficiency, and do not require much high pressure containment, as the liquid metal does not need to be kept at high pressure, even at very high temperatures. Superphénix in France was a reactor of this type, as was Fermi-I in the United States. All three use/used liquid sodium. These reactors are fast neutron, not thermal neutron designs. These reactors come in two types:

Lead cooled: Using lead as the liquid metal provides excellent radiation shielding, and allows for operation at very high temperatures. Also, lead is (mostly) transparent to neutrons, so fewer neutrons are lost in the coolant, and the coolant does not become radioactive. Unlike sodium, lead is mostly inert, so there is less risk of explosion or accident, but such large quantities of lead may be problematic from toxicology and disposal points of view. Often a reactor of this type would use a lead-bismuth eutectic mixture. In this case, the bismuth would present some minor radiation problems, as it is not quite as transparent to neutrons, and can be transmuted to a radioactive isotope more readily than lead.

Sodium cooled: Most LMFBRs are of this type. The sodium is relatively easy to obtain and work with, and it also manages to actually remove corrosion on the various reactor parts immersed in it. However, sodium explodes violently when exposed to water, so care must be taken, but such explosions wouldn't be vastly more violent than (for example) a leak of superheated fluid from a SCWR or PWR.

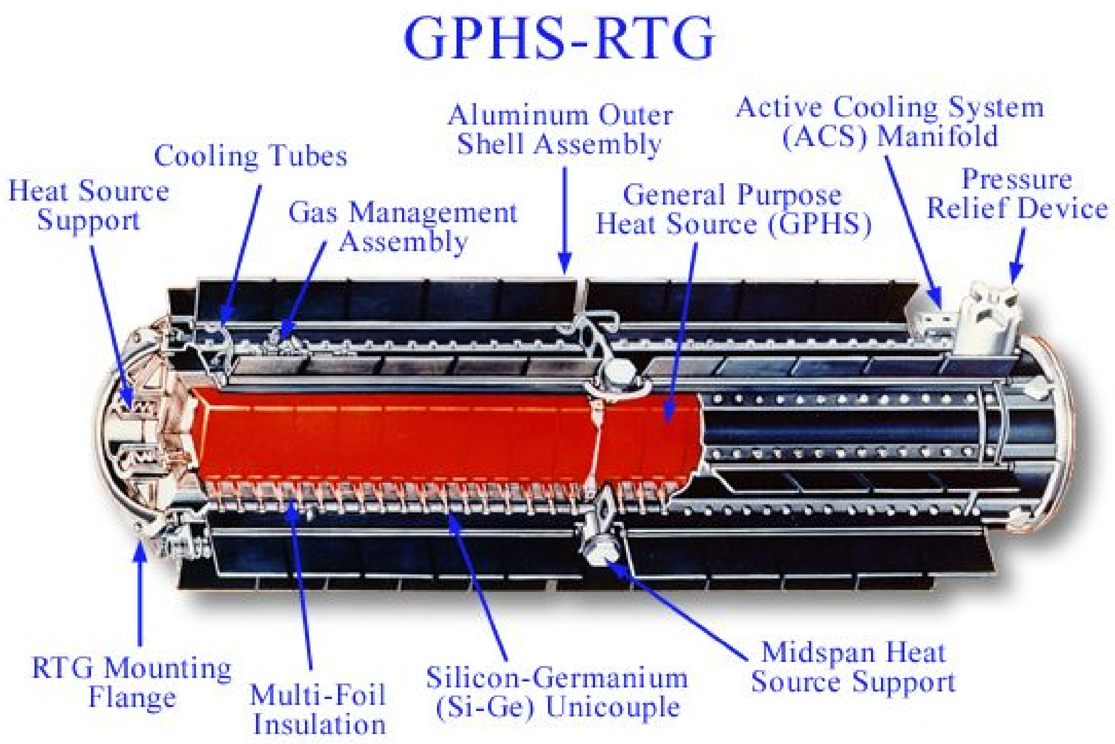
Radioisotope Thermoelectric Generator

The radioisotope thermoelectric generator (RTG) is a simple electrical generator which obtains its power from radioactive decay. In such a device, the heat released by the decay of a suitable radioactive material is converted into electricity by the Seebeck effect using an array of thermocouples. RTGs can be considered as a type of battery and have been used as power sources in satellites, space probes and unmanned remote facilities. RTGs are usually the most desirable power source for unmanned or unmaintained situations needing a few hundred watts or less of power for durations too long for fuel cells, batteries and generators to provide economically, and in places where solar cells are not viable.

Design

The design of an RTG is simple by the standards of nuclear technology: the main component is a sturdy container of a radioactive material (the fuel). Thermocouples are placed in the walls of the container, with the outer end of each thermocouple connected to a heat sink. Radioactive decay of the fuel produces heat which flows through the thermocouples to the heat sink, generating electricity in the process.

Figure 5: Radioisotope Thermoelectric Generator of Cassini Probe



A thermocouple is a thermoelectric device that converts thermal energy directly into electrical energy using the Seebeck effect. It is made of two kinds of metal (or semiconductors) that can both conduct electricity. They are connected to each other in a closed loop. If the two junctions are at different temperatures, an electric current will flow in the loop.

Fuels

The radioactive material used in RTGs must have several characteristics:

- The half-life must be long enough so that it will produce energy at a relatively continuous rate for a reasonable amount of time. However, at the same time, the half-life needs to be short enough so that it decays sufficiently quickly to generate a usable amount of heat. Typical half-lives for radioisotopes used in RTGs are therefore several decades, although isotopes with shorter half-lives could be used for specialized applications;

- For spaceflight use, the fuel must produce a large amount of energy per mass and volume (density). Density and weight are not as important for terrestrial use, unless there are size restrictions;

- It should produce high energy radiation that has low penetration, preferably alpha radiation. Beta radiation can give off considerable amounts of Gamma/X-ray radiation through bremsstrahlung secondary radiation production, thus requiring heavy shielding. Isotopes must not produce significant amounts of gamma, neutron radiation or penetrating radiation in general through other decay modes or decay chain products.

The first two criteria limit the number of possible fuels to fewer than 30 atomic isotopes within the entire isotope table of elements. Plutonium-238, curium-244 and strontium-90 are the most often cited candidate isotopes, but other isotopes such as polonium-210, promethium-147, caesium-137, cerium-144, ruthenium-106, cobalt-60, curium-242 and thulium isotopes have also been studied. Of the above, 238Pu has the lowest shielding requirements and longest half-life. Only three candidate isotopes meet the last criterion (not all are listed above) and need less than 25 mm of lead shielding to control unwanted radiation. 238Pu (the best of these three) needs less than 2.5 mm, and in many cases no shielding is needed in a 238Pu RTG, as the casing itself is adequate.

238Pu has become the most widely used fuel for RTGs, in the form of plutonium (IV) oxide (PuO2). 238Pu has a half-life of 87.7 years, reasonable energy density and exceptionally low gamma and neutron radiation levels. Some Russian terrestrial RTGs have used 90Sr; this isotope has a shorter half-life, much lower energy density and produces gamma radiation, but is cheaper. Some prototype RTGs, first built in 1958 by U.S. Atomic Energy Commission, have used 210Po; this isotope provides phenomenally huge energy density, but has limited use because of its very short half-life and some gamma ray production. A kilogram of pure 210Po in the form of a cube would be about 48 mm (about 2 inches) on a side and emit about 63.5 kilowatts of heat (about 140 W/g), easily capable of melting then vaporizing itself. 242Cm and 244Cm have also been studied well, but require heavy shielding from gamma and neutron radiation produced from spontaneous fission.

Americium-241 is a potential candidate isotope with a longer half-life than 238Pu: 241Am has a half-life of 432 years and could hypothetically power a device for centuries. However, the energy density of 241Am is only 1/4 that of 238Pu, and 241Am produces more penetrating radiation through decay chain products than 238Pu and needs about 18 mm worth of lead shielding. Even so, its shielding requirements in a RTG are the second lowest of all possible isotopes: only 238Pu requires less.

Use

The first RTG launched in space by the United States was in 1961 aboard the SNAP 3 in the Navy Transit 4A spacecraft. One of the first terrestrial uses of RTGs was in 1966 by the U.S. Navy at the uninhabited Fairway Rock Island in Alaska, where it remained in use until its removal in 1995.

A common application of RTGs is as power sources on spacecraft, Systems Nuclear Auxiliary Power Program (SNAP) units were used especially for probes that travel far enough from the Sun that solar panels are no longer viable. As such they are used with Pioneer 10, Pioneer 11, Voyager 1, Voyager 2, Galileo, Ulysses, Cassini and New Horizons. In addition, RTGs were used to power the two Viking landers and for the scientific experiments left on the Moon by the crews of Apollo 12 through 17 (SNAP 27s). RTGs were also used for the Nimbus, Transit and Les satellites. By comparison, only a few space vehicles have been launched using full-fledged nuclear reactors: the Soviet RORSAT series and the American SNAP-10A.

In addition to spacecraft, the Soviet Union constructed many unmanned lighthouses and navigation beacons powered by RTGs. Powered by 90Sr, they are very reliable and provide a steady source of power. However, critics argue that they could cause environmental and security problems, as leakage or theft of the radioactive material could pass unnoticed for years (or possibly forever: some of these lighthouses cannot be found because of poor record keeping). There has been even an instance where the radioactive compartments were opened by a thief; it was inferred that the resulting radiation poisoning has already killed the thief.

There are approximately 1,000 such RTGs in Russia. All of them have long exhausted their 10-year engineered life spans. They are likely no longer functional, and may be in need of dismantling. Some of them have become the prey of metal hunters, who strip the RTGs metal casings, regardless of the risk of radioactive contamination.

In the past, small "plutonium cells" (very small 238Pu-powered RTGs) were used in implanted heart pacemakers to ensure a very long "battery life". As of 2004 about 90 were still in use. They pose a hazard if the wearer is shot in the chest with a gun. If the wearer dies and the generator is not removed before cremation the device will be subject to great heat. It is unlikely however, if the plutonium is in the form of the dioxide, that contamination will occur. Note that plutonium 238 is more able to disperse than plutonium 239, but the dioxide is an air stable solid which is normally sintered in air at a temperature much higher than that used in the cremation of human remains (although they are designed to survive cremation).

Although not strictly RTGs, similar units called radioisotope heater units are also used by various spacecraft including the Mars Exploration Rovers, Galileo and Cassini. These devices use small samples of radioactive material to produce heat directly, instead of electricity.

Life Span

Most RTGs use 238Pu which decays with a half-life of 87.7 years. RTGs using this material will therefore lose 1 – 0.51/87.7 or 0.787% of their capacity per year - 23 years after production, such an RTG would produce at 0.523/87.7 or 83.4% of its starting capacity. Thus, with a starting capacity of 470 W, after 23 years it would have a capacity of 0.834 * 470 W = 392 W. However, the bi-metallic thermocouples used to convert thermal energy into electrical energy degrade as well; at the beginning of 2001, the power generated by the Voyager RTGs had dropped to 315 W for Voyager 1 and to 319 W for Voyager 2. Therefore in early 2001, the thermocouples were working at about 80% of their original capacity.

This life span was of particular importance during the Galileo mission. Originally intended to launch in 1986, it was delayed by the Space Shuttle Challenger accident. Due to this unforeseen event the probe had to sit in storage for four years before launching in 1989. Subsequently, its RTGs had decayed somewhat, necessitating replanning the power budget for the mission.

Efficiency

RTGs use thermoelectric couples or "thermocouples", to convert heat from the radioactive material into electricity. Thermocouples, though very reliable and long-lasting, are very inefficient; efficiencies above 10% have never been achieved and most RTGs have efficiencies between three to seven percent. However studies have been done on improving efficiency by using other technologies to generate electricity from heat. Achieving higher efficiency would mean less radioactive fuel is needed to produce the same amount of power, and therefore a lighter overall weight for the generator. This is a critically important factor in spaceflight launch cost considerations.

Energy conversion devices which rely on the principle of thermionic emission can achieve efficiencies between 10-20%, but require higher temperatures than those at which standard RTGs run. Some prototype 210Po RTG have used thermionics, and potentially other extremely radioactive isotopes could also provide power by this means, but short half-lives make these infeasible. Several space-bound nuclear reactors have used thermionics, but nuclear reactors are usually too heavy to use on most space probes.

Thermophotovoltaic cells work by the same principles as a photovoltaic cell, except that they convert infrared light emitted by a hot surface rather than visible light into electricity. Thermophotovoltaic cells have an efficiency slightly higher than thermocouples and can be overlaid on top of thermocouples, potentially doubling efficiency. Systems with radioisotope generators simulated by electric heaters have demonstrated efficiencies of 20%, but have not been tested with actual radioisotopes. Some theoretical thermophotovoltaic cell designs have efficiencies up to 30%, but these have yet to be built or confirmed. Thermophotovoltaic cells and silicon thermcouples degrade faster than thermocouples, especially in the presence of ionizing radiation. Further research is needed in this area.

Dynamic generators, unlike thermoelectrics, use moving parts to mechanically convert heat into electricity. Unfortunately, those moving parts can wear out and need maintenance, which may not be possible for certain applications like space probes. Dynamic power sources also cause vibration and RF noise. Even so, NASA has worked on developing a next generation RTG called a Stirling Radioisotope Generator (SRG) that uses Free-Piston Stirling engines to produce power. SRG prototypes demonstrated an average efficiency of 23%, and higher efficiency can be achieved with the use of greater temperature differentials between the hot and cold ends of the generator. The use of magnetically non-contacting moving parts, non-degrading flexural bearings, and a lubrication-free and hermetically sealed environment have, in test units, demonstrated no appreciable degradation over years of operation. Experimental results demonstrate that an SRG could continue running for decades without maintenance. Vibration can be reduced through damping and counter-piston movement. The most likely future use for SRGs may be future Mars Rovers where vibration is less of a worry.

Safety

Radioactive Contamination

RTGs are a potential source of radioactive contamination: if the container holding the fuel leaks, the radioactive material may contaminate the environment.

For spacecraft, the main concern is that if an accident were to occur during launch or a subsequent passage of a spacecraft close to Earth, harmful material could be released into the atmosphere; and their use in spacecraft and elsewhere has attracted controversy.

However, this event is not considered likely with current RTG cask designs. For instance, the environmental impact study for the Cassini-Huygens probe launched in 1997 estimated the probability of contamination accidents at various stages in the mission. The probability of an accident occurring which caused radioactive release from one or more of its 3 RTGs (or from its 129 RHUs) during the first 3.5 minutes following launch was estimated at 1 in 1,400; the chances of a release later in the ascent into orbit were 1 in 476; after that the likelihood of an accidental release fell off sharply to less than one in a million. If an accident which had the potential to cause contamination occurred during the launch phases (such as the spacecraft failing to reach orbit), the probability of contamination actually being caused by the RTGs was estimated at about 1 in 10. In the event, the launch was successful and Cassini-Huygens reached Saturn.

The plutonium 238 used in these RTGs has a half-life of 87.74 years, in contrast to the 24,110 year half-life of plutonium 239 used in nuclear weapons and reactors. A consequence of the shorter half-life is that plutonium 238 is about 275 times more radioactive than plutonium 239 (i.e. 17.3 Ci/g compared to 0.063 Ci/g). For instance, 3.6 kg of plutonium 238 undergoes the same number of radioactive decays per second as one ton of plutonium 239. Since the morbidity of the two isotopes in terms of absorbed radioactivity is almost exactly the same, plutonium 238 is around 275 times more toxic by weight than plutonium 239.

The alpha radiation both isotopes emit will not penetrate the skin, but can irradiate internal organs if plutonium is inhaled or ingested. Particularly at risk is the skeleton, whose surface it is likely to be absorbed on, and the liver, where it will collect and become concentrated.

There have been six known accidents involving RTG-powered spacecraft. The first one was a launch failure on 21 April 1964 in which the U.S. Transit-5BN-3 navigation satellite failed to achieve orbit and burnt up on re-entry north of Madagascar. Its 17,000 Ci (630 TBq) plutonium metal fuel was injected into the atmosphere over the Southern Hemisphere where it burnt up, and traces of plutonium 238 were detected in the area a few months later. The second was the Nimbus B-1 weather satellite whose launch vehicle was deliberately destroyed shortly after launch on 21 May 1968 because of erratic trajectory. Launched from the Vandenberg Air Force Base, its SNAP-19 RTG containing relatively inert plutonium dioxide was recovered intact from the seabed in the Santa Barbara Channel five months later and no environmental contamination was detected.

Two more were failures of Soviet Cosmos missions containing RTG-powered lunar rovers in 1969, both of which released radioactivity as they burnt up. There were also five failures involving Soviet or Russian spacecraft which were carrying nuclear reactors rather than RTGs between 1973 and 1993.

The failure of the Apollo 13 mission in April 1970 meant that the Lunar Module reentered the atmosphere carrying an RTG and burnt up over Fiji. It carried a SNAP-27 RTG containing 44,500 curies (1,650 TBq) of plutonium dioxide which survived reentry into the Earth's atmosphere intact, as it was designed to do, the trajectory being arranged so that it would plunge into 6-9 kilometers of water in the Tonga trench in the Pacific Ocean. The absence of plutonium 238 contamination in atmospheric and seawater sampling confirmed the assumption that the cask is intact on the seabed. The cask is expected to contain the fuel for at least 10 half-lives (i.e. 870 years).

The U.S. Department of Energy has conducted seawater tests and determined that the graphite casing, which was designed to withstand reentry, is stable and no release of plutonium should occur. Subsequent investigations have found no increase in the natural background radiation in the area. The Apollo 13 accident represents an extreme scenario due to the high re-entry velocities of the craft returning from cislunar space. This accident has served to validate the design of later-generation RTGs as highly safe.

To minimize the risk of the radioactive material being released, the fuel is stored in individual modular units with their own heat shielding. They are surrounded by a layer of iridium metal and encased in high-strength graphite blocks. These two materials are corrosion and heat-resistant. Surrounding the graphite blocks is an aeroshell, designed to protect the entire assembly against the heat of reentering the earth's atmosphere. The plutonium fuel is also stored in a ceramic form that is heat-resistant, minimizing the risk of vaporization and aerosolization. The ceramic is also highly insoluble.

The most recent accident involving a spacecraft RTG was the failure of the Russian Mars 96 probe launch on 16 November 1996. The two RTGs onboard carried in total 200 g of plutonium and are assumed to have survived reentry (as they were designed to do). They are thought to now lie somewhere in a northeast-southwest running oval 320 km long by 80 km wide which is centered 32 km east of Iquique, Chile.

Nuclear Fission

RTGs use a different process of heat generation from that used by nuclear power stations. Nuclear power stations generate power by a chain reaction in which the nuclear fission of an atom releases neutrons which cause other atoms to undergo fission. This allows the rapid reaction of large numbers of atoms, thereby producing large amounts of heat for electricity generation. However, if the reaction is not carefully controlled the number of atoms undergoing fission (and the heat production) can grow exponentially, very rapidly becoming hot enough to destroy the reactor.

Chain reactions do not occur inside RTGs, so such a nuclear meltdown is not possible. In fact, some RTGs are designed so that fission does not occur at all; rather, forms of radioactive decay which cannot trigger other radioactive decays are used instead. As a result, the fuel in an RTG is consumed much more slowly and much less power is produced.

There are no nuclear proliferation risks associated with plutonium-238 because it is unsuitable for making nuclear weapons. The major reason for this is that plutonium-238 undergoes spontaneous fission at a high rate and thus emits neutrons randomly, causing the chain reaction to start too early in the triggering process. This would cause a plutonium-238 bomb to "fizzle", greatly reducing its reliability and power. Moreover, plutonium-238 is very hot; this would complicate the manufacturing process.

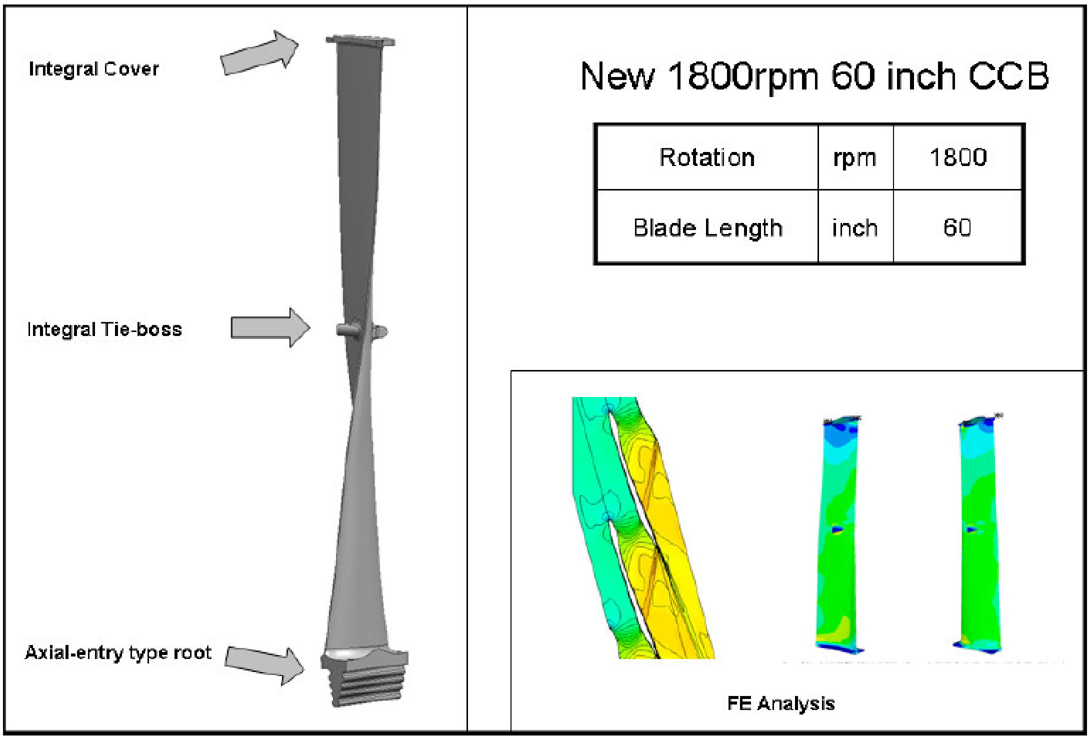
New & Upcoming Nuclear Technologies

Long Last Stage Blades

Long last stage blades produce approximately 10% of the total output of large steam turbines, and since they experience the largest centrifugal force, they are a critically important component affecting the performance and reliability of the overall product. The requirement for longer last stage blades results in larger steam flows and higher steam speeds, larger centrifugal forces, and various refined natural frequencies, thus requiring more advanced design technologies to optimize performance, strength and vibration characteristics of the blades.

Since the early 1980's many companies has continuously developed new and improved last stage blades. The next new blade designs offered today for nuclear turbine applications will be the 60 inch last stage blade for 60 Hz applications, followed by the same blade length for 50 Hz applications. Development of this new blade is in progress and is expected to be completed in 2013.

Figure 6: New 60 Hz Last Stage Blade



Rotation	rpm	1800
Blade Length	inch	60

Figure 7: 60 Hz Last Stage Blades for Nuclear Applications (Marked)

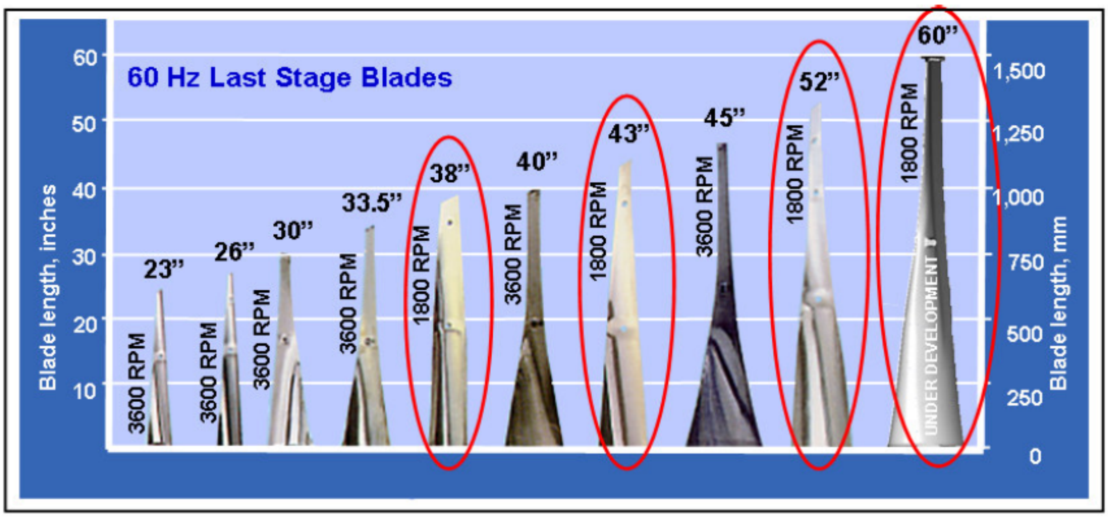
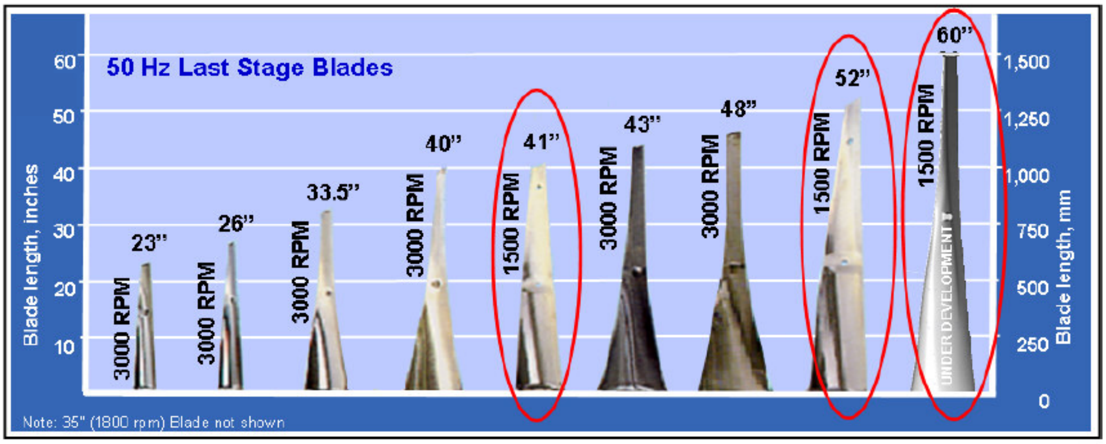


Figure 8: 50 Hz Last Stage Blades for Nuclear Applications (Marked)



Continuous Cover Blades (CCB)

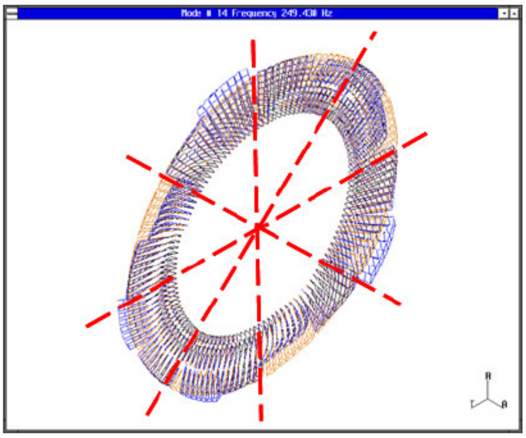
Based on a number of cutting-edge design technologies, Hitachi has developed and is in the process of developing, a series of new blades for nuclear turbines featuring a Continuous Cover Blade (CCB) structure and axial type blade roots that offer better overall performance and superior strength and vibration characteristics. The CCB and axial type root technology has been adopted from fossil turbines, where this mature technology has demonstrated an excellent operational track record, outstanding operating characteristics and high reliability since its introduction in 1991.

Hitachi's CCB design forms a continuously coupled blade structure to improve vibration characteristics relative to older designs. It also includes integral shrouds and mid-span supports to eliminate the reliability problems associated with tie-wires.

Adjacent blades in steam turbines are generally linked together to provide greater rigidity and to reduce or dampen vibrations. The old blade assemblies that were held together by tenons, caulked shrouds and tie wires had a number of drawbacks, mostly related to stress concentration and assembly.

The CCB blades have contact surfaces (cover and tie boss) that are integral to the construction of the blade and therefore create significantly lower stress concentrations. Moreover, the untwisting of the pre-twisted blades during rotation, which is caused by centrifugal force, is restrained by the contact surfaces between blades. As a result, at rated shaft speed all of the blades are connected and interlocked to form a continuous ring of blades.

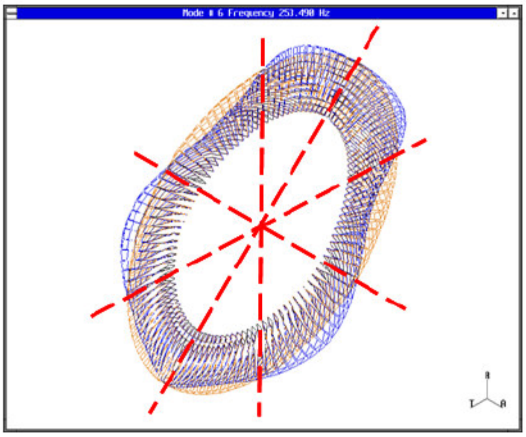
Conventional, Grouped Blade



Complex Mode

Blades are bundled together with tie wires. Each blade group has a separate natural frequency and amplitude.

New, Continuous Cover Blade



Pure Sinusoidal Mode

Each Blade is connected with the adjacent blade => Each blade operates in the same frequency mode

In comparison with the conventionally grouped blade configurations the CCB structure has better damping, fewer resonance points during rotation, more stable vibration characteristics (due to the interlocking of blades), reduced resonance stress levels, reduced random vibration stress levels, and suppressed flutter. Moreover, the CCB technology allows for the use of the high-low type radial fin as a tip seal, which leads to a better labyrinth effect and hence, increased stage efficiency. Such high-low type radial fins are not feasible for conventional blade tip portions that have shrouds with protruding tenons.

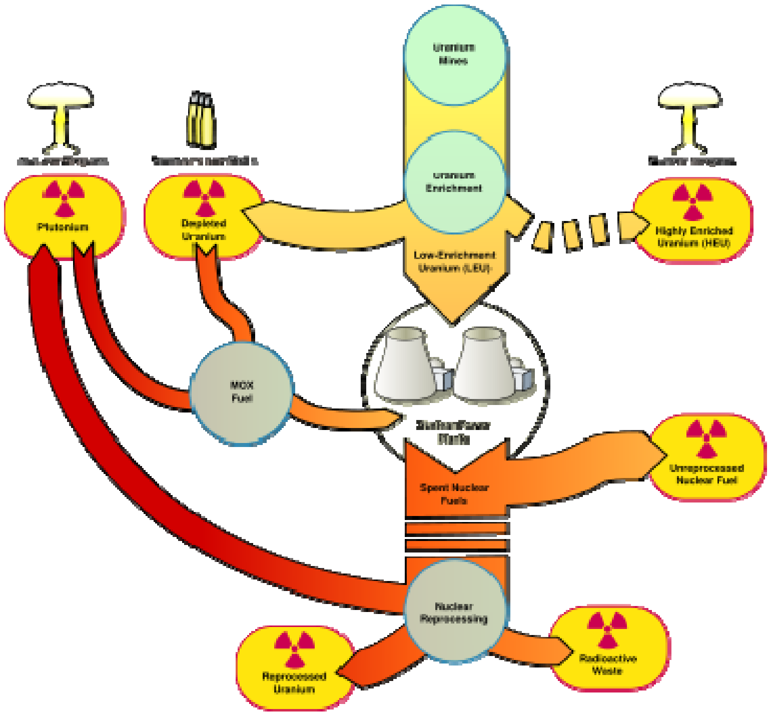
Components & Parts of a Nuclear Power Plant

The key components common to most types of nuclear power plants are described below:

Nuclear Fuel

Nuclear fuel is any material that can be consumed to derive nuclear energy, by analogy to chemical fuel that is burned to derive energy. By far the most common type of nuclear fuel is heavy fissile elements that can be made to undergo nuclear fission chain reactions in a nuclear fission reactor; nuclear fuel can refer to the material or to physical objects (for example fuel bundles composed of fuel rods) composed of the fuel material, perhaps mixed with structural, neutron moderating, or neutron reflecting materials. The most common fissile nuclear fuels are 235U and 239Pu, and the actions of mining, refining, purifying, using, and ultimately disposing of these elements together make up the nuclear fuel cycle, which is important for its relevance to nuclear power generation and nuclear weapons.

Figure 9: Process depicting Nuclear Fuel Cycle



Not all nuclear fuels are used in fission chain reactions. For example, 238Pu and some other elements are used to produce small amounts of nuclear power by radioactive decay in radiothermal generators, and other atomic batteries. Light isotopes such as 3H (tritium) are used as fuel for nuclear fusion. If one looks at binding energy of specific isotopes, there can be an energy gain from fusing most elements with a lower atomic number than iron, and fissioning isotopes with a higher atomic number than iron.

Figure 10: Comparison of Nucleon Number against Binding Energy

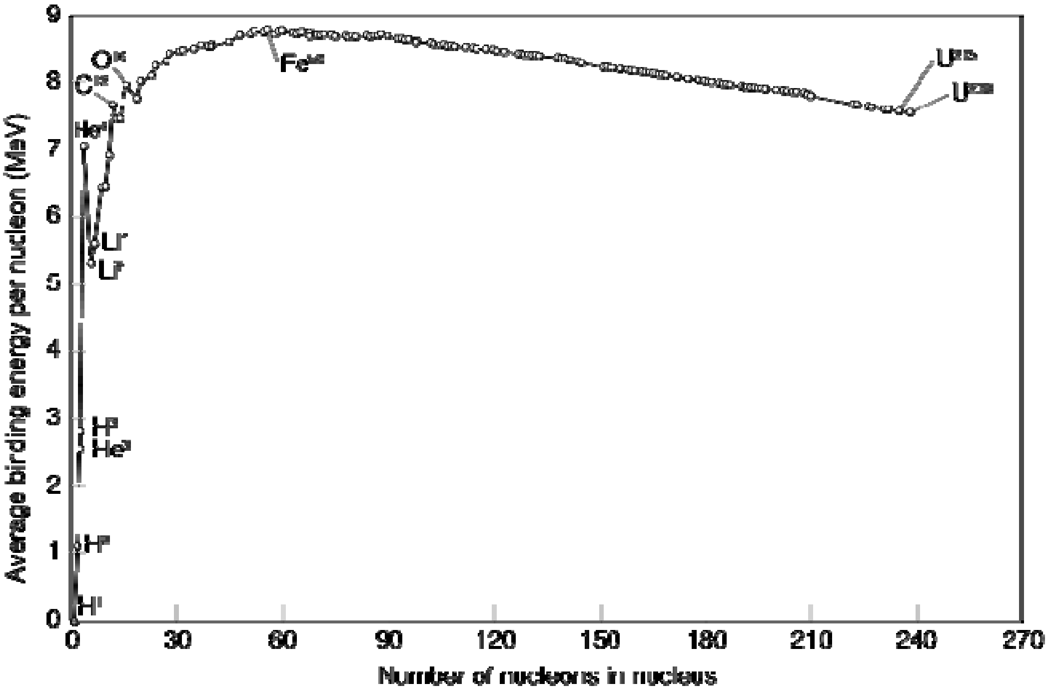
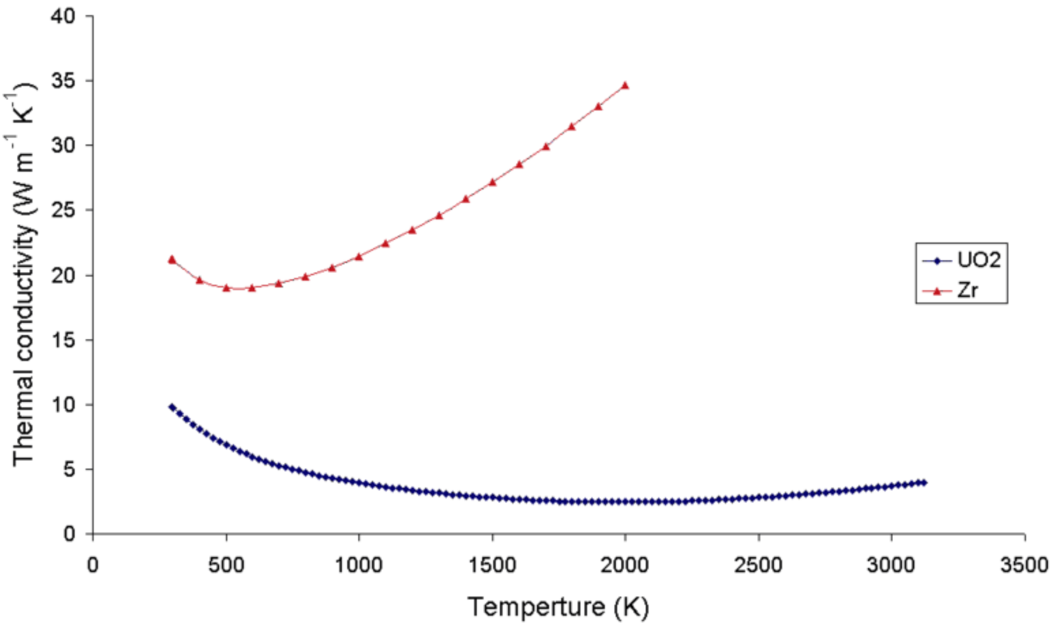


Figure 11: Thermal Conductivity of Zirconium Metal & Uranium Dioxide as a Function of Temperature



Neutron Moderator

In nuclear engineering, a neutron moderator is a medium which reduces the velocity of fast neutrons, thereby turning them into thermal neutrons capable of sustaining a nuclear chain reaction. Commonly used moderators include deuterium (as heavy water), hydrogen (as ordinary or light water) and graphite. Beryllium has also been used in some experimental types, and hydrocarbons have been suggested as another possibility.

In a thermal nuclear reactor, the nucleus of a heavy fuel element such as uranium absorbs a slow-moving free neutron, becomes unstable, and then splits ("fissions") into two smaller atoms ("fission products"). The fission process for uranium atoms yields two fission products, two to three fast-moving free neutrons, plus an amount of energy primarily manifested in the kinetic energy of the recoiling fission products. Because more free neutrons are released from a uranium fission event than are required to initiate the event, the reaction can become self-sustaining - a chain reaction - under controlled conditions, thus liberating a tremendous amount of energy.

However, the probability of further fission events occurring is dependent upon the speed (energy) of the incident neutrons. Faster neutrons are much less likely to cause further fission (Note: It is not impossible for fast neutrons to cause fission, just much less likely). The newly-released fast neutrons, moving at roughly 10% the vacuum speed of light, must be slowed down or "moderated", typically to speeds of a few kilometers per second, if they are likely to cause further fission in neighboring uranium nuclei and hence continue the chain reaction.

A good neutron moderator is a material full of atoms with light nuclei which do not easily absorb neutrons. The neutrons strike the nuclei and bounce off. In this process, some energy is transferred between the nucleus and the neutron. More energy is transferred per collision if the nucleus is lighter. After sufficiently many such impacts, the velocity of the neutron will be comparable to the thermal velocities of the nuclei; this neutron is then called a thermal neutron.

A fast reactor uses no moderator, but relies on fission produced by unmoderated fast neutrons to sustain the chain reaction.

Coolant

A coolant, or heat transfer fluid, is a fluid which flows through a device in order to prevent its overheating, transferring the heat produced by the device to other devices that utilize or dissipate it. An ideal coolant has high thermal capacity, is low-cost, and is chemically inert, neither causing nor promoting corrosion of the cooling system. Some applications also require the coolant to be an electrical insulator.

The coolant can either keep its phase and stay liquid or gaseous, or can undergo a phase change, with the latent heat adding to the cooling efficiency. The latter, when used to achieve low temperatures, is more commonly known as refrigerant.

Air is a common form of a coolant. Air cooling uses either convective airflow (passive cooling), or a forced circulation using fans.

Inert gases are also frequently used as coolants in gas-cooled nuclear reactors. Helium is the most favored coolant due to its low tendency to absorb neutrons and become radioactive. Nitrogen and carbon dioxide are frequently used as well.

Sulfur hexafluoride is used for cooling and insulating of some high-voltage power systems (circuit breakers, switches, some transformers, etc.).

Steam can be used where high specific heat capacity is required in gaseous form and the corrosive properties of hot water are accounted for.

The most common liquid coolant is water. Its high heat capacity and low cost makes it a suitable heat-transfer medium. It is usually used with additives, like corrosion inhibitors and antifreezes. Antifreeze, a solution of a suitable organic chemical (most often ethylene glycol, diethylene glycol, or propylene glycol) in water, is used when the water-based coolant has to withstand temperatures below 0 °C, or when its boiling point has to be raised.

Very pure deionized water, due to its relatively low electrical conductivity, is used to cool some electrical equipment, often high-power transmitters.

Heavy water is used in some nuclear reactors; it also serves as a neutron moderator.

Oils are used for applications where water is unsuitable.

Liquid fusible alloys can be used as coolants in applications where high temperature stability is required, e.g. some fast breeder nuclear reactors. Sodium or sodium-potassium alloy NaK are frequently used. Another liquid metal used as a coolant is lead, in e.g. lead cooled fast reactors, or a lead-bismuth alloy. Some early fast neutron reactors used mercury.

For very high temperature applications, e.g. molten salt reactors or very high temperature reactors, molten salts can be used as coolants. One of the possible combinations is the mix of sodium fluoride and sodium tetrafluoroborate (NaF-NaBF4).

Freons were frequently used for immersive cooling of e.g. electronics.

Refrigerants are coolants used for reaching low temperatures by undergoing phase change between liquid and gas. Halomethanes were frequently used, most often R-12 and R-22, but due to environmental concerns are being phased out, often with liquefied propane or other haloalkanes like R-134a. Anhydrous ammonia is frequently used in large commercial systems, and sulfur dioxide was used in early mechanical refrigerators. Carbon dioxide (R-744) is used as a working fluid in climate control systems for cars, residential air conditioning, commercial refrigeration, and vending machines.

Liquid gases are used as coolants for cryogenic applications, namely applications using superconductors, or extremely sensitive sensors and very low-noise amplifiers. The most common and least expensive coolant in use is liquid nitrogen. Liquid air is used to lower degree, due to its oxygen content which makes it prone to exploding in contact with combustible materials. Lower temperatures can be reached using liquefied neon. The lowest temperatures, used for the most powerful superconducting magnets, are reached using liquid helium.

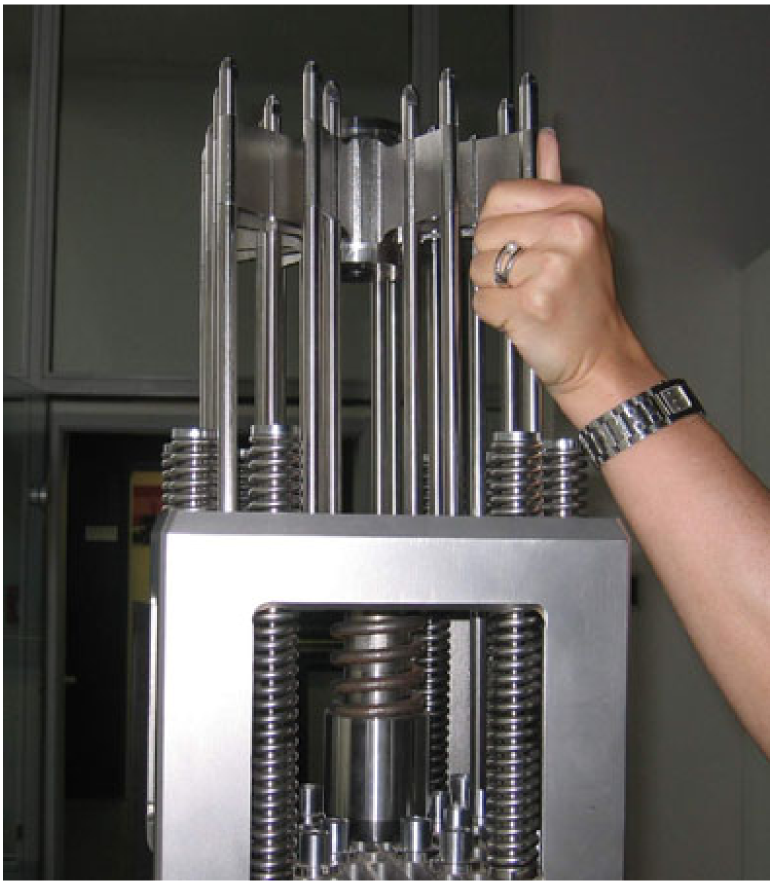
Fuels are frequently used as coolants for engines. A cold fuel flows over some parts of the engine, absorbing its waste heat and being preheated before combustion. Kerosene and other jet fuels frequently serve in this role in aviation engines, liquid hydrogen is used to cool nozzles and chambers of rocket engines.

Control Rods

A control rod is a rod made of chemical elements capable of absorbing many neutrons without fissioning themselves. They are used in nuclear reactors to control the rate of fission of uranium and plutonium. Chemical elements with a sufficiently high capture cross section for neutrons include silver, indium and cadmium. Other elements that can be used include boron, cobalt, hafnium, gadolinium, and europium. Because these elements have different capture cross sections for neutrons of varying energies the compositions of the control rods must be designed for the neutron spectrum of the reactor it is supposed to control. (Light water reactors (BWR, PWR) operate with "thermal" neutrons, breeder reactors with "fast" neutrons.)

Control rods are usually combined into control rod assemblies - typically 20 rods for a commercial PWR assembly - and inserted into guide tubes within a fuel element. A control rod is removed from or inserted into the central core of a nuclear reactor in order to control the neutron flux - increase or decrease the number of neutrons which will split further uranium atoms. This in turn affects the thermal power of the reactor, the amount of steam generated, and hence the electricity produced.

Figure 12: A Control Rod Assembly



Control rods often stand vertically within the core. In pressurized water reactors, (PWR) they are inserted from above, the control rod drive mechanisms being mounted on the reactor pressure vessel head. Due to the necessity of a steam dryer above the core of a boiling water reactor (BWR) this design requires insertion of the control rods from underneath the core. The control rods are partially removed from the core to allow a chain reaction to occur. The number of control rods inserted and the distance by which they are inserted can be varied to control the reactivity of the reactor.

Usually there are also other means of controlling reactivity: In the PWR design a soluble neutron absorber (boric acid) is added to the reactor coolant allowing the complete extraction of the control rods during stationary power operation ensuring an even power and flux distribution over the entire core. This chemical shim, along with the use of burnable neutron poisons within the fuel pellets, is used to assist regulation of the long term reactivity of the core, while the control rods are used for rapid changes to the reactor power (e.g. shutdown and startup). Operators of BWRs use the coolant flow through the core to control reactivity by varying the speed of the reactor recirculation pumps. (Increase in coolant flow through the core improves the removal of steam bubbles, increasing the density of the coolant/moderator)

In most reactor designs, as a safety measure, control rods are attached to the lifting machinery by electromagnets, rather than direct mechanical linkage. This means that automatically in the event of power failure, or if manually invoked due to failure of the lifting machinery, the control rods will fall, under gravity, fully into the pile to stop the reaction. A notable exception to this fail-safe mode of operation is the BWR which requires the hydraulical insertion of control rods in the event of an emergency shut-down, using water from a special tank that is under high nitrogen pressure. Quickly shutting down a reactor in this way is called scramming the reactor.

Pressure Vessel

A pressure vessel is a closed, rigid container designed to hold gases or liquids at a pressure different from the ambient pressure. The end caps fitted to the cylindrical body are called heads.

In addition to industrial compressed air receivers and domestic hot water storage tanks, other examples of pressure vessels are: diving cylinder, recompression chamber, distillation towers and many other vessels in oil refineries and petrochemical plants, nuclear reactor vessel, habitat of a space ship, habitat of a submarine, pneumatic reservoir, hydraulic reservoir under pressure, rail vehicle airbrake reservoir, road vehicle airbrake reservoir and storage vessels for liquefied gases such as ammonia, chlorine, propane, butane and LPG.

Figure 13: A Steel Pressure Vessel

In the industrial sector, pressure vessels are designed to operate safely at a specific pressure and temperature, technically referred to as the "Design Pressure" and "Design Temperature". A vessel that is inadequately designed to handle a high pressure constitutes a very significant safety hazard. Because of that, the design and certification of pressure vessels is governed by design codes such as the ASME Boiler and Pressure Vessel Code in North America, the Pressure Equipment Directive of the EU (PED), Japanese Industrial Standard (JIS), CSA B51 in Canada and other international standards like Lloyd's, Bureau Veritas, Germanische Lloyd, Det Norske Veritas, Stoomwezen etc.

Emergency Core Cooling Systems

An Emergency Core Cooling System (ECCS) is a component in nuclear power plants designed to deal with a loss of coolant accident (LOCA) by providing massive backup sources of coolant. An ECCS also may be used after a "partial" (incomplete) SCRAM to help bring a runaway reaction under control.

Each power plant has multiple independent ECCS systems, any one of which should be adequate to cool the core. ECCS systems are nuclear safety-grade components and can be powered by plant power (as long as the generator is on-line), offsite power, or the plant's Emergency Diesel Generators (another nuclear safety-grade system).

ECCS systems typically activate automatically upon occurrence of a LOCA (along with other automatic plant actions), to restore cooling as fast as possible so as to prevent a nuclear meltdown.

Reactor Protective System

A reactor protective system (RPS) is a set of components in a nuclear power plant designed to safely shutdown the reactor and prevent the release of radioactive materials. The system can "trip" automatically (initiating a Scram), or it can be tripped by the operators. Trips can occur for a wide variety of reasons, including strong vibrations and failure of critical sensors. In non-Soviet plants, the reactor scrams automatically if the two redundant channels of the RPS are damaged or disabled.

Steam Generators (not there in BWRs)

Steam generators are heat exchanger used to convert water into steam from heat produced in a nuclear reactor core. They are used in pressurized water reactors between the primary and secondary coolant loops.

In commercial power plants steam generators can measure up to 70 feet in height and weigh as much as 800 tons. Each steam generator can contain anywhere from 3,000 to 16,000 tubes, each about three-quarters of an inch in diameter. The coolant is pumped, at high pressure to prevent boiling, from the reactor coolant pump, through the nuclear reactor core, and through the tube side of the steam generators before returning to the pump. This is referred to as the primary loop. That water flowing through the steam generator boils water on the shell side to produce steam in the secondary loop that is delivered to the turbines to make electricity. The steam is subsequently condensed via cooled water from the tertiary loop and returned to the steam generator to be heated once again. The tertiary cooling water may be recirculated to cooling towers where it sheds waste heat before returning to condense more steam. Once through tertiary cooling may otherwise be provided by a river, lake, ocean. This primary, secondary, tertiary cooling scheme is the most common way to extract usable energy from a controlled nuclear reaction.

These loops also have an important safety role because they constitute one of the primary barriers between the radioactive and non-radioactive sides of the plant as the primary coolant becomes radioactive from its exposure to the core. For this reason, the integrity of the tubing is essential in minimizing the leakage of water between the two sides of the plant. There is the potential that if a tube bursts while a plant is operating; contaminated steam could escape directly to the secondary cooling loop. Thus during scheduled maintenance outages or shutdowns, some or all of the steam generator tubes are inspected by eddy-current testing.

In other types of reactors, such as the pressurized heavy water reactors of the CANDU design, the primary fluid is heavy water. Liquid metal cooled reactors such as the in Russian BN-600 reactor also use heat exchangers between primary metal coolant and at the secondary water coolant.

Boiling water reactors do not use steam generators, as steam is produced in the pressure vessel.

Containment Building

A containment building, in its most common usage, is a steel or concrete structure enclosing a nuclear reactor. It is designed to, in any emergency, contain the escape of radiation despite pressures in the range of 60 to 200 psi (410 to 1400 kPa). The containment is the final barrier to radioactive release, the first being the fuel ceramic itself, the second being the metal fuel cladding tubes, the third being the reactor vessel and coolant system.

The containment building itself is typically an airtight steel structure enclosing the reactor normally sealed off from the outside atmosphere. The steel is either free-standing or attached to the concrete missile shield. In the United States, the design and thickness of the containment and the missile shield are governed by federal regulations.

For a pressurized water reactor, the containment also encloses the steam generators and the pressurizer, and is the entire reactor building. The missile shield around it is typically a tall cylindrical or domed building. There are several common designs, but for safety-analysis purposes containments are categorized as either "large-dry," "sub-atmospheric," or "ice-condenser."

For a boiling water reactor, the containment and missile shield fit close to the reactor vessel. The reactor building wall forms a secondary containment during refueling operations. The containment designs are referred to by the names Mark I (oldest; drywell/torus), Mark II, and Mark III (newest). All three types house a large body of water used to quench steam released from the reactor system during transients.

During normal operation, the containment is air-tight and access is only through marine style airlocks. High air temperature and radiation from the core limit the time, measured in minutes, people can spend inside containment while the plant is operating at full power. In the event of a worst-case emergency, called a "design basis accident" in NRC regulations, the containment is designed to seal off and contain a meltdown. Redundant systems are installed to prevent a meltdown, but as a matter of policy, one is assumed to occur and thus the requirement for a containment building. For design purposes, the reactor vessel's piping is assumed to be breached, causing a "LOCA" (Loss Of Coolant Accident) where the water in the reactor vessel is released to the atmosphere inside the containment and flashes into steam. The resulting pressure increase inside the containment, which is designed to withstand the pressure, triggers containment sprays ("dousing sprays") to turn on to condense the steam and thus reduce the pressure. A SCRAM ("neutronic trip") initiates very shortly after the break occurs. The safety systems close non-essential lines into the air-tight containment by shutting the isolation valves. Emergency Core Cooling Systems are quickly turned on to cool the fuel and prevent it from melting. The exact sequence of events depends on the reactor design.

Containment buildings in the U.S. are subjected to Containment Integrated Leakage Rate Tests (CILRTs) on a periodic basis, both to identify the possible leakage in an accident and to locate and fix leakage paths.

In the Soviet Union, it was normal practice not to build containment buildings. This, along with the unstable nature of the RBMK reactors, led to the catastrophe of the Chernobyl accident. In the case of these types of reactors it would be more proper to refer to the building housing the reactor as a reactor building rather than as a containment building.

Boiler Feed water Pump

A boiler feed water pump is a specific type of pump used to pump water into a steam boiler. The water may be freshly supplied or returning condensate produced as a result of the condensation of the steam produced by the boiler. These pumps are normally high pressure units that use suction from a condensate return system and can be of the centrifugal pump type or positive displacement type.

Feed water pumps range in size up to many horsepower and the electric motor is usually separated from the pump body by some form of mechanical coupling. Large industrial condensate pumps may also serve as the feed water pump. In either case, to force the water into the boiler, the pump must generate sufficient pressure to overcome the steam pressure developed by the boiler. This is usually accomplished through the use of a centrifugal pump.

Feed water pumps usually run intermittently and are controlled by a float switch or other similar level-sensing device energizing the pump when it detects a lowered liquid level in the boiler. The pump then runs until the level of liquid in the boiler is substantially increased. Some pumps contain a two-stage switch. As liquid lowers to the trigger point of the first stage, the pump is activated. If the liquid continues to drop (perhaps because the pump has failed, its supply has been cut off or exhausted, or its discharge is blocked), the second stage will be triggered. This stage may switch off the boiler equipment (preventing the boiler from running dry and overheating), trigger an alarm, or both.

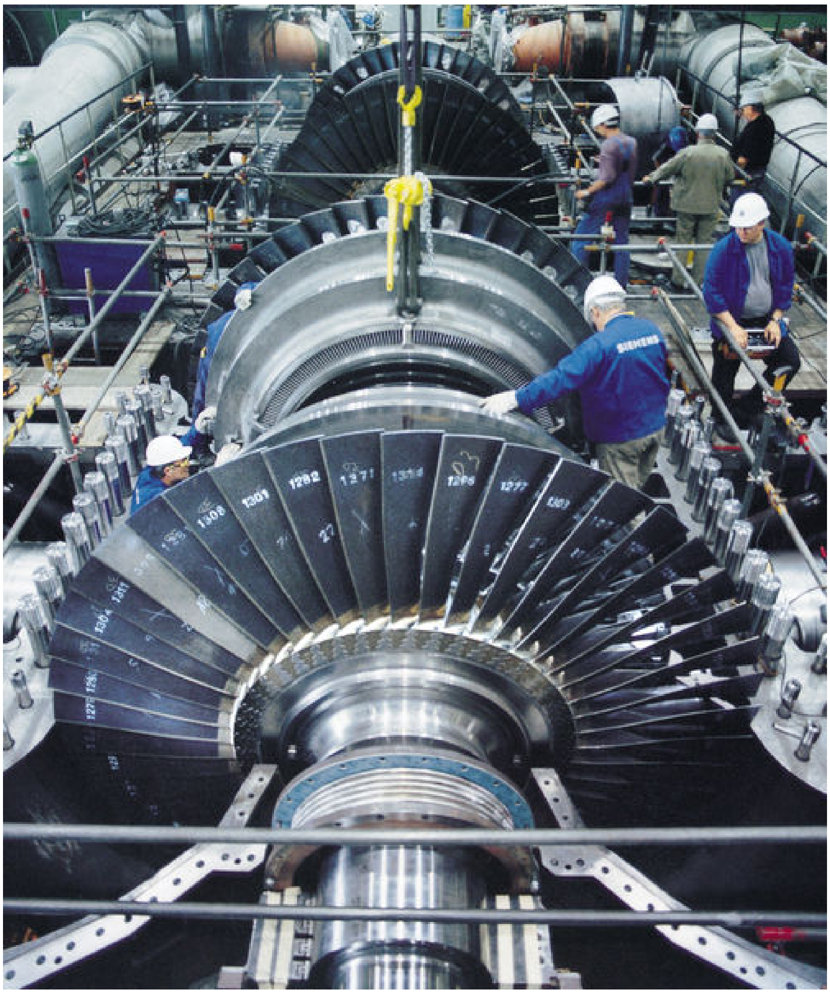
Turbine

A turbine is a rotary engine that extracts energy from a fluid flow. Claude Burdin coined the term from the Latin turbinis, or vortex, during an 1828 engineering competition. The simplest turbines have one moving part, a rotor assembly, which is a shaft with blades attached. Moving fluid acts on the blades, or the blades react to the flow, so that they rotate and impart energy to the rotor. Early turbine examples are windmills and water wheels.

Gas, steam, and water turbines usually have a casing around the blades that focuses and controls the fluid. The casing and blades may have variable geometry that allows efficient operation for a range of fluid-flow conditions.

A device similar to a turbine but operating in reverse is a compressor or pump. The axial compressor in many gas turbine engines is a common example.

Figure 14: A Siemens Steam Turbine with Open Case



Electrical Generator

An electrical generator is a device that converts mechanical energy to electrical energy, generally using electromagnetic induction. The source of mechanical energy may be a reciprocating or turbine steam engine, water falling through a turbine or waterwheel, an internal combustion engine, a wind turbine, a hand crank, or any other source of mechanical energy.

Condenser

Condenser refers here to the shell and tube heat exchanger (or surface condenser) installed at the outlet of every steam turbine in Thermal power stations of utility companies generally. These condensers are heat exchangers which convert steam from its gaseous to its liquid state, also known as phase transition. In so doing, the latent heat of steam is given out inside the condenser. Where water is in short supply an air cooled condenser is often used. An air cooled condenser is however significantly more expensive and cannot achieve as low a steam turbine backpressure (and therefore less efficient) as a surface condenser.

The purpose of a condenser is to condense the outlet (or exhaust) steam from steam turbine to obtain maximum efficiency and also to get the condensed steam in the form of pure water, otherwise known as condensate, (condensate-not to be mistaken with usage of the word condensate in Natural gas condensate in petroleum industry), back to steam generator or (boiler) as boiler feed water.

Analyzing the Fuel Cycle

A nuclear reactor is only part of the life-cycle for nuclear power. The process starts with mining. Generally, uranium mines are either open-pit strip mines, or in-situ leach mines. In either case, the uranium ore is extracted, usually converted into a stable and compact form such as yellowcake, and then transported to a processing facility. Here, the yellowcake is converted to uranium hexafluoride, which is then enriched using various techniques. At this point, the enriched uranium, containing more than the natural 0.7% U-235, is used to make rods of the proper composition and geometry for the particular reactor that the fuel is destined for. The fuel rods will spend about three years inside the reactor, generally until about three percent of their uranium has been fissioned, then they will be moved to a spent fuel pool where the short lived isotopes generated by fission can decay away. After about five years in a cooling pond, the spent fuel is radioactively cool enough to handle, and it can be moved to dry storage casks or reprocessed.

The nuclear fuel cycle, also called nuclear fuel chain, is the progression of nuclear fuel through a series of differing stages. It consists of steps in the front end, which are the preparation of the fuel, steps in the service period in which the fuel is used during reactor operation, and steps in the back end, which are necessary to safely manage, contain, and either reprocess or dispose of spent nuclear fuel. If spent fuel is not reprocessed, the fuel cycle is referred to as an open fuel cycle (or a once-through fuel cycle). Likewise, if the spent fuel is reprocessed, it is referred to as a closed fuel cycle.

Uranium Resources

Uranium is a common element, occurring almost everywhere on land and in the oceans. It is about as common as tin, and 500 times more common than gold. Most types of rocks and soils contain uranium, although often in low concentrations. At present, economically viable deposits are regarded as being those with concentrations of at least 0.1% uranium. At this cost level, available reserves would last for 50 years at the present rate of use. Doubling the price of uranium, which would have only little effect on the overall cost of nuclear power, would increase reserves to hundreds of years. To put this in perspective; a doubling in the cost of natural uranium would increase the total cost of nuclear power by five percent. On the other hand, if the price of natural gas was doubled, the cost of gas-fired power would increase by about 60%. Doubling the price of coal would increase the cost of power production in a large coal-fired power station by about 30%.

Uranium enrichment produces many tons of depleted uranium (DU) which consists of U-238 with most of the easily fissile U-235 isotope removed. U-238 is a tough metal with several commercial uses - for example, aircraft production, radiation shielding, and making bullets and armor - as it has a higher density than lead. There are concerns that U-238 may lead to health problems in groups exposed to this material excessively, like tank crews and civilians living in areas where large quantities of DU ammunition have been used.

Current light water reactors make relatively inefficient use of nuclear fuel, leading to energy waste. More efficient reactor designs or nuclear reprocessing would reduce the amount of waste material generated and allow better use of the available resources.

As opposed to current light water reactors which use uranium-235 (0.7% of all natural uranium), fast breeder reactors use uranium-238 (99.3% of all natural uranium). It has been estimated that there is up to five-billion years' worth of uranium-238 for use in these power plants. Breeder technology has been used in several reactors. Currently, the only breeder reactor producing power is BN-600 in Beloyarsk, Russia. (The electricity output of BN-600 is 600 MW - Russia has planned to build another unit, BN-800, at Beloyarsk nuclear power plant.) Also, Japan's Monju reactor is planned for restart (having been shut down since 1995), and both China and India intend to build breeder reactors.

Another alternative would be to use uranium-233 bred from thorium as fission fuel - the thorium fuel cycle. Thorium is three times more abundant in the Earth's crust than uranium, and (theoretically) all of it can be used for breeding, making the potential thorium resource orders of magnitude larger than the uranium fuel cycle operated without breeding. Unlike the breeding of U-238 into plutonium, fast breeder reactors are not necessary - it can be performed satisfactorily in more conventional plants.

Proposed fusion reactors assume the use of deuterium, an isotope of hydrogen, as fuel and in most current designs also lithium. Assuming a fusion energy output equal to the current global output and that this does not increase in the future, then the known current lithium reserves would last 3,000 years, lithium from sea water would last 60 million years, and a more complicated fusion process using only deuterium from sea water would have fuel for 150 billion years.

Mining and Milling

Uranium ore can be extracted through conventional mining in open pit and underground methods similar to those used for mining other metals. In situ leach mining methods also are used to mine uranium in the United States. In this technology, uranium is leached from the in-place ore through an array of regularly spaced wells and is then recovered from the leach solution at a surface plant. Uranium ores in the United States typically range from about 0.05 to 0.3% uranium oxide (U3O8). Some uranium deposits developed in other countries are of higher grade and are also larger than deposits mined in the United States. Uranium is also present in very low-grade amounts (50 to 200 parts per million) in some domestic phosphate-bearing deposits of marine origin. Because very large quantities of phosphate-bearing rock are mined for the production of wet-process phosphoric acid used in high analysis fertilizers and other phosphate chemicals, at some phosphate processing plants the uranium, although present in very low concentrations, can be economically recovered from the process stream.

Mined uranium ores normally are processed by grinding the ore materials to a uniform particle size and then treating the ore to extract the uranium by chemical leaching. This process is known as milling. The milling process commonly yields dry powder-form material consisting of natural uranium, "yellowcake," which is sold on the uranium market as U3O8.

Nuclear Reprocessing

Nuclear reprocessing separates any usable elements (e.g., uranium and plutonium) from fission products and other materials in spent nuclear reactor fuels. Usually the goal is to recycle the reprocessed uranium or place these elements in new mixed oxide fuel (MOX), but some reprocessing is done to obtain plutonium for weapons. It is the process that partially closes the loop in the nuclear fuel cycle.

The PUREX process is currently used for nuclear reprocessing. This process can be used to recover weapon-grade materials from spent nuclear reactor fuel, and as such, its component chemicals are monitored. PUREX is an acronym standing for Plutonium and Uranium Recovery by Extraction. The PUREX process is a liquid-liquid extraction method used to reprocess spent nuclear fuel, in order to extract uranium and plutonium, independent of each other, from the fission products. This is the most completely developed and widely used process in the industry at present.

Other Methods for Future Use

Aqueous Methods

- UREX: The PUREX process can be modified to make a UREX (URanium EXtraction) process which could be used to save space inside high level nuclear waste disposal sites, such as Yucca Mountain, by removing the uranium which makes up the vast majority of the mass and volume of used fuel and recycling it as reprocessed uranium. The UREX process is a PUREX process which has been modified to prevent the plutonium being extracted. This can be done by adding a plutonium reductant before the first metal extraction step. In the UREX process, ~99.9% of the Uranium and >95% of Technetium are separated from each other and the other fission products and actinides. The key is the addition of acetohydroxamic acid (AHA) to the extraction and scrub sections of the process. The addition of AHA greatly diminishes the extractability of Plutonium and Neptunium, providing greater proliferation resistance than with the plutonium extraction stage of the PUREX process.

- **TRUEX:** Adding a second extraction agent, octyl (phenyl)-N, N-dibutyl carbamoylmethyl phosphine oxide(CMPO) in combination with tributylphosphate, (TBP), the PUREX process can be turned into the TRUEX (TRansUranic EXtraction) process this is a process which was invented in the U.S. by Argonne National Laboratory, and is designed to remove the transuranic metals (Am/Cm) from waste. The idea is that by lowering the alpha activity of the waste, the majority of the waste can then be disposed of with greater ease. In common with PUREX this process operates by a solvation mechanism.

- DIAMEX: As an alternative to TRUEX, an extraction process using a malondiamide has been devised. The DIAMEX (DIAMideEXtraction) process has the advantage of avoiding the formation of organic waste which contains elements other than Carbon, Hydrogen, Nitrogen, and Oxygen. Such an organic waste can be burned without the formation of acidic gases which could contribute to acid rain. The DIAMEX process is being worked on in Europe by the French CEA. The process is sufficiently mature that an industrial plant could be constructed with the existing knowledge of the process. In common with PUREX this process operates by a solvation mechanism.

- **SANEX:** Selective ActiNide EXtraction. As part of the management of minor actinides it has been proposed that the lanthanides and trivalent minor actinides should be removed from the PUREX raffinate by a process such as DIAMEX or TRUEX. In order to allow the actinides such as americium to be either reused in industrial sources or used as fuel the lanthanides must be removed. The lanthanides has large neutron cross sections and hence they would poison a neutron driven nuclear reaction. To date the extraction system for the SANEX process has not been defined, but currently several different research groups are working towards a process. For instance the French CEA is working on a bis-triaiznyl pyridine (BTP) based process.

- **UNEX:** This is the UNiversal EXtraction process which was developed in Russia and the Czech Republic, it is a process designed to remove all of the most troublesome (Sr, Cs and minor actinides) radioisotopes from the raffinates left after the extraction of uranium and plutonium from used nuclear fuel. The chemistry is based upon the interaction of cesium and strontium with poly ethylene oxide (poly ethylene glycol) and a cobalt carborane anion (known as chlorinated cobalt dicarbollide). The actinides are extracted by CMPO, and the diluent is a polar aromatic such as nitrobenzene. Other diluents such as meta-nitrobenzotrifluoride and phenyl trifluoromethyl sulfone have been suggested as well.

Boosting Fuel's Potency

Uranium hexafluoride contains two different forms, or isotopes, of uranium, one of which (U-238) is heavier than the other (U-235). The lighter U-235 is fissionable, which means its atoms can be split, releasing large amounts of heat. However, it makes up less than one percent of uranium by weight, while U-238 accounts for more than 99%. Before uranium can be used as a fuel, its U-235 content must be increased to three to five percent by weight. The amount of U-235 in uranium (by weight) is increased by a process called enrichment.

There are currently two ways of enriching uranium - gaseous diffusion or centrifuge. Gaseous diffusion involves passing uranium hexafluoride in a gaseous form through barriers that are sensitive enough to be able to separate the isotopes of uranium by weight. The centrifuge enrichment process spins the uranium hexafluoride gas, using centrifugal force to separate the uranium isotopes by weight.

Energy companies buy uranium and have it converted and enriched, or they can buy uranium that has already been enriched. Uranium enrichment services are sold in Separative Work Units, or SWU. A SWU is a measure of the amount of energy needed to raise the concentration of U-235 to a specified level.

In the United States, the gaseous diffusion enrichment process is used. USEC Inc. currently is the only producer of enrichment services in the United States, but energy companies purchase SWU in a global market. Two companies, USEC Inc. and Louisiana Energy Services (LES), have plans to construct and operate new gas centrifuge enrichment facilities in the United States before the end of this decade.

Globally, there are three other major commercial enrichment services suppliers operating in France, the United Kingdom, Germany, the Netherlands and Russia. USEC supplies approximately 51% of the U.S. market needs.

Fabrication

For use as nuclear fuel, enriched uranium hexafluoride is converted into uranium dioxide (UO2) powder that is then processed into pellet form. The pellets are then fired in a high temperature sintering furnace to create hard, ceramic pellets of enriched uranium. The cylindrical pellets then undergo a grinding process to achieve a uniform pellet size. The pellets are stacked, according to each nuclear reactor core's design specifications, into tubes of corrosion-resistant metal alloy. The tubes are sealed to contain the fuel pellets: these tubes are called fuel rods. The finished fuel rods are grouped in special fuel assemblies that are then used to build up the nuclear fuel core of a power reactor.

The metal used for the tubes depends on the design of the reactor. Stainless steel was used in the past, but most reactors now use zirconium. For the most common types of reactors, boiling water reactors (BWR) and pressurized water reactors (PWR), the tubes are assembled into bundles with the tubes spaced precise distances apart. These bundles are then given a unique identification number, which enables them to be tracked from manufacture through use and into disposal.

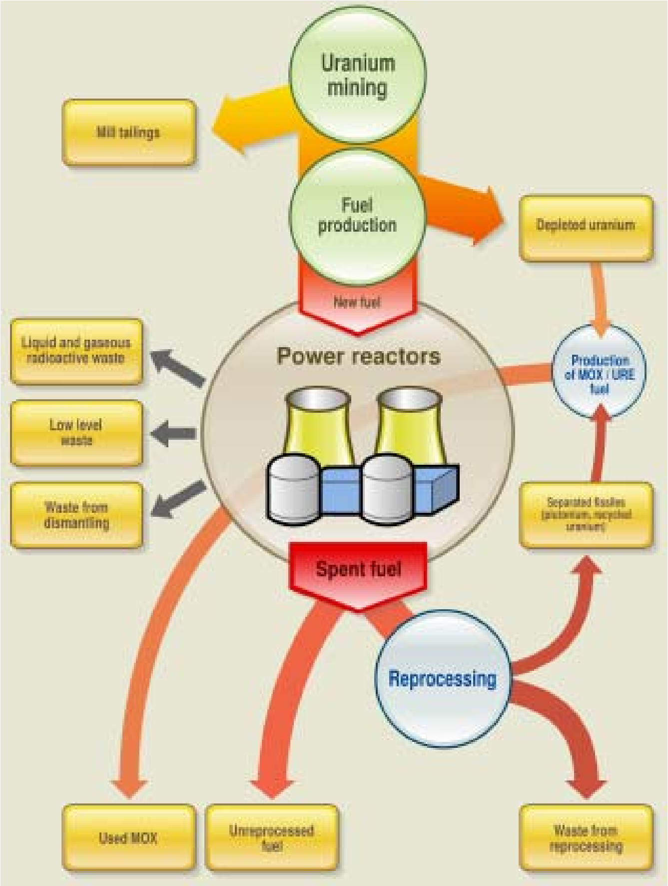
Managing the Radioactive Waste

Radioactive waste are waste types containing radioactive chemical elements that do not have a practical purpose. It is sometimes the product of a nuclear process, such as nuclear fission. The majority of radioactive waste is "low-level waste", meaning it has low levels of radioactivity per mass or volume. This type of waste often consists of items such as used protective clothing, which is only slightly contaminated but still dangerous in case of radioactive contamination of a human body through ingestion, inhalation, absorption, or injection.

In the United States alone, the Department of Energy acknowledges that there are "millions of gallons of radioactive waste" as well as "thousands of tons of spent nuclear fuel and material" and also quantities of contaminated soil and water. The Fernald site in Florida for example had "31 million pounds of uranium product", "2.5 billion pounds of waste", "2.75 million cubic yards of contaminated soil and debris", and a "223 acre portion of the underlying Great Miami Aquifer had uranium levels above drinking standards". The United States currently has at least 108 sites it currently designates, areas that are contaminated and unusable, sometimes many thousands of acres. The DOE wishes to try and clean or mitigate many by 2025, however it acknowledges that some will never be completely remediated, and just in one of these 108 larger designations, Oak Ridge National Laboratory, there were for example at least "167 known contaminant release sites" in one of the three subdivisions of the 37,000 acre site. Some of the U.S. sites were smaller in nature, however, and cleanup issues were simpler to address.

The issue of disposal methods for nuclear waste was one of the most pressing current problems the valuable international nuclear industry faced when trying to establish a long term energy production plan, yet there was hope it could be safely solved. In the U.S., the DOE acknowledged much progress in addressing the waste problems of this vital and critical industry, and successful remediation of some contaminated sites, yet also complications and setbacks in handling the issue properly and cost effectively. In other countries with lower ability or will to maintain environmental integrity the issue would be more problematic.

Figure 15: Sources of Nuclear Waste



When dealing with uranium and plutonium, the possibility that they may be used to build nuclear weapons is often a concern. Active nuclear reactors and nuclear weapons stockpiles are very carefully safeguarded and controlled. However, high-level waste from nuclear reactors may contain plutonium. Ordinarily, this plutonium is reactor-grade plutonium, containing a mixture of plutonium-239 (highly suitable for building nuclear weapons) and plutonium-240 (an undesirable contaminant and highly radioactive); the two isotopes are difficult to separate. Moreover, high-level waste is full of highly radioactive fission products. However, most fission products are relatively short-lived. This is a concern since if the waste is stored, perhaps in deep geological storage, over many years the fission products decay, decreasing the radioactivity of the waste and making the plutonium easier to access.

Moreover, the undesirable contaminant Pu-240 decays faster than the Pu-239, and thus the quality of the bomb material increases with time (although its quantity decreases). Thus, some have argued, as time passes, these deep storage areas have the potential to become "plutonium mines", from which material for nuclear weapons can be acquired with relatively little difficulty. Critics of the latter idea point out that the half-life of Pu-240 is 6,560 years and Pu-239 is 24,110 years, and thus the relative enrichment of one isotope to the other with time occurs with a half-life of 9,000 years (that is, it takes 9000 years for the fraction of Pu-240 in a sample of mixed plutonium isotopes, to spontaneously decrease by half-- a typical enrichment needed to turn reactor-grade into weapons-grade Pu). Thus "weapons grade plutonium mines" would be a problem for the very far future (>9,000 years from now), so that there remains a great deal of time for technology to advance to solve this problem, before it becomes acute.

Pu-239 decays to U-235 which is suitable for weapons and which has a very long half-life (roughly 109 years). Thus plutonium may decay and leave uranium-235. However, modern reactors are only moderately enriched with U-235 relative to U-238, so the U-238 continues to serve as denaturation agent for any U-235 produced by plutonium decay.

One solution to this problem is to recycle the plutonium and use it as a fuel e.g. in fast reactors. But the very existence of the nuclear fuel reprocessing plant needed to separate the plutonium from the other elements represents, in the minds of some, a proliferation concern. In pyrometallurgical fast reactors, the waste generated is an actinide compound that cannot be used for nuclear weapons.

C. Profiling the Global Nuclear Power Industry

Industry Overview

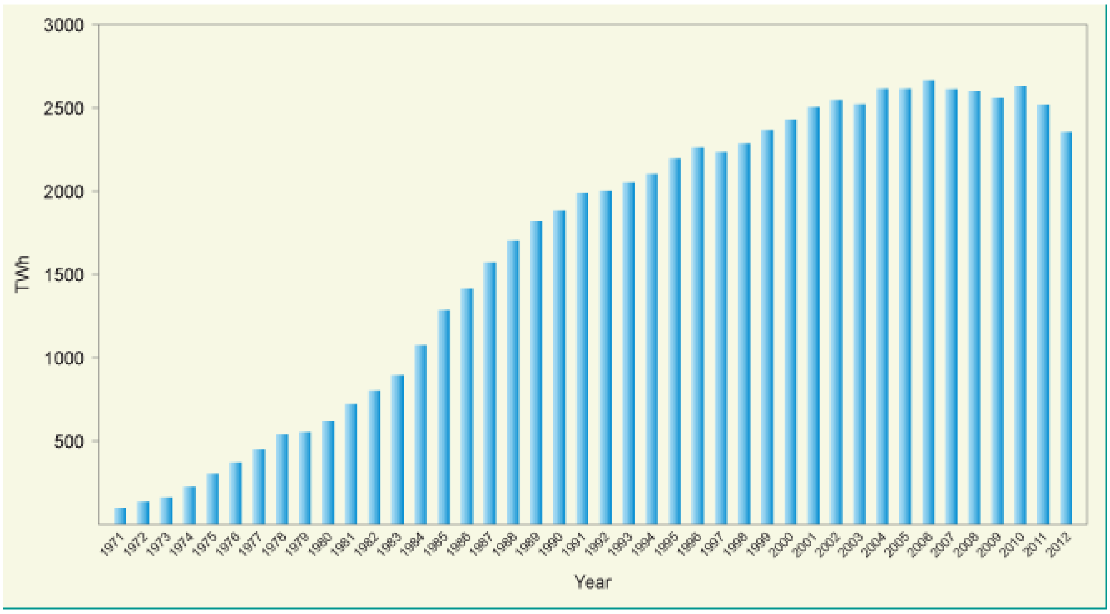
Nuclear technology uses the energy released by splitting the atoms of certain elements. It was first developed in the 1940s, and during the Second World War research initially focused on producing bombs by splitting the atoms of particular isotopes of either uranium or plutonium.

In the 1950s attention turned to the peaceful purposes of nuclear fission, notably for power generation. Today, the world produces as much electricity from nuclear energy as it did from all sources combined in 1960. Civil nuclear power can now boast over 15,500 reactor years of experience and supplies almost 11.5% of global electricity needs, from reactors in 31 countries. In fact, through regional grids, many more than those countries use nuclear-generated power.

Many countries have also built research reactors to provide a source of neutron beams for scientific research and the production of medical and industrial isotopes.

Today, only eight countries are known to have a nuclear weapons capability. By contrast, 56 operate about 240 civil research reactors, over one third of these in developing countries. Now 31 countries host over 430 commercial nuclear power reactors with a total installed capacity of over 370,000 MWe. This is more than three times the total generating capacity of France or Germany from all sources. About 70 further nuclear power reactors are under construction, equivalent to 20% of existing capacity, while over 160 are firmly planned, equivalent to half of present capacity.

Figure 16: Nuclear Electricity Production and Share of Total Electricity Production (in TWh), 1971-2012



Sixteen countries depend on nuclear power for at least a quarter of their electricity. France gets around three quarters of its power from nuclear energy, while Belgium, Czech Republic, Hungary, Slovakia, Sweden, Switzerland, Slovenia and Ukraine get one third or more. South Korea, Bulgaria and Finland normally get more than 30% of their power from nuclear energy, while in the USA, UK, Spain and Russia almost one fifth is from nuclear. Japan is used to relying on nuclear power for more than one quarter of its electricity and is expected to return to that level. Among countries which do not host nuclear power plants, Italy and Denmark get almost 10% of their power from nuclear.

Revival of Nuclear Power

Since about 2001 there has been much talk about an imminent nuclear revival or "renaissance" which implies that the nuclear industry has been dormant or in decline for some time. Whereas this may generally be the case for the Western world, nuclear capacity has been expanding in Eastern Europe and Asia. Indeed, globally, the share of nuclear in world electricity has remained constant at around 16% since the mid-1980s, with output from nuclear reactors actually increasing to match the growth in global electricity consumption.

Today nuclear energy is back on the policy agendas of many countries, with projections for new build similar to or exceeding those of the early years of nuclear power. This signals a revival in support for nuclear power in the West that was diminished by the accidents at Three Mile Island and Chernobyl and also by nuclear power plant construction cost overruns in the 1970s and 1980s.

What Drives this Revival?

The first generation of nuclear plants were justified by the need to alleviate urban smog caused by coal-fired power plants. Nuclear was also seen as an economic source of base-load electricity which reduced dependence on overseas imports of fossil fuels. Today's drivers for nuclear build have evolved:

Rising Demand for Energy

Global population growth in combination with industrial development will lead to a doubling of electricity consumption by 2030. Besides this incremental growth, there will be a need to renew a lot of generating stock in the USA and the EU over the same period. An increasing shortage of fresh water calls for energy-intensive desalination plants, electric vehicles will increase overnight (base-load) demand, and in the longer term hydrogen production for transport purposes will need large amounts of electricity and/or high temperature heat.

Global Climate Change

Increased awareness of the dangers and effects of global warming and climate change has led decision makers, media and the public to realize that the use of fossil fuels must be reduced and replaced by low-emission sources of energy, such as nuclear power, the only readily available large-scale alternative to fossil fuels for production of continuous, reliable supply of electricity (i.e. meeting base-load demand).

Economic Benefits of Nuclear Power

Increasing fossil fuel prices have greatly improved the economics of nuclear power for electricity now. Several studies show that nuclear energy is the most cost-effective of the available base-load technologies. In addition, as carbon emission reductions are encouraged through various forms of government incentives and emission trading schemes, the economic benefits of nuclear power will increase further.

Low Impact of Rising Fuel Prices

A longer-term advantage of uranium over fossil fuels is the low impact that increased fuel prices will have on the final electricity production costs, since a large proportion of those costs is in the capital cost of the plant. This insensitivity to fuel price fluctuations offers a way to stabilize power prices in deregulated markets.

Security of Supply

A re-emerging topic on many political agendas is security of supply, as countries realize how vulnerable they are to interrupted deliveries of oil and gas. The abundance of naturally occurring uranium and the large energy yield from each ton of it makes nuclear power attractive from an energy security standpoint.

As the nuclear industry is moving away from small national programs towards global cooperative schemes, serial production of new plants will drive construction costs down and further increase the competitiveness of nuclear energy.

Improving the Performance of Nuclear Reactors

There are currently 435 operable civil nuclear power nuclear reactors around the world, with a further 72 under construction. (This under construction total recent changes including Tianwan-4, Yangjiang 5, Shin Hanul 2, Barakah 2, Ostrovets 1, V.C. Summer 2 & 3 and Vogtle 3. The number of operable reactors excludes Kewaunee, which shut down on 7 May 2013, and San Onofre 2 & 3, and includes Kudankulam-1).

As nuclear power plant construction returns to the levels reached during the 1970s and 1980s, those plants now operating are producing more electricity. In 2011, production was 2518 billion kWh. The increase over the six years to 2006 (210 TWh) was equal to the output from 30 large new nuclear power plants. Yet between 2000 and 2006 there was no net increase in reactor numbers (and only 15 GWe in capacity). The rest of the improvement is due to better performance from existing units.

In a longer perspective, from 1990 to 2010, world capacity rose by 57 GWe (17.75%, due both to net addition of new plants and uprating some established ones) and electricity production rose 755 billion kWh (40%). The relative contributions to this increase were: new construction 36%, uprating 7% and availability increase 57%. In 2011 and 2012 both capacity and output diminished due to cutbacks in Germany and Japan following the Fukushima accident.

Considering 400 power reactors over 150 MWe for which data are available: over 1980 to 2000 world median capacity factor increased from 68% to 86%, and since then it has maintained around 85%. Actual load factors are slightly lower: 80% average in 2012 (excluding Japan), due to reactors being operated below their full capacity for various reasons. One quarter of the world's reactors have load factors of more than 90%, and nearly two thirds do better than 75%, compared with about a quarter of them over 75% in 1990. The USA now dominates the top 25 positions, followed by South Korea, but six other countries are also represented there. Four of the top ten reactors for lifetime load factors are South Korean.

US nuclear power plant performance has shown a steady improvement over the past twenty years, and the average load factor in 2012 was 81%, up from 66% in 1990 and 56% in 1980. This places the USA as the performance leader with nearly half of the top 50 reactors, the 50th achieving more than 94% in 2012. The USA accounts for nearly one third of the world's nuclear electricity.

In 2012, ten countries with four or more units averaged better than 80% load factor, while French reactors averaged 73.6%, despite many being run in load-following mode, rather than purely for base-load power.

Some of these figures suggest near-maximum utilization, given that most reactors have to shut down every 18-24 months for fuel change and routine maintenance. In the USA this used to take over 100 days on average but in the last decade it has averaged about 40 days. Another performance measure is unplanned capability loss, which in the USA has for the last few years been below 2%.

Figure 17: Global Electricity Production by Power Sources, 2010

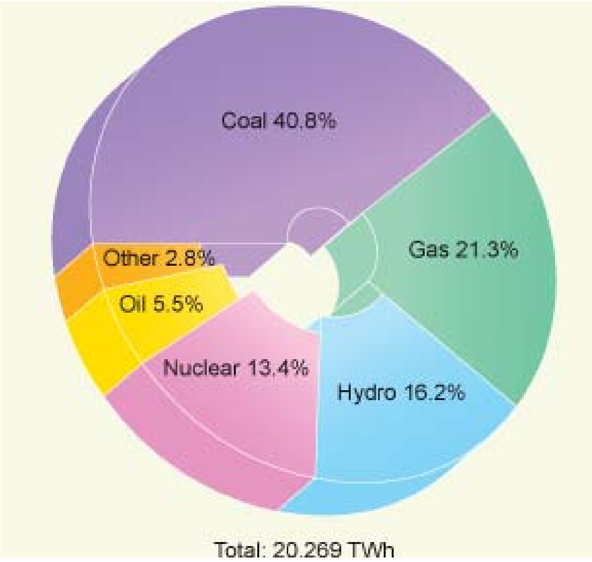
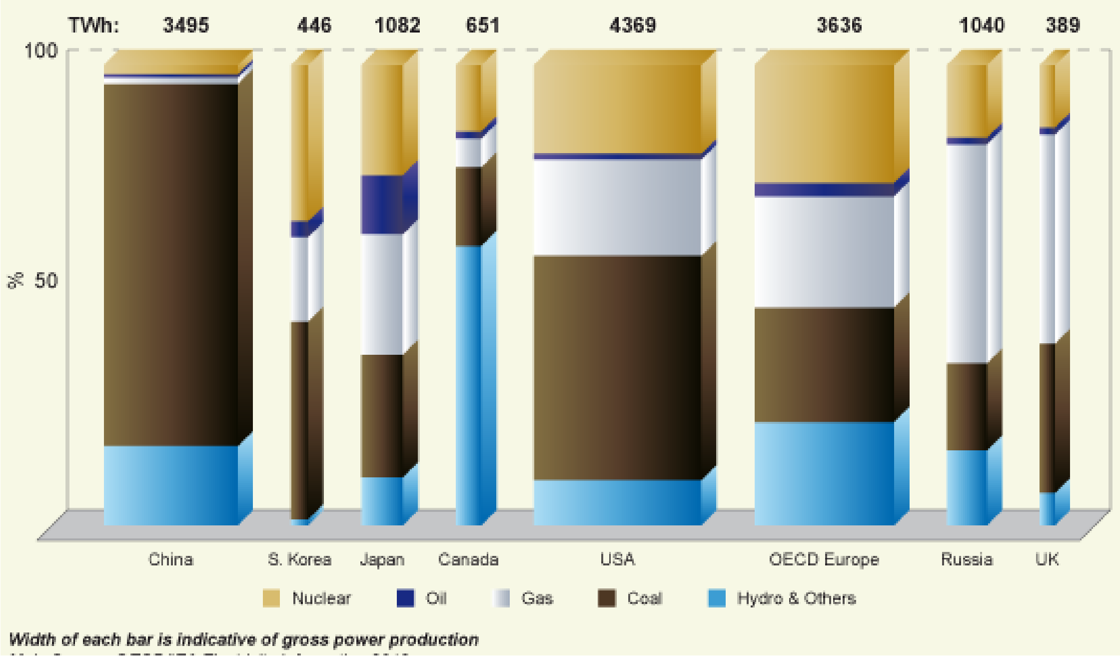


Figure 18: Fuel Used for Electricity Generation, 2010



Width of each bar is indicative of gross power production

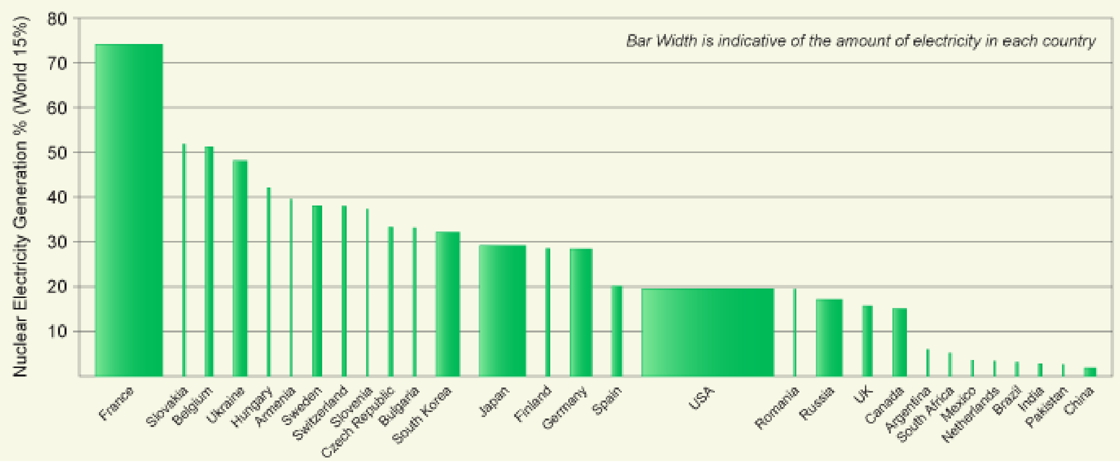
Role of Research Reactors

In addition to commercial nuclear power plants, there are about 240 research reactors operating, in 56 countries, with more under construction. These have many uses including research and the production of medical and industrial isotopes, as well as for training.

The use of reactors for marine propulsion is mostly confined to the major navies where it has played an important role for five decades, providing power for submarines and large surface vessels. About 150 ships are propelled by some 180 nuclear reactors and over 13,000 reactor-years of experience has been gained with marine reactors. Russia and the USA have decommissioned many of their nuclear submarines from the Cold War era.

Russia also operates a fleet of six large nuclear-powered icebreakers and a 62,000 ton cargo ship which are more civil than military. It is also completing a floating nuclear power plant with two 40 MWe reactors for use in remote regions.

Figure 19: Nuclear Electricity Generation 2010



Exploring the Possibility of Expansion of Nuclear Power Capacity

Most reactors today are built in under five years (first concrete to first power), with four years being state of the art and three years being the aim with modular prefabrication. Several years are required for preliminary approvals before construction.

It is noteworthy that in the 1980s, 218 power reactors started up, an average of one every 17 days. These included 47 in USA, 42 in France and 18 in Japan. The average power was 923.5 MWe. So it is not hard to imagine a similar number being commissioned in a decade after about 2015. But with China and India getting up to speed with nuclear energy and a world energy demand double the 1980 level in 2015, a realistic estimate of what is possible might be the equivalent of one 1000 MWe unit worldwide every 5 days.

A relevant historical benchmark is that from 1941 to 1945, 18 US shipyards built over 2700 Liberty Ships. These were standardized 10,800 dwt cargo ships of a very basic British design but they became symbolic of US industrial wartime productivity and were vital to the war effort. Average construction time was 42 days in the shipyard, often using prefabricated modules*. In 1943, three were being completed every day. They were 135 meters long and could carry 9100 tons of cargo.

** As a publicity stunt, and using a lot of prefabrication, in 1942 the Robert G. Peary was launched in under five days and ready for sea three days later.*

Addition of New Nuclear Power Capacity

Today there are some 435 nuclear power reactors operating in 31 countries plus Taiwan, with a combined capacity of over 370 GWe. In 2011 these provided 2518 billion kWh, about 13.5% of the world's electricity.

Over 60 power reactors are currently being constructed in 13 countries plus Taiwan, notably China, South Korea and Russia.

Each year, the OECD's International Energy Agency (IEA) sets out the present situation and also reference and other, particularly carbon reduction scenarios. Following the Fukushima accident, the World Energy Outlook 2011 New Policies scenario has a 60% increase in nuclear capacity to 2035, compared with about 90% the year before. "Although the prospects for nuclear power in the New Policies Scenario are weaker in some regions than in [WEO 2010] projections, nuclear power continues to play an important role, providing base-load electricity. Most non-OECD countries and many OECD countries are expected to press ahead with plans to install additional nuclear power plants, though there may be short-term delays as the safety standards of existing and new plants are reviewed. Globally, nuclear power capacity is projected to rise in the New Policies Scenario from 393 GW in 2009 to 630 GW in 2035." In this scenario the IEA expects the share of coal in total electricity to drop from 41% now to 33% in 2035. Electricity generation increases from 20 to 36 trillion kWh.

It is noteworthy that in the 1980s, 218 power reactors started up, an average of one every 17 days. These included 47 in USA, 42 in France and 18 in Japan. These were fairly large - average power was 923.5 MWe. So it is not hard to imagine a similar number being commissioned in a decade after about 2015. But with China and India getting up to speed in nuclear energy and a world energy demand double the 1980 level in 2015, a realistic estimate of what is possible (but not planned at this stage) might be the equivalent of one 1000 MWe unit worldwide every 5 days.

Increased Nuclear Capacity

Increased nuclear capacity in some countries is resulting from the uprating of existing plants. This is a highly cost-effective way of bringing on new capacity.
Numerous power reactors in USA, Belgium, Sweden and Germany, for example, have had their generating capacity increased.

In Switzerland, the capacity of its five reactors has been increased by 13.4%.

In the USA, the Nuclear Regulatory Commission has approved more than 140 uprates totaling over 6500 MWe since 1977, a few of them "extended uprates" of up to 20%.

Spain has had a program to add 810 MWe (11%) to its nuclear capacity through upgrading its nine reactors by up to 13%. Some 519 MWe of the increase is already in place. For instance, the Almarez nuclear plant was boosted by 7.4% at a cost of US$ 50 million.

Finland boosted the capacity of the original Olkiluoto plant by 29% to 1700 MWe. This plant started with two 660 MWe Swedish BWRs commissioned in 1978 and 1980. The Loviisa plant, with two VVER-440 (PWR) reactors, has been uprated by 90 MWe (10%).

Sweden's utilities have uprated all three plants. The Ringhals plant was uprated by about 400 MWe over 2006-11, and plans will take it to 660 MWe uprate over 25 years. Oskarshamn-3 was uprated by 21% to 1450 MWe at a cost of EUR 313 million, and a 27% uprate of unit 2 is in progress. Forsmark 2 had a 120 MWe uprate (12%) to 2010.

New Nuclear Plant Construction

Most reactors currently planned are in the Asian region, with fast-growing economies and rapidly-rising electricity demand.

Many countries with existing nuclear power programs (Argentina, Armenia, Brazil, Bulgaria, Canada, China, Czech Rep., France, India, Pakistan, Romania, Russia, Slovakia, South Korea, South Africa, Ukraine, UK, USA) have plans to build new power reactors (beyond those now under construction).

In all, about 160 power reactors with a total net capacity of some 177,000 MWe are planned and over 320 more are proposed. Energy security concerns and greenhouse constraints on coal have combined with basic economics to put nuclear power back on the agenda for projected new capacity in many countries.

In the USA there are plans for 13 new reactors, and two combined construction and operating licenses for these were issued early in 2012 while five more are under review. All are for late third-generation plants, and a further proposal is for two ABWR units. it is expected that some of the new reactors will be on line by 2020.

In Canada there are plans to build up to 2200 MWe or more of new capacity at Darlington in Ontario.

In Finland, construction is now under way on a fifth, very large reactor which will come on line in 2014, and plans are firming for another large one to follow it.

France is building a similar 1600 MWe unit at Flamanville, for operation from 2016, and a second may follow it at Penly.

In the UK, four similar 1600 MWe units are planned for operation by 2019, and a further 6000 MWe is proposed.

Romania's second power reactor started up in 2007, and plans are being implemented for two further Canadian units to operate by 2017.

Slovakia is completing two 470 MWe units at Mochovce, to operate from 2014.

Bulgaria is planning to build a large new reactor at Kozloduy.

Belarus is planning two large new Russian reactors at Ostrovets, the first to start in 2019.

In Russia, ten reactors are under active construction, one being a large fast neutron reactor. About 14 further reactors are then planned, some to replace existing plants, and by 2017 ten new reactors totaling at least 9.2 GWe should be operating. Further reactors are planned to add new capacity. This will increase the country's present nuclear power capacity by 50% in 2020. In addition about 5 GW of nuclear thermal capacity is planned. A small floating power plant is expected to be completed by 2014 and others are planned to follow.

Poland is planning two 3000 MWe nuclear power plants.

South Korea plans to bring a further four reactors into operation by 2017, and another five by 2021, giving total new capacity of 12,200 MWe. Of these, all but one are the Advanced PWRs of 1400 MWe. These APR-1400 designs have evolved from a US design which has US NRC design certification, and four been sold to the UAE.

Japan has two reactors under construction but another three which were likely to start building by mid-2011 have been deferred.

In China, now with 15 operating reactors on the mainland, the country is well into the next phase of its nuclear power program. Some 26 reactors are under construction and many more are likely to be so in 2012. Those under construction include the world's first Westinghouse AP1000 units, and a demonstration high-temperature gas-cooled reactor plant is due to start construction. Many more units are planned, with construction due to start within three years. But most capacity under construction is the largely indigenous CPR-1000 design. China aims at least to quadruple its nuclear capacity from that operating and under construction by 2020.

On Taiwan, Taipower is building two advanced reactors (ABWR) at Lungmen.

India has 20 reactors in operation, and seven under construction (two expected to be completed in 2013 but no update is available on the status). This includes two large Russian reactors and a large prototype fast breeder reactor as part of its strategy to develop a fuel cycle which can utilize thorium. Twenty further units are planned. 18 further units are planned, and proposals for more - including western and Russian designs - are taking shape following the lifting of trade restrictions.

Pakistan has third and fourth 300 MWe reactors under construction at Chashma, financed by China. There are plans for more Chinese power reactors.

In Kazakhstan, a joint venture with Russia's Atomstroyexport envisages development and marketing of innovative small and medium-sized reactors, starting with a 300 MWe Russian design as baseline for Kazakh units.

In Iran nuclear power plant construction was suspended in 1979 but in 1995 Iran signed an agreement with Russia to complete a 1000 MWe PWR at Bushehr. This started up in 2011 and was grid connected in August.

The United Arab Emirates has awarded a $20.4 billion contract to a South Korean consortium to build four 1400 MWe reactors by 2020. The first are under construction.

Jordan has committed plans for its first reactor to be operating by 2020, and is developing its legal and regulatory infrastructure.

Turkey has contracts signed for four 1200 MWe Russian nuclear reactors at one site and is negotiating similar capacity at another. Its legal and regulatory infrastructure is well-developed.

Vietnam has committed plans for its first reactors at two sites (2x2000 MWe), to be operating by 2020, and is developing its legal and regulatory infrastructure. The first plant will be a turnkey project built by Atomstroyexport. The second will be Japanese.

Plant Life Extension and Decommissions

Most nuclear power plants originally had a nominal design lifetime of 25 to 40 years, but engineering assessments of many plants have established that many can operate longer. In the USA over 70 reactors have been granted license renewals which extend their operating lives from the original 40 out to 60 years, and operators of most others are expected to apply for similar extensions. Such license extensions at about the 30-year mark justify significant capital expenditure for replacement of worn equipment and outdated control systems.

In France, there are rolling ten-year reviews of reactors. In 2009 the Nuclear Safety Authority (ASN) approved EdF's safety case for 40-year operation of the 900 MWe units, based on generic assessment of the 34 reactors.

The Russian government is extending the operating lives of most of the country's reactors from their original 30 years, for 15 years, or for 25 years in the case of the newer VVER-1000 units, with significant upgrades.

The technical and economic feasibility of replacing major reactor components, such as steam generators in PWRs, and pressure tubes in CANDU heavy water reactors, has been demonstrated. The possibilities of component replacement and license renewals extending the lifetimes of existing plants are very attractive to utilities, especially in view of the public acceptance difficulties involved in constructing replacement nuclear capacity.

On the other hand, economic, regulatory and political considerations have led to the premature closure of some power reactors, particularly in the United States, where reactor numbers have fell from 110 to 103, in eastern Europe, in Germany and likely in Japan.

It should not be assumed that reactors will close when their license is due to expire, since license renewal is now common. However, new plants coming on line are balanced by old plants being retired. Over 1996-2012, 60 reactors were retired as 66 started operation. There are no firm projections for retirements over the next two decades, but WNA estimates that at least 60 of those now operating will close by 2030, most being small plants. The 2011 WNA Market Report reference case has 156 reactors closing by 2030, using very conservative assumptions about license renewal, and 298 coming on line.

Table 1: Power Reactors Under Construction

Commercial Operation*		REACTOR	TYPE	MWe (net)
2013	Iran, AEOI	Bushehr 1*	PWR	950
2013	India, NPCIL	Kudankulam 1	PWR	950
2013	India, NPCIL	Kudankulam 2	PWR	950
2013	China, CGNPC	Hongyanhe 1*	PWR	1080
2013	China, CGNPC	Ningde 1*	PWR	1080
2013	Korea, KHNP	Shin Wolsong 2	PWR	1000
2013	Korea, KHNP	Shin-Kori 3	PWR	1350
2013	Russia, Rosenergoatom	Leningrad II-1	PWR	1070
2013	Argentina, CNEA	Atucha 2	PHWR	692
2013	China, CGNPC	Ningde 2	PWR	1080
2013	China, CGNPC	Yangjiang 1	PWR	1080
2013	China, CGNPC	Taishan 1	PWR	1700
2013	China, CNNC	Fangjiashan 1	PWR	1080
2013	China, CNNC	Fuqing 1	PWR	1080
2013	China, CGNPC	Hongyanhe 2	PWR	1080
2014	Russia, Rosenergoatom	Novovoronezh II-1	PWR	1070
2015	Russia, Rosenergoatom	Rostov 3	PWR	1070
2014	Slovakia, SE	Mochovce 3	PWR	440
2014	Slovakia, SE	Mochovce 4	PWR	440
2014	Taiwan Power	Lungmen 1	ABWR	1300
2014	China, CNNC	Sanmen 1	PWR	1250
2014	China, CPI	Haiyang 1	PWR	1250
2014	China, CGNPC	Ningde 3	PWR	1080
2014	China, CGNPC	Hongyanhe 3	PWR	1080
2014	China, CGNPC	Yangjiang 2	PWR	1080
2014	China, CGNPC	Taishan 2	PWR	1700
2014	China, CNNC	Fangjiashan 2	PWR	1080
2014	China, CNNC	Fuqing 2	PWR	1080
2014	Korea, KHNP	Shin-Kori 4	PWR	1350
2014?	Japan, Chugoku	Shimane 3	ABWR	1375
2014	India, Bhavini	Kalpakkam	FBR	470
2014	Russia, Rosenergoatom	Beloyarsk 4	FNR	750
2015	USA, TVA	Watts Bar 2	PWR	1180
2015	Taiwan Power	Lungmen 2	ABWR	1300
2015	China, CNNC	Sanmen 2	PWR	1250
2015	China, CGNPC	Hongyanhe 4	PWR	1080
2015	China, CGNPC	Yangjiang 3	PWR	1080
2015	China, CGNPC	Ningde 4	PWR	1080
2015	China, CGNPC	Fangchenggang 1	PWR	1080

2015	China, CNNC	Changjiang 1	PWR	650
2015	China, CNNC	Changjiang 2	PWR	650
2015	China, CNNC	Fuqing 3	PWR	1080
2015	India, NPCIL	Kakrapar 3	PHWR	640
2015?	Japan, EPDC/J Power	Ohma 1	ABWR	1350
2016	Finland, TVO	Olkilouto 3	PWR	1600
2016	France, EdF	Flamanville 3	PWR	1600
2016	Russia, Rosenergoatom	Novovoronezh II-2	PWR	1070
2016	Russia, Rosenergoatom	Leningrad II-2	PWR	1200
2016	Russia, Rosenergoatom	Vilyuchinsk	PWR x 2	70
2016	India, NPCIL	Kakrapar 4	PHWR	640
2016	India, NPCIL	Rajasthan 7	PHWR	640
2016	Pakistan, PAEC	Chashma 3	PWR	300
2016	China, China Huaneng	Shidaowan	HTR	200
2016	China, CPI	Haiyang 2	PWR	1250
2016	China, CGNPC	Yangjiang 4	PWR	1080
2016	China, CGNPC	Hongyanhe 5	PWR	1080
2015	China, CNNC	Hongshiding 1	PWR	1080
2015	China, CGNPC	Fangchenggang 2	PWR	1080
2016	China,	several others	PWR	
2017	USA, Southern	Vogtle 3	PWR	1200
2017	Russia, Rosenergoatom	Baltic 1	PWR	1200
2017	Russia, Rosenergoatom	Rostov 4	PWR	1200
2017	Russia, Rosenergoatom	Leningrad II-3	PWR	1200
2017	Ukraine, Energoatom	Khmelnitsky 3	PWR	1000
2017	Korea, KHNP	Shin-Ulchin 1	PWR	1350
2017	India, NPCIL	Rajasthan 8	PHWR	640
2017	Romania, SNN	Cernavoda 3	PHWR	655
2017?	Japan, JAPC	Tsuruga 3	APWR	1538
2017	Pakistan, PAEC	Chashma 4	PWR	300
2017	USA, SCEG	Summer 2	PWR	1200
2017	China,	several		
2018	Korea, KHNP	Shin-Ulchin 2	PWR	1350

* Latest announced year of proposed commercial operation. Rostov = Volgodonsk

Public Acceptance of Nuclear Power

During the early years of nuclear power, there was a greater tendency amongst the public to respect the decisions of authorities licensing the plants, but this changed for a variety of reasons. No revival of nuclear power is possible without the acceptance of communities living next to facilities and the public at large as well as the politicians they elect.

The Chernobyl disaster marked the nadir of public support for nuclear power. However, this tragedy underscored the reason for high standards of design and construction required in the West. It could never have been licensed outside the Soviet Union, incompetent plant operators exacerbated the problem, and partly through Cold War isolation, there was no real safety culture. The global cooperation in sharing operating experience and best practices in safety culture as a result of the accident has been of benefit worldwide. The nuclear industry's safety record over the last 20 years is unrivalled and has helped restore public faith in nuclear power. Over this period, operating experience has tripled, from about 4000 reactor-years to more than 13,500 reactor years.

Another factor in public reassurance is the much smaller than anticipated public health effects of the Chernobyl accident. At the time many scientists predicted that tens of thousands would die as a result of the dispersal of radioactive material. In fact, according to the UN's Chernobyl Forum report, as of mid-2005, fewer than 60 deaths had been directly attributed to radiation from the disaster, and further deaths from cancer are uncertain.

One of the criticisms often leveled against nuclear power is the alleged lack of strategy and provision for its long-lived wastes. It is argued that local communities would never be prepared to host a repository for such waste. However, experience has shown in Sweden and Finland that with proper consultation and compensation mostly in the form of long-term job prospects, communities are quite prepared to host repositories. Indeed in Sweden, two communities were competing to be selected for the siting of the final repository.

The recent Fukushima nuclear accident however, has had a profound impact on the public acceptance of nuclear power.

Japan’s earthquake, tsunami and nuclear meltdown emergency have begun not only to destabilize the world’s third-largest economy, but deepen the slump and financial fragility afflicting global capitalism as a whole. Widespread production halts, rising sovereign debt, disruptions to investment flows and soaring energy prices are delivering shocks to Japan’s economy, with profound international implications.

The three explosions at the Fukushima Daiichi nuclear plant in Japan have made the economic impact of the natural disaster far more difficult to assess than the two templates used by analysts – the Kobe earthquake in 1995 and Hurricane Katrina a decade later – would suggest. Normally, natural disasters are followed by v-shaped recessions. Output is badly affected in the short term, as infrastructure is knocked out and people can't work or shop. Output falls sharply for three to six months, but then rebounds as the reconstruction starts.

What makes this crisis different is the nuclear dimension. The three explosions at the Fukushima Daiichi plant puts this incident into a different category from either Kyoto or Katrina.

There has been disruption to power supplies and people have been evacuated from a 12-mile exclusion zone around the plant, but it could potentially become far more widespread unless the Japanese can shut the plant down safely and quickly.

In Europe Japan's crisis is already having an impact. Germany has already put a stop on the construction of any new nuclear power stations, which according to estimates account for 7% of the country's power. That is a significant energy loss for a country that is growing robustly.

The second factor is the impact the Sendai earthquake will have on consumer and business confidence. At present, the global economy is characterized by a high degree of uncertainty, over the situation in North Africa and the Middle East and now over Japan. Economists think they have a way of quantifying this uncertainty, but they don't.

The complexity of global supply chains for the goods in which Japan is world leader could mean delays and disruptions in some sectors, – such as consumer electronics and cars – depending on how badly the major Japanese multinationals are affected by shortages of power and materials.

One big unknown for the world is the oil price, which has been adding to inflationary pressure in recent months but has fallen since late last week because traders believe the paralysis in Japan will lead to a drop in global demand. That trend may not last. If it does have a v-shaped recovery Japan will quickly return to more normal levels of oil usage. Meanwhile, the unrest in Bahrain and Yemen is evidence that the problems for governments in the Middle East are far from over.

With large numbers of ports, airports, highways and manufacturing plants shut down, the Japanese government predicted “considerable impact on a wide range of our country’s economic activities.”

Following the quake, shares of Tokyo Electric Power Co. led the declines, plummeting 23.6 percent after two explosions hit the company’s nuclear reactors in Fukushima Prefecture. Shares in Japanese vehicle-makers fell by about 10 percent after they largely suspended domestic manufacturing because of factory damage and power outages. Sony shut eight factories and there were closures reported by Kirin, Asahi and Sapporo breweries, Fuji Heavy Industries, GlaxoSmithKline and Nestlé.

Stocks plummeted despite the Japanese central bank pumping a record amount of liquidity into financial markets in a bid to “pre-empt deterioration in business sentiment”. The Bank of Japan yesterday made 21.8 trillion yen ($US265 billion) available to financial institutions and doubled its asset-buying program to 10 trillion yen in a bid to calm markets.

“What we were most concerned about was the possibility that increases in anxiety and risk-aversion moves would negatively affect the real economy, so we judged it appropriate to mainly boost purchases of risk assets,” Bank of Japan governor Masaaki Shirakawa said.

The bank’s board boosted its purchases of riskier financial assets such as corporate debt, exchange-traded funds and real-estate investment trusts by a total of 3.5 trillion yen. It also will buy an additional 1.5 trillion yen of government debt. The bank left its unsecured overnight call loan rate unchanged in a range of 0.0 percent-0.1 percent, but after two decades of stagnation, the rates were already so close to zero that cutting them further would not have led to any increase in lending.

The Financial Times reported: “Economists generally welcomed the central bank’s move as a measure to quell potential panic over access to funds in the wake of a major disaster. But some said the liquidity injection was not likely to be enough to counter the negative impact of the quake and tsunami on the Japanese economy, already weakened by a strong yen and deflationary pressures.”

Analysts commented that the cash injection did not match the amounts that the US Federal Reserve had pumped into US markets via its similar "quantitative easing" program. Mitsumaru Kumagai, chief economist at Daiwa Institute of Research, told the financial newspaper: "It can be judged positive, but compared to the 50,000 billion yen the US pumped into its market in six months, the BoJ hasn't done enough so far (to stimulate the economy), so eventually it will have to take stronger measures."

Kumagai expected the earthquake and accompanying power cuts to reduce Japan's gross domestic product by 0.6 percentage points, but forecasted that reconstruction investment would eventually claw back a large part of the decline. Other market economists took an even dimmer view, warning that reconstruction spending would exacerbate Japan's public debt crisis, with government debt already standing at 228 percent of GDP, the highest in the industrialized world and twice the level of 1995, when the Kobe earthquake hit.

Ken Courtis, formerly vice-chairman of Goldman Sachs in Asia and now a founding partner of China-based Themes Investment Management, told the Sydney Morning Herald: "This earthquake symbolizes the gravity and extent of the larger crisis facing Japan."

Until the nuclear and natural disaster, Japan had been laboring under the triple burdens of debt, deflation and an aging population. "Unless it can produce a decisive program for deep reform, Japan's slow decrepitude will quicken under the added burden of reconstruction spending," Courtis stated. "I have not been able to put together a credible scenario for Japan to solve its debt problem."

Globally, as the Wall Street Journal noted, the Japanese disaster intensified "the ripple effects of the weekend euro-zone debt accord and the continuing crisis in Libya." Credit Suisse strategist Shun Maruyama in Tokyo told the Journal: "We possibly cannot ignore the impact that this quake will have in terms of geographical span and scale—as well as the psychological impact."

Because of the closely intertwined character of global production, the shutdowns in Japan will have knock-on effects throughout Asia and the world. Japan remains a critical part of the Asian and global economy despite recently losing its place as the world's second largest economy after the US to China. It is the biggest source of foreign direct investment for some parts of Asia and a major purchaser of the iron ore, coal, natural gas and other commodities produced in Indonesia, Australia and elsewhere.

In China, on which world capitalism increasingly depends for markets and cheap labor, government officials said they believed the country's economy would be only marginally affected, but they admitted that any protracted downturn in Japan could create problems. The economies of China and Japan are interconnected in numerous industries, including automobile and electronics manufacturing.

China has increasingly become a final-assembly hub for Japanese electronics in recent years, as Japanese firms have sought cheaper manufacturing operations. China is Japan's largest export destination and Japan is the third-largest destination for Chinese exports, according to a report by Bank of America Merrill Lynch.

Global financial and energy markets could be severely affected. In 2010, Japanese savers invested $166 billion in other countries, the International Monetary Fund estimated. Japan was also one of the largest buyers of US Treasury bonds. The Wall Street Journal warned: "As Japan's government and companies bring home the resources needed to rebuild, those capital flows could wane, pushing down the dollar and increasing US borrowing costs at a time when that country's government debt level is also a matter of global concern."

Japan is also the world's No. 3 oil importer, after the US and China. Disruptions in production may limit Japan's short-term demand for energy, but over time the shut nuclear plants could lead to increased imports of oil, natural gas and coal. Analysts estimate that replacing all of Japan's nuclear capacity with oil would mean importing 375,000 more barrels a day on top of the current demand of about 4.25 million barrels.

Section 2: Marine Applications of Nuclear Power

A. Introduction to Nuclear Marine Propulsion

Overview

Nuclear marine propulsion is propulsion of a registered ship class (cargo, bulk, tanker, container, etc.) by a nuclear reactor. Naval nuclear propulsion is propulsion that specifically refers to naval warships.

History of Nuclear Power in Marine Applications

Military Use

Under the direction of Admiral Hyman G. Rickover, the design, development and production of nuclear marine propulsion plants started in the USA in the 1940s, with the first test reactor being started up in 1953. The first nuclear-powered submarine, USS Nautilus, put to sea in 1955. Much of the early development work on naval reactors was done at the Naval Reactor Facility on the campus of the Idaho National Laboratory.

The Soviets were also involved in the production of a nuclear submarine. They produced the November class, the first of which, K-3 "Leninskiy Komsomol", was underway under nuclear power on July 4, 1958.

The large amounts of power produced by an air-independent nuclear reactor marked the transition of submarines from slow vessels required to surface often, to warships capable of sustaining 20-25 knots (37-46 km/h) submerged for many weeks.

Nautilus led to the parallel development of further Skate-class submarines, powered by single reactors, and a cruiser, USS Long Beach, in 1961, powered by two reactors. The aircraft carrier USS Enterprise, commissioned in 1961, is powered by eight reactor units.

By 1962 the United States Navy had 26 nuclear submarines operational and 30 under construction. Nuclear power had revolutionized the Navy. The technology was shared with the United Kingdom, while French, Soviet, Indian and Chinese developments proceeded separately.

After the Skate-class vessels, reactor development proceeded and in the USA a single series of standardized designs was built by both Westinghouse and General Electric, one reactor powering each vessel. Rolls-Royce built similar units for Royal Navy submarines and then developed the design further to the PWR-2 (pressurized water reactor).

The largest nuclear submarines ever built are the 26,500 ton Russian Typhoon class.

The most compact nuclear submarines to date ever built are the 2,700 ton French Rubis class submarine attack submarines.

USA and France have built nuclear aircraft carrier vessels.

Civilian Use

Development of nuclear merchant ships began in the 1950s, but has not generally been commercially successful. The US-built NS Savannah was commissioned in 1962 and decommissioned eight years later. It was a technical success, but not economically viable. The German-built Otto Hahn cargo ship and research facility sailed some 650,000 nautical miles (1,200,000 km) on 126 voyages in 10 years without any technical problems. However, it proved too expensive to operate and was converted to diesel. The Japanese Mutsu was the third civil vessel. It was dogged by technical and political problems and was an embarrassing failure. All three vessels used reactors with low-enriched uranium fuel.

The fourth nuclear merchant ship, Sevmorput, operates successfully in the specialized environment of the Northern Sea Route. Recently there has been renewed interest in nuclear propulsion, and some proposals have been drafted. For example, the cargo coaster is a new design for a nuclear cargo ship. Using the new micro nuclear reactors, other existing cargo ships could potentially be converted to nuclear propulsion as well.

Nuclear propulsion has proven both technically and economically feasible for nuclear powered icebreakers in the Soviet Arctic. The power levels and energy required for icebreaking, coupled with refueling difficulties for other types of vessels, are significant factors. The Soviet icebreaker Lenin was the world's first nuclear-powered surface vessel and remained in service for 30 years (new reactors were fitted in 1970). It led to a series of larger icebreakers, the 23,500 ton Arktika class, launched from 1975. These vessels have two reactors and are used in deep Arctic waters. NS Arktika was the first surface vessel to reach the North Pole.

For use in shallow waters such as estuaries and rivers, shallow-draft Taymyr class icebreakers with one reactor are being built in Finland and then fitted with their nuclear steam supply system in Russia. They are built to conform with international safety standards for nuclear vessels.

Marine-type Nuclear Reactors

The majority of marine reactors are of the pressurized water type, although the US and Soviet navies have designed and fielded warships powered with liquid metal cooled reactors. Marine-type reactors differ from commercial reactors in that:

- Marine reactors are compact but have high power density, i.e. they produce significant power in a small volume, however the total amount of power produced in a marine reactor is small (hundreds of MWt) compared to a commercial power reactor (thousands of MWt).

- The fuel used is typically of higher enrichment; some run on low-enriched uranium (requiring frequent refuelings), others run on highly enriched uranium (greater than 20% U-235, varying to over 96% in U.S. submarines (They do not need to be refueled as often and are quieter in operation from smaller core) to between 30–40% in Russian submarines to lower levels in some others),

- The fuel is not a ceramic UO2 (uranium oxide) but a metal-zirconium alloy (circa 15% U with 93% enrichment, or more U with lower enrichment),

- Marine reactors are designed for long core life, enabled by the relatively high enrichment of the uranium and by incorporating a "burnable poison" in the cores which is progressively depleted as fission products and minor actinides accumulate; the two effects cancel each other out. One of the technical difficulties is the creation of a fuel which will tolerate the very large amount of radiation damage. It is known that during use the properties of nuclear fuel change; it is quite possible for fuel to crack and for fission gas bubbles to form.

- The reactor, as the ship's propulsion system energy (heat) source, is mobile, not stationary, as in a land based nuclear reactor plant. So the reactor, and all of its auxiliary support equipment, must be of an exceptionally rugged design, to withstand the forces (sometimes very violent forces) associated with the movement of a ship over the world's oceans.

- Oceanic weather, the wide variations of air and water temperature, plus the corrosive nature of the salt air and water environments, place even greater, unique design demands upon the sea-based nuclear power propulsion plant.

- Finally, the marine reactor propulsion plant must be of cost effective design, construction and operation. It must be highly reliable and self-sufficient, so as to be easily reparable and sustainable through repairs, conducted many thousands of miles from its home port.

Long-term integrity of the compact reactor pressure vessel is maintained by providing an internal neutron shield. (This is in contrast to early Soviet civil PWR designs where embrittlement occurs due to neutron bombardment of a very narrow pressure vessel.)

The Russian, U.S. and British navies rely on steam turbine propulsion, while the French and Chinese use the turbine to generate electricity for propulsion (turbo-electric propulsion). Most Russian submarines as well as most American aircraft carriers are powered by two reactors, an exception being the first nuclear powered aircraft carrier the USS Enterprise with eight. The majority of U.S., British, French and Chinese submarines are powered by one, with the notable exception of the USS Triton, the first submarine to circumnavigate the world submerged, with two reactors.

Decommissioning nuclear-powered submarines has become a major task for US and Russian navies. After defueling, U.S. practice is to cut the reactor section from the vessel for disposal in shallow land burial as low-level waste (see the Ship-Submarine recycling program). In Russia, whole vessels, or sealed reactor sections, typically remain stored afloat, although a new facility near Sayda Bay is to provide storage in a concrete-floored facility on land for some submarines in the far north.

Russia is well advanced with plans to build a floating nuclear power plant for their far eastern territories. The design has two 35 MWe units based on the KLT-40 reactor used in icebreakers (with refueling every four years). Some Russian naval vessels have been used to supply electricity for domestic and industrial use in remote far eastern and Siberian towns.

Lloyd's Register is investigating the possibility of civilian nuclear marine propulsion and rewriting draft rules.

Nuclear-powered Naval Vessels

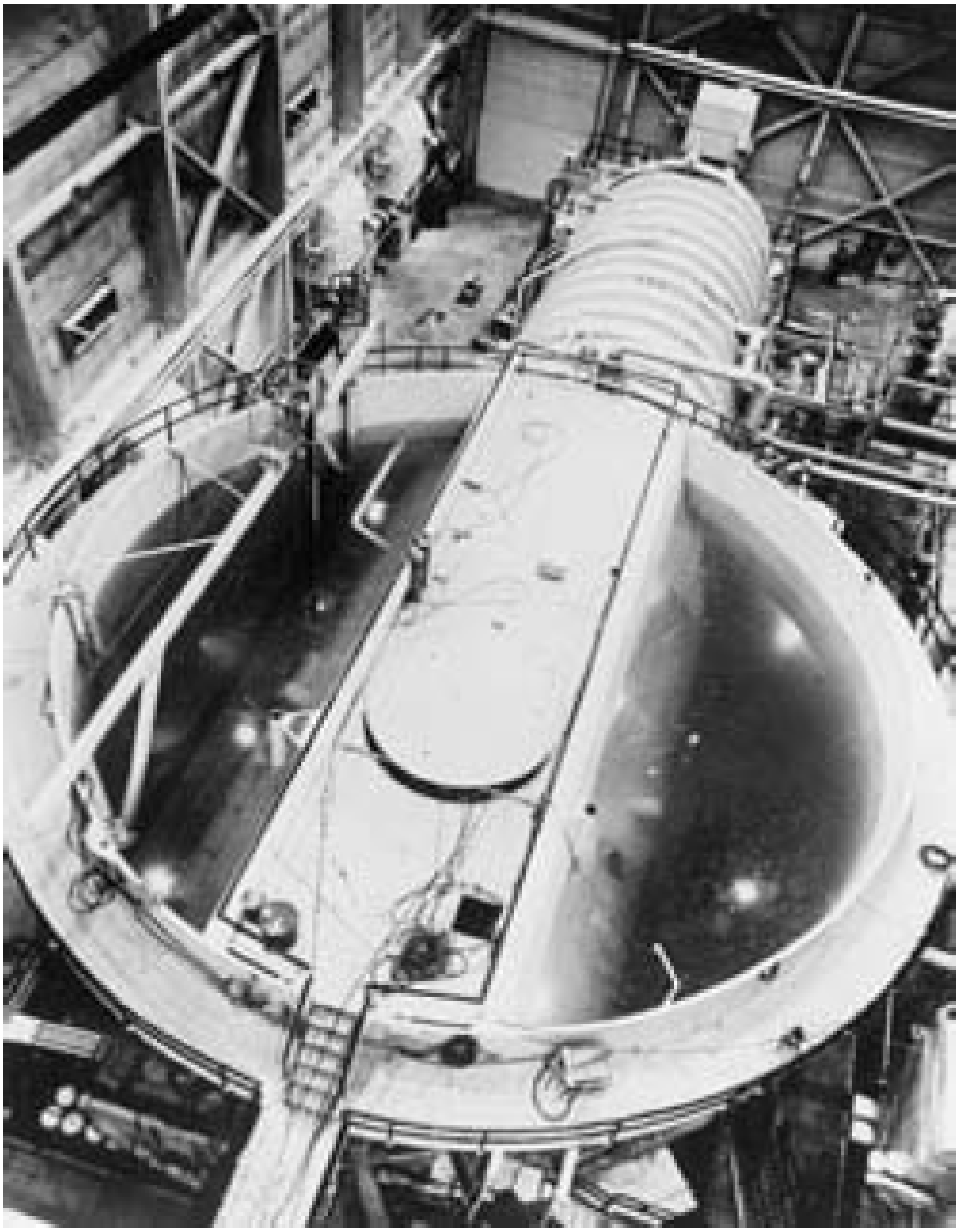
Jules Verne, the French author in his 1870 book: “20,000 Leagues Under the Sea,” related the story of an electric submarine. The submarine was called the “Nautilus,” under its captain Nemo. Science fiction became reality when the first nuclear submarine built by the USA Navy was given the same name. The figure below shows a photograph of the Nautilus, the first nuclear powered submarine.

Construction of the Nautilus (SSN-571) started on June 14, 1952, its first operation was on December 30, 1954 and it reached full power operation on January 13, 1955. It was commissioned in 1954, with its first sea trials in 1955. It set speed, distance and submergence records for submarine operation that were not possible with conventional submarines. It was the first ship to reach the North Pole. It was decommissioned in 1980 after 25 years of service, 2,500 dives, and a travelled distance of 513,000 miles. It is preserved at a museum at Croton, Connecticut.

Figure 20: The "Nautilus", the First Nuclear Powered Submarine

The figure below, meanwhile, shows the experimental setup S1W prototype for the testing of the Nautilus's nuclear reactor built at the Idaho National Laboratory (INL) in 1989. The section of the hull containing the reactor rested in a "sea tank" of water 40 feet deep and 50 feet in diameter. The purpose of the water was to help shielding specialists study "backscatter," radiation that might escape the hull, bounce off the water molecules, and reflect back into the living quarters of the ship.

Figure 21: Experimental setup for testing Nautilus type naval reactors at the Idaho National Engineering Laboratory



The advantage of a nuclear engine for a submarine is that it can travel long distances undetected at high speed underwater avoiding the surface wave resistance, without refueling. Unlike diesel engine driven submarines, the nuclear engine does not need oxygen to produce its energy.

The reactor for the Nautilus was a light water moderated, highly enriched in Uranium235 core, with zirconium clad fuel plates. The high fuel enrichment gives the reactor a compact size, and a high reactivity reserve to override the xenon poison dead time. The Nautilus beat numerous records, establishing nuclear propulsion as the ideal driving force for the world's submarine fleet. Among its feats was the first underwater crossing of the Arctic ice cap. It traveled 1,400 miles at an average speed of 20 knots. On a first core without refueling, it traveled 62,000 miles.

Zirconium has a low neutron absorption cross section and, like stainless steel, forms a protective, invisible oxide film on its surface upon exposure to air. This oxide film is composed of zirconia or ZrO2 and is on the order of only 50 to 100 angstroms in thickness. This ultra-thin oxide prevents the reaction of the underlying zirconium metal with virtually any chemical reagent under ambient conditions. The only reagent that will attack zirconium metal at room temperature is hydrofluoric acid, HF, which will dissolve the thin oxide layer off of the surface of the metal and thus allow HF to dissolve the metal itself, with the concurrent evolution of hydrogen gas.

Another nuclear submarine, the Triton reenacted Magellan's trip around the Earth. Magellan traveled on the surface, while the Triton did it completely submerged.

B. Analysis of Naval Nuclear Applications

Overview

Nuclear navy, or nuclear powered navy consists of ships powered by relatively small onboard nuclear reactors known as naval reactors. The concept was revolutionary for naval warfare when first proposed, as it meant that these vessels did not need to stop for fuel like their conventional counterparts, being limited only by crew endurance and supplies.

Nuclear-powered Aircraft Carriers

The United States Navy has by far the most powered aircraft carriers, with 11 in service. France's latest aircraft carrier, the R91 Charles de Gaulle, is nuclear powered. The United Kingdom rejected nuclear power early in the development of its Queen Elizabeth-class aircraft carriers on cost grounds. As currently envisaged, France's new aircraft carrier could be nuclear-powered or conventionally powered.

Nuclear-powered Submarines

The United States Navy operates the largest fleet of nuclear submarines. Only the United States Navy, the Royal Navy of the United Kingdom, and France's Marine Nationale field an all-nuclear submarine force. By 1989, there were over 400 nuclear-powered submarines operational or being built. Some 250 of these submarines have now been scrapped and some on order cancelled, due to weapons reduction programs. Russia and the United States had over one hundred each, with the United Kingdom and France fewer than twenty each and China six. The Indian Navy launched their first indigenous Arihant class nuclear-powered submarines on July 26, 2009. India is also reported to be leasing two additional nuclear submarines from Russia.

Nuclear-powered submarines can stay submerged for up to 400 days if the vessel is fully loaded.

Other Nuclear-powered Vessels

The United States no longer has nuclear cruisers, but they are still in use by Russia, the largest of which are the Kirov-class battle cruisers. Russia also has eight nuclear icebreakers in service or under construction.

C. Benefits of Nuclear Marine Propulsion

Flexibility

A nuclear surface ship brings optimum capability to bear. A recent study by the Navy found the nuclear option to be superior to conventional fuels in terms of surge ability, moving from one theater to another, and staying on station. Admiral Kirkland Donald, director of the U.S. Navy Nuclear Propulsion Program, said in recent congressional testimony, “Without the encumbrances of fuel supply logistics, our nuclear-powered warships can get to areas of interest quicker, ready to enter the fight, and stay on station longer than their fossil-fueled counterparts.”

High Power Density of Nuclear Power

The high density of nuclear power, i.e., the amount of volume required to store a given amount of energy, frees storage capacity for high value/high impact assets such as jet fuel, small craft, remote-operated and autonomous vehicles, and weapons. When compared to its conventional counterpart, a nuclear aircraft carrier can carry twice the amount of aircraft fuel, 30 percent more weapons, and 300,000 cubic feet of additional space (which would be taken up by air intakes and exhaust trunks in gas turbine powered carriers).

This means that ships can get to station faster and deliver more impact, which will be critical to future missions. This energy supply is also necessary for new, power-intensive weapons systems like rail-guns and directed-energy weapons as well as for the powerful radar that the Navy envisions.

Real-Time Response Time

Only a nuclear ship can change its mission and respond to a crisis in real time. On September 11, 2001, the USS Enterprise - then on its way home from deployment - responded to news of the terrorist attacks by rerouting and entering the Afghan theater.

End of Energy Dependency

The armed forces have acknowledged the vulnerability that comes from being too dependent on foreign oil. Delores Etter, Assistant Secretary of the U.S. Navy for Research, Development, and Acquisition, said in recent congressional testimony, "[We] take seriously the strategic implications of increased fossil fuel independence." The Navy's use of nuclear propulsion for submarines and aircraft carriers already saves 11 million barrels of oil annually. Using nuclear propulsion for all future major surface combatants will make the Navy more energy independent.

Increasing the Capabilities of the Naval Forces

Though effective, modern aircraft carriers still depend on less capable fossil-fueled counterparts in the battle group. Increasing the number of nuclear surface ships would increase the capability of U.S. naval forces to operate both independently and as part of a battle-group.

Environmentally Clean Source of Energy

The U.S. Congress is considering placing CO2 restrictions on all federal government activities, including the Pentagon's. This mandate would be highly detrimental to the armed forces. More people are starting to realize the often-overlooked environmental benefits of a nuclear navy. Expanding nuclear power would help to achieve many of the objectives of a CO2 mandate in addition to increasing a country's military capability. Unlike a conventionally powered ship, which emits carbon dioxide and other pollutants into the atmosphere, a nuclear ship is largely emissions-free.

D. Analysis of Naval Nuclear Reactor Development

Introduction

There have been more reactor concepts investigated in the naval propulsion area by different manufacturers and laboratories than in the civilian field, and much can be learned from their experience for land applications.

According to the type of vessel they power they have different first letter designations: A for Aircraft carrier, C for Cruiser, D for Destroyer or Cruiser and S for Submarine.

They are also designated with a last letter according to the designer institution or lead laboratory: B for Bechtel, C for Combustion Engineering, G for General Electric and W for Westinghouse.

A middle number between the first and last letter refers to the generation number of the core design. For instance, the A1B is the first generation of a core design for aircraft carriers with Bechtel operating the lead laboratory for the design.

Naval reactors designs use boron as a burnable neutron poison. The fuel is an alloy of 15 percent zirconium and 85 percent uranium enriched to a level of 93 percent in U235. The burnable poisons and high enrichment allow a long core lifetime and provides enough reactivity to overcome the xenon poisoning reactor dead time. The vertical direction doping provides a long core life, and the radial doping provides for an even power and fuel burnup distribution.

S1W Pressurized Water Reactor Design (STR)

The Westinghouse Electric Corporation under contract to the USA Navy constructed, tested and operated a prototype pressurized water reactor submarine reactor plant. This first reactor plant was called the Submarine Thermal Reactor, or STR. On March 30, 1953, the STR was brought to power for the first time and the age of naval nuclear propulsion was born. In 1953 it achieved a 96 hours sustained full power run simulating a crossing of the Atlantic Ocean. The second S1W core sustained in 1955 a 66 days continuous full power simulating a high speed run twice around the globe.

The STR was redesigned as the first generation submarine reactor S1W, which became critical on March 30, 1953, was the prototype of the USS Nautilus (SSN 571) reactor and was followed in the middle to late 1950s by the Aircraft carrier A1W, the prototype of the aircraft carrier USS Enterprise plant.

Westinghouse's Bettis Atomic Power Laboratory was assigned the responsibility for operating the reactor it had designed and built, hence the W in the name. The crew was increasingly augmented by naval personnel as the cadre of trained operators grew.

The fuel elements are sandwich plates made of U and Zr and clad in Zr. The maximum temperature in the fuel was 645^{o}F and the sheath temperature was 551^{o}F with an average cycle time of 600 hours or just 600 / 24 = 25 days. The reactor temperature is limited by the pressure needed to prevent boiling, necessitating high pressure vessels, piping and heat exchangers. The steam was generated at a relatively low pressure. A high level of pumping power was required, and the fuel was costly. However this design had few hazards, has been proven in service, and an expensive moderator was not needed.

The S1C reactor used an electric drive rather than a steam turbine like in the subsequent S5W reactor design rated at 78 MWth and a 93 percent U235 enriched core that was the standard in the 1970s. The S6G reactor plant was rated at 148 MWth and the D2W core was rated at 165 MWth.

The S6G reactor is reported to be capable of propelling a Los Angeles class submarine at 15 knots or 27.7 km/hr when surfaced and 25 knots or 46.3 km/hr while submerged.

The Sea wolf class of submarines was equipped with a single S6W reactor, whereas the Virginia class of submarines is expected to be equipped with an S9G reactor.

The higher achievable submerged speed is due to the absence of wave friction underwater suggesting that submarine cargo ships would offer a future energy saving alternative to surface cargo ships.

Large Ship Reactors, A1W-A, A1W-B

The A1W (aircraft carrier, first prototype, Westinghouse) plant consisted of a pair of prototype reactors for the USS Enterprise USA Navy nuclear-powered aircraft carrier. Located at the Naval Reactors Facility, the two pressurized-water reactors (designated A and B) were built within a portion of a steel hull. The plant simulated the Enterprise's engine room. All components could withstand seagoing use.

The A1W plant was the first in which two reactors powered one ship propeller shaft through a single-geared turbine propulsion unit. As the Navy program evolved, new reactor cores and equipment replaced many of the original components. The Navy trained naval personnel at the A1Wplant and continued a test program to improve and further develop operating flexibility.

The A1W prototype plant was started in 1956 for surface ships using two pressurized water reactors. The plant was built as a prototype for the aircraft carrier USS Enterprise (CVN 65), which was the first nuclear-powered aircraft carrier. Power operation of the A1W plant started in October of 1958.

In the A1W and A2W designs, the coolant was kept at a temperature between 525-545ºF or 274-285°C. In the steam generators, the water from the feed system is converted to steam at 535 °F or 279 °C and a pressure of about 600 psi or 4 MPa. The reactor coolant water was recirculated by four large electric pumps for each reactor.

The steam was channeled from each steam generator to a common header, where the steam is then sent to the main engine, electrical generators, aircraft catapult system, and various auxiliaries. The main propulsion turbines are double ended, in which the steam enters at the center and divides into two opposing streams.

The main shaft was coupled to a reduction gear in which the high rotational velocity of the turbine shaft is stepped down to a usable turn rate for propelling the ship.

In the A3W reactor design used on the USS John F. Kennedy a 4 reactor design is used. In the A4W design with a life span of 23 years on the Nimitz class carriers only two reactors per ship are used with each providing 104 MWth of power or 140,000 shaft HP. The A1B is also a two reactor design for the Gerald R. Ford class of carriers.

SIR OR S1G Intermediate Flux Beryllium Sodium Cooled Reactor

This reactor design was built by the General Electric (GE) Company, hence the G designation. The neutron spectrum was intermediate in energy. It used UO2 fuel clad in stainless steel with Be used as a moderator and a reflector. The maximum temperature in the fuel could reach 1,700 +/- 300°F with a maximum sheath temperature of 900°F, with a cycle time of 900 hours or 900 / 24 = 37.5 days.

A disadvantage is that the coolant becomes activated with the heat exchangers requiring heavy shielding. In addition Na reacts explosively with water and the fuel element removal is problematic. On the other hand high reactor and steam temperatures can be reached with a higher thermal efficiency. A low pressure is used in the primary system.

Beryllium has been used as a moderator in the Sea Wolf class of submarines reactors. It is a relatively good solid moderator, both from the perspectives of slowing down power and of the moderating ratio, and has a very high thermal conductivity. Pure Be has good corrosion resistance to water up to 500°F, to sodium to 1,000°F, and to air attack to 1,100°F. It has a noted vapor pressure at 1,400°F and is not considered for use much above 1,200°F even with an inert gas system. It is expensive to produce and fabricate, has poor ductility and is extremely toxic necessitating measures to prevent inhalation and ingestion of its dust during fabrication.

A considerably small size thermal reactor can be built using beryllium oxide as a moderator. It has the same toxicity as Be, but is less expensive to fabricate. It can be used with a sodium cooled thermal reactor design because BeO is corrosion resistant to sodium. It has similar nuclear properties to Be, has a very high thermal conductivity as a ceramic, and has a good resistance to thermal shock. It can be used in the presence of air, sodium and CO2. It is volatile in water vapor above 1,800°F. In its dense form, it resists attack by Na or Na-K at a temperature of 1,000°F. BeO can be used as a fuel element material when impregnated with uranium. Low density increases its resistance to shock. A BeO coating can be applied to cut down on fission products release to the system.

The USS Seawolf submarine, initially used a Na cooled reactor that was replaced in 1959 by a PWR to standardize the fleet, because of super heater bypass problems causing mediocre performance and as a result of a sodium fire. The steam turbines had their blades replaced to use saturated rather than superheated steam. The reactor was housed in a containment vessel designed to contain a sodium fire.

The eighth generation S8G reactor was capable of operating at a significant fraction of full power without reactor coolant pumps. The S8G reactor was designed by General Electric for use on the Ohio class (SSGN/SSBN-726) submarines. A land based prototype of the reactor plant was built at Knolls Atomic Power Laboratory at Ballston Spa, New York. The prototype was used for testing and crew training throughout the 1980s. In 1994, the core was replaced with a sixth generation S6W Westinghouse reactor, designed for the Sea Wolf class submarines.

Experimental Beryllium Oxide Reactor

The Experimental Beryllium Oxide Reactor's objective was to develop beryllium oxide as a neutron moderator in high-temperature, gas-cooled reactors. The project was canceled in 1966 before construction was complete.

Among the reasons for the cancellation was the encouraging progress achieved, concurrent with EBOR construction, in developing graphite as a moderator. This reduced the importance of developing beryllium oxide as an alternate.

No uranium fuel ever was loaded into the Experimental Beryllium Oxide reactor and it never operated or went critical before the program was canceled. It was "a reactor," but never an operating one.

SC-WR Super Critical Water Reactor

The Super Critical Water Reactor (SC-WR) was considered with an intermediate energy neutron spectrum. The fuel was composed of UO2 dispersed in a stainless steel matrix. It consisted of 1 inch square box with parallel plates and sine wave filters with a type 347 stainless steel cladding 0.007 inch thick. The maximum temperature in the fuel reached 1,300°F with an average cycle time of 144 hours or 144 / 24 = 6 days.

The materials for high pressure and temperature and the retention of mechanical seals and other components were a service problem.

The water coolant reached a pressure of 5,000 psi. The high pressure and temperature steam results in a high cycle efficiency, small size of the reactor with no phase change in the coolant.

Organic Moderated Reactor Experiment

The Organic Cooled and Moderated Reactor has been considered as a thermal neutron spectrum shipboard power plant.

The waxy coolant was considered promising because it liquefied at high temperatures but didn't corrode metal like water did.

Also, it operated at low pressures, significantly reducing the risk of leaking. A scaled-up reactor, the Experimental Organic Cooled Reactor, was built next door in anticipation of further development of the concept.

The rectangular-plates fuel clad in aluminum can be natural uranium since the Terphenyl organic coolant can have good moderating properties. The cladding temperature can reach 800°F with an average cycle time of 2,160 hours or 2,160 / 24 = 90 days.

The overall heat transfer coefficient of the coolant is low with the formation of polymers under irradiation that require a purification system. The advantages are negligible corrosion and the achievement of low pressure at a high temperature.

A diphenyl potential coolant broke down under irradiation. The hydrogen in the compound turned into a gas forming bubbles. The bubbles reduced the moderator density and made it difficult to maintain the chain reaction. The initially clear liquid turned into a gummy and black breakup product.

No uranium fuel ever was loaded into the reactor and it never operated or went critical before the program was canceled. It was "a reactor," but never "an operating reactor."

Lead-Bismuth Cooled Fast Reactors

The alpha class of Russian submarines used an alloy of Pb-Bi 45-50 percent by weight cooled fast reactors. The melting point of this alloy is 257°F. They faced problems of corrosion of the reactor components, melting point, pump power, polonium activity and problems in fuel unloading.

Refueling needed a steam supply to keep the liquid metal molten. Bismuth leads to radiation from the activated products, particularly polonium. An advantage is that at decommissioning time, the core can be allowed to cool into a solid mass with the lead providing adequate radiation shielding.

This class of submarines has been decommissioned.

Natural Circulation S5G Prototype

The S5G was the prototype of a pressurized-water reactor for USS Narwhal. Located at the Naval Reactors Facility, it was capable of operating in either a forced or natural circulation flow mode. In the natural circulation mode, cooling water flowed through the reactor by thermal circulation, not by pumps. Use of natural circulation instead of pumps reduced the noise level in the submarine.

To prove that the design concept would work in an operating ship at sea, the prototype was built in a submarine hull section capable of simulating the rolling motion of a ship at sea. The S5G continued to operate as part of the Navy's nuclear training program until that program was reduced after the end of the Cold War.

The S5G reactor had two coolant loops and two steam generators. It had to be designed with the reactor vessel situated low in the boat and the steam generators high in order for natural circulation of the coolant to be developed and maintained.

This nuclear reactor was installed both as a land-based prototype at the Nuclear Power Training Unit, Idaho National Engineering Laboratory near Idaho Falls, Idaho, and on board the USS Narwhal (SSN-671), now decommissioned.

The prototype plant in Idaho was given a rigorous performance check to determine if such a design would work for the USA Navy. It was largely a success, although the design never became the basis for any more fast attack submarines besides the Narwhal. The prototype testing included the simulation of essentially the entire engine room of an attack submarine. By floating the plant in a large pool of water, the whole prototype could be rotated along its long axis to simulate a hard turn. This was necessary to determine whether natural circulation would continue even during hard maneuvers, since natural circulation is dependent on gravity.

The USS Narwhal had the quietest reactor plant in the USA naval fleet. Its 90 MWth reactor plant was slightly more powerful than the other fast attack USA nuclear submarines of that era such as the third generation S3G and the fifth generation S5W. The Narwhal contributed significantly to the USA effort during the Cold War. With its quiet propulsion and the pod attached to its hull, it used a towed sonar array and possibly carried a Remotely Operated Vehicle (ROV) for tapping into communication cables and maintaining a megaphones tracking system at the bottom of the oceans.

It was intended to test the potential contribution of natural circulation technology to submarine noise suppression by the avoidance of forced flow pump cooling. The reactor primary coolant pumps are one of the primary sources of noise from submarines in addition to the speed reduction gearbox and cavitation from the propeller. The elimination of the coolant pumps and associated equipment would also reduce mechanical complexity and the space required by the propulsion equipment.

The S5G was the direct precursor to the eighth generation S8G reactor used on the Ohio class ballistic missile submarines; a quiet submarine design.

The S5G was also equipped with coolant pumps that were only needed in emergencies to attain high power and speed. The reactor core was designed with very smooth paths for the coolant. Accordingly, the coolant pumps were smaller and quieter than the ones used by the competing S5W core, a Westinghouse design. They were also fewer in numbers. In most situations, the submarine could be operated without using the coolant pumps, useful for stealth operation. The reduction in electrical requirements enabled this design to use only a single electrical turbine generator plant.

The S8G prototype used natural circulation allowing operation at a significant fraction of full power without using the reactor pumps, providing a silent stealth operation mode.

To further reduce engine plant noise, the normal propulsion setup of two steam turbines driving the propeller screw through a reduction gear unit was changed instead to one large propulsion turbine without reduction gears. This eliminated the noise from the main reduction gears, but at the expense of a large main propulsion turbine. The turbine was cylindrical, about 12 feet in diameter and 30 feet in length. This large size was necessary to allow it to turn slowly enough to directly drive the screw and be fairly efficient in doing so. The same propulsion setup was used on both the USS Narwhal and its land based prototype.

Fail Safe Control and Load Following S7G Design

The S7G core was controlled by stationary gadolinium clad tubes that were partially filled with water. Water was pumped from the portion of the tube inside the core to a reservoir above the core, or allowed to flow back down into the tube. A higher water level in the tube within the core slowed down the neutrons allowing them to be captured by the gadolinium tube cladding rather than the uranium fuel, leading to a lower power level.

The system had a failsafe control system. The pump needed to run continually to keep the water level pumped down. Upon an accidental loss of power, all the water would flow back into the tube, shutting down the reactor.

This design also had the advantage of a negative reactivity feedback and a load following mechanism. An increase in reactor power caused the water to expand to a lower density lowering the power. The water level in the tubes controlled average coolant temperature, not reactor power. An increase in steam demand resulting from opening the main engines throttle valves would automatically increase reactor power without action by the operator.

S9G High Energy Density Core

The S9G is a PWR built by General Electric with increased energy density, and new plant components, including a new steam generator design featuring improved corrosion resistance and a reduced life cycle cost. This reactor in the Virginia class SSN-774 submarines is designed to operate for 33 years without refueling and last the expected 30 year design life of a typical submarine.

The higher power density decreases not only size but also enhances quiet operation through the elimination of bulky control and pumping equipment. It would be superior to any Russian design from the perspective of noise reduction capability, with 30 units planned to be built.

Table 2: Power Ratings of Naval Reactor Designs

Reactor type	**Rated power**	
	shaft horse power, [shp]	**[MW]***
A2W	35,000	26.1
A4W/A1G	140,000	104.4
C1W	40,000	29.8
D2G	35,000	26.1
S5W	15,000	11.2
S5G	17,000	12.7
S6W	35,000	26.1
S8G	35,000	26.1
S9G	40,000	29.8

*1 shp = 745.6999 Watt = 0.7456999 kW

Expended Core Facility

The Expended Core Facility was built in 1957. It was used to examine expended naval reactor fuel to aid in the improvement of future generations of naval reactors. In the middle 1960s, the fifth generation S5G, the prototype of the submarine USS Narwhal reactor, and predecessor to the reactor plant used to propel the Trident Fleet Ballistic Missile Submarines, was built and placed in service by the General Electric Company.

The Expended Core Facility ECF was built to examine and test fuel from nuclear powered vessels, prototype plants, and the Shippingport Power Plant. It has examined specimens of irradiated fuel that were placed in a test reactor, such as the Advanced Test Reactor (ATR).

The information from detailed study of this fuel has enabled the endurance of naval nuclear propulsion plants to be increased from two years for the first core in Nautilus to the entire 30+ year lifetime of the submarines under construction today.

It originally consisted of a water pool and a shielded cell with a connecting transfer canal. It has been modified by the addition of three more water pools and several shielded cells. The water pools permit visual observation of naval spent nuclear fuel during handling and inspection while shielding workers from radiation. The shielded cells are used for operations which must be performed dry.

Ongoing R&D in Naval Reactors

The USA Navy's research and development expanded in eastern Idaho, and by late 1954, the Nuclear Power Training Unit was established. In 1961, the Naval Administrative Unit set up shop in Blackfoot. In 1965, the unit moved to a location at Idaho Falls

In the early 1950s work was initiated at the Idaho National Engineering and Environmental Laboratory (INEEL) to develop reactor prototypes for the USA Navy. The Naval Reactors Facility, a part of the Bettis Atomic Power Laboratory, was established to support development of naval nuclear propulsion. The facility was operated by the Westinghouse Electric Corporation under the direct supervision of the DOE's Office of Naval Reactors. The facility supports the Naval Nuclear Propulsion Program by carrying out assigned testing, examination, and spent fuel management activities.

The facility consisted of three naval nuclear reactor prototype plants, the Expended Core Facility, and various support buildings. The Submarine Thermal Reactor (STR) prototype was constructed in 1951 and shut down in 1989; the large ship reactor prototype was constructed in 1958 and shut down in 1994; and the submarine reactor plant prototype was constructed in 1965 and shut down in 1995.

The prototypes were used to train sailors for the nuclear navy and for research and development purposes. The Expended Core Facility, which receives, inspects, and conducts research on naval nuclear fuel, was constructed in 1958.

The initial power run of the prototype reactor (S1W) as a replacement of the STR for the first nuclear submarine, the Nautilus, was conducted at the INEEL Laboratory in 1953. The A1W prototype facility consisted of a dual-pressurized water reactor plant within a portion of the steel hull designed to replicate the aircraft carrier Enterprise. This facility began operations in 1958 and was the first designed to have two reactors providing power to the propeller shaft of one ship. The S5G reactor was a prototype pressurized water reactor that operated in either a forced or natural circulation flow mode. Coolant flow through the reactor was caused by natural convection rather than pumps. The S5G prototype plant was installed in an actual submarine hull section capable of simulating the rolling motions of a ship at sea.

The Test Reactor Area (TRA) occupied 102 acres in the southwest portion of the INEEL laboratory. The TRA was established in the early 1950s with the development of the Materials Test Reactor (MTR). Two other major reactors were subsequently built at the TRA: the Engineering Test Reactor (ETR) and the Advanced Test Reactor (ATR). The Engineering Test Reactor has been inactive since January 1982. The Materials Test Reactor was shut down in 1970.

The major program at the TRA became the Advanced Test Reactor. Since the Advanced Test Reactor achieved criticality in 1967, it was used almost exclusively by the Department of Energy's Naval Reactors Program. After almost 30 years of operation, it is projected to remain a major facility for research, radiation testing, and isotope production into the next century.

The Navy makes shipments of naval spent fuel to INEEL that are necessary to meet national security requirements to defuel or refuel nuclear powered submarines, surface warships, or naval prototype or training reactors, or to ensure examination of naval spent fuel from these sources. The total number of shipments of naval spent fuel to INEEL through 2035 would not exceed 575 shipments or 55 metric tons of spent fuel.

E. Analysis of US Naval Reactors

Overview

United States Naval reactor refers to nuclear reactors used by the United States Navy aboard certain ships to produce power for propulsion, electric power, catapulting airplanes in aircraft carriers, and a few more minor uses. Such Naval nuclear reactors have a complete power plant associated with them. These days all US Navy submarines and supercarriers built for the past couple of decades are nuclear-powered by such reactors. There are no commissioned conventional (non-nuclear) submarines or aircraft carriers left in the US Navy, since the last conventional carrier, USS Kitty Hawk, was decommissioned in May 2009.

The US Navy had nine nuclear-powered cruisers with such reactors also, but they are all decommissioned by now. Reactors are designed by a variety of contractors, then developed and tested at one of several government (Department of Energy)-owned and prime contractor-operated facilities. These facilities include Bettis Atomic Power Laboratory in West Mifflin, PA and its associated Naval Reactors Facility in Idaho, and Knolls Atomic Power Laboratory in Niskayuna, NY and its associated Kesselring site in West Milton, NY, all under the management of the office of Naval Reactors. Sometimes there were full-scale nuclear-powered prototype plants built at the Naval Reactors Facility, Kesselring, and Windsor Locks (in CT) to test the nuclear plants, which were operated for years to train nuclear-qualified sailors.

Designation System for Reactors

Each reactor design is given a three-character designation consisting of:

- A letter for the type of ship the reactor is intended for ("A" for aircraft carrier, "C" for cruiser, "D" for destroyer, and "S" for submarine)
- A consecutive generation number
- A letter for the reactor's designer ("W" for Westinghouse, "G" for General Electric, "C" for Combustion Engineering, and "B" for Bechtel)

For example, a S9G reactor represents a submarine (S), ninth-generation (9), General Electric designed reactor (G).

History of Naval Reactor Industry in the US

Conceptual analysis of nuclear marine propulsion started in the 1940s. Research on developing nuclear reactors for the Navy was done at Bettis Atomic Power Laboratory in West Mifflin, PA starting in 1948. Under the long-term leadership of Admiral Hyman G. Rickover, the first test reactor plant, a prototype referred to as S1W, started up in USA in 1953 at the Naval Reactors Facility in Idaho. Bettis Laboratory and Naval Reactors Facility were operated initially and for many decades afterwards by Westinghouse. The first nuclear-powered vessel, the submarine USS Nautilus (SSN-571), put to sea in 1955. USS Nautilus marked the beginning of the transition of submarines from relatively slow and short-ranged conventional submarines to ones capable of sustaining 20–25 knots (35–45 km/h) submerged for weeks on end.

Much of the early development work on naval reactors was done at the Naval Reactor Facility on the campus of the Idaho National Laboratory (INL, previously INEL). USS Nautilus was powered by the S2W reactor, and crew were trained on the land-based S1W reactor at INL.

The second nuclear submarine was USS Seawolf (SSN-575), which was initially powered by a sodium-cooled S2G reactor, and supported by the land-based S1G reactor at the Kesselring site under Knolls Atomic Power Laboratory operated by General Electric. A spare S2G was also built but never used.

USS Seawolf was plagued by superheater problems, with the result that USS Nautilus delivered far superior performance. This and the risks posed by liquid sodium in the event of an accident at sea led Admiral Rickover to select the PWR (pressurized water reactor) as the standard US naval reactor type. The S2G was removed from USS Seawolf and replaced by the S2Wa reactor, using components from the spare S2W that was part of the USS Nautilus program. All subsequent US naval reactors have been PWRs, while the Soviet Navy used mainly PWRs, but also used lead-bismuth cooled LMFRs of three types in eight submarines: K-27 and the seven-member Alfa class.

Experience with the USS Nautilus led to the parallel development of further (Skate-class) submarines, powered by single reactors, and an aircraft carrier, USS Enterprise (CVN-65), powered by eight A2W reactor units in 1960. A cruiser, USS Long Beach (CGN-9), followed in 1961 and was powered by two C1W reactor units. Remarkably, USS Enterprise remains in service.

Full-scale land-based prototype plants in Idaho, New York, and Connecticut preceded development of several types (generations) of US Naval nuclear reactors, although not all of them. After initial construction, some engineering testing was done and the prototypes were used to train nuclear-qualified sailors for many years afterwards. For example, the A1W prototype at Naval Reactors Facility led to development of A2W reactors used in USS Enterprise. By 1962, the US Navy had 26 nuclear submarines operational and 30 under construction. Nuclear power had revolutionized the Navy.

The technology was shared with the United Kingdom, while technological development in France, China and the Soviet Union proceeded separately.

After the Skate-class vessels, reactor development proceeded and in the USA a single series of standardized designs was built by both Westinghouse and General Electric, with one reactor powering each vessel. Rolls Royce built similar units for Royal Navy submarines and then developed the design further to the PWR-2. Numerous submarines with an S5W reactor plant were built.

At the end of the Cold War in 1989, there were over 400 nuclear-powered submarines operational or being built. Some 250 of these submarines have now been scrapped and some on order canceled, due to weapons reduction programs. The Russian Navy and United States Navy had over one hundred each, with the United Kingdom and France less than twenty each and China six. The total today is about 160.

The United States is the main navy with nuclear-powered aircraft carriers (10), while Russia has nuclear-powered cruisers. Russia has eight nuclear icebreakers in service or building. Since its inception in 1948, the U.S. Navy nuclear program has developed 27 different plant designs, installed them in 210 nuclear powered ships, taken 500 reactor cores into operation, and accumulated over 5,400 reactor years of operation and 128,000,000 miles safely steamed. Additionally, 98 nuclear submarines and six nuclear cruisers have been recycled. The U.S. Navy has never experienced a reactor accident.

Note that all nine of the US Navy nuclear-powered cruisers (CGN) have now been stricken from the Naval Vessel Register, and those not already scrapped by recycling are scheduled to be recycled. While reactor accidents have not sunk any US Navy ships or submarines, two nuclear-powered submarines, USS Thresher (SSN-593) and USS Scorpion (SSN-589) were lost at sea. The condition of these reactors has not been publicly released, although both wrecks have been investigated by Dr. Robert Ballard on behalf of the Navy using remotely operated vehicles (ROVs).

Congress has mandated that the U.S. Navy consider nuclear power as an option on all large surface combatants (cruisers, destroyers) and amphibious assault ships. If proven cost-effective in a life cycle cost analysis during the Analysis of Alternatives (AoA) phase of preliminary ship design, new ship classes (e.g. CG(X)) could proceed with nuclear propulsion.

Naval Reactors & Power Plants

U.S. Naval reactors are pressurized water reactors, which differ from commercial reactors producing electricity in that:

- They have a high power density in a small volume and run either on low-enriched uranium (as do some French and Chinese submarines) or on highly enriched uranium (>20% U-235, current U.S. submarines use fuel enriched to at least 93%, compared to between 21–45% in current Russian models, although Russian nuclear-powered icebreaker reactors are enriched up to 90%);

- The fuel is not UO2 but a metal-zirconium alloy (c.15% U with 93% enrichment, or more U with lower enrichment);

- They have long core lives, so that refueling is needed only after 10 or more years, and new cores are designed to last 50 years in carriers and 30–40 years in submarines;

- The design enables a compact pressure vessel while maintaining safety.

Long core life is enabled by high uranium enrichment and by incorporating a "burnable neutron poison", which is progressively depleted as non-burnable poisons like fission products and actinides accumulate. The loss of burnable poison counterbalances the creation of non-burnable poisons and result in stable long term fuel efficiency.

Long-term integrity of the compact reactor pressure vessel is maintained by providing an internal neutron shield. (This is in contrast to early Soviet civil PWR designs where embrittlement occurs due to neutron bombardment of a very narrow pressure vessel.)

Reactor sizes range up to ~500 MWt (about 165 MWe) in the larger submarines and surface ships. The French Rubis-class submarines have a 48 MW reactor that needs no refueling for 30 years.

The Russian, US and British navies rely on steam turbine propulsion, the French and Chinese use the turbine to generate electricity for propulsion. Most Russian submarines as well as all US surface ships since Enterprise are powered by two or more reactors. US, British, French and Chinese submarines are powered by one.

Decommissioning nuclear-powered submarines has become a major task for US and Russian navies. After defueling, US practice is to cut the reactor section from the vessel for disposal in shallow land burial as low-level waste (see the Ship-Submarine recycling program). In Russia the whole vessels, or the sealed reactor sections, remain stored afloat indefinitely.

Other small, easily field-deployed reactor designs have been developed but have no connection to the U.S. Naval Reactor program. A small reactor was used to supply power (1.5 MWe) and heating to McMurdo Station, a US Antarctic base, for ten years to 1972, testing the feasibility of such air-portable units for remote locations. Two others were installed in Arctic locations, all constructed as part of the US Army Nuclear Power Program. A fourth mounted on a barge provided power and fresh water in the Panama Canal Zone. Russia is well advanced with plans to build a floating power plant for their far eastern territories. The design has two 35 MWe units based on the KLT-40 reactor used in icebreakers (with refueling every 4 years).

Nuclear Reactors of the US Navy

A1B Reactor

The A1B reactor is a nuclear reactor being designed for use by the United States Navy to provide electricity generation and propulsion for the Gerald R. Ford-class aircraft carriers. The A1B designation stands for:

- A = Aircraft carrier platform
- 1 = First generation core designed by the contractor
- B = Bechtel is the contracted designer

Initial plans for the Ford-class carrier program include a two-reactor complex intended to replace the A4W reactor design used on the Nimitz-class carriers.

Gerald R. Ford-Class Aircraft Carriers

The Gerald R. Ford-class aircraft carriers (or Ford-class) are a class of super carrier for the United States Navy, intended to replace the current Nimitz-class carriers. The new vessels will use a hull design very similar to the Nimitz carriers, but many aspects of the design will be very different, implementing new technologies developed since the initial design of the previous class (such as the Electromagnetic Aircraft Launch System), as well as other design features intended to improve efficiency and running costs, including a reduced crew requirement. The first hull of the line will be named Gerald R. Ford, and will have the hull number CVN-78.

Carriers of the Ford class will incorporate fourteen new design features including:

- Advanced arresting gear.
- Automation, which reduces crew requirements by several hundred from the Nimitz class carrier.
- The updated RIM-162 Evolved Sea Sparrow missile system.
- AN/SPY-3 dual-band radar (DBR), as developed for Zumwalt class destroyers.
- An Electromagnetic Aircraft Launch System (EMALS) in place of traditional steam catapults for launching aircraft.
- A new nuclear reactor design (the A1B reactor) for greater power generation.
- Stealthier features to help reduce radar profile.
- The ability to launch the F-35C Lightning II.

The US Navy believes that with the addition of the most modern equipment and extensive use of automation, it will be able to reduce the crew requirement and the total cost of future aircraft carriers. The primary recognition feature compared to earlier supercarriers will be the more aft location of the navigation "island".

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Construction began on components of CVN-78 in the spring of 2007, and is planned to finish in 2015. It is under construction at Northrop Grumman Shipbuilding in Newport News, Virginia, the only shipyard in the United States capable of building nuclear-powered aircraft carriers. In 2005 it was estimated to cost at least $8 billion excluding the $5 billion spent on research and development (though that was not expected to be representative of the cost of future members of the class). A 2009 report said that the Ford would cost $14 billion including research and development, and the actual cost of the carrier itself would be $9 billion.

A total of three carriers have been authorized for construction, but if the Nimitz-class carriers and the Enterprise were to be replaced on a one-for-one basis, eleven carriers would be required over the life of the program. However, the last Nimitz-class aircraft carrier is not scheduled to be decommissioned until 2058.

In an April 6, 2009, speech, Secretary of Defense Robert Gates announced that the Navy Aircraft Carrier program would shift to a five year building program so as to place it on a "more fiscally sustainable path." Such a measure would result in ten carriers by 2040.

There was a movement by the USS America Carrier Veterans' Association to have CVN-78 named after the America rather than after President Ford. Eventually, LHA-6 was named America.

If the current USS Ford (FFG-54), a Perry-class frigate commissioned in 1985 (named after Vietnam era Gunner's Mate Patrick O. Ford), is still in commission when CVN-78 enters service, there will be two commissioned warships on the Naval Vessel Register named Ford.

On December 7, 2007, the 66th anniversary of the attack on Pearl Harbor, U.S. Representative Harry Mitchell proposed naming the second Ford-class carrier CVN-79, USS Arizona.

A petition has also been set up for the CVN-79 to be named as the ninth USS Enterprise.

There are expected to be ten ships of this class. To date, three have been announced:

- Gerald R. Ford (CVN-78), (2015) — Scheduled to replace Enterprise (CVN-65).
- CVN-79, unnamed (2018) — Scheduled to replace Nimitz (CVN-68).
- CVN-80, unnamed (2021) — Scheduled to replace Dwight D. Eisenhower (CVN-69).

The Ford class of carriers will be capable of carrying about 90 aircraft including the F-35 Lightning II, the F/A-18E/F Super Hornet, the EA-18G Growler, E-2D Advanced Hawkeye, C-2A Greyhound, MH-60R/S Seahawk helicopters and unmanned combat air vehicles such as the X-47B.

A1W Reactor

The A1W reactor is a prototype nuclear reactor used by the United States Navy to provide electricity generation and propulsion on warships. The A1W designation stands for:

- A = Aircraft carrier platform
- 1 = First generation core designed by the contractor
- W = Westinghouse was the contracted designer

The reactor was a Westinghouse Electric Corporation-built naval reactor power plant, installed in the Naval Reactors Facility in the desert at the Idaho National Engineering Laboratory near Arco, Idaho. It first operated in October 1958. This reactor plant consisted of two reactors, A1W-A and A1W-B, operated in tandem so that the steam produced by both reactors was used to power one turbine connected to a drive shaft.

This nuclear reactor was the prototype for the A2W reactor used in the world's first nuclear-powered aircraft carrier, the USS Enterprise (CVN-65).

The A1W prototype was used to train nuclear-qualified sailors for almost 34 years until its reactor plants were shut down on January 26, 1994.

A2W Reactor

The A2W reactor is a naval reactor used by the United States Navy to provide electricity generation and propulsion on warships. The A2W designation stands for:

- A = Aircraft carrier platform
- 2 = Second generation core designed by the contractor
- W = Westinghouse was the contracted designer

This nuclear reactor was used in the world's first nuclear-powered aircraft carrier, the USS Enterprise (CVN-65). The four propulsion plants on Enterprise each contain two reactors, numbered 1A-1B, 4A-4B, 2A-2B, and 3A-3B (numbered as they are located from fore to aft). Each propulsion plant is capable of operating on one reactor plant through most of the power range required to propel the ship at speeds in excess of 33 knots (60 km/h) (with a possible maximum speed up to approximately 35 knots (65 km/h). Both reactors would be on-line to simultaneously provide maximum ship speed and plane launching capability. The prodigious steam available from eight reactors led to many urban legends crediting Enterprise (and the later Nimitz-class carriers) with maximum speeds substantially higher than this; however, since the turbines used on Enterprise are identical to those on previous oil-fired carriers, the maximum burst speed cannot be substantially higher.

The reactors are pressurized water reactors fueled by highly-enriched (upwards of 93%) uranium-235. Light water is used as both neutron-moderator and reactor coolant. Hafnium Control rods are used to control the operation of the reactor. Extracting the rods to a calculated height allows the reactor to reach criticality — the point at which the nuclear fission reactions reach a self-sustaining level. Thereafter, steam flow (from the steam generators) regulates reactor power as explained below. The control rods are "shimmed" in or out to regulate average coolant temperature or lowered to the bottom of the reactor vessel to shut the reactor down (either done in a slow controlled manner or dropped rapidly during what is referred to as a SCRAM to immediately shut the reactor down.

Much of the reactor power control during steady state operation comes as a result of the coolant water's negative temperature coefficient. The power of the reactor is determined by the number of fission events that takes place in the fuel at any given moment. As the water heats up, it expands and becomes less dense which provides fewer molecules per volume to moderate the neutrons, hence fewer neutrons are slowed to the required thermal energies to sustain thermal fission. Conversely, when the coolant water temperature decreases, its density increases and a greater number of neutrons reach the required thermal energy, increasing the number of fissions per unit of time, creating more heat. This has the effect of allowing "steam demand" to control reactor power, requiring little intervention by the Reactor Operator for changes in the power demanded by the ship's operations.

The hot water from the reactors is sent, via large pipes, into heat exchangers called steam generators. There the heat from the reactor coolant water is transferred, through tube walls, to water being fed into the steam generators from a separate feed system. In the A1W and A2W systems, the pressurized water reactor coolant is kept between 525 and 545 °F (274–285 °C). In the steam generators, the water from the feed system is converted to steam at 535 °F (279 °C) and a pressure of about 600 psi (4 MPa). Once the reactor coolant water has given off its heat in the steam generators, it is returned, via large electric pumps (four per reactor), to the reactors to repeat the cycle.

Saturated steam at 600 psi is channeled from each steam generator to a common header, where the steam is then sent to the main engine, electrical generators, aircraft catapult system, and various auxiliaries. The main propulsion turbines are double-ended, in which the steam enters at the center and divides into two streams as it enters the actual turbine wheels, expanding and giving up its energy as it does so, causing the turbine to spin at high speed. The main shaft enters a reduction gear in which the high rotational velocity of the turbine shaft is stepped down to a usable turn rate for propelling the ship. The expended steam from the main engine and other auxiliaries enters condensers to be cooled into water and recycled to the feed system.

USS Enterprise (CVN-65)

USS Enterprise (CVN-65), formerly CVA(N)-65, is a retired United States Navy aircraft carrier. She was the world's first nuclear-powered aircraft carrier and the eighth United States naval vessel to bear the name. Like her predecessor of World War II fame, she is nicknamed "Big E". At 1,123 ft (342 m), she is the longest naval vessel in the world. Her 93,284-long-ton (94,781 t) displacement ranks her as the 11th-heaviest supercarrier, after the 10 carriers of the Nimitz class. Enterprise had a crew of some 4,600 people.

The only ship of her class, Enterprise is the third oldest commissioned vessel in the United States Navy after the wooden-hulled USS Constitution and USS Pueblo. She was originally scheduled for decommissioning in 2014 or 2015, depending on the life of her reactors and completion of her replacement, USS Gerald R. Ford, but the National Defense Authorization Act for Fiscal Year 2010 slated the ship's retirement for 2013, when she would have served for 51 consecutive years, longer than any other U.S. aircraft carrier.

Enterprise's home port was Naval Station Norfolk, Virginia as of September 2012. Her final deployment, the last before her decommissioning, began on 10 March 2012 and ended 4 November 2012. She was inactivated on 1 December 2012, with her official decommissioning taking place sometime after the completion of an extensive terminal offload program currently underway. The name has been adopted by the future Gerald R. Ford-class aircraft carrier USS Enterprise (CVN-80).

Enterprise is a commissioned navy ship, but is inactive. She has undergone enough of the four-year long inactivation process to render her unfit for further service. Inactivation removes fuel, fluids, furnishings, tools, fittings, oil, and de-energizes the electrical system. Enterprise has already been cut open to allow the removal of useable systems.

Figure 22: USS Enterprise

Enterprise was meant to be the first of a class of six, but construction costs ballooned and the remaining vessels were never laid down. Because of the huge cost of her construction, Enterprise was launched and commissioned without the planned RIM-2 Terrier missile launchers. These were never installed and the ship's self-defense suite instead consisted of three shorter-range RIM-7 Sea Sparrow, Basic Point Defense Missile System (BPDMS) launchers. Later upgrades added two NATO Sea Sparrow (NSSM) and three Mk 15 Phalanx CIWS gun mounts. One CIWS mount was later removed and two 21-cell RIM-116 Rolling Airframe Missile launchers were added.

Enterprise is also the only aircraft carrier to house more than two nuclear reactors, having an eight-reactor propulsion design, with each A2W reactor taking the place of one of the conventional boilers in earlier constructions. She is the only carrier with four rudders, two more than other classes, and features a more cruiser-like hull.

Enterprise also had a phased array radar system known as SCANFAR. SCANFAR was intended to be better at tracking multiple airborne targets than conventional rotating antenna radars. SCANFAR consisted of two radars, the AN/SPS-32 and the AN/SPS-33. The AN/SPS-32 was a long-range air search and target acquisition radar developed by Hughes for the US Navy. The AN/SPS-32 operated together with the AN/SPS-33, which was the square array used for 3D tracking, into one system. It was installed on only two vessels, Enterprise and the cruiser USS Long Beach, placing a massive power drain on the ship's electric system.

The technology of the AN/SPS-32 was based on vacuum tubes and the system required constant repairs. The SPS-32 was a phased array radar which had a range of 400 nautical miles against large targets, and 200 nautical miles against small, fighter-size targets. These early phased arrays, replaced around 1980, were responsible for the distinctive square-looking island. The AN/SPS-32 and AN/SPS-33 radars, while ahead of their time, suffered from issues relating to electrical beam steering mechanism and were not pursued in further ship classes. While they are considered to be an early form of "phased array" radar, they were ahead of their time and it would take the later technology of the Aegis phased array AN/SPY-1 with its electronically controlled beam steering to make phased array radars both reliable and practical for the USN.

Enterprise was inactivated on 1 December 2012 at Norfolk Naval Station, Virginia. The deactivation of Enterprise will result in a one-time increase of approximately $857.3 million in depot maintenance costs for the U.S. Navy's operation and maintenance budget for Fiscal Year 2013.

Enterprise will be the first nuclear-powered aircraft carrier to be decommissioned. Naval enthusiasts have requested that Enterprise be converted into a museum. While the costs of doing so regarding her nuclear reactors has yet to be calculated by the United States Department of Defense, by 2012 they had been deemed too expensive to make such an effort practical. A petition had also been set up for the next carrier (CVN-80) to be named as the ninth USS Enterprise. At her inactivation ceremony, Secretary of the Navy Ray Mabus announced in his taped message that the next Ford Class Carrier, CVN-80 would indeed be named "Enterprise".

Speaking at the ceremony was Chaplain John Owen, CAPT William C. Hamilton, Jr. (CO), VADM David H. Buss (Commander, Naval Air Force Pacific), ADM John Richardson (Director, Naval Reactors), Matt Mulherin (President, Newport News Shipbuilding), ADM Jonathan W. Greenert (Chief of Naval Operations), a video speech from Ray Mabus, and the M.C. was the ship's Executive Officer. SECNAV had to deliver his speech via taped video as he was in China at the time. VIPs present for the ceremony included several former Commanding Officers, a granddaughter of the ship's sponsor, and a former A-6 pilot who had been captured in North Vietnam returning to the ship for the first time that day since he launched. He received a standing ovation at his introduction.

During the ceremony, the representative of the ship's sponsor received a flag flown from the ship during its last underway and a piece of wooden railing leading to the CO's inport cabin. Also the CNO was presented with a time capsule produced by ship's crew with artifacts and pieces of the ship. Enterprise crew and visitors were encouraged to add the items or messages the week before inactivation. While presenting the capsule, Commanding Officer William C. "Boomer" Hamilton informed the CNO that the only stipulation would be that the capsule could only be opened by the crew of the next ship to be named Enterprise. When it was announced shortly after that CVN-80 would be the 9th Navy vessel to carry the name "Enterprise", the entire crowd cheered and gave a standing ovation.

Newport News Shipbuilding will deactivate and de-fuel the ship, which will then be formally decommissioned once all nuclear fuel has been removed. The process is scheduled to begin in mid-2013 and be completed in 2015. Once the Navy dismantles and recycles the ship's reactors, there will be very little left to turn into a museum; virtually everything two decks below the hangar bay would have to be cut apart.

What remains of Enterprise following 2015 is currently scheduled to be taken to Washington state for scrapping. It remains possible the ship's island could be removed and used as a memorial. As of June 2013, the ship has had all antennas, radars (including the main-mast on top of the island), weapons launchers, anchors, and other miscellaneous items removed from her exterior. Additionally, the inside of the ship has been removed of much gear that can be reused on other ships, and all fluids systems drained. She has been towed to Newport News Shipyard for continued dismantling.

On 8 February 2013, the United States Department of Defense announced that a number of nuclear projects would have to be postponed until the upcoming budget sequestration issue was resolved. These include the planned de-fuelling of Enterprise as well as mid-life overhauls (including nuclear refueling) for two Nimitz class ships.

A3W Reactor

The A3W reactor is a naval reactor used by the United States Navy to provide electricity generation and propulsion on warships. The A3W designation stands for:

- A = Aircraft carrier platform
- 3 = Third generation core designed by the contractor
- W = Westinghouse was the contracted designer

The reactor was intended for use aboard USS John F. Kennedy. This four-reactor design was intended to reduce the cost involved in the construction and operation, as compared with the Enterprise and its eight nuclear reactors.

Early in the construction, the United States Secretary of the Navy had the plans changed to save money, and fossil fuel boilers were installed on the Kennedy. Because the plans for the ship did not include a funnel, the funnel on the Kennedy protrudes out from the ship at an angle.

The return to nuclear power for carriers came with the Nimitz class's A4W reactor's two reactor per ship design. The reduced cost of building carriers with two reactors makes the cost of the power plants still account for just over half the cost of the entire ship.

USS John F. Kennedy (CV-67)

USS John F. Kennedy (CV-67) (formerly CVA-67) is the only ship of her class, a subclass of the Kitty Hawk-class aircraft carrier, and the last conventionally powered carrier built for the United States Navy. The ship is named after the 35th President of the United States, John F. Kennedy, and is nicknamed "Big John." Kennedy was originally designated a CVA (fixed wing attack carrier); however, the designation was changed to CV to denote that the ship was capable of anti-submarine warfare, making her an all-purpose carrier.

After nearly 40 years of service in the United States Navy, Kennedy was officially decommissioned on 1 August 2007. She is berthed at the NAVSEA Inactive Ships On-site Maintenance facility in Philadelphia, Pennsylvania. She is available for donation as a museum and memorial to a qualified organization. The name has been adopted by the future Gerald R. Ford-class aircraft carrier John F. Kennedy (CVN-79).

Figure 23: USS John F. Kennedy

Contracted as Ship Characteristic Board SCB-127C, the ship's keel was laid on 22 October 1964 by Newport News Shipbuilding. The ship was officially christened 27 May 1967 by Jacqueline Kennedy and her 9-year-old daughter, Caroline, two days short of what would have been Kennedy's 50th birthday. The ship entered service 7 September 1968.

The John F. Kennedy is a modified version of the earlier Kitty Hawk-class aircraft carriers. Originally scheduled to be the fourth Kitty Hawk-class carrier, the ship received so many modifications during construction she formed her own class. The ship was originally ordered as a nuclear carrier, using the A3W reactor, but converted to conventional propulsion after construction had begun. The island is somewhat different from that of the Kitty Hawk class, with angled funnels to direct smoke and gases away from the flight deck. Kennedy is also 17 feet (5.2 m) shorter than the Kitty Hawk class.

In November 2009, the Navy placed the Kennedy on donation hold for use as a museum and memorial. A report that showed up in the Boston Herald newspaper on 26 November 2009 mentioned the possibility of bringing the Kennedy to the Boston, MA area, as a museum or memorial at no cost to the city, if desired.

In August 2010, two groups successfully passed into Phase II of the U.S. Navy Ship Donation Program:

- Rhode Island Aviation Hall of Fame, Providence, Rhode Island
- USS John F. Kennedy Museum, Portland, Maine

On 19 January 2011 the Portland, Maine City Council voted 9–0 to not continue with the project to bring the ship to Maine.

A4W Reactor

The A4W reactor is a naval reactor used by the United States Navy to propel warships and generate onboard electricity.

The A4W designation stands for:

- A = Aircraft carrier platform
- 4 = Fourth-generation core designed by the contractor
- W = Westinghouse, the contracted designer

These nuclear fission pressurized water reactors (PWRs) were jointly designed by Bettis Atomic Power Laboratory and Knolls Atomic Power Laboratory and built by Westinghouse Electric Corporation. Their reactor cores are expected to operate for about 20 years. The only ships to use these nuclear reactors are the Nimitz class supercarriers, which have two apiece, each of which generates enough steam to produce 140,000 shaft horsepower (104 MW).

Nimitz-Class Aircraft Carriers

The Nimitz-class supercarriers are a class of ten nuclear-powered aircraft carriers in service with the United States Navy. With an overall length of 1,092 ft (333 m) and full-load displacements of over 100,000 long tons, they are the largest capital ships in the world. Instead of the gas turbines or diesel-electric systems used for propulsion on many modern warships, the carriers use two A4W pressurized water reactors which drive four propeller shafts and can produce a maximum speed of over 30 knots (56 km/h) and maximum power of around 260,000 shp (190 MW). As a result of the use of nuclear power, the ships are capable of operating for over 20 years without refueling and are predicted to have a service life of over 50 years. They are categorized as nuclear-powered aircraft carriers and are numbered with consecutive hull numbers between CVN-68 and CVN-77.

All ten carriers were constructed by Newport News Shipbuilding Company in Virginia. Nimitz, the lead ship of the class, was commissioned on 3 May 1975 and George H. W. Bush, the tenth and last of the class, was commissioned on 10 January 2009. Since the 1970s, Nimitz-class carriers have participated in many conflicts and operations across the world, including Operation Eagle Claw in Iran, the Gulf War, and more recently in Iraq and Afghanistan.

The angled flight decks of the carriers use a CATOBAR arrangement to operate aircraft, with steam catapults and arrestor wires for launch and recovery. As well as speeding up flight deck operations, this allows for a much wider variety of aircraft than with the STOVL arrangement used on smaller carriers. An embarked carrier air wing consisting of up to around 90 aircraft is normally deployed on board. The air wings' strike fighters are primarily F/A-18F Super Hornets and F/A-18C Hornets, after the retirement of the F-14 Tomcat. In addition to their aircraft, the vessels carry short-range defensive weaponry for anti-aircraft warfare and missile defense.

The Nimitz-class aircraft carriers were ordered to supplement the aircraft carriers of the Kitty Hawk class and Enterprise class, maintaining the strength and capability of the US Navy after the older carriers were decommissioned. The ships were designed to be improvements on previous US aircraft carriers, in particular the Enterprise and Forrestal-class supercarriers, by using a more modern design, although the arrangement of the ships, in particular that of their flight decks, is relatively similar to that of the Kitty Hawk class.

Among other design improvements, the two reactors on Nimitz class carriers take up less space than those on Enterprise, which uses eight, meaning there is more interior space. This, along with a more generally improved design, means that Nimitz-class carriers can carry 90 percent more aviation fuel and 50 percent more ordnance when compared to the Forrestal class. The US Navy has also stated that the carriers could withstand three times the damage sustained by the Essex class inflicted by Japanese air attacks during World War 2. The hangars on the ships are divided into three fire bays by thick steel doors that are designed to restrict the spread of fire. This addition has been present on US aircraft carriers since World War 2, after the fires caused by Kamikaze attacks.

The first ships were designed around the time of the Vietnam war, and certain aspects of the design were influenced by operations there. To a certain extent, the carrier operations in Vietnam demonstrated the need for increased capabilities of aircraft carriers, over their survivability, as they were used to send sorties into the war, and were therefore less subject to attack. As a result of this experience, Nimitz carriers were designed with larger stores of aviation fuel and larger magazines in relation to previous carriers, although this was partly as a result of increased space available due to the arrangement of the ships' propulsion systems.

A major purpose of the ships was initially to support the US military during the Cold War, and they were designed with capabilities for that role, including using nuclear power instead of oil, for greater endurance when deployed in blue water, and the ability to make adjustments to the carriers' weapons systems on the basis of new intelligence and technological developments. They were initially categorized only as attack carriers, but ships have been constructed with anti-submarine capabilities since Carl Vinson. As a result, the ships and their aircraft are now able to participate in a wide range of operations, which can include sea and air blockades, mine laying, and missile strikes on land, air and sea. The total cost of construction for each ship was around $4.5 billion.

All ten Nimitz-class aircraft carriers were constructed between 1968 and 2006 at Newport News Shipbuilding Company, in Newport News, Virginia, in the largest dry dock in the western hemisphere, dry dock 12, now 2,172 feet (662 m) in length after a recent expansion.

Since Roosevelt, the carriers were manufactured in modular construction (George H.W. Bush was constructed from 161 'super-lift' modules). This means that whole sections could be welded together with plumbing and electrical equipment already fitted, improving efficiency. Using gantry cranes, which can lift 2,000,000 pounds (910 t), the modules could then be lifted into the dry dock and welded. In the case of the bow section, these can weigh over 1,500,000 pounds (680 t). This method was originally developed by Ingalls Shipbuilding and increases the rate of work because much of the fitting out does not have to be carried out within the confines of the already finished hull.

The Nimitz class carriers have an overall length of 1,092 ft (333 m) and a full-load displacement of about 100,000–104,000 long tons (102,000–106,000 metric tons). They have a beam at the waterline of 135 ft (41 m) and the maximum width of their flight decks is 251 ft 10 in to 257 ft 3 in (77.76 m to 78.41 m) (depending on the variant). The ships' companies can number up to 3,200, not including an air wing of 2,480. Due to a design flaw, ships of this class have inherent lists to starboard when under combat loads that exceed the capability of their list control systems. The problem appears to be especially prevalent on some of the more modern vessels, due to their design differences. This problem has been previously rectified by using damage control voids for ballast, but a solution using solid ballast which does not affect the ship's survivability has been proposed.

All ships of the class are powered by two A4W nuclear reactors, kept in separate compartments. The power four propeller shafts, and can produce a maximum speed of over 30 knots (56 km/h) and maximum power of 260,000 bhp (190 MW). The reactors produce heat through nuclear fission which heats water. This is then passed through four turbines (manufactured by General Electric) which are shared by the two reactors. The turbines in turn power the four bronze propellers, each with a diameter of 25 feet (7.6 m) and a weight of 66,000 pounds (30 t). Behind these are the two rudders, which are 29 feet (8.8 m) high and 22 feet (6.7 m) long, and each weigh 110,000 pounds (50 t). The Nimitz-class ships constructed since Reagan also have bulbous bows in order to improve speed and fuel efficiency by reducing hydrodynamic drag. As a result of the use of nuclear power, the ships are capable of operating continuously for over 20 years without refueling, and are predicted to have a service life of over 50 years.

In addition to the aircraft carried onboard, the ships carry defensive equipment for direct use against missiles and hostile aircraft. These consist of either three or four NATO RIM-7 Sea Sparrow missile launchers, designed for defense against aircraft and anti-ship missiles as well as either three or four 20 mm Phalanx CIWS missile defense cannons. Ronald Reagan has none of these, having been built with the RIM-116 Rolling Airframe Missile system, two of which have also been installed on Nimitz and George Washington. These will be installed on the other ships as they return for Refueling Complex Overhaul (RCOH). Since Theodore Roosevelt, the carriers have been constructed with 2.5 in (64 mm) kevlar armor over vital spaces, and earlier ships have been retrofitted with it: Nimitz in 1983–1984, Eisenhower from 1985–1987 and Vinson in 1989.

The other countermeasures the ships use are four Sippican SRBOC (super rapid bloom off-board chaff) six-barrel MK36 decoy launchers, which deploy infrared flares and chaff to disrupt the sensors of incoming missiles; an SSTDS torpedo defense system, and an AN/SLQ-25 Nixie torpedo countermeasures system. The carriers also use Raytheon AN/SLQ-32(V) electronic warfare systems to detect and disrupt hostile radar signals in addition to the electronic warfare capabilities of some of the aircraft onboard.

The presence of nuclear weapons on board U.S. aircraft carriers since the end of the Cold War has neither been confirmed nor denied by the U.S. government. As a result of this, as well as concerns over the safety of nuclear power, the presence of a U.S. aircraft carrier in a foreign port has occasionally provoked protest from local people, for example when Nimitz docked in Chennai, India, in 2007. At that time, the Strike Group commander Rear Admiral John Terence Blake stated that: "The US policy is that we do not routinely deploy nuclear weapons on board Nimitz." Concern was also voiced after the arrival and docking of the USS George Washington (CVN-73) in Yokosuka, Japan on 10 March 2011 following the 2011 Sendai earthquake and tsunami disaster. Hundreds of protesters were present to make their voices heard concerning the safety of the nuclear reactor on board the warship providing aid.

While the designs of the final seven ships (from Theodore Roosevelt) are slightly different to those of the earlier ships, the US Navy nevertheless regards all vessels as a single class. As the older carriers come in for Refueling and Complex Overhaul (RCOH), they are upgraded to the standards of the latest ships, as well as having their nuclear power plants refueled. This is the most substantial overhaul the ships receive, although other, smaller refits also update the ships' equipment. The ships were initially categorized only as attack carriers, but have been constructed with anti-submarine capabilities since Carl Vinson. These improvements include better radar systems, and facilities which enable the ships to operate aircraft in a more effective anti-submarine role, including the fitting of common undersea picture (CUP) technology which uses sonar to allow for better assessment of the threat from submarines.

Theodore Roosevelt and those completed after her have slight structural differences from the earlier carriers, and improved protection for ordnance storage in their magazines. Other improvements to the ships since that time include upgraded flight deck ballistic protection, first implemented on George Washington, and the high-strength low-alloy steel (HSLA-100) used for constructing ships since John C. Stennis. More recently, older ships have had their flight decks refitted with a non-slip material fitted on new-build ships, to improve safety for both crew and aircraft.

The final ship George H.W. Bush was designed as a "transition ship" to the Nimitz class replacement, the Gerald R. Ford class. Bush incorporates new technologies including improved propeller and bulbous bow designs, a reduced radar signature and electronic and environmental upgrades. As a result, the ship's cost was US$6.2 billion, higher than that of the earlier Nimitz-class ships which each cost around US$4.5 billion. To lower costs, some new technologies and design features were also incorporated into the Ronald Reagan, the previous carrier, including a redesigned island.

The ships were designed to have a fifty-year service life. Each will continue operating at full capacity until that time when they will be decommissioned. This process will first take place on Nimitz and is estimated to cost from US$750 to $900 million. This compares with an estimate of US$53 million for a conventionally powered carrier. Most of the difference in costs is due to the deactivation of the nuclear power plants and safe removal of radioactive material and other contaminated equipment. A new class of carriers, the Gerald R. Ford class, is being constructed to replace previous vessels after decommissioning. Ten of these are expected, and the first will enter service in 2015 to replace Enterprise. The rest of these new carriers will gradually replace the oldest Nimitz vessels as they reach the end of their service life. The new carriers will have a similar design to Bush (using an almost identical hull shape), but will also have further technological and structural improvements.

Figure 24: Flight Deck of USS Harry S. Truman (CVN-75)

C1W Reactor

The C1W reactor is a nuclear reactor used by the United States Navy to provide electricity generation and propulsion on warships. The C1W designation stands for:

- C = Cruiser platform
- 1 = First generation core designed by the contractor
- W = Westinghouse was the contracted designer

This type of nuclear propulsion plant was used exclusively on the Long Beach-class guided missile cruiser, the world's first nuclear-powered cruiser. The C1W was the only nuclear reactor ever explicitly earmarked for a cruiser (two of them, powering two geared turbines) with all subsequent nuclear cruisers powered by "D"-class (or destroyer-type) reactors.

The USS Long Beach (CGN-9), commissioned September 1961, was decommissioned May 1995.

Long Beach Class Cruiser

The Long Beach class cruiser is a single-ship class (sole member, USS Long Beach (CGN-9), ex-CGN-160, ex-CLGN-160) of the United States Navy. The class is noted as the world's first nuclear-powered surface combatant, and the last cruiser built in the US Navy to a cruiser design; all subsequent cruiser classes were built on scaled-up destroyer hulls, or, in the case of the Albany class, converted from already existent cruisers.

During the design phase, the only ship of the Long Beach class was initially classified as CLGN-160, then reclassified CGN-160 on 6 December 1956. The keel of the USS Long Beach was laid by Bethlehem Steel on 2 December 1957 at the Fore River Shipyard in Quincy, Massachusetts. On 1 July 1958 she received her third and final classification, this time as CGN-9. The ship was launched on 14 July 1959 and commissioned on 9 September 1961. The Long Beach class under overhaul from 6 October 1980 until 26 March 1983. She was both decommissioned and stricken on 1 May 1995.

Figure 25: USS Long Beach (CGN-9)

D1G Reactor

The D1G reactor was a prototype naval reactor designed for the United States Navy to provide electricity generation and propulsion on warships. The D1G designation stands for:

- D = Destroyer platform
- 1 = First generation core designed by the contractor
- G = General Electric was the contracted designer

This prototype nuclear reactor was constructed for the United States Department of Energy's Office of Naval Reactors as part of the Naval Nuclear Propulsion Program. The reactor was built by General Electric and operated by the Knolls Atomic Power Laboratory at the Kesselring Site Operation in West Milton, New York. It was used for testing components and as a training tool for the Nuclear Power Training Unit. The reactor operated from 1962 to 1996, when it was shut down in March of that year. It was later defueled, with the pressure vessel eventually removed in 2002.

The containment vessel — which housed both the primary (nuclear reactor) and secondary (steam plant) systems — is referred to as the "DIG-ball" due to its unique shape: a Horton Sphere. The sphere was originally constructed by Chicago Bridge and Iron Works to house the liquid metal cooled reactor of the USS Seawolf (SSN-575), with the dome designed to contain a liquid sodium explosion.

D2G Reactor

The D2G reactor was a naval reactor used by the United States Navy to provide electricity generation and propulsion on warships. The D2G designation stands for:

- D = Destroyer platform
- 2 = Second generation core designed by the contractor
- G = General Electric was the contracted designer

This model of nuclear reactor was installed on the Bainbridge, Truxtun, California, and Virginia classes of guided missile cruisers. The only nuclear-powered cruiser in the United States Navy not equipped with a D2G reactor was the world's first nuclear cruiser, the USS Long Beach (CGN-9), which used a C1W reactor. All of the Navy's nuclear cruisers have been decommissioned.

Rated for a maximum thermal output of 150 megawatts, the reactors were designed to last 15 years with normal usage. The Navy's nuclear cruisers were outfitted with two reactors per ship, each having the ability to cross-connect the steam and condensate systems between plants to power both engine rooms from a single reactor. With both reactors running and the steam plants split, the average cruiser could reach 32 knots (59.2 km/h). With one reactor running and the steam plants cross-connected, the ship could reach 25–27 knots (46.3–50 km/h). With one reactor running, the steam plants split, and running on one shaft, the ship could reach only 15 knots (27.7 km/h).

These reactors were boron-doped vertically for longer core life, and axially for even power distribution without hot spots. They employ 12 X-shaped control rods driven by DC-powered movable armature reluctance motors. Three main loops driven by three variable-speed reactor coolant pumps supplied three steam generators with water, which in turn supplied saturated steam to the engine room.

Bainbridge Class Cruiser

USS Bainbridge (CGN-25) was a nuclear-powered version of the Leahy-class cruiser double-ended guided missile frigate. Originally a guided missile destroyer leader, the class was re-designated guided missile cruiser in 1975. As with USS Long Beach (CGN-9) and USS Enterprise (CVN-65), Bainbridge was a single-ship class.

Figure 26: USS Bainbridge (CGN-25)

Statistically and mechanically speaking, Bainbridge (DLGN-25) was virtually identical to the Leahy-class except for the replacement of her four 1200 psi boilers with two D2G reactors. Because of the greater maintenance requirements of 1960s nuclear reactors, Bainbridge carried 23 more crew members than Leahy.

The lessons learned on Bainbridge were later adapted to the next nuclear-powered ship, USS Truxtun (CGN-35) and the California and Virginia classes of nuclear-powered cruiser.

Truxtun Class Cruiser

The Truxtun class cruiser was a nuclear-powered class of single-ended guided missile cruisers (their missile armament was installed only aft, unlike "double-ended" cruisers with missile armament installed both forward and aft) based on a heavily modified version of the Belknap class. Truxtun was the third class of nuclear cruisers to operate in the United States Navy, after the Long Beach and Bainbridge classes, and was powered by the same D2G reactors as the Bainbridge class. The class was originally designated as a destroyer leader (DLG), but in the 1975 cruiser realignment, it was reclassified as a guided missile cruiser (CG).

Figure 27: USS Truxtun

Virtually identical to the Belknap class in weapons systems, the Truxtun class was powered by two D2G reactors rather than her sister class's four 1,200 psi boilers. This resulted in the Truxtun class being larger overall: 17 feet (5.2 m) longer, 3 feet (0.91 m) greater across the beam, a 2-foot-deeper (0.61 m) draft, and a displacement of almost 1,200 more tons. The lessons learned on the Truxtun class were later adapted to the next nuclear classes, the California and Virginia classes of nuclear-powered cruisers.

The Truxtun class was commissioned with a 5"/54 caliber Mark 42 gun on the foredeck and a twin-rail Mk 10 Missile Launcher on the quarterdeck, for the RIM-2 Terrier. The Terrier system was later upgraded to utilizing the RIM-67A Standard missiles in place of the less reliable Terrier missile. The missile depot was located under the helicopter deck and could store 40 RIM-67 Standard and 20 RUR-5 ASROC missiles. The class initially used two twin 3"/50 caliber guns, however in 1980 these were replaced with two Harpoon missile launchers. The ASW suite of the Truxtun class originally included the un-manned DASH, but in 1971 the hangar was upgraded to LAMPS Mk. I and the SH-2 Seasprite helicopter. While the class was not upgraded via the NTU program, two Phalanx CIWS systems were installed, and new electronics were installed during overhaul and nuclear refueling in the mid-1980s.

California Class Cruiser

The California class cruisers were a set of two of nuclear-powered guided missile cruisers operated by the United States Navy between 1974 and 1998. Other than their nuclear power supply and lack of helicopter hangars, ships of the California class were comparable to other guided missile cruisers of their era, such as the Belknap class. The class was built as a follow-up to the nuclear-powered Long Beach, Bainbridge, and Truxtun classes. Like all of the nuclear cruisers which could steam for years between refuelings, the California class was designed in part to provide high endurance escort for the navy's nuclear aircraft carriers, which were often limited in range due to their conventionally powered escorts continuously needing to be refueled.

The USS California (CGN-36) was the fourth nuclear powered cruiser in the U.S. Navy; the previous three were the USS Long Beach (CGN-9), USS Bainbridge (CGN-25) and USS Truxtun (CGN-35). The second California class cruiser, USS South Carolina (CGN-37), was the fifth nuclear-powered cruiser in the United States Navy. Other than the four ships of the Soviet Navy's Kirov class (which were actually built with a combination of nuclear and fossil-fuel propulsion), no other country has launched nuclear-powered cruisers.

Only two ships of the class were built, the California and the South Carolina, and both were decommissioned in the autumn of 1999. These ships were followed on by the four nuclear-powered cruisers of the Virginia class. These cruisers were named for states because they were seen as quite large, powerful, capable, and survivable ships. Also, in the meantime, the names of cities had been given to the nuclear submarines in the very large Los Angeles class, which eventually expanded to 62 boats, all (but one) named for American cities.

The USS California and her sister ship the USS South Carolina were equipped with two Mk-13 launchers, fore and aft, capable of firing the Standard SM-1MR or SM-2MR surface-to-air missiles, one Mk-112 launcher for ASROC missiles, and eight Mk-141 launch tubes for Harpoon missiles. They were equipped with two Mk-45 5" rapid-fire guns, fore and aft. Four 12.75" torpedo launchers (two on each side, protruding from their magazine space on the main deck) were fitted for light weight anti-submarine torpedoes. Two Mk-15 Phalanx 20 mm gun systems were fitted in the 1980s.

The ships were originally designed to carry and launch the Mark 48 torpedo from a large space beneath the flight deck aft. Although a surface-launched version of the Mk 48 was never produced, the ships retained this large magazine space until their retirement.

Both ships underwent a mid-life refueling overhaul in the early 1990s. This modernization upgraded their two 150 MW D2G reactor plants with new 165 MW D2W reactor cores, installed the New Threat Upgrade (NTU) to improve their AAW capability, and removed their ASW capability, which involved disabling their SQS-26 sonar and removing their anti-submarine weapons. External differences resulting from this modernization included the removal of the ASROC launcher and the large deckhouse forward of it that served as the ASROC magazine, replacement of the SPS-40 radar antenna with the SPS-49 antenna, and replacement of the SPS-48C with the larger SPS-48E antenna. Both ships retained the bulbous sonar domes at the forefoot (beneath the waterline) until retirement, even after their sonar systems were disabled.

Figure 28: USS California (CGN-36)

Virginia Class Cruiser

Figure 29: USS Virginia (CGN-38)

The Virginia-class nuclear guided-missile cruisers (CGN-38 class) were a series of four double-ended (with armament carried both fore and aft) guided-missile cruisers commissioned in the late 1970s, which served in the US Navy until the mid- to late-1990s. With their nuclear power plants and the resulting capability of steaming at high speeds for long periods of time, these were excellent escorts for the fast nuclear-powered aircraft carriers, such as the Nimitz class. Their main mission was as air-defense ships, though they did have capabilities as anti-submarine (ASW) ships, surface-to-surface warfare (SSW) ships, and in gun and missile bombardment of shore targets.

The ships were derived from the earlier California class nuclear cruiser (CGN-36 class). They were decommissioned as part of the early 1990s "peace dividend" after the Cold War ended. A fifth warship, the CGN-42, was canceled before being named or laid down. It was found that while it was possible to mass-produce nuclear-powered warships, the ships were less cost-efficient than conventionally-powered warships, and the new gas-turbine-powered ships then entering the fleet (the Spruance class destroyers) required much less manpower. Following the end of production of this class, the U.S. Navy continued conventional destroyer/cruiser production, and it redesignated the DDG-47 class of guided missile destroyers as the CG-47 Ticonderoga class cruisers. Three of the four Virginia-class ships were authorized as guided missile frigates (in the pre-1975 definition), and they were redesignated as cruisers either before commissioning or before their launching. The last warship, the USS Arkansas, was authorized, laid down, launched, and commissioned as a guided-missile cruiser.

The early retirement of the Virginia class (CGN 38-41) cruisers has been widely criticized. They were new, modern ships; given a New Threat Upgrade electronics overhaul they would have been well-suited to modern threats. They had rapid-fire Mk 26 launchers which could fire the powerful Standard SM-2MR medium-range surface-to-air missile. Earlier decommissioned cruisers used the slower-firing Mk-10 launchers which required manual fitting of the fins of the missiles prior to launch.

Nevertheless, the CGN-38-class cruisers, with their missile magazines and Mk-26 missile launchers, were incapable of carrying the SM-2ER long-range surface-to-air missile, being restricted to the SM-2MR medium-range surface-to-air missile. This was a significant limitation in their capabilities.

Another weakness was a lack of LAMPS helicopters, which had been replaced by the Tomahawk cruise missile. In the end, what really doomed the ships was economics. They were coming due for their first nuclear refuelings, mid-life overhauls, and NTU refittings, all expensive projects, together costing about half the price of a new ship. Further, they required relatively large crews, straining USN personnel resources. The 1996 Navy Visibility and Management of Operating and Support Costs (VAMOSC) study determined the annual operating cost of a Virginia class cruiser at $40 million, compared to $28 million for a Ticonderoga class cruiser, or $20 million for an Arleigh Burke class destroyer. Given a lower requirement for cruisers, it was decided to retire these nuclear ships as a money-saving measure. The early non-VLS Ticonderoga class cruisers had equally short careers, serving between 18 and 21 years.

NR-1 Reactor

Figure 30: Deep Submergence Vessel NR-1

Deep Submergence Vessel NR-1 was a unique United States Navy nuclear-powered ocean engineering and research submarine. Built by the Electric Boat Division of General Dynamics at Groton, Connecticut NR-1 was launched on 25 January 1969, completed initial sea trials 19 August 1969, and was home-ported at Naval Submarine Base New London. NR-1 was the smallest nuclear submarine ever put into operation. Casually known as "Nerwin", NR-1 was never officially named or commissioned. The U.S. Navy is allocated a specific number of warships by the U.S. Congress. Admiral Hyman Rickover not only avoided using one of those allocations, but he also wanted to avoid the oversight that a warship receives from various bureaus.

NR-1's missions included search, object recovery, geological survey, oceanographic research, and installation and maintenance of underwater equipment. NR-1's unique capability to remain at one site and completely map or search an area with a high degree of accuracy was a valuable asset on several occasions.

Through the 1970s and 1980s, "NR-1" conducted numerous classified missions involving recovery of objects from the floor of the deep-sea. These missions remain classified and few details have been made public. One publicly acknowledged mission in 1976 was to recover parts of an F-14 that was lost from the deck of an aircraft carrier and sank with at least one of the then-new AIM-54A Phoenix air-to-air missiles. The secrecy normal to USN submarine operations was heightened by Rickover's personal involvement. Rickover shared details of "NR-1" operations on a need-to-know basis. Rickover envisioned building a small fleet of NR-1 type submarines, but only one was built due to budget restrictions.

Following the loss of the Space Shuttle Challenger in 1986, NR-1 was used to search for, identify, and recover critical parts of the Challenger craft. Because it could remain on the sea floor without resurfacing frequently, NR-1 was a major tool for searching deep waters. NR-1 remained submerged and on station even when heavy weather and rough seas hit the area and forced all other search and recovery ships into port.

In 1995, Dr. Robert Ballard used the NR-1 and its support ship, MV Carolyn Chouest, to explore the wreck of HMHS Britannic, the sister ship of RMS Titanic, which sank off the coast of Greece while serving as a hospital ship during World War I.

On 25 February 2007, NR-1, towed by Carolyn Chouest, arrived in Galveston, Texas, in preparation for an expedition to survey the Flower Garden Banks National Marine Sanctuary and other sites in the Gulf of Mexico.

NR-1 was deactivated on 21 November 2008 at the U.S. Navy submarine base at Groton, Connecticut, defueled at Portsmouth Naval Shipyard in Kittery, Maine, then sent to Puget Sound Naval Shipyard to be scrapped. On 13 November, 2013, the U.S. Navy announced that salvaged pieces of the sub would be put on display at the Submarine Force Library and Museum in Groton.

NR-1 performed underwater search and recovery, oceanographic research missions and installation and maintenance of underwater equipment to a depth of almost half a nautical mile. Its features included extending bottoming wheels, three viewing ports, exterior lighting, television and still cameras for color photographic studies, an object recovery claw, a manipulator that could be fitted with various gripping and cutting tools and a work basket that could be used in conjunction with the manipulator to deposit or recover items in the sea. Surface vision was provided by a television periscope permanently installed on a fixed mast it’s her sail area.

NR-1 had sophisticated electronics, computers and sonar systems that aided in navigation, communications, and object location and identification. It could maneuver or hold a steady position on or close to the seabed or underwater ridges, detect and identify objects at a considerable distance, and lift objects off the ocean floor.

NR-1 was equipped with two electric-motor driven propellers and its maneuverability was enhanced by four ducted thrusters, two forward and two aft. The vehicle had diving planes mounted on the sail, and a conventional rudder.

NR-1 could travel submerged at approximately four knots for long periods, limited only by consumable supplies — primarily food. It could study and map the ocean bottom, including temperature, currents, and other information for military, commercial and scientific uses. Its nuclear propulsion provided independence from surface support ships and essentially unlimited endurance.

The NR-1's size limited its crew comforts. The crew of about 10 men could stay at sea for as long as a month, but had no kitchen or bathing facilities. They ate frozen TV dinners, bathed once a week with a bucket of water and burned chlorate candles to produce oxygen. The sub was so slow that it was towed to sea by a surface vessel, and so tiny that the crew felt the push and pull of the ocean's currents. "Everybody on NR-1 got sick," said Allison J. Holifield, who commanded the sub in the mid-1970s. "It was only a matter of whether you were throwing up or not throwing up."

NR-1 was generally towed to and from remote mission locations by an accompanying surface tender, which was also capable of conducting research in conjunction with the submarine. NR-1's last mother ship was MV Carolyn Chouest, which provided towing, communications, berthing and direct mission support for all NR-1 operations. An extremely versatile platform, she was an indispensable member of the NR-1 deep submergence team. NR-1 command was manned with thirty-five Navy personnel and ten civilian contractor personnel. NR-1 carried as many as thirteen persons (crew and specialists) at one time, including three of the four assigned officers. (The operations officer rode on Carolyn Chouest). All personnel that crewed NR-1 were nuclear-trained and specifically screened and interviewed by the Director, Navy Nuclear Propulsion Program.

S1C Reactor

The S1C reactor was a prototype naval reactor designed for the United States Navy to provide electricity generation and propulsion on warships. The S1C designation stands for:

S = Submarine platform
1 = First generation core designed by the contractor
C = Combustion Engineering (C-E) was the contracted designer

This nuclear reactor was built in Windsor, Connecticut as a prototype for the experimental USS Tullibee (SSN-597) submarine, though that boat was in fact powered by a S2C reactor. The propulsion plant was unusual in that the steam turbines powered an electric motor, rather than a set of reduction gears. The USS Tullibee was an early advanced-design, fast-attack submarine constructed by Electric Boat and commissioned in 1960.

Throughout the Cold War, the S1C Prototype nuclear submarine propulsion plant at the Windsor Site supported the submarines and surface ships of the Navy's nuclear fleet by testing new equipment and training Naval propulsion plant operators. S1C was the prototype for the USS Tullibee. The S1C Prototype was operated at the Windsor Site from 1959 until 1993. During that time, over 14,000 Naval operators were trained there, including Admiral Kirkland H. Donald early in his career.

Full clean-up of the S1C site was recently declared to be complete by the Connecticut Department of Environmental Protection in 2006. Remediation of the site was undertaken by Knolls Atomic Power Laboratory (KAPL), based out of Schenectady, New York. KAPL had taken over operation of the S1C site in the 1960s after expiration of the Navy's original contract with C-E.

The reactor was situated on land and known as the S1C Nuclear Power Training Unit (NPTU). Except for its size and electric drive, the system layout was very similar to the S5W reactor used in most nuclear-powered submarines at the time.

S1G Reactor

The S1G reactor is a naval reactor used by the United States Navy to provide electricity generation and propulsion on warships. The S1G designation stands for:

- S = Submarine platform
- 1 = First generation core designed by the contractor
- G = General Electric was the contracted designer

This nuclear reactor was constructed by General Electric as a prototype for the USS Seawolf (SSN-575) submarine. It was a liquid metal cooled reactor using pure sodium to cool the core instead of water, because the higher temperature of liquid sodium (compared to pressurized water) enabled the production of more superheated steam in the steam generators. This resulted in a more efficient thermal cycle, yielding more shaft horsepower for a given reactor size. The reactor design had problems because of limited operating temperature constraints. The major disadvantage of this concept was the ignition of sodium when exposed to air.

S1G was used for testing and training. Eventually a sodium leak resulted in a fire, and the facility was shut down. In the meantime, the S1W and S2W pressurized water reactors, conceived for the USS Nautilus (SSN-571), had demonstrated their superior reliability. The S1G reactor facility and its Horton Sphere were later reused for the D1G prototype destroyer reactor.

S1W Reactor

The S1W reactor was the first prototype naval reactor used by the United States Navy to prove that the technology could be used for electricity generation and propulsion on submarines. The S1W designation stands for

- S = Submarine platform
- 1 = First generation core designed by the contractor
- W = Westinghouse was the contracted designer

The land-based nuclear reactor was built at the National Reactor Testing Station, later called Idaho National Engineering Laboratory near Arco, Idaho. The plant was the prototype for the USS Nautilus (SSN-571), the world's first nuclear-powered submarine. The specific location within the vast Idaho National Laboratory where the S1W prototype was located was the Naval Reactors Facility.

S2C Reactor

The S2C reactor is a naval reactor used by the United States Navy to provide electricity generation and propulsion on warships. The S2C designation stands for:

- S = Submarine platform
- 2 = Second generation core designed by the contractor
- C = Combustion Engineering was the contracted designer

This nuclear reactor is the shipboard equivalent of the S1C reactor, and was installed on the experimental USS Tullibee (SSN-597) submarine.

USS Tullibee (SSN-597)

Figure 31: USS Tullibee (SSN-597)

USS Tullibee (SSN-597), a unique submarine, was the second ship of the United States Navy to be named for the tullibee, any of several whitefishes of central and northern North America.

At 273 feet long and 2,300 tons displacement, USS Tullibee was the smallest nuclear-powered attack submarine in the US submarine fleet. The initial manning complement was 7 officers and 60 enlisted men. However before inactivation, the crew included 13 officers and over 100 enlisted men.

During her career, Tullibee achieved much and conducted many submarine firsts. During her commissioned service she submerged and surfaced 730 times and traveled approximately 325,000 nautical miles (602,000 km; 374,000 mi) equal to the distance from the earth to the moon and halfway back.

Tullibee was the result of "Project Nobska", a study ordered in 1956 by Admiral Arleigh Burke, then Chief of Naval Operations, from the Committee on Undersea Warfare of the National Academy of Sciences. That report emphasized the need for deeper-diving, ultra quiet submarine designs using long-range sonar. Tullibee incorporated three design changes based on Project Nobska. First, it incorporated the first bow-mounted spherical sonar array. This required the second innovation: amidships, angled torpedo tubes. Thirdly, Tullibee was propelled by a very quiet turboelectric power plant based on the S2C reactor.

The contract to build Tullibee was awarded to the Electric Boat Division of the General Dynamics Corporation on 15 November 1957. Her keel was laid down in Groton, Connecticut, on 26 May 1958. She was launched on 27 April 1960, sponsored by Mrs. John F. Davidson, the widow of Commander Charles F. Brindupke, and commissioned on 9 November 1960, with Commander Richard E. Jortberg in command.

Decommissioned and stricken from the Naval Vessel Register on 25 June 1988, ex-Tullibee entered the Navy's Nuclear Powered Ship and Submarine Recycling Program on 5 January 1995.

S2G Reactor

The S2G reactor was a naval reactor used by the United States Navy to provide electricity generation and propulsion on warships, and the only liquid metal cooled reactor yet deployed by the US Navy. The S2G designation stands for:

- S = Submarine platform
- 2 = Second generation core designed by the contractor
- G = General Electric was the contracted designer

An S2G was the initial power plant of USS Seawolf (SSN-575). This was one of three sodium cooled fast reactors ordered for the Seawolf program at the same time as three PWR units were ordered to support the USS Nautilus (SSN-571) program; In each case, one reactor was land-based for training and research, one intended for installation on a submarine, and one spare. The land-based unit corresponding to S2G was S1G reactor.

Persistent superheater problems on Seawolf caused the superheaters to be bypassed, resulting in mediocre performance. This and concern for the dangers posed by liquid sodium coolant led to the PWR type being selected instead as the standard US naval reactor type, and the S2G on Seawolf was replaced by the spare S2Wa reactor from the Nautilus program.

USS Seawolf (SSN-575)

USS Seawolf (SSN-575), a unique submarine, was the third ship of the United States Navy to be named for the seawolf, the second nuclear submarine, and the only U.S. submarine built with a liquid metal cooled (sodium) nuclear reactor.

Figure 32: USS Seawolf (SSN-575)

Seawolf was technologically more advanced than her predecessor, USS Nautilus (SSN-571). Carrying a superheated steam power plant, rather than a traditional saturated steam plant, reduced the size of the machinery spaces nearly 40%. Her liquid-sodium cooled reactor was more efficient than a water-cooled one, and quieter, but posed several safety hazards for the ship and crew. The phrase "Blue Haze" was often associated with the boat, even though there was only one sodium coolant leak ever noted, and that was while she was fitting out in the yards.

Although fully armed, Seawolf, like the first nuclear submarine, Nautilus, was primarily an experimental vessel. Seawolf was originally thought of publicly as a 'hunter-killer' sub, but in fact was intended to be a one off test platform for the LMSR reactor and future sonar platforms. Her future uses, however, would include covert operations in foreign waters, the likes of which were never envisioned by Admiral Rickover.

In August 1981, Seawolf deployed on her fifth Pacific Fleet deployment. She returned to homeport in October 1981 and received the Navy Expeditionary Medal. In 1983, Seawolf conducted her sixth Pacific Fleet deployment of 76 days and returned to Mare Island Naval Shipyard in May 1983. She was awarded the Navy Expeditionary Medal, another Battle Efficiency "E," another Engineering "E," a Supply "E," and a Damage Control "DC." In 1984, Seawolf conducted a 93-day deployment to the Western Pacific, returned in July, and continued her high operating tempo with numerous local operations. She was awarded her third consecutive Supply "E," a Communications "C," and the Deck Seamanship Award.

In April 1986, Seawolf conducted her last Western Pacific deployment and returned to Mare Island in June 1986 to prepare for decommissioning. Decommissioned 30 March 1987, Seawolf was stricken from the Naval Vessel Register the following 10 July. The former submarine began the Navy's Ship-Submarine Recycling Program on 1 October 1996 and completed it on 30 September 1997.

S2W Reactor

The S2W reactor is a naval reactor used by the United States Navy to provide electricity generation and propulsion on warships. The S2W designation stands for:

- S = Submarine platform
- 2 = Second generation core designed by the contractor
- W = Westinghouse was the contracted designer

This nuclear reactor is the shipboard equivalent of the prototype S1W reactor, with minor design changes, that was installed on the USS Nautilus (SSN-571). As installed in Nautilus it generated 13,400 horsepower (10.0 MW). It was originally designated STR.

After Nautilus was decommissioned, the reactor equipment was removed. The submarine is now moored and displayed as a museum ship at the Naval Submarine Base New London in Groton, Connecticut.

USS Nautilus (SSN-571)

Figure 33: USS Nautilus (SSN-571)

USS Nautilus (SSN-571) was the world's first operational nuclear-powered submarine. She was also the first vessel to complete a submerged transit across the North Pole.

Named after the submarine in Jules Verne's Twenty Thousand Leagues Under the Sea, Nautilus was authorized in 1951 and launched in 1954. Because her nuclear propulsion allowed her to remain submerged for far longer than diesel-electric submarines, she broke many records in her first years of operation and was able to travel to locations previously beyond the limits of submarines. In operation, she revealed a number of limitations in her design and construction; this information was used to improve subsequent submarines.

The Nautilus was decommissioned in 1980 and designated a National Historic Landmark in 1982. She has been preserved as a museum of submarine history in Groton, Connecticut, where she receives some 250,000 visitors a year.

In July 1951 the US Congress authorized the construction of a nuclear-powered submarine for the U.S. Navy, which was planned and personally supervised by Admiral Hyman G. Rickover, known as the "Father of the Nuclear Navy." On 12 December 1951 the U.S. Department of the Navy announced that the submarine would be called Nautilus - the fourth U.S. Navy vessel officially so named - and would carry the hull number SSN-571.

Nautilus's keel was laid at General Dynamics' Electric Boat Division in Groton, Connecticut by Harry S. Truman, President of the United States, on 14 June 1952, and the ship was designed by John Burnham. She was christened on 21 January 1954 and launched into the Thames River, sponsored by Mamie Eisenhower, the wife of Truman's successor Dwight D. Eisenhower. Nautilus was commissioned on 30 September 1954, under the command of Commander Eugene P. Wilkinson, USN.

Nautilus was powered by the S2W naval reactor, a pressurized water reactor produced for the U.S. Navy by Westinghouse Electric Corporation. The prototype reactor was built at Idaho National Laboratory.

Following her commissioning, Nautilus remained dockside for further construction and testing. At 11 a.m. on 17 January 1955 she put to sea for the first time and signaled her historic message: "Underway on nuclear power." On 10 May, she headed south for shakedown. Submerged throughout, she traveled 2,100 km (1,100 nautical miles) from New London to San Juan, Puerto Rico and covered 2,223 km (1,200 nm) in less than ninety hours. At the time this was the longest submerged cruise by a submarine and at the highest sustained speed (for at least one hour) ever recorded.

From 1955 to 1957, Nautilus continued to be used to investigate the effects of increased submerged speeds and endurance. The improvements rendered the progress made in anti-submarine warfare during the Second World War virtually obsolete. Radar and anti-submarine aircraft, which had proved crucial in defeating submarines during the War, proved ineffective against a vessel able to move out of an area in record time, change depth quickly and stay submerged for very long periods.

On 4 February 1957, Nautilus logged her 60,000th nautical mile (111,120 km), matching the endurance of her namesake, the fictional Nautilus described in Jules Verne's novel Twenty Thousand Leagues Under The Sea. In May, she departed for the Pacific Coast to participate in coastal exercises and the fleet exercise, operation "Home Run," which acquainted units of the Pacific Fleet with the capabilities of nuclear submarines.

Nautilus returned to New London, Connecticut, on 21 July and departed again on 19 August for her first voyage of 2,226 km (1,202 nmi) under polar pack ice. Thereafter, she headed for the Eastern Atlantic to participate in NATO exercises and conduct a tour of various British and French ports where she was inspected by defense personnel of those countries. She arrived back at New London on 28 October, underwent upkeep, and then conducted coastal operations until the spring.

Operation Sunshine - under the North Pole

On 25 April 1958, she was underway again for the West Coast, now commanded by Commander William R. Anderson, USN. Stopping at San Diego, San Francisco, and Seattle, she began her history-making polar transit, operation "Sunshine," as she departed the latter port 9 June. On 19 June she entered the Chukchi Sea, but was turned back by deep draft ice in those shallow waters. On 28 June she arrived at Pearl Harbor to await better ice conditions. By 23 July her wait was over and she set a course northward. She submerged in the Barrow Sea Valley on 1 August and on 3 August, at 2315 (EDST) she became the first watercraft to reach the geographic North Pole. From the North Pole, she continued on and after 96 hours and 2,945 km (1,590 nmi) under the ice, she surfaced northeast of Greenland, having completed the first successful submerged voyage around the North Pole. The technical details of this mission were planned by scientists from the Naval Electronics Laboratory including Dr. Waldo Lyon who accompanied Nautilus as chief scientist and ice pilot.

Navigation beneath the arctic ice sheet was difficult. Above 85 degrees both magnetic compasses and normal gyrocompasses become inaccurate. A special gyrocompass built by Sperry Rand was installed shortly before the journey. There was a risk that the submarine would become disoriented beneath the ice and that the crew would have to play "longitude roulette". Commander Anderson had considered using torpedoes to blow a hole in the ice if the submarine needed to surface.

As mentioned above, the most difficult part of the journey was in the Bering Strait. The ice extended as much as 60 feet (18 m) below sea level. During the initial attempt to go through the Bering Strait, there was insufficient room for the submarine to pass between the ice and the sea bottom. During the second, successful attempt to pass through the Bering passage, the submarine passed through a known channel close to Alaska (this was not the first choice way through the Bering Strait as the submarine wanted to avoid detection).

The trip beneath the ice cap was an important boost to America as the Soviets had recently launched Sputnik but had no nuclear submarine of their own. During the address announcing the journey the president mentioned that one day nuclear cargo submarines might use that route for trade.

In the spring of 1979, Nautilus set out from Groton, Connecticut on her final voyage under the command of Richard A. Riddell. She reached Mare Island Naval Shipyard of Vallejo, California on 26 May 1979 — her last day underway. She was decommissioned and stricken from the Naval Vessel Register on 3 March 1980.

The hull and superstructure of Nautilus vibrated sufficiently that sonar became ineffective at more than 4 knots (7.4 km/h) speed. Also, noise generation is undesirable in stealth operations and facilitates detection of the vessel. Lessons learned from this problem were applied in later nuclear submarines.

S2Wa Reactor

The S2Wa reactor is a naval reactor used by the United States Navy to provide electricity generation and propulsion on warships. The S2Wa designation stands for:

- S = Submarine platform
- 2 = Second generation core designed by the contractor
- W = Westinghouse was the contracted designer

After pressurized water reactor technology had proved its superiority in the S1W and S2W applications, the USS Seawolf (SSN-575) had her S2G liquid metal cooled reactor replaced using spare S2W components. During the conversion, the steam turbines in the power plant were also re-bladed to utilize saturated, rather than superheated, steam.

S3G Reactor

The S3G reactor is a naval reactor used by the United States Navy to provide electricity generation and propulsion on warships. The S3G designation stands for:

- S = Submarine platform
- 3 = Third generation core designed by the contractor
- G = General Electric was the contracted designer

This nuclear reactor generates 78 MW. It consists of a highly enriched uranium core with a 2-loop pressurized water reactor. This design, designated as S4G, was used for the two reactors on the USS Triton (SSRN-586); no other ships used this reactor plant. The plant had unique design features such as horizontal steam generator U-tubes, and it was one of the only submarine plants with a deareating feed tank (DFT).

A prototype reactor was built ashore at Knolls Atomic Power Laboratory's Kesselring Site in West Milton, New York in 1958 to test the reactor design. Once the design was proven, the prototype continued operation to train students and test new systems and materials. This prototype training reactor was taken off line in 1992 and subsequently decommissioned.

Although the design of the entire S3G reactor plant (core, piping, pumps, etc.) saw only limited use, a design version of the reactor core ("S3G3" or "S3G core 3") was later used for replacement cores for the Navy's 100 S5W reactor plants when refueled. Another unique feature of the S3G core 3 was the use of "Y" shaped control rods versus the standard cruciform shaped control rods used in the S5W core. The core also utilized a rod configuration called "skewed divergent". Think of a bunch of pencils in a bundle twisted at a plane. This allowed more rods to be used in the allotted space.

S3W Reactor

The S3W reactor is a naval reactor used by the United States Navy to provide electricity generation and propulsion on warships. The S3W designation stands for:

- S = Submarine platform
- 3 = Third generation core designed by the contractor
- W = Westinghouse was the contracted designer

This nuclear reactor was a variant of the Submarine Fleet Reactor (SFR), an advance on the pressurized water reactor (PWR) plant design employed on the USS Nautilus (SSN-571). The S3W's major innovation was the adoption of vertical U-tube steam generators. This concept was further developed in the S5W reactor, and is in common use today on commercial PWR power plants.

The USS Halibut (SSGN-587) and two boats of the Skate class were built with S3W reactors: USS Skate (SSN-578) and USS Sargo (SSN-583). During later overhauls, the S3W reactors in both Skate and Sargo were replaced with S5W reactors.

USS Skate (SSN-578)

Figure 34: USS Skate (SSN-578)

USS Skate (SSN-578), the third submarine of the United States Navy named for the skate, a type of ray, was the lead ship of the Skate class of nuclear submarines. She was the third nuclear submarine commissioned, the first to make a completely submerged trans-Atlantic crossing, and the second submarine to reach the North Pole and the first to surface there.

The contract to build her was awarded to the Electric Boat division of General Dynamics on 18 July 1955, and her keel was laid in Groton, Connecticut on 21 July 1955. She was launched on 16 May 1957 sponsored by Mrs. Lewis L. Strauss, and commissioned on 23 December 1957 with Commander James F. Calvert in command.

Skate conducted shakedown training out of New London, Connecticut until 29 January 1958, when she cruised to the Bermuda operating area, then returned to her home port on 8 February. Sixteen days later, the nuclear powered submarine set a course for the Isle of Portland, England. Before returning home, she had also visited ports in France and the Netherlands.

In October 1968, Skate was deployed to the Mediterranean where she operated with the Sixth Fleet for two months. The polar veteran operated under the Arctic ice again in March and April 1969, in October 1970, and in February 1971 . The remainder of her at sea time was spent in various Atlantic Fleet and NATO exercises. In July 1971, she began her third regular overhaul at the Norfolk Naval Shipyard and did not return to New London until 17 November 1973. In August 1974, Skate operated as a unit of the Atlantic Fleet.

Skate was decommissioned on 12 September 1986, stricken from the Naval Vessel Register on 30 October 1986, and disposed of by submarine recycling at Puget Sound Naval Shipyard on 6 March 1995.

USS Sargo (SSN-583)

USS Sargo (SSN-583), a Skate-class nuclear-powered submarine, was the second ship of the United States Navy to be named for the sargo, a food and game fish of the porgy family, inhabiting coastal waters of the southern United States.

The contract to build her was awarded to Mare Island Naval Shipyard in Vallejo, California, on 29 September 1955 and her keel was laid down on 21 February 1956. She was launched on 10 October 1957 sponsored by Mrs. Frank T. Watkins, and commissioned on 1 October 1958 with Commander Daniel P. Brooks in command.

Decommissioned and stricken from the Naval Vessel Register on 21 April 1988, ex-Sargo entered the Navy's Nuclear-Powered Ship and Submarine Recycling Program on 14 April 1994. Upon completing the program on 5 April 1995, the former submarine ceased to exist.

Figure 35: USS Sargo (SSN-583)

USS Halibut (SSGN-587)

Figure 36: USS Halibut (SSGN-587)

USS Halibut (SSGN-587), a unique guided missile submarine turned special operations platform, later redesignated as an attack submarine SSN-587, was the second ship of the United States Navy to be named for the halibut.

Halibut's keel was laid down by Mare Island Naval Shipyard at Vallejo, California, on 11 April 1957. She was launched on 9 January 1959, sponsored by Mrs. Chet Holifield, wife of Congressman Chet Holifield of California, and commissioned on 4 January 1960 with Lieutenant Commander Walter Dedrick in command.

Halibut was decommissioned on 30 June 1976. She was "mothballed" at Keyport/Bangor Trident Base, Washington in 1976, struck from the Naval Vessel Register on 30 April 1986, and disposed of through the Ship-Submarine Recycling Program at Puget Sound Naval Shipyard, Bremerton, Washington, on 9 September 1994.

S4G Reactor

The S4G reactor is a naval reactor used by the United States Navy to provide electricity generation and propulsion on warships. The S4G designation stands for:

- S = Submarine platform
- 4 = Fourth generation core designed by the contractor
- G = General Electric was the contracted designer

This nuclear reactor is the shipboard equivalent of the S3G reactor. It was installed in a dual-configuration on the USS Triton (SSRN-586).

USS Triton (SSN-586)

Figure 37: USS Triton (SSN-586)

USS Triton (SSRN/SSN-586), a United States Navy nuclear-powered radar picket submarine, was the first vessel to execute a submerged circumnavigation of the Earth (Operation Sandblast) in early 1960. Triton accomplished this objective during her shakedown cruise while under the command of Captain Edward L. "Ned" Beach, Jr. The only member of her class, she also had the distinction of being the only non-Soviet submarine powered by two nuclear reactors.

Triton was the second submarine and the fifth ship of the United States Navy to be named for the Greek god Triton. At the time of her commissioning in 1959, Triton was the largest, most powerful, and most expensive submarine ever built, at $109 million excluding the cost of nuclear fuel and reactors.

After operating for only two years in her designed role, Triton's role as a radar picket submarine was made obsolete by the introduction of the carrier-based Grumman WF-2 Tracer airborne early warning aircraft. Converted to an attack submarine in 1962, she became the flagship for the Commander Submarine Forces U.S. Atlantic Fleet (COMSUBLANT) in 1964. She was decommissioned in 1969, the first U.S. nuclear submarine to be taken out of service.

Triton's hull was moored at the St. Julien's Creek Annex of Norfolk Naval Shipyard in Portsmouth, Virginia as part of the reserve fleet until 1993, though she was struck from the Naval Vessel Register in 1986. In 1993, she was towed to Puget Sound Naval Shipyard to await the Nuclear Powered Ship and Submarine Recycling Program. The former Triton landed on the keel resting blocks in the drydock basin on 1 October 2007 to begin this recycling process which was completed effective 30 November 2009.

Triton's main air search radar was the AN/SPS-26 electronically scanned, three-dimensional (3-D) radar system. The SPS-26 radar had a range of 65 nautical miles (120 km; 75 mi), and it was capable of tracking aircraft up to an altitude of 75,000 feet (23,000 m). Since it scanned electronically in elevation, it did not need a separate height-finding radar system. When not in use, the SPS-26 radar was lowered into its fairwater housing for stowage within Triton's massive sail. A submarine version of SPS-26, designated BPS-10, was under development at the time of Triton's construction, and it was slated for eventual installation on the Triton.

Triton's active/passive sonar detecting-ranging set was the AN/BQS-4, which had a listening range up to 20 nautical miles (37 km; 23 mi) for surfaced or snorkeling submarines, optimized to 35 nautical miles (65 km; 40 mi) with target tracking capability within 5 degrees of accuracy. The hull-mounted passive sonar AN/BQR-2 array supplemented the BQS-4 system, with a range up to 10 nautical miles (19 km; 12 mi) and a bearing accuracy of 1/10 of degree, allowing the BQR-2 to be used for fire control in torpedo attacks.

Triton's target fire-control system (TFCS) was the MK-101, a post-war development that incorporated target tracking and ranging data into a position keeper, with a pair of analyzers that automatically revised torpedo gyros and settings as the target position changed. This automation greatly simplified a targeting solution for a plotting party. Previously targeting solutions were manually estimated target bearings and then feed them into the Torpedo Data Computer (TDC) system initially introduced in fleet submarines prior to World War II. However, while entirely capable of providing efficient fire control solutions against post-war non-nuclear hunter-killer submarines, the MK-101 proved to be less responsive to the rapid changes associated with nuclear submarine operations.

Triton's torpedo system consisted of six Mark 60 torpedo tubes, four bow and two stern. The Mark 60 system was a 249.8 inches (6,340 mm) long hydraulic torpedo tube that did not have power handling capability. The standard torpedo carried by Triton was the Mark 37, with a weapon load of ten forward and five aft. Triton's first commanding officer, "Ned" Beach, noted the torpedo load in the forward torpedo room could have been doubled with the removal of a single support girder.

The number 2 periscope was Triton's navigational periscope, and it had a built-in sextant developed by the Kollmorgen Optical Company that allowed navigators to observe celestial bodies to order to obtain an accurate star fix to plot the ship's course and position.

Triton entered the Portsmouth Naval Shipyard in June 1962 for conversion to an attack submarine. Her crew complement was reduced from 172 to 159. She was overhauled and refueled at Groton, Connecticut, from September 1962 to January 1964, which included modification to serve as the flagship for COMSUBLANT. Since the Navy no longer had any plans to use Triton's radar picket capability, her SPS-26 radar set was replaced by a two-dimensional AN/BPS-2 air search radar, with Triton now providing the fleet with an at-sea air strike control capability.

Because she subsequently served as COMSUBLANT's flagship following her overhaul, one area of continuing speculation is whether Triton was part of the National Emergency Command Post Afloat (NECPA) program. NECPA was tasked to provide afloat facilities for the President of the United States in case of an emergency or war, with the command cruisers Northampton and Wright assigned to perform this mission. Triton had a number of attributes that made her a potential NECPA platform. Her size allowed ample room for additional shipboard systems and accommodations. Her designed speed provided the capability for rapid transit, and her nuclear power plant offered virtually unlimited endurance and range. The Combat Information Center (CIC) provided substantial command and control capabilities as did the communication buoy system that could receive and send radio transmissions while submerged. As she was a submarine, Triton offered superior protection against nuclear-biological-chemical (NBC) contaminants over surface ships or airborne command center. However, the record remains unclear if such an explicit conversion was ever undertaken.

In March 1964, upon completion of her overhaul, Triton's home port was changed from New London, to Norfolk. On 13 April 1964, she became the flagship for COMSUBLANT. In January 1965, Triton rescued the pilot and a passenger of a charter aircraft that had ditched in the Atlantic Ocean off St. Croix in the Virgin Islands. Triton was relieved as COMSUBLANT's flagship by the Sturgeon-class attack submarine Ray on 1 June 1967. Eleven days later, the Triton was shifted to her original home port of New London, Connecticut.

Due to cutbacks in defense spending, as well as the expense of operating her twin nuclear reactors, Triton's scheduled 1967 overhaul was canceled, and the submarine—along with 60 other vessels—was slated for inactivation. While Triton's twin reactor plant was designed to be refueled by a submarine tender like other U.S. nuclear submarines, because of the complexity of her zirconium-clad fuel elements, Triton's previous re-fueling had been done in a shipyard during her 1962–1964 overhaul. Although new fuel elements were procured and available for installation, Triton's overhaul was canceled, a source of controversy. One speculation suggests that the cancellation of Triton's overhaul allowed funds to be redirected for the repairs to the supercarrier Forrestal which had been extensively damaged off Vietnam.

From October 1968 through May 1969, she underwent preservation and deactivation processes, and she was decommissioned on 3 May 1969. Triton became the U.S. Navy's first nuclear-powered submarine to be taken out of service, and second in the world, after the Soviet Navy's November-class submarine K-27 in 1968.

On 6 May 1969, Triton departed New London under tow and proceeded to Norfolk, Virginia, where she was placed in the reserve fleet. She remained berthed at Norfolk or at the St. Julien's Creek Annex of Norfolk Naval Shipyard in Portsmouth, Virginia, into 1993. She was stricken from the Naval Vessel Registry on 30 April 1986. In August 1993, the hulks of the ex-Triton and the ex-Ray were towed by the salvage tug Bolster to the Puget Sound Naval Shipyard (PNSY), in Bremerton, Washington, arriving on 3 September 1993, to await their turn in the Nuclear Powered Ship and Submarine Recycling Program (SRP). Effective 1 October 2007, ex-Triton landed on the keel resting blocks in the drydock basin to begin recycling. The long delay in the disposal of ex-Triton has been attributed to the complexity of her dual reactor plant. Final recycling was completed effective 30 November 2009.

Triton was the 2003 inductee into the Submarine Hall of Fame following her nomination by the Tidewater chapter and Hampton Roads Base of the United States Submarine Veterans, Inc. (USSVI). A shadow box filled with Triton memorabilia was placed in Alcorn Auditorium of Ramage Hall located at the U.S. Navy Submarine Learning Center, Naval Station Norfolk.

S4W Reactor

The S4W reactor is a naval reactor used by the United States Navy to provide electricity generation and propulsion on warships. The S4W designation stands for:

- S = Submarine platform
- 4 = Fourth generation core designed by the contractor
- W = Westinghouse was the contracted designer

This nuclear reactor was a variant of the Submarine Fleet Reactor (SFR) with the horizontal steam generators pioneered in S1W and S2W.

Two boats of the Skate class were built with S4W reactors: USS Swordfish (SSN-579) and USS Seadragon (SSN-584). During later overhauls, the S4W reactors in both subs were replaced with S5W reactors.

USS Swordfish (SSN-579)

USS Swordfish (SSN-579), a Skate-class submarine, was the second submarine of the United States Navy named for the swordfish, a large fish with a long, sword like beak and a high dorsal fin.

The contract to build her was awarded to the Portsmouth Naval Shipyard of Kittery, Maine on 18 July 1955, and her keel was laid down on 25 January 1956. She was launched on 27 August 1957 sponsored by Mrs. Eugene C. Riders, and commissioned on 15 September 1958 with Commander Shannon D. Cramer, Jr., in command.

In late October 1985, Swordfish was delayed in departing Pearl Harbor due to the failure of the drain pump. A replacement was obtained from USS Skate (SSN-578), in the shipyard for decommissioning, but Swordfish put to sea before the pump was fully connected and tested, and the crew could not get the pump to operate. Since the engine room bilges could not be pumped, by the evening of 23 October, the first day at sea, the water in the engine room lower level bilge was over the deck plates (more than four feet). The crew tried to use a portable submersible pump, but were not successful.

When the water level got high enough to get up into the bottoms of the motors for the main lube oil pumps, causing grounds, the Captain came aft and saw the situation and decided to take the boat shallow to allow pumping bilges. When the planesmen put a slight up-angle on the boat to come shallow the water in the bilges instantly rushed aft, greatly increasing its effect on trim (this is known as "free surface effect", later classes of subs have flood control bulkheads in engine room lower level to prevent this) and causing an up-angle of about 45 degrees.

When "fire in engine room lower level" was announced, due to water in the main lube oil pump motors, a man in the aft end of engine room upper level opened the watertight door into the stern room, which swung into the stern room, to retrieve a fire extinguisher. Just then the up-angle increased dramatically and the bilge water began pouring in. The door was shut before the boat surfaced. With the boat on an even keel, the water came up to the deadlight in the door.

The maneuvering watchstanders began to take the immediate actions for loss of shaft lube oil; the throttleman began to shut the throttles for the main engines. Without propulsion, the extreme up-angle caused the ship to quickly stop and begin moving backwards, sinking stern first. When the fire was announced, the Engineer had gone to Maneuvering (the control center of the engine room). He saw the depth gage indicating a rapid increase in depth, ordered "Ahead Full" on his own initiative, and opened the starboard forward throttle himself in an effort to drive the ship to the surface. In Control, the Captain saw similar indications, and ordered "Blow Aft!" Before the Chief of the Watch could initiate the blow on the aft group the up-angle became so steep that he was unable to maintain footing and slid to the rear of the Control compartment. He quickly climbed back up to the emergency blow "chicken switches" and opened the after group valve.

Swordfish surfaced successfully. However, during the up-angle the freshwater drain collecting tank vents were submerged and sucked contaminated water into the feed system. The steam generator water could not be analyzed immediately because nucleonics laboratory in the stern room had been inundated by the wave of bilge water. After a while, the leading ELT found the necessary reagents and analyzed samples from both steam generators on the top hat in reactor compartment upper level. By this time the boat was in direct communication with Naval Reactors, which ordered the reactor shut down and cooled down and steam generators drained and refilled. The emergency diesel generator, located in engine room lower level, initially had water in the generator from the incident but it was drained and the diesel was online before the reactor was shut down.

The reactor was cooled down and steam generators were blown down with service air and refilled until all fresh water on the boat was exhausted, which was a couple of hours before arriving back in Pearl Harbor; the cooks broke out cans of juice and distributed them around the boat. Subsequent analysis of steam generator water revealed no leakage of reactor coolant into the steam generators.

Three of the boat's four air conditioning compressors were shut down as part of the rig for reduced electrical. The temperature in the ship exceeded 80°F (27C) with near 100% humidity for the several hours required for a tug to be dispatched from Pearl Harbor and tow Swordfish home. The tug, USS Reclaimer (ARS-42) arrived the next morning and began the tow around noon, arriving back in Pearl Harbor just after midnight.

The actions of the Chief of the Watch and the Engineer saved Swordfish and her crew. The boat spent the rest of 1985 in port making repairs and returned to sea in January, 1986, making a successful deployment to the western Pacific later in 1986.

Swordfish was decommissioned and stricken from the Naval Vessel Registry on 2 June 1989. Her disposal through the Ship-Submarine Recycling Program (SRP) was completed at Puget Sound Naval Shipyard on 11 September 1995.

Swordfish earned the Armed Forces Expeditionary Medal, two Meritorious Unit Commendations, two Navy "E"s, eight Navy Unit Commendations, four Vietnam Service Medals, and a number of classified awards.

Russia has repeatedly requested copies of Swordfish's logs to trace her at the time K-129 was lost, but The Pentagon refuses to release them; Swordfish was involved in highly sensitive operations at that time. The United States has salvaged some parts of K-129, and has provided the Russian government with a videotape of a burial-at-sea ceremony for six crew members whose remains were recovered when Hughes Glomar Explorer recovered parts of K-129 in 1974.

USS Seadragon (SSN-584)

USS Seadragon (SSN-584), a Skate-class submarine, was the second ship of the United States Navy to be named for the seadragon, a small fish commonly called the dragonet.

The contract to build her was awarded to Portsmouth Naval Shipyard in Kittery, Maine on 29 September 1955 and her keel was laid down on 20 June 1956. She was launched on 16 August 1958 sponsored by Mrs. Robert L. Dennison, and commissioned on 5 December 1959, with Lieutenant Commander George P. Steele in command.

Following a Caribbean shakedown cruise, Seadragon returned to Portsmouth, whence, on 1 August 1960, she sailed for the Pacific. Ordered to proceed via the Northwest Passage, she moved north to Parry Channel, at mid-month reached Lancaster Sound, the eastern end of the channel, and continued westward with Edward Parry's 1819 journal as a guide.

Decommissioned on 12 June 1984 and stricken from the Naval Vessel Register on 30 April 1986, ex-Seadragon entered the Navy's Nuclear-Powered Ship and Submarine Recycling Program on 1 October 1994. On 18 September 1995, Seadragon ceased to exist.

S5G Reactor

The S5G reactor was a prototype naval reactor designed for the United States Navy to provide electricity generation and propulsion on submarines. The S5G designation stands for:

- S = Submarine platform
- 5 = Fifth generation core designed by the contractor
- G = General Electric was the contracted designer

The S5G was a pressurized water reactor plant with two coolant loops and two steam generators. The design featured a reactor vessel situated low in the boat and the steam generators located high in the boat to support natural circulation of the primary coolant.

This nuclear reactor was installed both as a land-based prototype at the Nuclear Power Training Unit, Idaho National Laboratory near Arco, Idaho, and on board the USS Narwhal (SSN-671); both have been decommissioned. It was intended to test the potential contribution of natural circulation technology to submarine quieting. Reactor primary coolant pumps are a main source of noise from submarines. The elimination of coolant pumps and associated equipment would also reduce mechanical complexity and the space required by propulsion equipment. Its design was the direct ancestor of the S8G reactor used on the Ohio class ballistic missile submarines, another very quiet submarine.

The S5G had primary coolant pumps, but they were only needed for very high speeds. And since the reactor core was designed with very smooth paths for the coolant, the coolant pumps were smaller and quieter than the pumps used by the competing S5W core. In most cases, the submarine could be operated without using coolant pumps at all. The reduction in electrical requirements enabled this design to use two lower-capacity, but quieter electrical turbine generators. The quiet design resulted in a larger hull diameter and a larger primary coolant intake pipe than the competing S5W reactor. Due to the larger size, the S5G was not used in subsequent attack submarines, but was a precursor to the S8G reactor used in the larger Ohio class submarines.

To further reduce engine plant noise, the typical propulsion setup of two steam turbines driving the screw through a reduction gear unit was changed instead to one large propulsion turbine with no reduction gears. This eliminated the noise from the main reduction gears, but at the cost of a huge main propulsion turbine. The turbine was cylindrical, about 12 feet in diameter, and about 30 feet long. The massive size was a result of the slow rotations needed to directly drive the screw. The same propulsion setup was used for both the USS Narwhal and the land-based prototype.

The concept of a natural circulation plant was relatively new when the Navy requested this design. The prototype plant in Idaho was therefore given quite a rigorous performance shakedown to determine if such a design would work for the U.S. Navy. It was largely a success, although the design never became the basis for any more fast-attack submarines besides the Narwhal. The prototype testing included the simulation of the entire engine room of a submarine. Floating the plant in a large pool of water allowed the prototype to be rotated on its long axis by torquing large flywheels mounted ahead of the reactor compartment to simulate a hard turn. The effects on natural circulation were evaluated at various angles and during simulated hard maneuvers.

The S5G prototype was permanently shut down in May 1995.

S5W Reactor

The S5W reactor is a nuclear reactor used by the United States Navy to provide electricity generation and propulsion on warships. The S5W designation stands for:

- S = Submarine platform
- 5 = Fifth generation core designed by the contractor
- W = Westinghouse was the contracted designer

This pressurized water reactor's simplicity, overdesign, and redundancy was intended for ease of operation and tolerance of battle damage. These characteristics contributed greatly to the type's reliability, longevity, and excellent safety record. The S5W was the standard reactor for submarines of the United States Navy from its first use in 1959 on USS Skipjack (SSN-585) until the introduction of the Los Angeles-class submarines in the mid-1970s. One S5W plant was also used in the United Kingdom on the Royal Navy's first nuclear-powered submarine HMS Dreadnought (S101).

Sometime before 1971, the S5W vessel and core replaced the S1W reactor vessel and core at the S1W prototype facility. Even though operating an S5W reactor core, the facility continued to be called S1W. To use the additional power generated by the S5W reactor at higher power levels, steam dumps were constructed in the same S1W building but outside the original submarine style hull.

As of 2005, two S5W reactor plants remain in service: ex-USS Daniel Webster (MTS-626) and ex-USS Sam Rayburn (MTS-635). These "moored training ships" are used to train U.S. naval nuclear operators at Naval Weapons Station Charleston.

Later-model S5W reactor plants were often refueled with a S3G core-3, the third version of the S3G core.

Skipjack Class Submarine (SSN-585 class)

The Skipjack class was a class of United States Navy nuclear submarines. This class was named after its lead ship, the USS Skipjack (SSN-585). This new class introduced the Teardrop hull and the S5W reactor to U.S. nuclear submarines. The Skipjacks were the fastest U.S. nuclear submarines until the Los Angeles class submarines. The Skipjacks design was based off of the successful Barbel class submarines that were based on the USS Albacore design. The design of the Skipjacks was very different from the Skate class submarines that preceded the Skipjacks. Unlike the Skates, this new design was maximized for underwater speed while by shaping the hull like a blimp. This required that the single screw was aft of the rudders and dive planes. This so called "body-of-revolution hull reduced her surface sea-keeping, but was essential for underwater performance. The Skipjacks' hull was also a single hull design, where the pressure hull and outer hull are the same for most of the length of the ship.

The bow planes were moved to the massive sail to cut down on flow-induced noise near the bow sonar array. This design feature would be repeated on all U.S. nuclear submarines until the Improved Los Angeles class. The small "turtleback" behind the sail was the exhaust piping of the auxiliary diesel generator.

The Skipjacks also introduced the S5W reactor to U.S. nuclear submarines. The S5W was used on 98 U.S. nuclear submarines and the first British nuclear submarine, the HMS Dreadnought (S101).

The George Washington class submarines were based off of the Skipjack design. The hull of USS Scorpion (SSN-589) was laid down twice as the original hull was redesigned to become the first US ballistic missile submarine USS George Washington (SSBN-598). Also, the material for building USS Scamp (SSN-588) was diverted into building USS Patrick Henry (SSBN-599) which delayed her progress.

The first Skipjack class was authorized in the FY 1956 new construction programmed with the first of the class commissioned in April 1959. Each hull cost around $40 million.

The Skipjacks saw service in Vietnam and throughout the Cold War.

The Skipjack class submarines were withdrawn from service in the late 1980s and early 1990s except for the USS Scorpion (SSN-589), which sank on 5 June 1968 in the south west Azores, while returning from a Mediterranean deployment.

George Washington Class Submarine (SSBN-598 class)

The George Washington class was a class of nuclear-powered ballistic missile submarines employed by the United States Navy. The Navy ordered a class of nuclear-powered submarines armed with long-range strategic missiles on 31 December 1957, and tasked Electric Boat with converting two existing attack submarine hulls to ballistic missile-carrying boats to quickly create the deterrent force. To accomplish this conversion, Electric Boat persuaded the Navy in January 1958 to slip the launch dates for two Skipjack-class fast attack submarines, the just-begun Scorpion (SSN-589) and the not-yet-started Sculpin (SSN-590). On 12 February 1958, President of the United States Dwight D. Eisenhower signed funding for three ballistic missile submarines.

The George Washingtons were essentially Skipjacks with a 130 foot (40 m) missile compartment ("Sherwood Forest"), inserted between the ship's control navigation areas and the nuclear reactor compartment. In the case of the lead ship, George Washington (SSBN-598), that is literally the case: the keel already laid by Electric Boat at Groton, Connecticut for Scorpion was cut apart and extended to become the keel for George Washington. Then Electric Boat and Mare Island Naval Shipyard began construction of one other boat each from extended plans. President Eisenhower authorized construction of two more submarines on 29 July 1958. Newport News Shipbuilding and Portsmouth Naval Shipyard began work immediately.

The first ship of the class, the George Washington was ordered by the Navy 31 December 1957 and awarded to Electric Boat Corporation. Her keel was laid 1 November 1957 and launched 9 June 1959 in Groton Connecticut. Sponsored by Mrs. Robert B. Anderson, she was delivered to the U.S. Navy and commissioned on 30 December 1959, Commander James B. Osborn (blue crew) and Commander John L. From, Jr. (gold crew) in command.

The first of a new class of ballistic missile submarines, George Washington sailed from Groton 28 June 1960 for Cape Canaveral, Fla., where she loaded two solid propellant Polaris missiles. Standing out into the Atlantic Missile Test Range with Rear Admiral William F. Raborn, head of the phenomenal Polaris Submarine development program on board as an observer, the nuclear submarine made history 20 July 1960 when she successfully launched the first Polaris missile from a submerged submarine. At 1239 George Washington's commanding officer sent President Eisenhower the historic message: "Polaris—from out of the deep to target. Perfect." Less than 2 hours later another missile from the submerged submarine homed in on the impact area 1,100 miles down range.

George Washington returned to Cape Canaveral to embark her gold crew, and 30 July 1960 duplicated her earlier successes by launching two more missiles while submerged. Shakedown for the gold crew ended at Groton 30 August and the submarine got underway from that port 28 October for Charleston, S.C., to load her full complement of 16 Polaris missiles. There she was awarded the Navy Unit Commendation, after which her blue crew took over; and George Washington embarked on her first patrol.

Figure 38: George Washington Class Submarine (SSBN-598 class)

Submarines of the George Washington Class:

- (SSBN-598) USS George Washington
- (SSBN-599) USS Patrick Henry
- (SSBN-600) USS Theodore Roosevelt
- (SSBN-601) USS Robert E. Lee
- (SSBN-602) USS Abraham Lincoln

Thresher/Permit Class Submarine (SSN-593/SSN-594 class)

The Thresher/Permit class of United States Navy nuclear attack submarines were the replacement for the Skipjack class. They were used primarily in the 1960s and 1970s, until replaced by the Sturgeon and Los Angeles classes.

The Thresher/Permit class were the result of a study commissioned in 1956 by the Chief of Naval Operations (CNO), Admiral Arleigh Burke. In "Project Nobska," the Committee on Undersea Warfare of the National Academy of Sciences considered the lessons learned from various prototypes and experimental platforms.

The new class kept the proven S5W reactor plant from the immediately preceding Skipjack's, but were a radical change in many other ways. The Threshers had the large bow-mounted sonar and angled, amidships torpedo tubes pioneered by the Tullibee. Although it used the same HY-80 as the Skipjacks, the Treshers' pressure hulls were made using and improved process that extended test depth to 1,300 ft. The engineering spaces were also redesigned, with the turbines supported on "rafts" that were suspended from the hull on sound damping isolation mounts. Their hulls were more effectively streamlined and had smaller sails, but the increased displacement over the Skipjacks lead to top speed of around 28kts, five knots slower than the Skipjacks.

The ships had torpedo launchers moved to the middle of the hull. This made available the required large space in the bow for the BQQ-2, BQQ-5 in modernized boats, sonar system, a new and powerful detection low-frequency sensor. Initially armed with Mark 37 torpedoes, they later carried the improved Mark 48, the UGM-84 Harpoon (replacing four of the Mk-48s) and the UUM-44 SUBROC (replacing six Mk-48s, four after Harpoon was adopted). The maximum weapons load was 23 torpedoes/missiles or, theoretically 46 Mk-57, 60 or 67 mines. Or a mix of mines, torpedoes and missiles.

The first submarine commissioned in this class was the ill-fated Thresher, and so the class was known by her name. When Thresher was lost, the class took the name of the second ship in the class, Permit, and the SubSafe Program began. SubSafe includes specific training of SubSafe Quality Assurance inspectors in the engine room crew, and tracks extremely detailed information about every component of a submarine's engine room that contacts seawater. In addition, joints in any equipment carrying seawater must be welded (not brazed), and every hull penetration larger than a specified size can be quickly shut by a remote hydraulic mechanism.

The engine room of Jack was lengthened by ten feet to accommodate an experimental direct-drive propulsion system using concentric counter-rotating propellers. Although counter-rotating propellers produced impressive gains in speed on the experimental Albacore, in Jack the results were disappointing because of the difficulty in sealing the shaft. Jack was also used to test polymer ejection that could reduce flow noises that degraded sonar performance.

Flasher, Greenling, and Gato were fitted with heavier machinery and a larger sail, to house additional masts, and made ten feet longer than the other units of the class to more SUBSAFE features, additional reserve buoyancy, more intelligence gathering equipment and improved accommodations.

Ethan Allen Class Submarine (SSBN-608 class)

The Ethan Allen class of fleet ballistic missile submarine was an evolutionary development from the George Washington class. Together with the George Washington, the Lafayette, the James Madison, and the Benjamin Franklin classes, they comprised the "41 for Freedom."

Rather than being designed as Skipjack-class attack submarines with a missile compartment added, the Ethan Allens were designed from scratch as fleet ballistic missile submarines carrying the Polaris A-2 missile. In the early and mid-1970s, they were further upgraded to Polaris A3s. They were unable to be modified to carry the larger diameter Poseidon missile, and were refitted as SSNs (attack submarines), with the missile tubes being filled with concrete and their fire control systems being removed in the early 1980s. Two were further converted to carry SEALs, accommodating 67 troops each. The Ethan Allen class submarines were decommissioned between 1983 and 1992. All have now been broken up.

Submarines of the Ethan Allen class:

- USS Ethan Allen (SSBN-608)
- USS Sam Houston (SSBN-609)
- USS Thomas A. Edison (SSBN-610)
- USS John Marshall (SSBN-611)
- USS Thomas Jefferson (SSBN-618)

Lafayette Class Submarine (SSBN-616 class)

The Lafayette class of submarine was an evolutionary development from the Ethan Allen class of fleet ballistic missile submarine, slightly larger and generally improved. Together with the George Washington, Ethan Allen, James Madison, and Benjamin Franklin classes, they comprised the "41 for Freedom."

The first eight submarines initially deployed with the Polaris A-2 missile, later being refitted with the longer ranged Polaris A-3, with USS Daniel Webster having the A-3 missile from the start. In the mid-1970s they were upgraded to carry the Poseidon C3 missile.

Unlike the similar James Madison and Benjamin Franklin classes, none of the Lafayette class submarines were refitted with Trident missiles. They were decommissioned between 1986 and 1992, with one (USS Daniel Webster) remaining in use as a Moored Training Ship.

Submarines of the Lafayette class:

- USS Lafayette (SSBN-616)
- USS Alexander Hamilton (SSBN-617)
- USS Andrew Jackson (SSBN-619)
- USS John Adams (SSBN-620)
- USS James Monroe (SSBN-622)
- USS Nathan Hale (SSBN-623)
- USS Woodrow Wilson (SSBN-624)
- USS Henry Clay (SSBN-625)
- USS Daniel Webster (SSBN-626)

Figure 39: Lafayette Class Submarine USS Woodrow Wilson

James Madison Class Submarine (SSBN-627 class)

The James Madison class of submarine was an evolutionary development from the Lafayette class of fleet ballistic missile submarine. They were identical to the Lafayettes except for being designed to carry the Polaris A-3 missile instead of the earlier A-2. During the late 1970s and early 1980s, select units were further modified to carry Trident-I (C-4) missiles. Together with the George Washington, the Ethan Allen, the Lafayette, and the Benjamin Franklin classes, they comprised the "41 for Freedom."

Improvements in the James Madison class included the ballistic missile, guidance, fire control, navigation, and launcher systems. The improved missile system introduced was the Polaris A3 missile. The A3 was restricted by size because it had to fit into the existing submarine launch tube. But it was 1.5 inches longer, weighed 4,000 lbs more, and had a 1000 nm longer range, than the A2. Additionally, the number of reentry systems was increased from 1 to 3, making this the first multiple reentry vehicle missile.

The guidance, fire control, and navigation systems were improved to account for the longer range of the A3 missile. The launcher system was improved by replacing the liquid springs on which the launch tube rested with polyurethane foam.

Submarines of the James Madison class:

- (SSBN-627) USS James Madison
- (SSBN-628) USS Tecumseh
- (SSBN-629) USS Daniel Boone
- (SSBN-630) USS John C. Calhoun
- (SSBN-631) USS Ulysses S. Grant
- (SSBN-632) USS Von Steuben
- (SSBN-633) USS Casimir Pulaski
- (SSBN-634) USS Stonewall Jackson
- (SSBN-635) USS Sam Rayburn
- (SSBN-636) USS Nathanael Greene

Benjamin Franklin Class Submarine (SSBN-640 class)

Figure 40: USS Benjamin Franklin (SSBN-640)

The Benjamin Franklin class of submarine was an evolutionary development from the James Madison class of fleet ballistic missile submarine. Having quieter machinery and other improvements, they are considered a separate class. A subset of this class is the re-engineered 640 class starting with USS George C. Marshall (SSBN-654). Together with the George Washington, Ethan Allen, Lafayette, and James Madison classes, they comprised the "41 for Freedom" original 41 fleet ballistic missile submarines.

The Benjamin Franklin-class submarines were built with the Polaris A-3 ballistic missile, and later converted to carry the Poseidon C-3. During the late 1970s and early 1980s, selected units were further modified to carry Trident-I (C-4) ballistic missiles.

Two submarines of this class were converted for delivery of special warfare units ashore. In the early 1990s, to make room for the Ohio-class ballistic missile submarines within the limits set by the SALT II strategic arms limitation treaty, the ballistic missile tubes of USS Kamehameha (SSBN-642) and USS James K. Polk (SSBN-645) were disabled. Those boats were redesignated special operations attack submarines and given attack submarine (SSN) hull numbers.

USS Kamehameha was decommissioned on 2 April 2002, the last ship of the Benjamin Franklin class to be decommissioned.

Sturgeon Class Submarine (SSN-637 class)

The Sturgeon-class (colloquially in Navy circles, the 637 class) attack submarine (SSN) were the "work horses" of the submarine attack fleet throughout much of the Cold War. They were phased out in the 1990s and early 21st century, as their successors, the Los Angeles, followed by the Seawolf and Virginia class boats, entered service.

The Sturgeons were essentially lengthened and improved variants of the Thresher/Permit class that directly preceded them. The biggest difference was the much larger sail, which permitted the return of intelligence gathering masts to U.S. nuclear submarines. The fairwater planes mounted on the sail could rotate 90 degrees, allowing the submarine to surface through thin ice. Because the S5W reactor was used, the same as in the Skipjacks and Thresher/Permits, and the displacement was increased, the Sturgeons' top speed was 26 knots, 2 knots slower than the Thresher/Permits. The last nine Sturgeons were lengthened 10 feet to provide more space for intelligence-gathering equipment and to facilitate the use of dry dock shelters.

They were equipped to carry the Harpoon missile, the Tomahawk cruise missile, and the MK-48 and ADCAP torpedoes. Torpedo tubes were located amidships to accommodate the bow-mounted sonar. The bow covering the sonar sphere was made from poly-carbonate to improve the bow sonar sphere performance though for intelligence gathering missions, the towed-array sonar was normally used as it was much more sensitive array. The sail-mounted dive planes rotate to a vertical position for breaking through the ice when surfacing in Arctic regions.

Beginning with Archerfish, units of this class had a 10-foot (3 meter) longer hull, giving them more living and working space than previous submarines. Parche received an additional 100-foot (30 meter) hull extension containing cable tapping equipment that brought her total length to 401 feet (122 m). A number of the long hull Sturgeon-class SSNs, including Parche, Rivers, and Russell were involved in top-secret reconnaissance missions, including cable tap operations in the Barents and Okhotsk seas.

A total of seven boats were modified to carry the SEAL Dry Deck Shelter (DDS). The DDS is a submersible launch hangar with a hyperbaric chamber attached to the ship's weapon shipping hatch. DDS-equipped boats were tasked with the covert insertion of special forces troops.

USS Parche (SSN-683)

USS Parche (SSN-683), a Sturgeon-class submarine, was the second ship of the United States Navy to be named for the parche, a small, coral reef butterfly fish.

In 1975-76 Parche was in the Mediterranean Sea. In December 1975 the Parche was claimed to be the prize of the Mediterranean for finding something on the Sea floor left over from WWII. The Parche docked in Italy a week late just in time for Christmas.

Parche served as a unit of the United States Atlantic Fleet Submarine Force until 1976 before transferring to the United States Pacific Fleet. Once arriving at her new home port at Mare Island Naval Shipyard in Vallejo, California, Parche received ocean engineering modifications.

Parche successfully tapped into Soviet underwater military communication cables in the Barents Sea in 1979 as part of Operation Ivy Bells.

Parche's research and development duties will be assumed by Jimmy Carter, a Seawolf-class submarine whose construction period was extended to include modifications that will allow her to carry out the same types of research and development. According to Robert Karniol, Jimmy Carter in succeeding Parche has become "Washington's premier spy submarine."

USS Glenard P. Lipscomb (SSN-685)

USS Glenard P. Lipscomb (SSN-685), a unique submarine, was the only ship of the United States Navy to be named for Glenard P. Lipscomb (19 August 1915–1 February 1970), who served as a Congressman from the 24th District of California from 1953 until his death (intestinal cancer) in 1970.

Glenard P. Lipscomb was the Navy's second design using a turbo-electric power plant similar to USS Tullibee (SSN-597). Intended to test the potential advantages of this propulsion system for providing quieter submarine operations, with a displacement of 6,400 tons and a length of 365 feet, it was heavier and larger than similar vessels with conventional drive trains, which resulted in slower speeds. Those disadvantages, along with reliability issues, led to the decision not to use the design for the follow-on Los Angeles-class submarines. Other than the engine room, Glenard P. Lipscomb was generally similar to the Sturgeon-class, and although serving as a test platform, the "Lipscomb Fish" -- her nickname—was a fully combat-capable attack submarine.

Construction of Glenard P. Lipscomb began on 5 June 1971 at the Electric Boat Company shipyard in Groton, Connecticut. Secretary of Defense Melvin R. Laird, a long-time colleague and friend of Glenard Lipscomb, spoke at the keel-laying ceremony and was presented with a model in memory of the event. (Ref Press Release 497-71). Glenard P. Lipscomb was launched on 4 August 1973, sponsored by Mrs. Glenard P. Lipscomb, and was commissioned on 21 December 1974 with Commander James F. Caldwell in command. Speaking at the commissioning was the Secretary of Defense Melvin R. Laird.

Lipscomb was decommissioned and struck from the Naval Vessel Register on 11 July 1990 and disposed of by submarine recycling at Puget Sound Naval Shipyard on 1 December 1997.

Figure 41: USS Glenard P. Lipscomb (SSN-685)

S6G Reactor

The S6G reactor is a naval reactor used by the United States Navy to provide electricity generation and propulsion on warships. The S6G designation stands for:

- S = Submarine platform
- 6 = Sixth generation core designed by the contractor
- G = General Electric was the contracted designer

This nuclear reactor was designed by General Electric for use on the Los Angeles class attack submarines. The S6G reactor plant consists of the reactor coolant, steam generation, and other support systems that supply steam to the engine room. The 688-class engine room also contains the steam turbines that generate electricity and drive the propeller shaft. While exact specifications are classified, the S6G reactor can propel a Los Angeles class submarine at over 15 knots (28 km/h) when surfaced and over 25 knots (46 km/h) while submerged.

Design and operational support for the S6G is provided by Knolls Atomic Power Laboratory (KAPL). The S6G reactor plant was originally designed to use the D1G-2 core, similar to the D2G reactor used on the Bainbridge class guided missile cruiser, which is rated at 148 MW. All Los Angeles class submarines from USS Providence (SSN-719) on were built with a D2W core rated at 165 MW, as opposed to the older 150 MW cores found on older ships. The D1G-2 cores are being replaced with D2W cores when the ships are refueled.

S6W Reactor

The S6W reactor is a naval reactor used by the United States Navy to provide electricity generation and propulsion on warships. The S6W designation stands for:

- S = Submarine platform
- 6 = Sixth generation core designed by the contractor
- W = Westinghouse was the contracted designer

This pressurized water reactor was prototyped in the land-based S8G plant at Knolls Atomic Power Laboratory's Kesselring Site in West Milton, NY starting in March 1994. It has a shaft horsepower of 45,000 shp.

The three ships of the Seawolf class submarine were built with S6W reactors.

S7G Reactor

The S7G reactor was a prototype naval reactor designed for the United States Navy to provide electricity generation and propulsion on warships. The S7G designation stands for:

- S = Submarine platform
- 7 = Seventh generation core designed by the contractor
- G = General Electric was the contracted designer

This prototype design was a land-based nuclear reactor that did not use control rods. It was tested in the late 1970s and early 1980s at the Modifications and Additions to a Reactor Facility (MARF) plant located at the Knolls Atomic Power Laboratory's Kesselring Site in Ballston Spa, New York. It consisted of an experimental reactor core installed in a modified S5W reactor plant.

Instead of the movable hafnium-based control rods used in all of the other United States Naval reactors, reactivity in the S7G core was controlled by stationary gadolinium-clad tubes partially filled with water. Water could be pumped from the portion of the tube inside the core up to a reservoir above the core, or allowed to flow back down into the tube. A higher water level in the tube slowed more neutrons in the core, causing more neutron capture by the gadolinium tube cladding rather than by the uranium fuel, thus lowering the power level.

The system was configured with the pump running continually to keep the water level low; on loss of electrical power, all of the water would flow back into the tube, shutting down the reactor. As with all pressurized water reactors, the design also had the advantage of negative feedback: an increase in reactor power caused the water to expand, leading to reduced thermalization of neutrons and lowering absorption by the fuel, therefore lowering the power. Thus, changes in the average coolant temperature, notably from the steam demand of engine throttles, naturally maintains reactor power without intervention from a reactor operator.

The S7G reactor was never used on a ship, and the prototype was fitted with rods in the late 1980s when the reactor was refueled.

S8G Reactor

The S8G reactor is a naval reactor used by the United States Navy to provide electricity generation and propulsion on warships. The S8G designation stands for:

- S = Submarine platform
- 8 = Eighth generation core designed by the contractor
- G = General Electric was the contracted designer

This nuclear reactor utilizes natural circulation which is capable of operating at a significant fraction of full power without reactor coolant pumps.

The S8G reactor was designed by General Electric for use on the Ohio class (SSGN/SSBN-726 class) submarines. A land-based prototype of the reactor plant was built at Knolls Atomic Power Laboratory's Kesselring Site in West Milton, NY. The prototype was used for testing and crew training throughout the 1980s. In 1994, the core was replaced with an S6W reactor, designed for the then-new Seawolf class submarine.

The prototype is equipped with a high speed reactor fill system that can flood the reactor compartment with borated water in the event of a loss of coolant accident.

S9G Reactor

The S9G reactor is a naval reactor used by the United States Navy to provide electricity generation and propulsion on Virginia class submarines. The S9G designation stands for:

- S = Submarine platform
- 9 = Ninth generation core designed by the contractor
- G = General Electric was the contracted designer

This pressurized water reactor style nuclear reactor, designed by Knolls Atomic Power Laboratory (then managed by General Electric), is designed to have increased energy density, and new plant components, including a new steam generator design featuring improved corrosion resistance and reduced life-cycle costs. This steam generator will alleviate the corrosion concerns encountered in existing designs of steam generators, while reducing component size and weight and providing greater flexibility in overall arrangement.

This reactor is designed to operate for 33 years without refueling.

F. Economic Viability of the Nuclear Navy for US

The Navy recently did a cost analysis of nuclear ships versus conventionally powered ships. Delores Etter on March 1, 2007 said:

[M]edium surface combatants [like cruisers], with their anticipated high-combat system energy demands, th[e] break-even point is between $70 and $225 per barrel [of oil]. This indicates that nuclear power should be considered for near-term applications for those ships.

At the time of that statement, the price of a barrel of crude oil was about $65; oil is currently trading at nearly $100 per barrel. The Navy pegged the cost premium for a nuclear cruiser at between zero to 10 percent with the oil price at $74.15. That premium would obviously be much lower with today's prices. Given that every $10 hike in the price of oil costs the Department of Defense $1.3 billion, policymakers must consider nuclear propulsion for future ships. Furthermore, the Navy's cost comparisons do not even consider the savings that would result from additional volume going through under-utilized shipbuilding infrastructure.

Economies of Scale Savings

Increasing construction of nuclear ships and submarines yields significant cost reductions. For example, increased workloads could save the Navy 5 percent to 9 percent on propulsion plant component costs. Building two Virginia-class submarines annually would result in approximately $200 million in savings per submarine. Adding a nuclear cruiser every two years to the workload would reduce the price of other nuclear ship power plants by about 7 percent.

This equates to savings of approximately $115 million for each aircraft carrier and $35 million for each submarine.

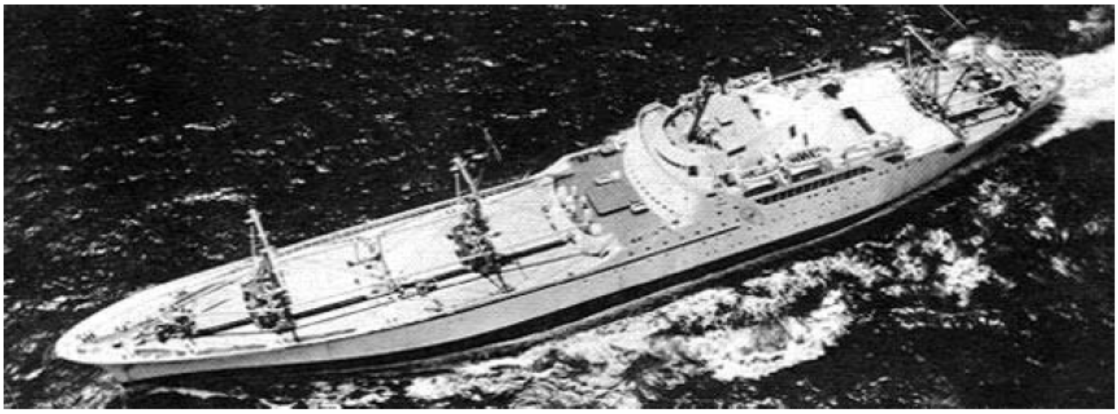
Furthermore, the cost of a nuclear ship includes its life-cycle costs. While nuclear ships can cost more up front, policymakers should consider lifetime costs, which include operations and maintenance, fuel, and decommissioning. Cost-comparison studies have not considered many of the costs unique to fossil-fueled ships, such as the cost of protecting fuel supply lines, which the Navy will protect as primary combat ships or the environmental costs of emissions.

G. Analysis of Commercial Nuclear Ships

Overview

The USA built one single nuclear merchant ship: the Savannah. It was designed as a national showpiece, and not as an economical merchant vessel. For compactness, the steam generators and steam drums surround the reactor core. This configuration also provides shielding for the crew. It was retired in 1970.

Figure 42: The Savannah, the First US Merchant Ship



The 630-A reactor, a low-power critical experiment, was operated at the Idaho National Laboratory (INL) to explore the feasibility of an air-cooled, water-moderated system for nuclear-powered merchant ships. Further development was discontinued in December 1964 when decisions were made to lower the priority of the entire nuclear power merchant ship program.

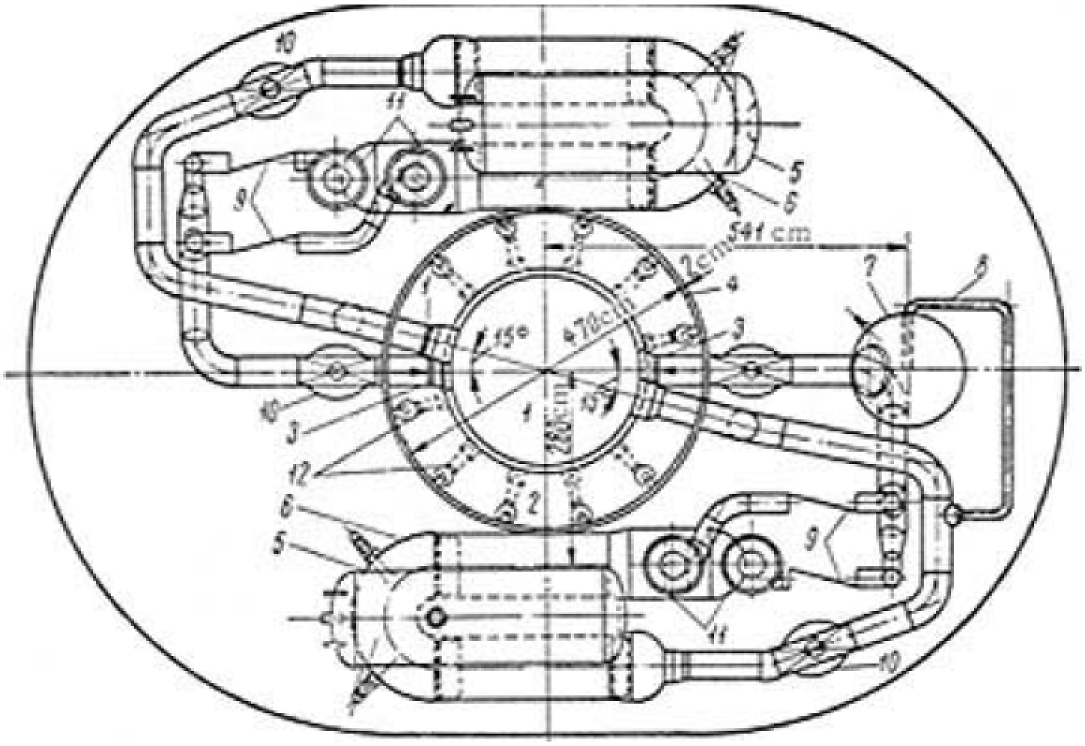
Nuclear Ice Breakers like the Russian Lenin and the Arktica were a good success, not requiring refueling in the arctic regions.

The Otto Hahn bulk ore carrier was built by Germany. It operated successfully for ten years.

The Mutsu was an oceanographic research vessel built in Japan in 1974. Due to a design flaw causing a radiation leakage from its top radiation shield, it never became fully operational.

The Sturgis MH-1A was a floating nuclear power plant ship (Fig. 6). It was carrying a 45 Megawatts Thermal (MWth) Pressurized water Reactor (PWR) for remote power supplies for the USA Army.

Figure 43: Loop Type of Naval Reactor Design for the Nuclear Ship Savannah



The reactor core is surrounded by the heat exchangers and the steam drums. The horizontal steam generator was replaced by a vertical tube steam generator and an integrated system in future designs.

Reactor Designs

The nuclear navy benefited the civilian nuclear power program in several ways. It first demonstrated the feasibility of the Pressurized Water Reactor (PWR) concept, which is being currently used in the majority of land based power reactors. Second, naval reactors accumulated a large number of operational experience hours, leading to improvements in the land based reactors. The highly trained naval operational crews also become of great value to the civilian nuclear utilities providing them with experienced staffs in the operation and management of the land based systems.

Land based reactors differ in many way from naval reactors. The power of land based reactors is in the range of 3,000 MWth or higher. In contrast, a submarine reactor's power is smaller in the range of the hundreds of MWths. Land based systems use uranium fuel enriched to the 3-5 percent range. Highly enriched fuel at the 93-97 percent level is used in naval reactors to provide enough reactivity to override the xenon poison dead time, compactness as well as provide higher fuel burnup and the possibility for a single fuel loading over the useful service time of the powered ship.

The table below shows the composition of highly enriched fuel used in nuclear propulsion as well as space reactor designs such as the SAFE-400 and the HOMER-15 designs. Most of the activity is caused by the presence of U234, which ends up being separated with the U235 component during the enrichment process. This activity is primarily alpha decay and does not account for any appreciable dose. Since the fuel is highly purified and there is no material such as fluorine or oxygen causing any (α, n) reactions in the fuel, the alpha decay of U234 does not cause a neutron or gamma ray dose. If uranium nitride (UN) is used as fuel, the interaction threshold energy of nitrogen is well above the alpha emission energies of U234. Most of the dose prior to operation from the fuel is caused by U235 decay gammas and the spontaneous fission of U238. The total exposure rate is 19.9 [μRöntgen / hr] of which the gamma dose rate contribution is 15.8 and the neutron dose rate is 4.1.

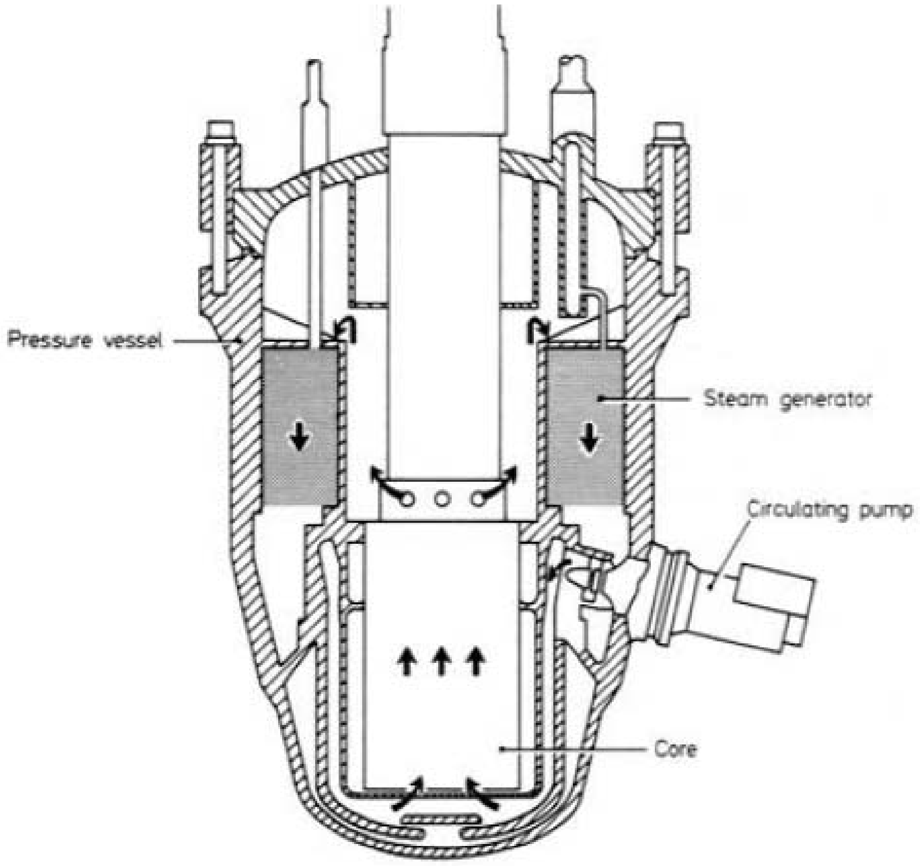
Table 3: Composition of Highly Enriched Fuel for Naval and Space Reactors Designs

Isotope	Composition (percent)	Activity (Curies)	Decay Mode	Exposure Contribution [μR/hr]
U^{234}	0.74	6.1	Alpha decay	unappreciable
U^{235}	97.00		Decay gammas	appreciable
U^{238}	2.259		Spontaneous fissions	appreciable
Pu^{239}	0.001		Alpha decay	unappreciable
Total		6.5		19.9

Reactor operators can wait for a 24 hours period; the reactor dead time, on a land based system for the xenon fission product to decay to a level where they can restart the reactor. A submarine cannot afford to stay dead in the water for a 24 hour period if the reactor is shutdown, necessitating highly enriched fuel. A nuclear submarine has the benefit of the ocean as a heat sink, whereas a land based reactor needs large amounts of water to be available for its safety cooling circuits

For these reasons, even though the same principle of operation is used for naval and land based reactor designs, the actual designs differ substantially. Earlier naval reactors used the loop type circuit for the reactor design as shown in the figure above for the Savannah reactor. There exists a multitude of naval reactor designs. More modern designs use the Integral circuit type.

Figure 44: Integral Type of Naval Reactor Vessel



Because of the weight of the power plant and shielding, the reactor and associated steam generation equipment is located at the center of the ship. Watertight bulkheads isolating the reactor components surround it. The greater part of the system is housed in a steel containment, preventing any leakage of steam to the atmosphere in case of an accident. The containment vessel for the Savannah design consisted of a horizontal cylindrical section of 10.7 meters diameter, and two hemispherical covers. The height of the containment was 15.2 meters. The control rod drives are situated in a cupola of 4.27 m in diameter, on top of the containment. The containment vessel can withstand a pressure of 13 atm. This is the pressure attained in the maximum credible accident, which is postulated as the rupture of the primary loop and the subsequent flashing into steam of the entire coolant volume.

The secondary shielding consists of concrete, lead, and polyethylene and is positioned at the top of the containment. A prestressed concrete wall with a thickness of 122 cm surrounds the lower section of the containment. This wall rests on a steel cushion. The upper section of the secondary shielding is 15.2 cm of lead to absorb gamma radiation, and 15.2 cm of polyethylene to slow down any neutrons. The space between the lead plates is filled with lead wool. The lead used in the shielding is cast by a special method preventing the formation of voids and inhomogeneities.

The polyethylene sheets are spaced so as to allow thermal expansion. Thick collision mats consisting of alternate layers of steel and wood are placed on the sides of the containment. The effective dose rate at the surface of the secondary sheet does not exceed 5 rem/year.

The containment is airtight. Personnel can remain in it for up to 30 minutes after reactor shutdown and the radiation level would have fallen to less than 0.2 rem/hr.

The primary shielding is here made of an annular water tank that surrounds the reactor and a layer of lead attached to the outer surface of the tank, to minimize space. The height of the tank is 5.2 m, the thickness of the water layer, 84 cm, and the thickness of the lead is 5-10 cm.

The weight of the primary shields is 68.2 tons, and with the water it is 118.2 tons. The weight of the containment is 227 tons. The secondary shielding weights 1795 tons consisting of: 561 tons of ordinary concrete, 289 tons of lead, 69 tons of polyethylene, and 160 tons of collision mats. The latter consist of 22 tons of wood and 138 tons of steel.

The shielding complex is optimized to minimize the space used, while providing low radiation doses to the crew quarters. It is comparatively heavy because of the use of lead and steel, and is complicated to install.

Figure 40 above shows a naval reactor of the Integral circuit type. In this case, the design offers a substantial degree of inherent safety since the pumps; the steam generators and reactor core are all contained within the same pressure vessel. Since the primary circulating fluid is contained within the vessel, any leaking fluid would be contained within the vessel in case of an accident. This also eliminates the need for extensive piping to circulate the coolant from the core to the steam generators. In loop type circuits, a possibility exists for pipe rupture or leakage of the primary coolant pipes. This source of accidents is eliminated in an integral type of a reactor.

H. Analysis of Nuclear Navies

Overview

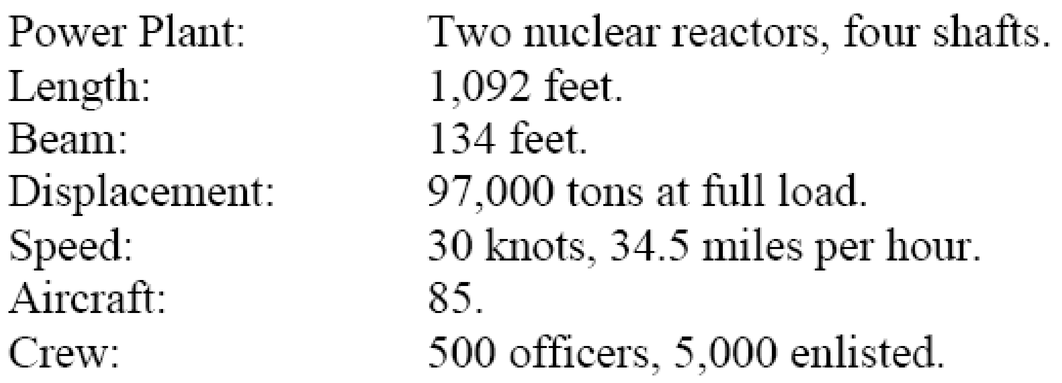
The USA nuclear fleet grew rapidly at the height of the east west cold war in the 1980s. About one fourth of the submarine fleet carried intercontinental ballistic missiles. These can be ejected by the use of compressed air while the submarine is totally submerged, with the rocket engine starting once the missile is above the water surface.

In the Falkland Islands War, a single nuclear British submarine paralyzed the entire Argentina Naval fleet. It sunk the cruiser “General Belgrano” and forced the Argentine Navy to not deploy out of port..

During the first and second the Gulf Wars, the USA Navy had unchallenged use of the oceans and protected 85 percent of the war supplies that were transported by ships.

Navy Carrier Force

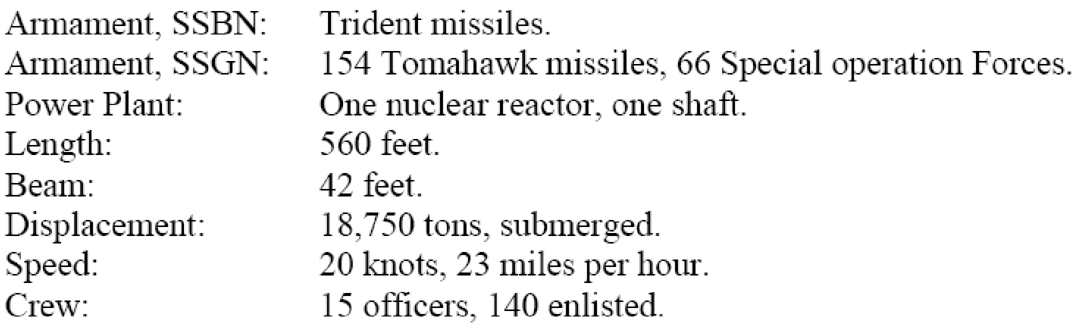
The mission of the aircraft carrier force is to provide a credible, sustainable, independent forward presence and a conventional deterrence in peace times. In times of crisis, it operates as the cornerstone of joint and/or allied maritime expeditionary forces. It operates and support air attacks on enemies, protects friendly forces and engages in sustained independent operations in times of war. The vital statistics of the nuclear Nimitz Class aircraft carrier are:



Power Plant:	Two nuclear reactors, four shafts.
Length:	1,092 feet.
Beam:	134 feet.
Displacement:	97,000 tons at full load.
Speed:	30 knots, 34.5 miles per hour.
Aircraft:	85.
Crew:	500 officers, 5,000 enlisted.

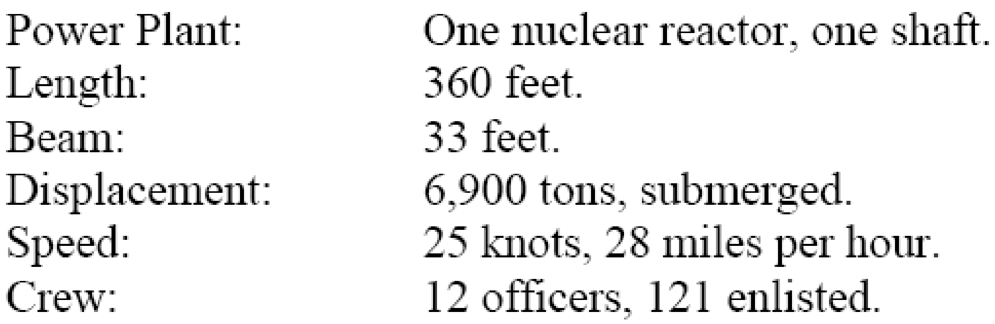
Nuclear Submarine Force

The USA submarine force maintains its position as the world's preeminent submarine force. It incorporates new and innovative technologies allowing it to maintain dominance throughout the naval battle space. It incorporates the multiple capabilities of submarines and develops tactics supporting national objectives through battle space preparation, high seas control, land battle support as well as strategic deterrence. It also fills the role of a stealthy signal and intelligence gathering and a full spectrum of special operations and expeditionary missions. It includes forces of ballistic missiles submarines (SSBN), guided missile submarines (SSGN), and attack submarines (SSN). The vital statistics of the Ballistic Missile Trident submarines and the guided missiles submarines are:



Armament, SSBN:	Trident missiles.
Armament, SSGN:	154 Tomahawk missiles, 66 Special operation Forces.
Power Plant:	One nuclear reactor, one shaft.
Length:	560 feet.
Beam:	42 feet.
Displacement:	18,750 tons, submerged.
Speed:	20 knots, 23 miles per hour.
Crew:	15 officers, 140 enlisted.

The statistics for the fast attack Los Angeles class submarines are:



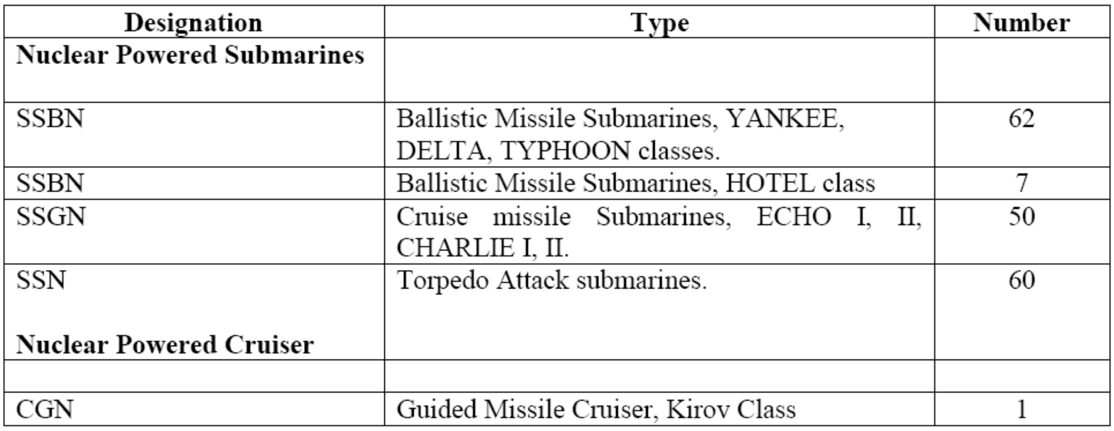
Power Plant:	One nuclear reactor, one shaft.
Length:	360 feet.
Beam:	33 feet.
Displacement:	6,900 tons, submerged.
Speed:	25 knots, 28 miles per hour.
Crew:	12 officers, 121 enlisted.

Figure 45: Christening of a Trident Submarine, with Two Other Submarines in Different Stages of Assembly

Russian Navy

The nuclear Russian navy also reached its peak at the same time as the USA navy. The first of the TYPHOON class 25,000 ton strategic ballistic missile submarines was launched in 1980 from the Severodvinsk Shipyard on the White Sea. In the same year the first OSCAR class guided missile was launched. It is capable of firing 24 long range anti-ship cruise missiles while remaining submerged. Five shipyards produced seven different classes of submarines. The table below shows some of the nuclear powered components of the Russian Navy as it existed then.

Table 4: Principal Components of the Russian Nuclear Navy



Designation	Type	Number
Nuclear Powered Submarines		
SSBN	Ballistic Missile Submarines, YANKEE, DELTA, TYPHOON classes.	62
SSBN	Ballistic Missile Submarines, HOTEL class	7
SSGN	Cruise missile Submarines, ECHO I, II, CHARLIE I, II.	50
SSN **Nuclear Powered Cruiser**	Torpedo Attack submarines.	60
CGN	Guided Missile Cruiser, Kirov Class	1

The Delta IV class is nuclear-powered with two VM-4 pressurized water reactors rated at 180 MWth. There are two turbines, type GT3A-365 rated at 27.5MW. The propulsion system drives two shafts with seven-bladed fixed-pitch propellers.

Chinese Navy

Five hundred years ago the contender for the dominance of the world's oceans was the Chinese imperial exploration fleet which was at its peak technologically centuries ahead of its competitors. A strategic mistake by its emperor was to neglect its sea access with the result of opening the door to European and then Japanese military intervention and occupation. Being the world's second largest importer of petroleum after the USA, China seeks to protect its energy corridors by sea and free access to Southeast Asia sea lanes beyond the Indochinese Peninsula.

China's naval fleet as of 2012 had 5 nuclear powered fast attack submarines and one ballistic missiles submarine carrying 12-16 nuclear tipped missiles with arrange of 3,500 km. This is in addition to 30 diesel electric submarines with 20 other submersibles under construction.

The Chinese submarine fleet is expected to exceed the number of USA's Seventh Fleet ships in the Pacific Ocean by 2020 with the historic patience and ambition to pursue a long term strategy of eventually matching and then surpassing the USA's dominance of the sea.

Nuclear Surface Vessels

Around 1986, the USA's nuclear navy reached the level of 134 nuclear submarines, 9 cruisers, and 4 aircraft carriers. By 2001, the number of nuclear carriers increased to 9, for the Nimitz class of carriers. These aircraft carriers are powered by two nuclear reactors providing propulsion to 4 shafts each. Typically, the power produced is 280,000 Horse Power (HP). Since 1 HP is equal to 745.7 Watts, this corresponds to a power of:

$$280{,}000 \times 745.7 = 208.8 \text{ MWth}$$

Smaller reactors are used in the Enterprise class each of a power of about 26 MWth. With four propulsion plants each consisting of 2 reactors for a total of 8 reactors corresponding to 8 steam boilers the total produced power is about 8 x 26 = 208 MWth. Hafnium is used in the control rods as a neutron absorber. In the newer Nimitz class, reactor sizes are larger at about 105 MWth, all that is needed are two reactors with a total power of 2 x 105 = 210 MWth. The figure below shows the Enterprise nuclear aircraft carrier (CVN-65).

Figure 46: USS Nuclear Powered Aircraft Carrier Enterprise CVN-65, 1998

The crew of the Enterprise is about 5,000 sailors with an average age of 25 years, and its first military operation was in the Cuban missile crisis in 1962. It can top a speed of 30 knots. Its bridge rises six decks above the flight deck. Its flight deck has an area of 4.47 acres.

It is armed with eight air-wing squadrons, Sea Sparrow missiles, and sophisticated intelligence gathering and countermeasures equipment. Its mission is to carry military force within striking range of any point on the planet.

Airplanes land and are catapult launched on two runways. Its air wing has 250 pilots, but thousands of other sailors plan each flight, maintain the planes and move them using massive elevators from the hangar deck to the flight deck. The ship is maneuvered so that the head wind is "sweet" across the deck. Catapults driven with steam from the nuclear reactors fling 30 ton aircraft to full flight in a space shorter than a football field accelerating it from zero to 165 miles/hr in 2 seconds. Carrier pilots have 350 feet of runway to land. They must come at the right angle and position to hook one of the four arresting cables or wires. That will bring the plane to a dead stop. This maneuver has to be completed with engines at full power in case all the four wires are missed, and the plane has to abort the landing.

Figure 47: Nuclear Powered Guided Missile Cruiser, KIROV

Figure 48: Phalanx Radar-Guided Gun

The Russian navy's nuclear powered guided missile cruiser KIROV, shown in Fig. 43, from astern, reveals a superstructure massed with radars and electronic sensors, a stern door for Anti-Submarine Warfare (ASW) sonar, and a Ka-25 HORMONE ASW helicopters deck. The deck is bordered by Gatling guns (figure above) using depleted uranium munitions, short range surface to air missiles and 100 mm dual purpose gun mounts.

Table 5: Principal Components of the USA Nuclear Aircraft Carrier Fleet

Designation	Name	Class
	Enterprise	**Enterprise Class**, 8 reactors, 4 shafts, 1961. 93,000 tons full load displacement, 1,123 feet length, 257 ft flight deck width, 33 knots speed, 70 aircraft
CVN68	Nimitz	Nimitz Class, 2 reactors, 4 shafts, 1975.
CVN69	Dwight D. Eisenhower	97,000 tons full load displacement,
CVN70	Carl Vinson	1.073 feet flight deck width,
CVN71	Theodore Roosevelt	252 ft flight deck width,
CVN72	Abraham Lincoln	32 knots speed,
CVN73	George Washington	70 aircraft.
CVN74	John C. Stennis	
CVN75	Harry S. Truman	
CVN76	Ronald Reagan	
CVN77	George W. H. Bush	

This kind of nuclear powered ship has a displacement of 23,000 tons, larger than any surface combatant other than an aircraft carrier built since World War II. It is meant as a multipurpose command ship capable of providing a battle group with enhanced air defense and surface strike capability. Its primary armament is heavy, highly sophisticated surface to air and long range antiship cruise missiles. It carries 20 long range cruise missiles, and includes 12 vertical launch tubes for surface to air missiles.

The Russian navy has conducted research and experimentation on new types of propulsion concepts. It recognized, for instance the advantages of gas turbines for naval propulsion, and dramatically shifted toward it. Gas turbines offer low weight and volume, in addition to operational flexibility, reduced manning levels, and ease of maintenance. Even though gas turbines have been used in surface vessels, it is not clear whether the Brayton gas turbine cycle has been used instead of the Rankine steam cycle on the nuclear powered ships. They have built fast reactors, and studied the use of less reactive lead and lead-bismuth alloys instead of sodium cooling in them. They may also have considered new propulsion concepts such as dissociating gases and magneto hydrodynamic propulsion.

Nuclear Cruise Missile Submarines

Figure 49: Russian Cruise Missile Submarine Project 949A Orel

The nuclear powered ECHO I and II, and the CHARLIE I and II can fire eight antiship weapons cruise missiles while remaining submerged at a range of up to 100 kilometers from the intended target. These cruise missile submarines also carry ASW and antiship torpedoes.

The nuclear cruise missile submarines are meant to operate within range of air bases on land. Both forces can then launch coordinated attacks against an opponent's naval forces. Reconnaissance aircraft can provide target data for submarine launched missiles.

Nuclear Ballistic Missile Submarines

Submarine Launched Ballistic Missiles (SLBMs) on Nuclear Powered Ballistic Missile Submarines (SSBNs) have been the basis of strategic nuclear forces. Russia had more land based Intercontinental Ballistic Missiles (ICBMs) than the SLBM forces.

The Russian ICBM and SLBM deployment programs initially centered on the SS-9 and SS-11 ICBMs and the SS-N-6/YANKEE SLBM/SSBN weapons systems. They later used the Multiple Independently targetable Reentry Vehicles (MIRVs) SS-N-18 on the DELTA class nuclear submarines, and the SS-NX-20 on the nuclear TYPHOON class SSBN submarine.

The Russian SLBM force has reached 62 submarines carrying 950 modern SLBMs with a total of almost 2,000 nuclear warhead reentry vehicles. Russia deployed 30 nuclear SSBNs, and the 20 tube very large TYPHOON SSBN in the 1980s. These submarines were capable to hit targets across the globe from their homeports.

Figure 50: Nuclear Powered Russian Ballistic Missile Submarine Project 667 DRM

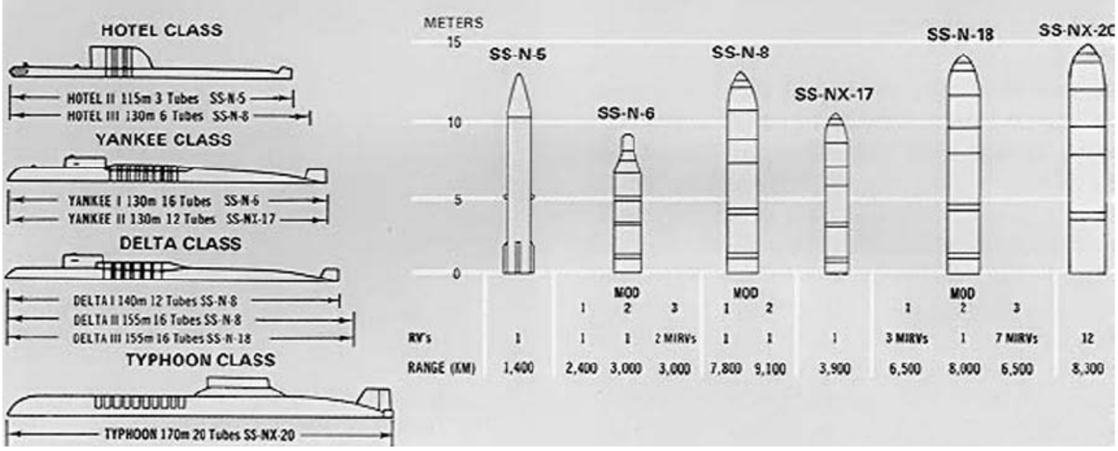
Figure 51: USA Ballistic Missile Nuclear Submarine SSN Ohio

The 34 deployed YANKEE class nuclear submarines each carried 16 nuclear tipped missiles. The SS-N-6/YANKEE I weapon system is composed of the liquid propellant SS-N-6 missile in 16 missile tubes launchers on each submarine. One version of the missiles carries a single Reentry Vehicle (RV) and has an operational range of about 2,400 to 3,000 kilometers. Another version carries 2 RVs, and has an operational range of about 3,000 kilometers.

The DELTA I and II classes of submarines displaced 11,000 tons submerged and have an overall length of about 140 meters. These used the SS-N-8 long range, two stages, liquid propellant on the 12-missile tube DELTA I and the 16 missile tube DELTA II submarines. The SS-N-8 has a range of about 9,000 kilometers and carries one RV. The SS-N-18 was used on the 16 missile tube DELTA III submarines, and has MIRV capability with a booster range of 6,500 to 8,000 kilometers, depending on the payload configuration. The DELTA III nuclear submarines could cover most of the globe from the relative security of their home waters with a range of 7,500 kilometers.

The TYPHOON class at a 25,000 tons displacement, twice the size of the DELTA III with a length of 170 m and 20 tubes carrying the SS-NX-20 missile each with 12 RVs, has even greater range at 8,300 kms, higher payload , better accuracy and more warheads.

Figure 52: Nuclear Ballistic Missile Submarines and their Missiles Characteristics



Nuclear Attack Submarines

At some time the Russian navy operated about 377 submarines, including 180 nuclear powered ones, compared to 115 in the USA navy.

The Russian navy operated 220 attack submarines, 60 of them were nuclear powered. These included designs of the NOVEMBER, ECHO, VICTOR, and ALFA classes.

Figure 53: SSN 23, Jimmy Carter Nuclear Attack Submarine, 2005

Alfa Class Submarines

The ALFA class submarine was the fastest submarine in service in any navy. It was a deep diving, titanium hull submarine with a submerged speed estimated to be over 40 knots. The titanium hull provided strength for deep diving. It also offered a reduced weight advantage leading to higher power to weight ratios resulting in higher accelerations. The higher speed could also be related to some unique propulsion system. The high speeds of Russian attack submarines were meant to counter the advanced propeller cavitation and pump vibration reduction technologies in the USA designs, providing them with silent and stealth hiding and maneuvering.

The alpha class of Russian submarines used a lead and bismuth alloy cooled fast reactors. They suffered corrosion on the reactor components and activation through the formation of the highly toxic Po210 isotope. Refueling needed a steam supply to keep the liquid metal molten above 257°F.

Advantages are a high cycle efficiency and that the core can be allowed to cool into a solid mass with the lead providing adequate radiation shielding. This class of submarines has been decommissioned.

I. Emergence of the All-Electric Propulsion System & Stealth Ships

Industry Overview

Three trends are shaping the future of naval ship technology: the all electrical ship, stealth technology and littoral vessels.

The all-electric ship propulsion concept was adopted from the propulsion system of cruise ships for the future surface combatant power source. It would encompass new weapon systems such as modern electromagnetic rail-guns and lasers under development.

Planned as an all-electric ship is the CVN-21 next-generation USA Navy aircraft carrier, scheduled for launch around 2014, to replace the then half-century-old USS Enterprise CVN 65.

The CVN-21's new nuclear reactor not only will provide three times the electrical output of current carrier power plants, but also will use its integrated power system to run an Electro Magnetic Aircraft Launch System, EMALS to replace the current steam-driven catapults. Combined with an Electromagnetic Aircraft Recovery System, EARS, EMALS will enable the new carrier to conduct high-intensity aircraft launch and recovery operations consistently with minimal recovery or maintenance downtime.

To store large amounts of energy, flywheels, large capacitor banks or other energy storage systems would have to be used.

A typical ship building experience involved the design conversion of one class of submarines to an all-electric design. The electric drive reduced the propulsion drive system size and weight; eliminating the mechanical gearbox. However, the power system required extensive harmonic filtering to eliminate harmonic distortion with the consequence that the overall vessel design length increased by 10 feet.

Tests have been conducted to build stealth surface ships based on the technology developed for the F-117 Nighthawk stealth fighter. The first such system was built by the USA Navy as “The Sea Shadow.”

Figure 54: Sea Shadow Stealth Ship Used Radar Deflecting Technology Used in the F-117 Nighthawk Stealth Fighter

Figure 55: Lockheed-Martin RQ-170 Sentinel Stealth Unmanned Aerial Vehicle (UAV) Drone Known as the Beast of Kandahar

Figure 56: To hide it from satellite imaging, the Sea Shadow stealth ship was moored under the canopy of the "Hughes Miner Barge" that was allegedly used to retrieve a section of a sunken Russian submarine with possibly its code machine and weapons systems

Figure 57: Stealth Radar Deflecting Technology Implemented into a French Lafayette Class Frigate, 2001

Figure 58: DDG-1000 stealth destroyer is optimized for firing land-attack missiles; not Ballistic Missile Defense, BMD missiles. The Raytheon Company builds the DDG-1000's SPY-3 radar, and Bath Iron Works, the Maine shipyard builds the DDG-1000.

The threat from ballistic anti-ship missiles and the potential of nuclear tipped missiles has slowed down the development of stealth surface ships. The USA Navy cut its $5 billion each DDG-1000 stealth destroyer ships from an initially planned seven to two units.

Missile defense emerged as a major naval mission at the same time that the DDG-1000's stealth destroyer design limitations and rising costs converged, all while shipbuilding budgets were getting squeezed.

The SM-3 Standard missile, fired only by warships, is the most successful naval missile defense system; having passed several important trials while other Ballistic Missile Defense, BMD weapons are under testing. The ballistic-missile threat is such that the USA Navy decided it needed 89 ships capable of firing the SM-3 and that the DDG-1000 realistically would never be able to fire and guide the SM-3 since the stealth destroyer is optimized for firing land-attack missiles not Standard missiles.

The USA Navy has 84 large surface combatants, split between Arleigh-Burke Class destroyers and the Ticonderoga Class cruisers, capable of carrying the combination of Standard missiles and the BMD capable Aegis radar. The DDG-1000 cannot affordably be modified to fire SM-3s. So the Navy needs another 12 SM-3 “shooters” to meet the requirement for missile defense, and there was no time to wait for the future CG-X cruiser. With new amphibious ships, submarines, carriers and Littoral Combat Ships in production alongside the DDG-1000s, there was no room in the budget for five extra DDG-1000s.

Littoral Combat Ship

Littoral Combat Ships are designed to operate closer to the coastlines than existing vessels such as destroyers. Their mission is signal intelligence gathering, insertion of special forces, mine clearance, submarine hunting and humanitarian relief. New missions involve pirates and drug smuggling interdiction.

The two firms Austal and Lockheed-Martin are to build 10 LCS apiece through 2015, each using their own distinct design. The cost per ship is $450 million, at least $200 million below the cost of each of four built prototypes.

The Lockheed-Martin’s version has in its USS Freedom prototype the largest marine gas turbines in the world; essentially the engines of a Boeing 777 jetliner. The turbines’ 100,000 horsepower can propel the LCS at up to 50 knots, compared to 30 for most warships. That high speed would use up a fuel supply in half a day.

The high speed could help the LCS respond better to pirate attacks and assaults by small fast boats. However, an extra 20 knots are not likely to make much difference against supersonic anti-ship missiles.

The 20 LCS ships would help the USA Navy reverse the slow decline of its 280-strong fleet. After retiring many of its minesweepers, patrol boats and frigates, the Navy does not have is enough low-end warships for all the mundane work of a busy, globally deployed military. The LCS can help correct that imbalance. This at a time when the USA Navy is not involved in at-sea combat, and instead spends much of its time in pirates and smuggler “other-than-war” tasks. In these cases, speed and sheer numbers of vessels o matter.

The LCS includes a large hangar for carrying Marine troops, manned helicopters, aerial drones and surface-skimming robots.

An ocean-going robot quiet sonar-equipped submarine chaser could come into service aboard the LCS.

Figure 59: Trimaran Littoral Combat Ship

Anti-Submarine Warfare, ASW Continuous Trail Unmanned Vessel Program

As new submarine classes achieve ever increasing levels of acoustic quieting and operational performance, tracking submarines has become more difficult. Some modern diesel-electric submarines are able to challenge conventional tracking approaches, risking future USA capability in the undersea battle-space. This creates the incentive for the Anti-Submarine Warfare, ASW Continuous Trail Unmanned Vessel, ACTUV program.

The ACTUV concept is based on an independently deployed unmanned naval vessel optimized for continuous trail of quiet submarines. It would be a clean sheet unmanned ship design with no person stepping aboard at any point in its operating cycle and enable a unique architecture for robust platform performance across a range of conventional and non-conventional.

The program seeks to advance autonomous operations technology with a goal of full compliance with safe navigation requirements while executing its tactical mission under a sparse remote supervisory control model.

It will leverage its unique characteristics to employ a novel suite of sensors capable of robustly tracking quiet diesel electric submarines to deliver a game changing operational capability.

Six contractor teams will support the development of concept designs for the ACTUV system: Northrop Grumman Undersea Systems, based in Annapolis, Maryland; Science Applications International Corp (SAIC) Intelligence, Security, and Technology Group, based in Long Beach, Mississippi.; Qinetiq North America Technology Solutions Group, based in Waltham, Massachusetts, the University of Washington Applied Physics Laboratory, in Seattle, Washington for testing of high frequency active sonar for acquisition and tracking of submarine targets; Spatial Integrated Systems, based in Kinston, North Carolina, for development and at-sea demonstration of unmanned surface vessel autonomous algorithms for submarine tracking and Rules of the Road compliance; and Sonalysts based in Waterbury, Connecticut., for development of an exploratory crowd-sourced tactics simulator.

Free Electron Lasers

The Free Electron laser is contemplated as a directed energy weapon system that can replace the radar-guided Phalanx gun used for close-in ship defense and used against rocket and mortar attacks.

Lasers require a medium to turn light into a directed energy beam. Solid state lasers use crystals. Chemical lasers use gaseous media. These two types generate the lasers at a specific wave length. The chemical lasers use toxic chemical reactants such as ethylene and nitrogen trifluoride.

Free Electron Lasers (FELs) do not need a gain medium and use a stream of energetic electrons to generate variable wave length lasers. An FEL system can adjust its wavelength for a variety of task and to cope with different environmental conditions. It can also run from a vessel’s electrical power supply rather than its own, and does not need to stop and reload. Such a system for naval vessel needs to have a power of 100 kW. More than that would be needed to counter anti-ship ballistic missiles.

The tunable laser is a desirable feature since particles in the sea air like condensation can reduce the effectiveness of a defined wavelength laser. The Free Electron laser can fire can fire at different points along the spectrum picking out the frequency that would penetrate the moist air.

The FEL is composed of a relativistic electron tube that uses an oscillator and an open optical resonator running at 10 percent efficiency. An electron beam is injected into a high gain amplifier series of alternating magnets called a “wiggler.” In the wiggler, the electron beam bends or wiggles back and forth undergoing acceleration and emitting coherent laser radiation.

It can be used for multiple uses, for instance as a sensor for detection and tracking when it is not used to hit an incoming missile. It could also be used for location, time-of-flight location, information exchange, communications, for target location and for disruption of radar and communications.

Electrical generators planned in the all-electric fleet can have a capacity of about 2 MW of power, and can easily provide the future MW level of power to the FEL, particularly if more than one generator is installed on a given ship.

Electromagnetic Rail Gun

A 32 MJ rail gun can generate a projectile travelling 10 nautical miles in 6 minutes. A 64 MJ gun the projectile would travel 200 miles in six minutes.

A rail gun powered from a ship’s electrical supply can shoot 20 rocket propelled artillery shells in less than a minute on targets 63 nautical miles away. Two rail guns would have the firepower of a 640 persons artillery battalion.

A plasma armature method of propulsion is used where a plasma arc is generated behind the metallic projectile along copper rails.

The rounds would travel at 6 km/sec. This means that the rounds fired per ship would increase from 232 to 5,000. These inert rounds also travel at around Mach 7, carrying a large amount of kinetic energy at double the energy of conventional explosive shells. The force of the projectile hitting a target have been compared to hitting a target with a medium size car at 380 mph. They would also travel farther to 200-300 nautical miles.

Each projectile would cost about $1,000, whereas a cruise missile would cost about $1,000,000. A ship can have thousands of the small projectiles stored on board instead of just about 100 cruise missiles.

The key technology hurdle is the development of an intermediate energy storage system that can release the power as needed. From a pulse-capacitor storage approach, those systems exist today. Ships, by the very nature of their size, have the amount of energy available and those will be seen there long before they are seen on aircraft or tanks or wheeled vehicles, because of the power availability.

For a rail-gun system, the capacitors can be charged for several seconds, then discharged in milliseconds. Achieving those levels of power in a system small enough to fit on a ship requires high energy densities. Volumetric energy densities of 4 joules/cm3 were achieved during the 1980s; and capacitors storing 40,000 joules were built.

Higher densities in smaller scales, on the order of 5.8 joules/cm3 are currently achievable with a goal of 8 joules/cm3 that is approaching a level where a rail gun can be installed on a tank.

High Powered Microwave Directed Beams

A “defense-suppression mission” involves taking out air defenses, radars, missile launchers and command centers. It can be achieved by degrading, damaging or frying their electronics using directed microwave beams.

Directed energy microwave weapons have been successfully used to destroy buried Improvised Explosive Devices (IEDs) in Iraq.

Cryogenic technology can be used to develop a high-power microwave active denial system. This allows the setting up of an electric fence around an area to prevent people from entering it.

For a ship at sea, a perimeter can be set around the ship. It would be designed to be non-lethal heating up the skin up very fast and would force an intruder to turn away. The primary interest in the USA Navy is for protecting shore facilities."

Multipurpose Floating Barges

The vision of floating barges with nuclear reactors to produce electrical power for industrial and municipal use, hydrogen for fuel cells, as well as fresh desalinated water at the shores of arid areas of the world may become promising future prospects. The electricity can be used to power a new generation of transportation vehicles equipped with storage batteries, or the hydrogen can be used in fuel cells vehicles.

An urban legend is related about a USA Navy nuclear submarine under maintenance at Groton, Connecticut, temporarily supplying the neighboring port facilities with electricity when an unexpected power outage occurred.

Figure 60: Multi-Purpose Military Barge Concept

This would have required the conversion, of the 120 Volts and 400 Hz military electricity standard to the 10-12 kV and 60 Hz civilian one. Submarines tied up at port connect to a connection network that matches frequency and voltage so that the reactors can be shut down. The two electrical generators on a typical submarine would provide about 3 MWe x 2 = 6 MWe of power, with some of this power used by the submarine itself. In case of a loss of local power, docked vessels have to start their reactors or their emergency diesel generators anyway.

Antisubmarine Warfare

Submarines are vulnerable to deep underwater nuclear explosions. Anti-Submarine Warfare (ASW) uses conventional torpedoes as well as nuclear devices. The Wigwam nuclear underwater test was conducted on May 15, 1955. It used an underwater 30 kT TNT-equivalent charge. It took place 450 miles SW of San Diego, California in the open ocean. The device had to be reinforced for operation at the large pressures encountered at great water depth. It was a large 8,250 lbs (5,700 lbs when submerged) B7 Betty depth charge suspended with 2,000 feet cable from a floating barge. A shock wave resulted with the fireball rising to the water surface.

Figure 61: Wigwam B3 Betty Nuclear Depth Charge Test in Open Water off San Diego, California, May 15, 1955

Figure 62: Nuclear B57 Depth Charge Anti-Submarine Warfare (ASW) Device

A navy Lockheed S3 carrier-based aircraft was used as a delivery vehicle for both conventional torpedoes and nuclear charges. It was used as aircraft carrier ASW defense. It was equipped with a surface search radar and could drop sono-buoys submarines listening devices.

Figure 63: Navy Lockheed S3 ASW Aircraft has been Withdrawn from Service

A side effect of underwater shock waves is the oceanographic effect of bottom bounce. In this case, a sound wave would be reflected or refracted from water layers of different salinities or temperatures. It could be reflected back from the ocean's bottom and can divert uncontrolled substantial amounts of energy miles away on subsurface and surface floating structures.

J. Analysis of Nuclear-powered Ships

Industry Overview

Work on nuclear marine propulsion started in the 1940s, and the first test reactor started up in USA in 1953. The first nuclear-powered submarine, USS Nautilus, put to sea in 1955.

This marked the transition of submarines from slow underwater vessels to warships capable of sustaining 20-25 knots submerged for weeks on end. The submarine had come into its own.

Nautilus led to the parallel development of further (Skate-class) submarines, powered by single pressurized water reactors, and an aircraft carrier, USS Enterprise, powered by eight reactor units in 1960. A cruiser, USS Long Beach, followed in 1961 and was powered by two of these early units. Remarkably, the Enterprise remains in service.

By 1962 the US Navy had 26 nuclear submarines operational and 30 under construction. Nuclear power had revolutionized the Navy.

The technology was shared with Britain, while French, Russian and Chinese developments proceeded separately.

After the Skate-class vessels, reactor development proceeded and in the USA a single series of standardized designs was built by both Westinghouse and GE, one reactor powering each vessel. Rolls Royce built similar units for Royal Navy submarines and then developed the design further to the PWR-2.

Russia developed both PWR and lead-bismuth cooled reactor designs, the latter not persisting. Eventually four generations of submarine PWRs were utilized, the last entering service in 1995 in the Severodvinsk class.

The largest submarines are the 26,500 ton Russian Typhoon-class, powered by twin 190 MWt PWR reactors, though these were superseded by the 24,000 t Oscar-II class (e.g. Kursk) with the same power plant.

The safety record of the US nuclear navy is excellent, this being attributed to a high level of standardization in naval power plants and their maintenance, and the high quality of the Navy's training program. However, early Soviet endeavors resulted in a number of serious accidents - five where the reactor was irreparably damaged, and more resulting in radiation leaks. However, by Russia's third generation of marine PWRs in the late 1970s safety and reliability had become a high priority.

Lloyd's Register shows about 200 nuclear reactors at sea, and that some 700 have been used at sea since the 1950s.

Nuclear Naval Fleets

Russia built 248 nuclear submarines and five naval surface vessels (plus 9 icebreakers) powered by 468 reactors between 1950 and 2003, and was then operating about 60 nuclear naval vessels.

At the end of the Cold War, in 1989, there were over 400 nuclear-powered submarines operational or being built. At least 300 of these submarines have now been scrapped and some on order cancelled, due to weapons reduction programs*. Russia and USA had over one hundred each in service, with UK and France less than twenty each and China six. The total today is understood to be about 130, including new ones commissioned.

** In 2007 Russia had about 40 retired subs from its Pacific fleet alone awaiting scrapping. In November 2008 it was reported that Russia intended to scrap all decommissioned nuclear submarines by 2012, the total being more than 200 of the 250 built to date. Most Northern Fleet submarines had been dismantled at Severodvinsk, and most remaining to be scrapped were with the Pacific Fleet.*

India launched its first submarine in 2009, the 6000 dwt Arihant SSBN, with a single 85 MW PWR driving a 70 MW steam turbine. It is reported to have cost US$ 2.9 billion, and several more are planned. India is also leasing an almost-new 7900 dwt (12,770 ton submerged) Russian Akula-II class nuclear attack submarine for ten years from 2010, at a cost of US$ 650 million: the Chakra, formerly Nerpa. It has a single 190 MWt VM-5/ OK-650 PWR driving a 32 MW steam turbine and two 2 MWe turbogenerators.

The USA has the main navy with nuclear-powered aircraft carriers, while both it and Russia have had nuclear-powered cruisers (USA: 9, Russia 4). The USA had built 219 nuclear-powered vessels to mid-2011, and then had five submarines and an aircraft carrier under construction. All US aircraft carriers and submarines are nuclear-powered.

The US Navy has accumulated over 6200 reactor-years of accident-free experience over the course of 230 million kilometers, and operated 82 nuclear-powered ships (11 aircraft carriers, 71 submarines - 18 SSBN/SSGN, 53 SSN) with 103 reactors as of March 2012.

The Russian Navy has logged over 6000 nautical reactor-years. It appears to have eight strategic submarines (SSBN/SSGN) in operation and 13 nuclear-powered attack submarines (SSN), plus some diesel subs. Russia has announced that it will build eight new nuclear SSBN submarines in its plan to 2015. It's only nuclear-powered carrier project was cancelled in 1992. It has one nuclear-powered cruiser in operation and three others being overhauled.

France has a nuclear-powered aircraft carrier and ten nuclear submarines (4 SSBN, 6 Rubis class SSN). The UK has 12 submarines, all nuclear powered (4 SSBN, 8 SSN). China is understood to have about ten nuclear submarines (possibly 3 SSBN, 7 SSN).

Nuclear Civil Vehicles

Nuclear propulsion has proven technically and economically essential in the Russian Arctic where operating conditions are beyond the capability of conventional icebreakers. The power levels required for breaking ice up to 3 meters thick, coupled with refueling difficulties for other types of vessels, are significant factors. The nuclear fleet, with six nuclear icebreakers and a nuclear freighter, has increased Arctic navigation from 2 to 10 months per year, and in the Western Arctic, to year-round.

The icebreaker Lenin was the world's first nuclear-powered surface vessel (20,000 dwt), commissioned in 1959. It remained in service for 30 years to 1989, being retired due to the hull being worn thin from ice friction. It initially had three 90 MWt OK-150 reactors, but these were badly damaged during refueling in 1965 and 1967. In 1970 they were replaced by two 171 MWt OK-900 reactors providing steam for turbines which generated electricity to deliver 34 MW at the propellers.

It led to a series of larger icebreakers, the six 23,500 dwt Arktika-class, launched from 1975. These powerful vessels have two 171 MWt OK-900 reactors delivering 54 MW at the propellers and are used in deep Arctic waters. The Arktika was the first surface vessel to reach the North Pole, in 1977. Rossija, Sovetskiy Soyuz and Yamal were in service towards the end of 2008, with Sibir decommissioned and Arktika retired in October 2008.

The seventh and largest Arktika class icebreaker - 50 Years of Victory (50 Let Pobedy) - was built by the Baltic shipyard at St Petersburg and after delays during construction it entered service in 2007 (twelve years later than the 50-year anniversary of 1945 it was to commemorate). It is 25,800 dwt, 160 m long and 20m wide, and is designed to break through ice up to 2.8 meters thick. Its performance in service has been impressive.

For use in shallow waters such as estuaries and rivers, two shallow-draft Taymyr-class icebreakers of 18,260 dwt with one reactor delivering 35 MW were built in Finland and then fitted with their nuclear steam supply system in Russia. They are built to conform with international safety standards for nuclear vessels and were launched from 1989.

Development of nuclear merchant ships began in the 1950s but on the whole has not been commercially successful. The 22,000 ton US-built NS Savannah, was commissioned in 1962 and decommissioned eight years later. It was a technical success, but not economically viable. It had a 74 MWt reactor delivering 16.4 MW to the propeller. The German-built 15,000 ton Otto Hahn cargo ship and research facility sailed some 650,000 nautical miles on 126 voyages in 10 years without any technical problems. It had a 36 MWt reactor delivering 8 MW to the propeller. However, it proved too expensive to operate and in 1982 it was converted to diesel.

The 8000 ton Japanese Mutsu was the third civil vessel, put into service in 1970. It had a 36 MWt reactor delivering 8 MW to the propeller. It was dogged by technical and political problems and was an embarrassing failure. These three vessels used reactors with low-enriched uranium fuel (3.7 - 4.4% U-235).

In 1988 the NS Sevmorput was commissioned in Russia, mainly to serve northern Siberian ports. It is a 61,900 ton 260 m long LASH-carrier (taking lighters to ports with shallow water) and container ship with ice-breaking bow. It is powered by the same KLT-40 reactor as used in larger icebreakers, delivering 32.5 propeller MW from the 135 MWt reactor, and it needed refueling only once to 2003.

A more powerful Russian icebreaker of 110 MW net and 55,600 dwt is planned, with further dual-draught ones of 32,400 dwt and 60 MW power at propellers. The first of these third-generation icebreakers is expected to be finished in 2015 at a cost of RUB 17 billion.

Russian experience with nuclear powered Arctic ships totals about 300 reactor-years in 2012. In 2008 the Arctic fleet was transferred from the Murmansk Shipping Company under the Ministry of Transport to Atomflot, under Rosatom.

In August 200 1two Arktika-class icebreakers escorted the 100,000 dwt tanker Baltika, carrying 70,000 tons of gas condensate, from Murmansk to China via the Arctic route, saving some 8000 km compared with the Suez Canal route. There are plans to ship iron ore and base metals on the northern sea route also.

Nuclear Propulsion Systems

Naval reactors (with the exception of the ill-fated Russian Alfa class described below) have been pressurized water types, which differ from commercial reactors producing electricity in that:

- They deliver a lot of power from a very small volume and therefore run on highly-enriched uranium (>20% U-235, originally c 97% but apparently now 93% in latest US submarines, c 20-25% in some western vessels, 20% in the first and second generation Russian reactors (1957-81)*, then 45% in 3rd generation Russian units, 40% in India's Arihant).

- The fuel is not UO2 but a uranium-zirconium or uranium-aluminum alloy (c15%U with 93% enrichment, or more U with less - e.g. 20% - U-235) or a metal-ceramic (Kursk: U-Al zoned 20-45% enriched, clad in zircaloy, with c 200kg U-235 in each 200 MW core),

- They have long core lives, so that refueling is needed only after 10 or more years, and new cores are designed to last 50 years in carriers and 30-40 years (over 1.5 million kilometers) in most submarines,

- The design enables a compact pressure vessel while maintaining safety. The Sevmorput pressure vessel for a relatively large marine reactor is 4.6 m high and 1.8 m diameter, enclosing a core 1 m high and 1.2 m diameter.

- Thermal efficiency is less than in civil nuclear power plants due to the need for flexible power output, and space constraints for the steam system,

- There is no soluble boron used in naval reactors (at least US ones).

** An IAEA Tecdoc reports discharge assay of early submarine used fuel reprocessed at Mayak being 17% U-235.*

The long core life is enabled by the relatively high enrichment of the uranium and by incorporating a "burnable poison" such as gadolinium - which is progressively depleted as fission products and actinides accumulate. These accumulating poisons would normally cause reduced fuel efficiency, but the two effects cancel one another out.

However, the enrichment level for newer French naval fuel has been dropped to 7.5% U-235, the fuel being known as 'caramel', which needs to be changed every ten years or so. This avoids the need for a specific military enrichment line, and some reactors will be smaller versions of those on the Charles de Gaulle. In 2006 the Defense Ministry announced that Barracuda class subs would use fuel with "civilian enrichment, identical to that of EdF power plants," which may be an exaggeration but certainly marks a major change there.

Long-term integrity of the compact reactor pressure vessel is maintained by providing an internal neutron shield. (This is in contrast to early Soviet civil PWR designs where embrittlement occurs due to neutron bombardment of a very narrow pressure vessel.)

The Russian, US, and British navies rely on steam turbine propulsion, the French and Chinese in submarines use the turbine to generate electricity for propulsion.

Russian ballistic missile submarines as well as all surface ships since the Enterprise are powered by two reactors. Other submarines (except some Russian attack subs) are powered by one. A new Russian test-bed submarine is diesel-powered but has a very small nuclear reactor for auxiliary power.

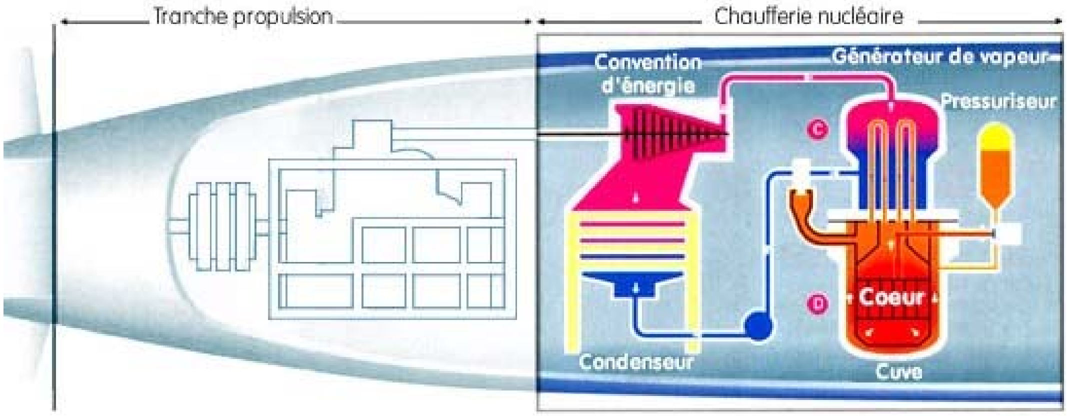
The Russian Alfa-class submarines had a single liquid metal cooled reactor (LMR) of 155 MWt and using very highly enriched uranium - 90% enriched U-Be fuel. These were very fast, but had operational problems in ensuring that the lead-bismuth coolant did not freeze when the reactor was shut down. The design was unsuccessful and used in only eight trouble-plagued vessels.

The US Navy's second nuclear submarine had a sodium-cooled power plant (S2G). The USS Seawolf, SSN-575, operated for nearly two years 1957-58 with this. The intermediate-spectrum reactor raised its incoming coolant temperature over ten times as much as the Nautilus' water-cooled plant, providing superheated steam, and it offered an outlet temperature of 454°C, compared with the Nautilus’ 305°C. It was highly efficient, but offsetting this, the plant had serious operational disadvantages. Large electric heaters were required to keep the plant warm when the reactor was down to avoid the sodium freezing. The biggest problem was that the sodium became highly radioactive, with a half-life of 15 hours, so that the whole reactor system had to be more heavily shielded than a water-cooled plant, and the reactor compartment couldn’t be entered for many days after shutdown. The reactor was replaced with a PWR type (S2Wa) similar to Nautilus.

Reactor power ranges from 10 MWt (in a prototype) up to 200 MWt in the larger submarines and 300 MWt in surface ships such as the Kirov-class battle cruisers.

The smallest nuclear submarines are the French Rubis-class attack subs (2600 dwt) in service since 1983, and these have a 48 MW integrated PWR reactor from Technicatome which is variously reported as needing no refueling for 30 years, or requiring refueling every seven years. The French aircraft carrier Charles de Gaulle (38,000 dwt), commissioned in 2000, has two K15 integrated PWR units driving 61 MW Alstom turbines and the system can provide 5 years running at 25 knots before refueling. The Le Triomphant class of ballistic missile submarines (12,640 dwt - the last launched in 2008) uses these K15 naval PWRs of 150 MWt and 32 shaft MW. The Barracuda class (4765 dwt) attack submarines, will have hybrid propulsion: electric for normal use and pump-jet for higher speeds. Areva TA (formerly Technicatome) will provide six reactors apparently of only 50 MWt and based on the K15 for the Barracuda submarines, the first to be commissioned in 2017. As noted above, they will use low-enriched fuel.

Figure 64: French Integrated PWR System for Submarine



(steam generator within reactor pressure vessel)

British Vanguard class ballistic missile submarines of 15,800 t have a single PWR2 reactor with two steam turbines driving a single pump jet of 20.5 MW. New versions of this with "Core H" will require no refueling over the life of the vessel*. UK Astute class attack subs of 7800t have a modified PWR2 reactor driving two steam turbines and a single pump jet variously reported as 11.5 or 20.5 MW, and have been commissioned since 2010. Russia's 19,400 ton Oscar-II class has two 190 MWt reactors with steam turbines delivering 73 MW, and its 12,700 ton Akula-II class has a single 190 MWt unit powering a 32 MW steam turbine.

**Rolls Royce claims that the Core H PWR2 has six times the (undisclosed) power of its original PWR1 and runs four times as long. The Core H is Rolls Royce's sixth-generation submarine reactor core.*

Russia's large Arktika class icebreakers use two OK-900A (essentially KLT-40) nuclear reactors of 171 MW each with 241 or 274 fuel assemblies of 45-75% enriched fuel and 3-4 year refueling interval. They drive steam turbines and each produces up to 33 MW at the propellers, though overall power is 54 MW. The two Tamyr class icebreakers have a single 171 MW KLT-40 reactor giving 35 MW propulsive power. Sevmorput uses one 135 MW KLT-40 unit producing 32.5 MW propulsive, and all those use 90% enriched fuel. (The now-retired Lenin's first OK-150 reactors used 5% enriched fuel but were replaced by OK-900 units with 45-75% enriched fuel.) Most of the Arktika-class vessels have had operating life extensions based on engineering knowledge built up from experience with Arktika itself. It was originally designed for 100,000 hours of reactor life, but this was extended first to 150,000 hours, then to 175,000 hours.

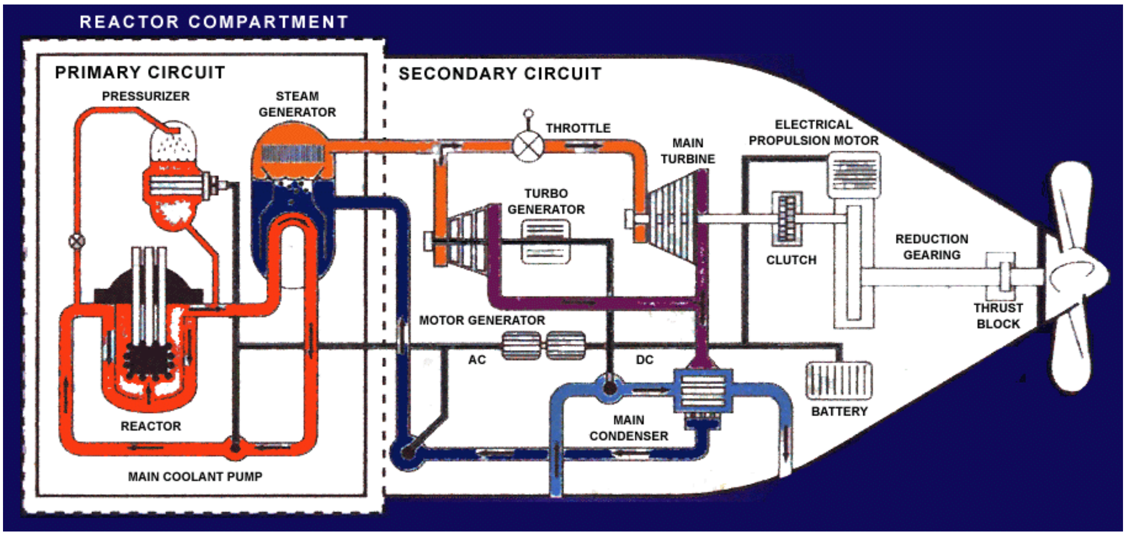
In practice this equated to a lifespan of eight extra years of operation on top of the design period of 25. In that time, Arkitka covered more than 1 million nautical miles.

For the next generation of Russian icebreakers, integrated light water reactor designs are being investigated possibly to replace the conventional PWR. OKBM Afrikantov is developing a new icebreaker reactor – RITM-200 – to replace the current KLT reactors. This is an integral 210 MWt, 55 MWe PWR with inherent safety features. The first icebreaker to be equipped with this is due to start construction in 2010. For floating nuclear power plants (see below) a single RITM-200 would replace twin KLT-40S (but yield less power).

India's Arihant (6000 dwt) has an 85 MWe PWR using 40% enriched uranium driving a 35 MW steam turbine.

Brazil's navy is proposing to build an 11 MW prototype reactor by 2014 to operate for about eight years, with a view to a full-sized version using low-enriched uranium being in a submarine to be launched in 2021.

Figure 65: UK Nuclear Submarine Layout



Dismantling decommissioned nuclear-powered submarines has become a major task for US and Russian navies. After defueling, normal practice is to cut the reactor section from the vessel for disposal in shallow land burial as low-level waste (the rest being recycled normally). In Russia the whole vessels, or the sealed reactor sections, sometimes remain stored afloat indefinitely, though western-funded programs are addressing this and all decommissioned submarines were dismantled by 2012.

Floating Nuclear Power Plants

A marine reactor was used to supply power (1.5 MWe) to a US Antarctic base for ten years to 1972, testing the feasibility of such air-portable units for remote locations.

Between 1967 and 1976 an ex-army US Liberty ship of about 12,000 tons built in 1945, the Sturgis (but renamed SS Green Port) functioned as a Floating Nuclear Power Plant, designation MH-1A, moored on Gatun Lake, Panama Canal Zone. It had a 45 MWt/ 10 MWe (net) PWR which provided power to the Canal Zone.

Russia has under construction at St Petersburg the first of a series of floating power plants for their northern and far eastern territories. Two OKBM KLT-40S reactors derived from those in icebreakers, but with low-enriched fuel (less than 20% U-235), are mounted on a 21,500 ton, 144 m long barge. Refueling interval is 3-4 years on site, and at the end of a 12-year operating cycle the whole plant is returned to a shipyard for a 2-year overhaul and storage of used fuel, before being returned to service.

Future Perspective

With increasing attention being given to greenhouse gas emissions arising from burning fossil fuels for international air and marine transport and the excellent safety record of nuclear powered ships, it is quite conceivable that renewed attention will be given to marine nuclear powered ships, it is likely that there will be renewed interest in marine nuclear propulsion.

The head of the large Chinese shipping company Cosco suggested in December 2009 that container ships should be powered by nuclear reactors in order to reduce greenhouse gas emissions from shipping. He said that Cosco is in talks with China's nuclear authority to develop nuclear powered freight vessels.

In 2010 Babcock International's marine division completed a study on developing a nuclear-powered LNG tanker. The study indicated that particular routes and cargoes lent themselves well to the nuclear propulsion option, and that technological advances in reactor design and manufacture had made the option more appealing.

In November 2010 the British Maritime classification society Lloyd's Register embarked upon a two-year study with US-based Hyperion Power Generation, British vessel designer BMT Group, and Greek ship operator Enterprises Shipping and Trading SA "to investigate the practical maritime applications for small modular reactors. The research is intended to produce a concept tanker-ship design," based on a 70 MWt reactor such as Hyperion's. Hyperion has a three-year contract with the other parties in the consortium, which plans to have the tanker design certified in as many countries as possible. The project includes research on a comprehensive regulatory framework led by the International Maritime Organization (IMO), and supported by the International Atomic Energy Agency (IAEA) and regulators in countries involved. In response to its members' interest in nuclear propulsion Lloyd's Register has recently rewritten its 'rules' for nuclear ships, which concern the integration of a reactor certified by a land-based regulator with the rest of the ship. Nuclear ships are currently the responsibility of their own countries, but none are involved in international trade. Lloyds expects to "see nuclear ships on specific trade routes sooner than many people currently anticipate."

Nuclear power seems most immediately promising for the following:

- Large bulk carriers that go back and forth constantly on few routes between dedicated ports – e.g. China to South America and NW Australia. They could be powered by a reactor delivering 100 MW thrust.

- Cruise liners, which have demand curves like a small town. A 70 MWe unit could give base-load and charge batteries, with a smaller diesel unit supplying the peaks.

- Nuclear tugs, to take conventional ships across oceans

- Some kinds of bulk shipping, where speed is essential.

K. Nuclear-powered Surface Ships in the US

Nuclear versus Conventional Power for Ships

Most military ships and large commercial ships are conventionally powered, meaning that they burn a petroleum-based fuel, such as marine diesel, to generate power for propulsion and for operating shipboard equipment. Conventionally powered ships are sometimes called fossil fuel ships.

Some military ships are nuclear-powered, meaning that they use an on-board nuclear reactor to generate power for propulsion and shipboard equipment.2 Nuclear-powered military ships are operated today by the United States, the United Kingdom, France, Russia, China, and India. Some other countries have expressed interest in, or conducted research and development work on, nuclear-powered military ships. A military ship's use of nuclear power is not an indication of whether it carries nuclear weapons—a nuclear-powered military ship can lack nuclear weapons, and a conventionally powered military ship can be armed with nuclear weapons.

US Navy Nuclear-powered Ships

Navy's Nuclear Propulsion Program

The Navy's nuclear propulsion program began in 1948. The Navy's first nuclear-powered ship, the submarine Nautilus (SSN-571), was commissioned into service on September 30, 1954, and went to sea for the first time on January 17, 1955. The Navy's first nuclear-powered surface ships, the cruiser Long Beach (CGN-9) and the aircraft carrier Enterprise (CVN-65), were commissioned into service on September 9, 1961, and November 25, 1961, respectively.

The Navy's nuclear propulsion program is overseen and directed by an office called Naval Reactors (NR), which exists simultaneously as a part of both the Navy (where it forms a part of the Naval Sea Systems Command) and the Department of Energy (where it forms a part of the National Nuclear Security Administration). NR has broad, cradle-to-grave responsibility for the Navy's nuclear-propulsion program.

This responsibility is set forth in Executive Order 12344 of February 1, 1982, the text of which was effectively incorporated into the U.S. Code (at 50 USC 2511) by Section 1634 of the FY1985 defense authorization act (H.R. 5167/P.L. 98-525 of October 19, 1984) and again by section 3216 of the FY2000 defense authorization act (S. 1059/P.L. 106-65 of October 5, 1999). NR has established a reputation for maintaining very high safety standards for engineering and operating Navy nuclear power plants.

The first director of NR was Admiral Hyman Rickover, who served in the position from 1948 until 1982. Rickover is sometimes referred to as the father of the nuclear Navy. The current director is Admiral Kirkland Donald, who became director in November 2004. He is the fifth person to hold the position.

Current Navy Nuclear-Powered Ships

All of the Navy's submarines and all of its aircraft carriers are nuclear-powered. No other Navy ships are currently nuclear-powered. The Navy's combat submarine force has been entirely nuclear-powered since 1990. The Navy's aircraft carrier force became entirely nuclear-powered on May 12, 2009, with the retirement of the Kitty Hawk (CV-63), the Navy's last remaining conventionally powered carrier.

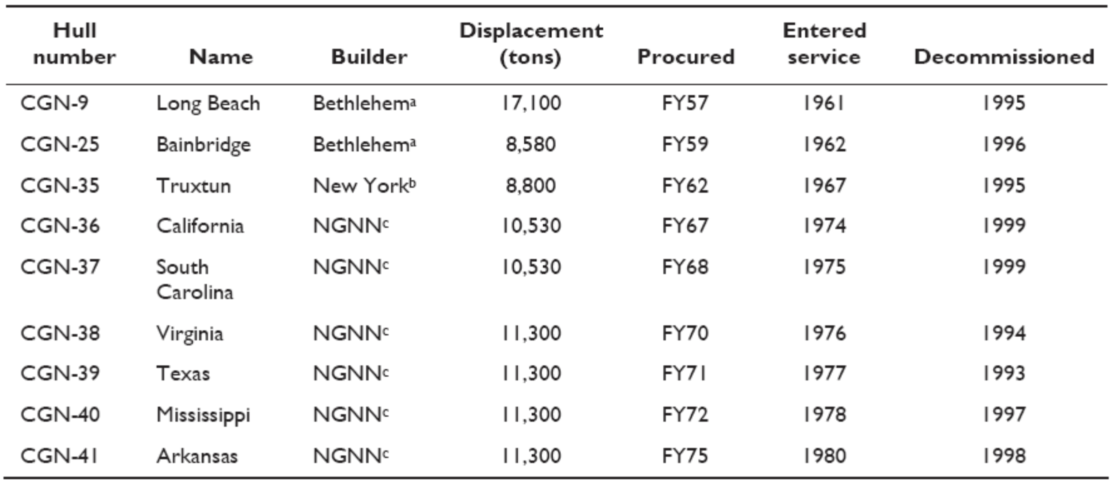
Historical Data for Navy Nuclear-powered Cruisers

Although no Navy surface ships other than aircraft carriers are currently nuclear-powered, the Navy in the past built and operated nine nuclear-powered cruisers (CGNs). The nine ships include three one-of-a-kind designs (CGNs 9, 25, and 35) followed by the two-ship California (CGN-36) class and the four-ship Virginia (CGN-38) class. All nine ships were decommissioned in the 1990s.

The nuclear-powered cruisers shown in the table below were procured to provide nuclear-powered escorts for the Navy's nuclear-powered carriers. Procurement of nuclear-powered cruisers was halted after FY1975 largely due to a desire to constrain the procurement costs of future cruisers.

In deciding in the late 1970s on the design for the new cruiser that would carry the Aegis defense system, two nuclear-powered Aegis-equipped options—a 17,200-ton nuclear-powered strike cruiser (CSGN) and a 12,100-ton derivative of the CGN-38 class design—were rejected in favor of a third option of placing the Aegis system onto the smaller, conventionally powered hull originally developed for the Spruance (DD-963) class destroyer. The CSGN was estimated to have a procurement cost twice that of the DD-963-based option, while the CGN-42 was estimated to have a procurement cost 30%-50% greater than that of the DD-963-based option. The DD-963-based option became the 9,500-ton Ticonderoga (CG-47) class Aegis cruiser. The first Aegis cruiser was procured in FY1978.

Table 6: Earlier Navy Nuclear-Powered Cruisers



Hull number	**Name**	**Builder**	**Displacement (tons)**	**Procured**	**Entered service**	**Decommissioned**
CGN-9	Long Beach	Bethlehem[a]	17,100	FY57	1961	1995
CGN-25	Bainbridge	Bethlehem[a]	8,580	FY59	1962	1996
CGN-35	Truxtun	New York[b]	8,800	FY62	1967	1995
CGN-36	California	NGNN[c]	10,530	FY67	1974	1999
CGN-37	South Carolina	NGNN[c]	10,530	FY68	1975	1999
CGN-38	Virginia	NGNN[c]	11,300	FY70	1976	1994
CGN-39	Texas	NGNN[c]	11,300	FY71	1977	1993
CGN-40	Mississippi	NGNN[c]	11,300	FY72	1978	1997
CGN-41	Arkansas	NGNN[c]	11,300	FY75	1980	1998

Analysis of the Initial Fuel Core

The initial fuel core for a Navy nuclear-powered ship is installed during the construction of the ship. The procurement cost of the fuel core is included in the total procurement cost of the ship, which is funded in the Navy's shipbuilding budget, known formally as the Shipbuilding and Conversion, Navy (SCN) appropriation account. In constant FY2011 dollars, the initial fuel core for a Virginia (SSN-774) class submarine cost about $170 million, and the initial fuel cores for an aircraft carrier (which uses two reactors and therefore has two fuel cores) had a combined cost of about $660 million.

The procurement cost of a conventionally powered Navy ship, in contrast, does not include the cost of petroleum-based fuel needed to operate the ship, and this fuel is procured largely through the Operation and Maintenance, Navy (OMN) appropriation account.

Looking at the CG(X) Cruiser Program

The CG(X) program, also known as the Next Generation Cruiser program, was a United States Navy program to replace its 22 Ticonderoga class cruisers after 2017. Original plans were for 18–19 ships, based on the 14,500 ton Zumwalt class destroyer but providing ballistic missile defense and area air defense for a carrier group. The program was cancelled in 2010; its mission is to be taken by Flight III Arleigh Burke–class destroyers instead.

The Navy assessed CG(X) design options in a large study called the CG(X) Analysis of Alternatives (AOA), known more formally as the Maritime Air and Missile Defense of Joint Forces (MAMDJF) AOA. The Navy did not announce whether it would prefer to build the CG(X) as a nuclear-powered ship. The Navy stated that it wanted to equip the CG(X) with a combat system featuring a powerful radar capable of supporting ballistic missile defense (BMD) operations. The Navy testified that this combat system was to have a power output of 30 or 31 megawatts, which is several times the power output of the combat system on the Navy’s existing cruisers and destroyers. This suggested that in terms of power used for combat system operations, the CG(X) might have used substantially more energy over the course of its life than the Navy’s existing cruisers and destroyers. As discussed later in this report, a ship’s life-cycle energy use is a factor in evaluating the economic competitiveness of nuclear power compared to conventional power.

The CG(X) program was announced on 1 November 2001. An initial requirement for 18 CG(X) was raised to 19 under the plan for a 313-ship Navy in 2005.

A reassessment in 2007 suggested splitting the CG(X) into two classes, fourteen Zumwalt-sized "escort cruisers" and five 23,000 ton ballistic missile defense (BMD) ships. There was political pressure for some or all of these ships to be nuclear powered, which would have given them the hull classification symbol of CGN(X).

The FY2009 budget called for procurement of the first CG(X) in 2011, and the second in 2013. On 1 February 2010, U.S. President Barack Obama unveiled his proposed budget for FY2011. This budget called for, among other things, canceling the entire CG(X) program.

The program was cancelled in the 2010 Quadrennial Defense Review. The CG(X)'s mission will instead be performed by DDG-51 Flight III destroyers, after the U.S. Navy concluded that the ships could rely on off-board and space-based sensors and so did not need a radar bigger than the DDG could carry.

In April 2002, John Young, Assistant Secretary of the Navy for Research, Development and Acquisition, stated that "the DD(X) hull will be the base from which they propose the design changes necessary to evolve this to CG(X). That could include various things from lengthening the hull and changing the size, but it will be, to our view, likely the basic hull form shape, appropriately sized and with the proper features added to accommodate the CG(X) mission".[6] The Chief of Naval Operations claimed in 2005 that "the DD(X) hull and propulsion plant will be spiraled into the CG(X) platform with about 80% design overlap". In the same testimony, he stated that designing a new hull would cost about $4B.

However, concerns began to grow about the stability of the Zumwalt's hull. Naval architect Ken Brower said in April 2007 that "as a ship pitches and heaves at sea, if you have tumblehome instead of flare, you have no righting energy to make the ship come back up. On the [Zumwalt], with the waves coming at you from behind, when a ship pitches down, it can lose transverse stability as the stern comes out of the water - and basically roll over." There were also doubts whether the Zumwalt hull was big enough to accommodate ballistic defense weapons, and a possible nuclear propulsion system. In July 2007 came the first suggestions that the AOA might recommend a two-class solution, a 14,000 ton "escort cruiser" based on the Zumwalt's stealthy "tumblehome" hull, and a ballistic missile defense ship of 23,000 tons. The latter would use a more conventional shape than the tumblehome, as its use of radars to search for missiles while on station would make a stealthy hull pointless. In July 2008, Roscoe Bartlett of the House Seapower subcommittee stated that it was "unlikely the [Zumwalt] hull could be used in the CG(X) program".

The CG(X) would have used the IPS electric propulsion system of the Zumwalt, as of the FY09 budget estimates in February 2008. The Zumwalt's gas turbines are capable of generating 78 MW,[9] and that was thought barely sufficient for the radar and future weapon systems on the CG(X) - the working assumption is that the entire ship's electric load, including a Theater Ballistic Missile Defense (TBMD) radar will consume 31 MW. In July 2008, Young said that "for the most capable radar suites under consideration, the [Zumwalt] hull cannot support the radar".

Meanwhile members of the House Projection Forces Subcommittee had been pressing the Navy to use nuclear power for major combatants, partly as a response to concerns about the price and availability of oil. They prompted studies in 2005 and 2006, the second of which stated that nuclear power broke even at an oil price of $70–$225/barrel for escort ships of 21-26,000 tons with heavy radar use. This led to a requirement in the FY2008 Defense Authorization Act[14] that all major combatant vessels be nuclear powered unless it was not in the national interest.

The Navy studied nuclear power as a design option for the CG(X), but has never announced whether it would prefer to build the CG(X) as a nuclear-powered ship - it would have added $600–800M to the initial cost of the ship, but save on running costs. Under normal budgeting practices, long lead-time items for nuclear propulsion would have needed to be procured in FY2009 if the main ship were to be procured in FY2011. If the two-class solution had been pursued, it seems probable that the escort cruiser would have used gas turbines like the Zumwalt, and the larger ballistic missile defense ship would have been nuclear powered, and hence known as the CGN(X).

The AOA apparently looked at two options, using two of the Seawolf class submarines' 34 MW reactors, and halving the 209 MW double reactor used in aircraft carriers. The first option would not even match the Zumwalt for power, while the second option probably would not fit into the Zumwalt hull. On the other hand, it would give plenty of headroom for future weapon systems such as directed-energy weapons and railguns, hence the proposal for the BMD ship of a larger hull with nuclear propulsion.

The CG(X) radar system would likely have been a development of the AN/SPY-3 dual-band radar of the Zumwalt class. It might also have been influenced by the replacement for the AN/SPQ-11 Cobra Judy missile-tracking radar on USNS Observation Island. As mentioned above, a future Theater Ballistic Missile Defense (TBMD) radar is being modelled as consuming 31 MW of electrical power, compared to 5 MW for the AEGIS system on an Arleigh Burke-class destroyer.

A CG(X) based on the Zumwalt hull would lose one or both of its guns, and replace them with more VLS launchers for anti-aircraft missiles. However, the Zumwalt's lack of capability in air defense and BMD was cited as a major reason for the near-cancellation of the class in July 2008. Recent intelligence that P.R. China is developing targetable anti-ship ballistic missiles based on the DF-21 appears to be shaping the Navy's thinking on the CG(X)'s capabilities, when previously the Zumwalt's air defense was believed to be good enough to justify delaying the introduction of the CG(X).

The Kinetic Energy Interceptor (KEI) program is developing new weapons against ballistic missiles, but the KEI missiles take up six times more space than SM-3s and a Zumwalt-sized hull could not carry a meaningful number.[9] The KEI may be dropped from the CG(X) program.

Analysis of the Construction Shipyards

Shipyards Building Nuclear-powered Ships

Two U.S. shipyards are currently certified to build nuclear-powered ships—Northrop Grumman Newport News (NGNN) of Newport News, VA, and General Dynamics' Electric Boat Division (GD/EB) of Groton, CT, and Quonset Point, RI. NGNN can build nuclear-powered surface ships and nuclear-powered submarines. GD/EB can build nuclear-powered submarines. NGNN has built all the Navy's nuclear-powered aircraft carriers. NGNN and GD/EB together have built every Navy nuclear powered submarine procured since FY1969.

Although NGNN and GD/EB are the only U.S. shipyards that currently build nuclear-powered ships for the Navy, five other U.S. shipyards once did so as well. These five yards built 44 of the 107 nuclear-powered submarines that were procured for the Navy through FY1968.

Surface Combatant Shipyards

All cruisers and destroyers procured for the Navy since FY1978 have been built at two shipyards - General Dynamics' Bath Iron Works (GD/BIW) of Bath, ME, and the Ingalls shipyard at Pascagoula, MS, that now forms part of Northrop Grumman Ship Systems (NGSS). GD/BIW has never built nuclear-powered ships. Ingalls is one of the five U.S. yards other than NGNN and GD/EB that once built nuclear-powered ships. Ingalls built 12 nuclear-powered submarines, the last being the Parche (SSN-683), which was procured in FY1968, entered service in 1974, and retired in 2005. Ingalls also overhauled or refueled 11 nuclear-powered submarines. Ingalls' nuclear facility was decommissioned in 1980, and NGSS is not certified to build nuclear-powered ships.

Issues Facing the Navy

Cost Factor

Designing and Development Cost

The cost calculations presented in the 2010 Navy alternative propulsion study do not include the additional up-front design and development costs, if any, for a nuclear-powered surface ship. As discussed in the "Background" section, if the CG(X) were to displace 21,000 or more metric tons, the Navy could have the option of fitting the CG(X) with a modified version of one-half of the Ford (CVN-78) class aircraft carrier nuclear power plant. This could minimize the up-front development cost of the CG(X) nuclear power plant. If the CG(X) were not large enough to accommodate a modified version of one-half of the Ford-class plant, then a new nuclear plant would need to be designed for the CG(X). Although this new plant could use components common to the Ford-class plant or other existing Navy nuclear plants, the cost of developing this new plant would likely be greater than the cost of modifying the Ford-class plant design.

Cost for Procurement

For Submarines and Aircraft Carriers

The Navy in 2007 estimated that building the CG(X) or other future Navy surface ships with nuclear power could reduce the production cost of nuclear propulsion components for submarines and aircraft carriers by 5% to 9%, depending on the number of nuclear-powered surface ships that are built. Building one nuclear-powered cruiser every two years, the Navy has testified, might reduce nuclear-propulsion component costs by about 7%. In a steady-state production environment, the Navy testified in 2007, the savings might equate to about $115 million for each aircraft carrier, and about $35 million for each submarine.

The Navy stated that this "is probably the most optimistic estimate." The Navy states that these savings were not included in the cost calculations presented in the 2006 Navy study. BWXT, a principal maker of nuclear-propulsion components for Navy ships, estimated in 2007 that increasing Virginia-class submarine procurement from one boat per year to two boats per year would reduce the cost of nuclear propulsion components 9% for submarines and 8% for aircraft carriers, and that "Adding a nuclear[-powered] cruiser or [nuclear-powered] large-deck amphibious ship would significantly drive down nuclear power plant costs across the fleet, even beyond the savings associated with the second Virginia-class [submarine per year]."

Life Cycle Cost

As suggested by the 2010 Navy study, the total-life-cycle cost break-even analysis can be affected by projections of future oil prices and ship operating tempo.

Future Oil Prices

Views on potential future oil prices vary. Some supporters of using nuclear power for the CG(X) and other future Navy surface ships, such as Representatives Gene Taylor and Roscoe Bartlett, the chairman and ranking member, respectively, of the Seapower and Expeditionary Forces Subcommittee of the House Armed Services Committee, believe that oil in coming decades may become increasingly expensive, or that guaranteed access to oil may become more problematic, and that this is a central reason for making the CG(X) or other future Navy surface ships nuclear-powered.

Ship Operating Tempo

A ship's average lifetime operating tempo can be affected by the number of wars, crises, and other contingency operations that it participates in over its lifetime, because such events can involve operating tempos that are higher than those of "normal" day-today operations. Ship operating tempo can also be affected by the size of the Navy. The lower the number of ships in the Navy, for example, the higher the operating tempo each a ship might be required to sustain for the fleet to accomplish a given set of missions.

Operational Issues

Operational Value

What is the operational value of increased ship mobility? How much better can a ship perform its missions as a result of this increased mobility? And is there some way to translate the mobility advantages of nuclear power into dollar terms? One potential way to translate the value of increased ship mobility into dollar terms would be to determine how much aggregate capability a force of 19 conventionally powered CG(X)s would have for surging to distant theaters and for maintaining on-station presence in theater, then determine how many nuclear-powered CG(X)s would be required to provide the same aggregate capability, and then compare the total cost of the 19 conventionally powered CG(X)s to the total cost of the nuclear-powered CG(X) force.

Other Operational Advantages

Are there operational advantages of nuclear power for a surface ship other than increased ship mobility? One possibility concerns ship detectability. A nuclear-powered ship does not require an exhaust stack as part of its deckhouse, and does not emit hot exhaust gases. Other things held equal, this might make a nuclear-powered surface ship less detectible than a conventionally powered ship, particularly to infrared sensors. This possible advantage for the nuclear-powered ship might be either offset or reinforced by possible differences between the nuclear-powered ship and the conventionally powered ship in other areas, such as the temperature of the engine compartment (which again might affect infrared detectability) or the level of machinery noise (which might affect acoustic detectability).

Some supporters of building future Navy surface ships with nuclear power have argued that an additional operational advantage of nuclear power for surface ships would be to reduce the Navy's dependence on its relatively small force of refueling oilers, and thus the potential impact on fleet operations of an enemy attack on those oilers. The Navy acknowledges that potential attacks on oilers are a concern, but argues that the fleet's vulnerability to such attacks is recognized and that oilers consequently are treated as high-value ships in terms of measures taken to protect them from attack.

Another potential advantage of nuclear power postulated by some observers is that a nuclear powered ship can use its reactor to provide electrical power for use ashore for extended periods of time, particularly to help localities that are experiencing brownouts during peak use periods or whose access to electrical power from the grid has been disrupted by a significant natural disaster or terrorist attack. The Navy stated that the CG(X) was to have a total power-generating capacity of about 80 megawatts (MW). Some portion of that would be needed to operate the reactor plant itself and other essential equipment aboard the ship. Much of the rest might be available for transfer off the ship.

For purposes of comparison, a typical U.S. commercial power plant might have a capacity of 300 MW to 1000 MW. A single megawatt can be enough to meet the needs of several hundred U.S. homes, depending on the region of the country and other factors.

Skeptics of the idea of using nuclear-powered ships to generate electrical power for use ashore could argue that if the local transmission system has been disrupted, the ship's generation capacity may be of limited use in restoring electric power. If the local transmission system is intact, they could argue, onshore infrastructure would be required to transmit the ship's power into the local system. The military or a local utility, they could argue, would likely bear the cost for this infrastructure, which would be used only on a sporadic basis. Skeptics could argue that a Navy ship would be helpful only if the power emergency lasts longer than the time it would take for the ship to reach the connection point. If the nearest available Navy ship is several steaming days away from the connection point when the power emergency occurs, they could argue, the ship might not be able arrive before local power is partially or fully restored. Skeptics could argue that critical facilities in the area of the power emergency, such as hospitals, would likely be equipped with emergency back-up diesel generators to respond to short-term loss of power.

Issues with Ship Construction

Shipyard Challenges

Another potential issue for Congress to consider in weighing whether future Navy surface ships (in addition to aircraft carriers) should be nuclear-powered concerns the shipyards that would be used to build the ships. There are at least three potential approaches for building a nuclear powered version of a major surface combatant like the CG(X):

- Build them at NGNN, with GD/EB possibly contributing to the construction of the ships' nuclear portions.
- Certify NGSS and/or GD/BIW to build nuclear-powered ships, and then build the CG(X)s at those yards.
- Build the nuclear portions of the CG(X)s at NGNN and/or GD/EB, the nonnuclear portions at NGSS and/or GD/BIW, and perform final assembly, integration, and test work for the ships at either
    - NGNN and/or GD/EB, or
    - NGSS and/or GD/BIW

These options have significant potential implications for workloads and employment levels at each of these shipyards.

On the question of what would be needed to certify NGSS and/or GD/BIW to build nuclear powered ships, the director of NR testified that:

Just the basics of what it takes to have a nuclear-certified yard, to build one from scratch, or even if one existed once upon a time as it did at Pasacagoula, and we shut it down, first and foremost you have to have the facilities to do that. What that includes, and I have just some notes here, but such things as you have to have the docks and the dry-docks and the pier capability to support nuclear ships, whatever that would entail. You would have to have lifting and handling equipment, cranes, that type of thing; construction facilities to build the special nuclear components, and to store those components and protect them in the way that would be required.

The construction facilities would be necessary for handling fuel and doing the fueling operations that would be necessary on the ship—those types of things. And then the second piece is, and probably the harder piece other than just kind of the brick-and-mortar type, is building the structures, the organizations in place to do that work, for instance, nuclear testing, specialized nuclear engineering, nuclear production work. If you look, for instance, at Northrop Grumman Newport News, right now, just to give you a perspective of the people you are talking about in those departments, it is on the order of 769 people in nuclear engineering; 308 people in the major lines of control department; 225 in nuclear quality assurance; and then almost 2,500 people who do nuclear production work. So all of those would have to be, you would have to find that workforce, certify and qualify them, to be able to do that.

The director of NR testified that NGNN and GD/BIW "have sufficient capacity to accommodate nuclear-powered surface ship construction, and therefore there is no need to make the substantial investment in time and dollars necessary to generate additional excess capacity." In light of this, the Navy testified, only the first and third options above are "viable." The director of NR testified that:

my view of this is we have some additional capacity at both Electric Boat and at Northrop Grumman Newport News. My primary concern is if we are serious about building another nuclear-powered warship, a new class of warship, cost is obviously going to be some degree of concern, and certainly this additional costs, which would be—and I don't have a number to give you right now, but I think you can see it would be substantial to do it even if you could. It probably doesn't help our case to move down the path toward building another nuclear-powered case, when we have the capability existing already in those existing yards.

With regard to the third option of building the nuclear portions of the ships at NGNN and/or GD/EB, and the non-nuclear portions at NGSS and/or GD/BIW, the Navy testified that the "Location of final ship erection would require additional analysis." One Navy official, however, expressed a potential preference for performing final assembly, integration, and test work at NGNN or GD/EB, stating that:

we are building warships in modular sections now. So if we were going to [ask], "Could you assemble this [ship], could you build modules of this ship in different yards and put it together in a nuclear-certified yard?", the answer is yes, definitely, and we do that today with the Virginia Class [submarine program]. As you know, we are barging modules of [that type of] submarine up and down the coast.

What I would want is, and sort of following along with what [NR director] Admiral [Kirkland] Donald said, you would want the delivering yard to be the yard where the reactor plant was built, tooled, and tested, because they have the expertise to run through all of that nuclear work and test and certify the ship and take it out on sea trials. But the modules of the non-reactor plant, which is the rest of the ship, could be built theoretically at other yards and barged or transported in other fashion to the delivering shipyard. If I had to do it ideally, that is where I would probably start talking to my industry partners, because although we have six [large] shipyards [for building large navy ships], it is really two corporations [that own them], and those two corporations each own what is now a surface combatant shipyard and they each own a nuclear-capable shipyard. I would say if we were going to go do this, we would sit down with them and say, you know, from a corporation standpoint, what would be the best work flow? What would be the best place to construct modules? And how would you do the final assembly and testing of a nuclear powered warship?

<u>Lack of Component Manufacturers</u>

A related issue that Congress may consider in weighing whether future Navy surface ships (in addition to aircraft carriers) should be nuclear-powered is whether there is sufficient capacity at the firms that make nuclear-propulsion components to accommodate the increase in production volume that would result from building such ships with nuclear power. On this question, the Navy has testified:

Right now, as I look across the industrial base that provides [for nuclear-powered ships], let's just talk about the components, for instance, and I just look across that base, because we have been asserting earlier that we were going to go to [a procurement rate of two Virginia class submarines per year] earlier [than the currently planned year of FY2012], we had facilitized and have sustained an over-capacity in those facilities to support construction of those additional components. So right now, it depends on the vendor and which one is doing what, the capacity is running right now at probably about 65 percent of what it could be doing, on the order of that. Again, it varies depending on the vendor specifically.

So there is additional capacity in there, and even with the addition of a second Virginia-class submarine, there is still a margin in there, if you are talking about a single cruiser in the early phases of design, we still have margin in there that I believe we can sustain that work in addition to the submarine work within the industrial base.

We would have to look at that in more detail once we determine what the design looks like and the degree to which we can use existing components. If you had to design new components, that would add a little bit more complexity to it, but that is a rough estimate of what I would provide for you now.

Environmental Impact

Conventionally powered ships exhaust greenhouse gases and other pollutants that are created through combustion of petroleum-based fuel. They can also leak fuel into the water, particularly if they are damaged in an accident (such as a collision) or by enemy attack. Other environmental impacts of conventionally powered ships include those associated with extracting oil from the ground, transporting it to a refinery, refining it into fuel, and transporting that fuel to the ship.

Most of these activities produce additional greenhouse gases and other pollutants. Nuclear-powered ships do not exhaust greenhouse gases and other pollutants created through conventional combustion. The environmental impacts of nuclear-powered ships include those associated with mining and processing uranium to fuel reactors, and with storing and disposing of spent nuclear fuel cores, radioactive waste water from reactors, and the reactors and other radioactive components of retired nuclear-powered ships.

NREL has established a reputation for maintaining very high safety standards for engineering and operating Navy nuclear power plants. In addition, Navy combat ships are built to withstand significant shock and battle damage. It is possible, however, that a very serious accident involving a nuclear-powered Navy ship (such as a major collision) or a major enemy attack on a nuclear-powered Navy ship might damage the ship's hull and reactor compartment enough to cause a release of radioactivity, which may have adverse effects on the environment.

L. Analysis of Nuclear-powered Icebreakers

Overview

A nuclear powered icebreaker is a purpose-built ship for use in waters continuously covered with ice. Icebreakers are ships capable of cruising on ice-covered water by breaking through the ice with their strong, heavy, steel bows. Nuclear powered icebreakers are far more powerful than their diesel powered counterparts, and have been constructed by Russia primarily to aid shipping in the frozen Arctic waterways in the north of Siberia.

During the winter, the ice along the northern seaways varies in thickness from 1.2 to 2.0 meters (3.9 to 6.5 feet). The ice in central parts of the Arctic Ocean is on average 2.5 meters (8.2 ft) thick. Nuclear-powered icebreakers can force through this ice at speeds up to 10 knots (19 km/h, 12 mph). In ice-free waters the maximum speed of the nuclear-powered icebreakers is as much as 21 knots (35 km/h, 24 mph).

Use of Nuclear-powered Icebreaker

The nuclear ice breakers of the Arktika class are used to force through the ice for the benefit of cargo ships and other vessels along the northern seaway. The northern seaway comprises the eastern part of the Barents Sea, the Petchora Sea, the Kara Sea, the Laptev Sea and the Eastern Siberian Sea to the Bering Strait. Important ports on the northern seaway are, among others, Dikson, Tiksi, and Pevek.

Two nuclear-powered icebreakers, NS Vaigach and NS Taimyr, have been built for shallow waters and are usually used from the Yenisei River to Dikson, where they break through the ice followed by cargo ships with lumber from Igarka and cargo ships with ore and metals from the Norilsk Company's port in Dudinka. These nuclear powered icebreakers can also be used as fireboats.

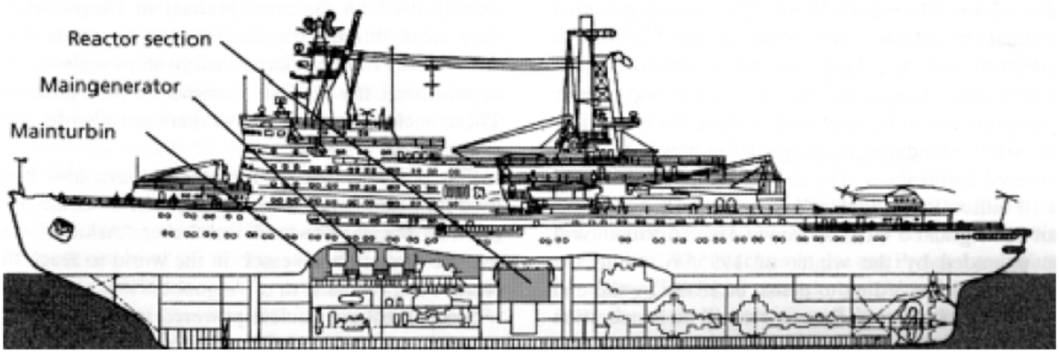
The icebreakers have also been used for a number of scientific expeditions in the Arctic. On August 17, 1977, the NS Arktika was the first surface vessel in the world to reach the North Pole. Since 1989, some icebreakers have been used for Arctic tourism cruises.

Applications of Icebreakers

Russia operated at some time up to eight nuclear powered civilian vessels divided into seven icebreakers and one nuclear-powered container ship. These made up the world's largest civilian fleet of nuclear-powered ships. The vessels were operated by Murmansk Shipping Company (MSC), but were owned by the Russian state. The servicing base Atomflot is situated near Murmansk, 2 km north of the Rosta district.

Figure 66: Nuclear Icebreaker Arktika

Figure 67: Schematic of Russian Nuclear Icebreaker Arktika Showing Emplacement of Nuclear Reactor at its Center

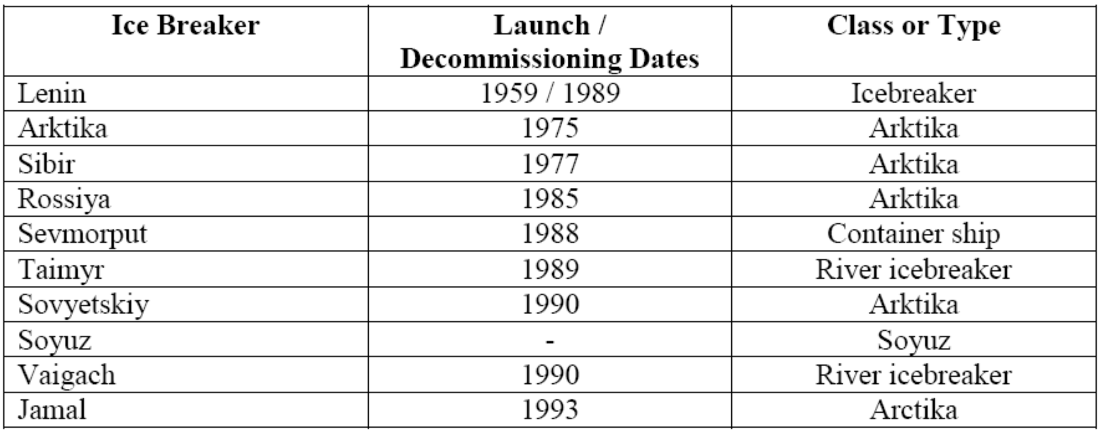


Icebreakers facilitated ores transportation from Norilsk in Siberia to the nickel foundries on the Kola Peninsula, a journey of about 3,000 kms.

Since 1989 the nuclear icebreakers have been used to transport wealthy Western tourists to visit the North Pole. A three week long trip costs $ 25,000.

The icebreaker Lenin, launched in 1957 was the world's first civilian vessel to be propelled by nuclear power. It was commissioned in 1959 and retired from service in 1989. Eight other civilian nuclear-powered vessels were built: five of the Arktika class, two river icebreakers and one container ship. The nuclear icebreaker Yamal, commissioned in 1993, is the most recent nuclear-powered vessel added to the fleet as shown in the table below.

Table 7: Russian Civilian Ice Breakers Operated by the Murmansk Shipping Company



Ice Breaker	Launch / Decommissioning Dates	Class or Type
Lenin	1959 / 1989	Icebreaker
Arktika	1975	Arktika
Sibir	1977	Arktika
Rossiya	1985	Arktika
Sevmorput	1988	Container ship
Taimyr	1989	River icebreaker
Sovyetskiy	1990	Arktika
Soyuz	-	Soyuz
Vaigach	1990	River icebreaker
Jamal	1993	Arctika

Russian Expertise in the Industry

In all, ten civilian nuclear powered vessels have been built in Russia. Nine of these are icebreakers, and one is a container ship with an ice-breaking bow. All nuclear-powered icebreakers of the NS Arktika design have been built at the Admiralty Shipyard in St. Petersburg. The NS Vaigach and NS Taimyr were built at the Helsinki New Shipyard in Finland and then brought to Russia for installation of the reactors and steam propulsion systems.

Ship Name	Launched	Project Number	Type	Class	Comments
NS *Lenin*	1959	92M	Icebreaker	*Lenin*	Decommissioned 1989. Museum ship.
NS *Arktika*	1975	1052-1	Icebreaker	*Arktika*	Not operational.
NS *Sibir*	1977	1052-2	Icebreaker	*Arktika*	Defueled and not operational since 1993.
NS *Rossiya*	1985	10521-1	Icebreaker	*Arktika*	
NS *Sevmorput*	1988	10081	Container ship	*Sevmorput*	Has ice-breaking bow
NS *Taimyr*	1989	10580-1	River Icebreaker	*Taimyr*	
NS *Sovetskiy Soyuz*	1990	10521-2	Icebreaker	*Arktika*	
NS *Vaigach*	1990	10580-2	River Icebreaker	*Taimyr*	
NS *Yamal*	1993	10521-3	Icebreaker	*Arktika*	
NS *50 Let Pobedy*	1993	10521	Icebreaker	*Arktika*	Built as NS *Ural*, completed in 2007.

Reactor Types

The nuclear icebreakers are powered by pressurized water reactors of the KLT-40 type. The reactor contains fuel enriched to 30-40 percent in U235. By comparison, nuclear power plants use fuel enriched to only 3-5 percent. Weapons grade uranium is enriched to over 90 percent. American submarine reactors are reported to use up to 97.3 percent enriched U235. The irradiated fuel in test reactors contains about 32 percent of the original U235, implying a discharge enrichment of 97.3 x 0.32 = 31.13 percent enrichment.

Under normal operating conditions, the nuclear icebreakers are only refueled every three to four years. These refueling operations are carried out at the Atomflot service base. Replacement of fuel assemblies takes approximately 1 1/2 months.

For each of the reactor cores in the nuclear icebreakers, there are four steam generators that supply the turbines with steam. The third cooling circuit contains sea water that condenses and cools down the steam after it has run through the turbines. The icebreaker reactors' cooling system is especially designed for low temperature Arctic sea water.

Analysis of Nuclear-powered Icebreakers

Lenin Nuclear Icebreaker

At its launch in 1957 the icebreaker NS Lenin was both the world's first nuclear powered surface ship and the first nuclear powered civilian vessel. Lenin was put into ordinary operation in 1959. Lenin had two nuclear accidents, the first in 1965, and the second in 1967. The second accident resulted in one of the three OK-150 reactors being damaged beyond repair. All three reactors were removed, and replaced by two OK-900 reactors; the ship returned to service in 1970. The Lenin was taken out of operation in November 1989 and laid up at Atomflot, the base for nuclear powered icebreakers, in the Murmansk Fjord. Conversion to a museum ship has been completed in 2005.

Arktika Icebreaker

Arktika class icebreakers are the bulk of the Russian nuclear icebreaker fleet; six of Russia's ten nuclear civilian ships are Arktikas. Since they have been built over a period of thirty years, there is a fair bit of variation between ships of the class; thus specifications are listed as a range of values. In general, the newer ships are larger, faster, and require smaller crews.

Specifications:

- Length: 148 m to 159 m (approximately 136 m at the waterline)
- Beam: 30 m (28 m at the waterline)
- Draft: approximately 11.08 m.
- Height (keel to masthead): approximately 55 m
- Displacement: 23,000 to 25,000 tons
- Maximum speed: 18 to 22 knots
- Cruising speed: approximately 18 to 20 knots
- Crew: 138 to over 200
- Passengers: approximately 100
- Reactors: 2 OK-900A, 171 megawatt each
- Propulsion: 3 propellers totaling approximately 75,000 hp
- Maximum Ice Thickness: 2 to 2.8 m
- Endurance: 7.5 months at sea, 4 years between refuelings

Arktika-class icebreakers have a double hull, with the outer hull being approximately 48 mm thick at the ice-breaking areas and 25 mm thick elsewhere. There is water ballast between the inner and outer hulls which can be shifted to aid icebreaking. Icebreaking is also assisted by an air bubbling system which can deliver 24 m^3/s of air from jets 9 m below the surface. Some ships have polymer coated hulls to reduce friction. Arktika-class ships can break ice while making way either forwards or backwards. These ships must cruise in cold water, in order to cool their reactors. As a result, they cannot pass through the tropics to undertake voyages in the Southern Hemisphere. Although they have two reactors, normally only one is used to provide power, with the other being maintained in a standby mode.

Some ships carry one or two helicopters and several Zodiac boats. Radio and satellite systems can include navigation, telephone, fax, and email capabilities.

Most nuclear powered icebreakers in the Russian service today have a swimming pool, a sauna, a cinema, and a gymnasium. In the restaurants aboard there is a bar and facilities for live music performances. Some also have a library and at least one has a volleyball court.

Individual Ships

On 17 August 1977, the NS Arktika ("Arctic") became the first surface ship ever to reach the North Pole.

The NS Arktika and NS Sibir ("Siberia") are presently not in operation but are stationed at Atomflot for extensive repair. Among other things, the nuclear reactors and turbine generators are to be upgraded as these do not satisfy the safety standards established for newer nuclear powered icebreakers. The Arktika's reactors have operated for over 150,000 hours, and research is underway to determine if they can be refitted to yield another 25,000 to 50,000 hours of service.

Neither the NS Arktika, nor the NS Sibir might ever come into operation again due to the operational economics. Unless there is a significant increase of transport in the Arctic it will not be profitable to operate all six Arktika-class icebreakers. It is to be expected that the oldest icebreakers would be the first ones to be taken out of operation.

The NS Rossiya ("Russia") carries two helicopters. Rossiya was used to transport an expedition of around 40 West Germans to the North Pole in the Summer of 1990; this may have been the first non-communist charter of a nuclear icebreaker. Rossiya was in refit as of December 2004.

The NS Sovetskiy Soyuz ("Soviet Union") was trapped in ice for three days in 1998. In 2004, it was one of three icebreakers used for an Arctic ice core expedition intended to research climate change and global warming. One tourism operator lists it as being possibly used for North Pole cruises.

The NS Yamal is mostly used for tourism and scientific expeditions. It has 50 passenger cabins and suites, and carries one helicopter. The crew is 150, including 50 officers and engineers. Yamal was the 12th surface ship ever to reach the North Pole.

The NS 50 Lyet Pobyedi ("50 Years of Victory") is the final Arktika class ship. It was launched from the shipyard at Saint Petersburg on December 29, 1993 as the NS Ural, and delivered to Murmansk in 1994. It was later renamed and not actually completed and commissioned until 2006 due to funding delays. The crew is expected to normally number 138 persons. It has an environmental waste processing module added to the hull which accounts for 9 m of the ship's 159 m length; this makes it the largest of the Arktika class and the largest nuclear powered icebreaker in the world. It carries two Ka-32 helicopters. It entered service on April 2, 2007.

Taymyr Nuclear Icebreaker

Taimyr is also sometimes spelled Taymyr in English, and Vaigach is sometimes spelled Vayguch. The ships were built at the Helsinki New Shipyard in Finland by Wärtsilä. The nuclear reactors were installed at the Leningrad Baltic Shipyard in the Soviet Union after delivery from Finland.

Taimyr class specifications:

- Length: 150.2 m (Taimyr), 151.8 m (Vaiguch)
- Beam: 29.2 m
- Draft: 8.0 m
- Height: 15.2 m keel to main deck, 8 stories from main deck to bridge
- Displacement: 20,000 tons
- Speed: 18.5 knots
- Crew: 120 to 138
- Reactors: One KLT-40M reactor producing 135 MW
- Propulsion: 3 propellers totaling 52,000 hp

The bow hull plating is approximately 32 mm thick. As of December 2004, both vessels were undergoing refitting.

Planned Nuclear Icebreakers

Russia is planning to start building new icebreakers (Project 22220 or ЛК60Я) after 2010. In June 2008 the head of the state nuclear corporation Rosatom, Sergei Kiriyenko, said "It is important to not only use the existing fleet of icebreakers, but also to build new ships, and the first nuclear icebreaker of a new generation will be built by 2015. This should be an icebreaker capable of moving in rivers and seas", he said. He went on saying that the Iceberg Design Bureau in St. Petersburg would prepare the design of the icebreaker by 2009.

According to the BBC the LK-60 (ЛК60Я) will be the biggest nuclear-powered icebreaker that was ever built. Vladimir Putin said in 2010, Russia builds at least three nuclear icebreakers of the new generation in the period from 2012 to 2020. Sergei Kiriyenko, head of the state nuclear corporation Rosatom ordered the responsible operator Atomflot to build up to three nuclear icebreakers until 2016.

The construction of a nuclear-powered icebreaker takes eight years, the fuel endurance is about 25 years and the reactor can be refueled. According to the Transport Ministry, Russia needs six new icebreakers in the future.

Supporting Infrastructure

Support facilities include the fuel transports Imandra and Lotta which are used for refueling and spent fuel. The Volodarsky is used for storage of solid waste; it can hold 300 cubic meters. Serebryanka is a tanker used for liquid waste which can hold 1,000 cubic meters of material. The Rosta-1 boat is used for radiation monitoring and control, including sanitization of workers.

A third fuel vessel, Lepse, is filled with spent nuclear fuel elements, many of them damaged and thus difficult to handle. The vessel was used for dumping of nuclear waste in the Barents and Kara Seas from 1963 to 1984.[9] During a dumping operation in 1984, Lepse encountered very rough seas, and high-level reactor waste mixed with water was splashed all over the inside of the cargo compartment. The contamination was so severe that the crew were forced to immediately return to port at the Atomflot harbor with most of the nuclear waste still in the hold.

The ship was immediately recognized as being far too dangerous to decontaminate and return to service, and has been essentially abandoned with a cargo hold full of leaking spent reactor fuel vessels, in the harbor for over 15 years. It forms one of the world's most difficult and potentially dangerous nuclear waste disposal problems; an accident there could release more radiation than the Chernobyl catastrophe into the immediate vicinity of Murmansk.[citation needed] A small crew monitors the ship on a constant basis while Russia tries to raise the money and perform the research needed for safe disposal. In September 2012 the Lepse was removed from the Atomflot harbor and transported to the Nerpa shipyard where it will be carefully scrapped.

In all, about 2,000 people work aboard the icebreakers, the nuclear-powered container ship, and aboard the service and storage ships stationed at the Atomflot harbor. The crew on the civil nuclear-powered vessels receive special training at the Makarov college in St. Petersburg, Russia.

Icebreakers generally try to navigate paths with the least possible ice in order to make speedier progress and to help ensure that they do not become trapped in ice too thick for them to break. In the 1970s and 1980s, land-based aircraft would observe and map the ice to help with course plotting. Over time, most of this work has been taken over by satellite surveillance systems, sometimes aided by the helicopters carried by the icebreakers.

Use of Nuclear-powered Icebreakers in Tourism

Since 1989 the nuclear powered icebreakers have also been used for tourist purposes carrying passengers to the North Pole. Each participant pays up to US$ 25,000 for a cruise lasting three weeks. The NS Sibir was used for the first two tourist cruises in 1989 and 1990. In 1991 and 1992, the tourist trips to the North Pole were undertaken by NS Sovyetski Soyuz. During the summer of 1993 the NS Yamal was used for three tourist expeditions in the Arctic. The NS Yamal has a separate accommodation section for tourists. The NS 50 Let Pobedy contains an accommodation deck customized for tourists.

Quark Expeditions has chartered the nuclear-powered icebreaker "50 Years of Victory" for expeditions to the North Pole in 2008. The vessel's maiden voyage to the North Pole embarked in Murmansk, on June 24, 2008. The ship carried 128 guests in 64 cabins in 5 categories. "50 Years of Victory" completed a total of 3 expeditions to the North Pole in 2008 for the polar adventure company. As of February 2013, Quark Expeditions was listing the 50 Years of Victory in the company fleet and offering it for a North Pole cruise.

Decommissioning and Defueling

Navy nuclear ships are decommissioned and defueled at the end of their useful lifetime, when the cost of continued operation is not justified by their military capability, or when the ship is no longer needed. The Navy faces the necessity of downsizing the fleet to an extent that was not envisioned in the 1980's before the end of the Cold War. Most of the nuclear-powered cruisers will be removed from service, and some Los Angeles Class submarines are scheduled for removal from service. Eventually, the Navy will also need to decommission Ohio Class submarines.

Nuclear ships are defueled during inactivation and prior to transfer of the crew. The defueling process removes the nuclear fuel from the reactor pressure vessel and consequently removes most of the radioactivity from the reactor plant. Defueling is an operation routinely accomplished using established processes at shipyards used to perform reactor servicing work.

After a nuclear-powered ship no longer has sufficient military value to justify continuing to maintain the ship or the ship is no longer needed, the ship can be: (1) placed in protective storage for an extended period followed by permanent disposal or recycling; or (2) prepared for permanent disposal or recycling. The preferred alternative is land burial of the entire defueled reactor compartment at the Department of Energy Low Level Waste Burial Grounds at Hanford, Washington.

A ship can be placed in floating protective storage for an indefinite period. Nuclear-powered ships can also be placed into storage for a long time without risk to the environment. The ship would be maintained in floating storage. About every 15 years each ship would have to be taken out of the water for an inspection and repainting of the hull to assure continued safe waterborne storage. However, this protective storage does not provide a permanent solution for disposal of the reactor compartments from these nuclear-powered ships. Thus, this alternative does not provide permanent disposal.

Unlike the low-level radioactive material in defueled reactor plants, the Nuclear Waste Policy Act of 1982, as amended, requires disposal of spent fuel in a deep geological repository.

The Hanford Site is used for disposal of radioactive waste from DOE operations. The pre Los Angeles Class submarine reactor compartments are placed at the Hanford Site Low Level Burial Grounds for disposal, at the 218-E-12B burial ground in the 200 East area. The land required for the burial of approximately 100 reactor compartments from the cruisers, Los Angeles, and Ohio Class submarines would be approximately 4 hectares or 10 acres.

An estimated cost for land burial of the reactor compartments is $10.2 million for each Los Angeles Class submarine reactor compartment, $12.8 million for each Ohio Class submarine reactor compartment, and $40 million for each cruiser reactor compartment.

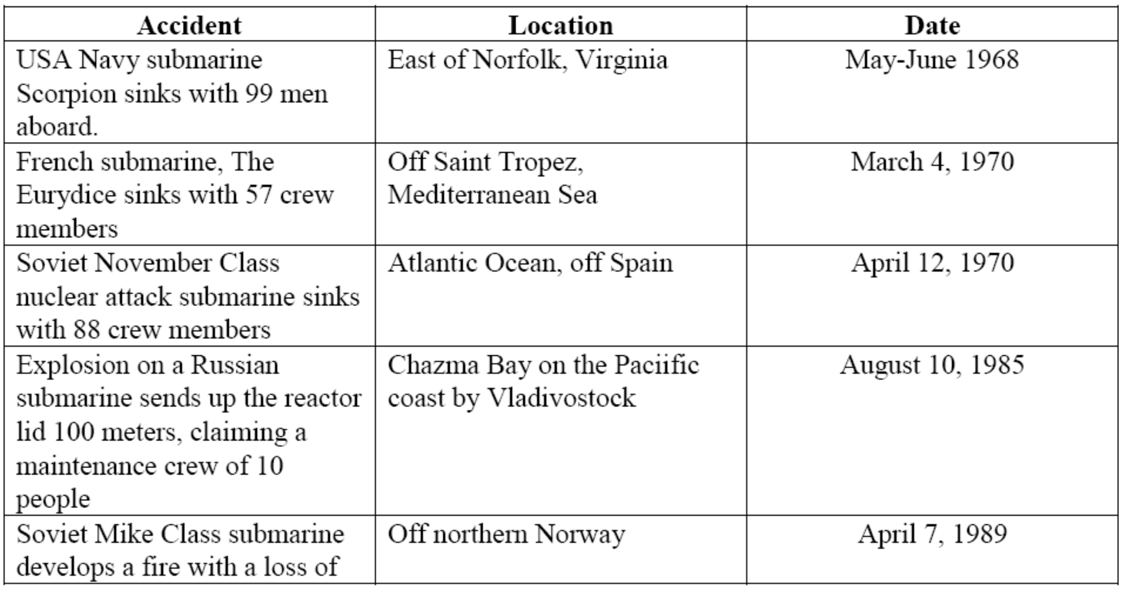
The estimated total Shipyard occupational radiation exposure to prepare the reactor compartment disposal packages is 13 rem generating a risk of approximately 0.005 additional latent cancer fatalities for each Los Angeles Class submarine package, 14 rem or a risk of approximately 0.006 additional latent cancer fatalities for each Ohio Class submarine package and 25 rem or a risk of approximately 0.01 additional latent cancer fatalities for each cruiser package.

Accidents with Icebreakers

Naval vessels are built in a highly sturdy fashion to withstand combat conditions and their crews are highly professional and well trained. Accordingly, accidents occurrences have been rare, but reporting about them is sketchy even though there is a need to learn from their experience to avoid their future occurrence. The Naval Reactors office at the USA Department of Energy (USDOE) defines an “accident” as an event in which a person is exposed to radiation above the prescribed safe federal limits.

The most notable accidents for the USA Navy were the loss of the Thresher and the Scorpion nuclear submarines. The discovery of the Titanic wreck was a spinoff of the technology developed for investigating these accidents at great water depths.

Table 8: Nuclear Submarine Accidents Since 1968



Accident	Location	Date
USA Navy submarine Scorpion sinks with 99 men aboard.	East of Norfolk, Virginia	May-June 1968
French submarine, The Eurydice sinks with 57 crew members	Off Saint Tropez, Mediterranean Sea	March 4, 1970
Soviet November Class nuclear attack submarine sinks with 88 crew members	Atlantic Ocean, off Spain	April 12, 1970
Explosion on a Russian submarine sends up the reactor lid 100 meters, claiming a maintenance crew of 10 people	Chazma Bay on the Paciific coast by Vladivostock	August 10, 1985
Soviet Mike Class submarine develops a fire with a loss of	Off northern Norway	April 7, 1989

42 lives		
Toxic fuel leaked from a ballistic missile and poisoned several Russian serice men	Russia'a far east	June 16, 2000
Russian Oscar-II Class submarine Kursk sinks with 118 crew members after a possible collision and two explosions onboard	Barents Sea	August 12, 2000
USA Navy 360 feet submarine, The Greenville sinks a Japanese fishing trawler after colliding with it in a resurfacing training maneuver, killing 9 sailors aboard the boat	Pacific Ocean off Pearl Harbor, Hawaii	February 9, 2001
Russian K-139 submarine sank while being towed to a shipyard with 9 crew members aboard		August 28, 2003
USA San Francisco runs into undocumented underground mountain, killing one crew member	Off Guam, Pacific Ocean	January 2005
Fire on board the Viktor-3 class Russian Navy submarine St. Daniel of Moscow kills 2 crew members	Moored near Finnish border	September 6, 2006
British submarine the Tireless during an exercise has 2 soldiers killed and 1 injured	Arctic Ocean	March 21, 2007
The Nerpa, Akula class Russian submarine fire causes the death of 20 people and injuring 21 while on sea trials	Pacific Ocean	November 8, 2008
The Hartford nuclear submarine while submerged but near the surface collides with the surface ship USS New Orleans. The collision caused 15 injuries on the Hartford.	Strait of Hormuz	March 20, 2009

USS Thresher, SSN-593 Accident

The USS Thresher of the Permit class attack submarine was powered with a Westinghouse S5W nuclear reactor, with a displacement of 4,300 metric tons, a length of 85 meters, and a maximum speed of 30 knots. The crew of 129 comprised 12 officers, 96 enlisted men, 4 shipyard officers, and 17 civilian specialists.

On April 9, 1963 the USS Thresher, accompanied by the submarine rescue ship USS Skylark (ASR-20), sailed out of Portsmouth, New Hampshire for a planned 2 days of deep diving test trials.

On the morning of April 10, 1963 at 8:53 am, the Thresher dived contacting the Skylark at every 49 meters of its dive. As it neared its test depth, around 9:10 am it did not respond to the Skylark's communications. The Skylark's queries were answered by the ominous sound of compartments collapsing. Surface observers realized that the Thresher was lost when their sonar operations heard the sound of compressed air for 20-30 seconds. The Skylark reported to headquarters that it lost contact with the Thresher at 9:17 am. The accident sequence lasted about 7 minutes.

The possible causes of the accident were surmised to be:

1. Water leaking from damaged pipes inside the pressure hull,

2. The pressure hull disintegrating when the submarine approached its maximum diving depth of 3,000 feet or (304 x 3,000) / 1,000 = 912 meters. (1,000 feet = 304 meters),

3. The submarine dived below its maximum diving depth due to crew error in an area with a depth of 8,400 feet or (304 x 8,400) / 1,000 = 2,560 meters.

An extensive underwater search using the deep diving bathyscaphe Trieste located the Thresher on the sea floor broken into 6 major sections. The debris field covered an area of 134,000 m2 or 160,000 square yards. A possible human error could be related to the initial testing being undertaken at a relatively high depth location.

USS Scorpion, SSN-589 Accident

The USS Scorpion was a 3,500 ton Skipjack class nuclear-powered attack submarine built at Groton, Connecticut. It was commissioned in July 1960 and assigned to the Atlantic Fleet. The Scorpion was assigned to a Mediterranean cruise in February 1968. The following May, while homeward bound from that tour, she was lost with her entire crew some 400 miles southwest of the Azores Island.

The Scorpion was designed primarily for anti-submarine warfare against the USSR nuclear submarine fleet and it carried special teams of Russian-speaking linguists to eavesdrop on transmissions by the USSR Navy and other military units.

On May 17, 1968, led by Cmdr. Francis Slattery, the Scorpion had just completed a three month deployment to the Mediterranean Sea with the USA 6th Fleet and was on its way home to Norfolk, Virginia. Vice Adm. Arnold Schade, commander of the Atlantic Submarine Force in Norfolk, had a new mission for the Scorpion. The submarine was ordered to head at high speed toward the Canary Islands, 1,500 miles away off the east coast of Africa, to gather intelligence on a group of USSR ships lurking in the eastern Atlantic southwest of the Azores island chain. The Soviet ships there included an Echo-II class nuclear submarine designed to attack aircraft carriers but also armed with anti-submarine torpedoes.

In late October 1968, the remains of the Scorpion were found on the sea floor over 10,000 feet below the surface by a towed deep-submergence vehicle deployed from the USNS submersible craft Mizar (T-AGOR-11).

Photographs showed that her hull had suffered fatal damage while she was running submerged and that even more severe damage occurred as she sank. The cause of the initial damage continues to generate controversy decades later and may have been a casualty of the Cold War.

On May 17, 1968, the USS Scorpion had received a top secret message shortly before midnight to change course and head for the Canary Islands, where a collection of USSR ships had caught the Navy's attention. Thirty three minutes later, the Scorpion surfaced at the USA submarine base at Rota, Spain, to transfer two crewmen ashore via a Navy tug. The men had emergency leave orders, one for a family matter and the other for medical reasons. The submarine sank five days later on May 22, 1968.

More than five months later, the Scorpion's wreckage was found on the ocean floor, two miles deep in the Atlantic. All 99 men aboard were lost.

The USA Navy's initial position was that the Scorpion sank because of a malfunction while returning to its home port of Norfolk, Virginia. While the precise cause of the loss remained undetermined, there was no information to support the theory that the submarine's loss resulted from hostile action of any involvement by a USSR ship or submarine.

Another opinion suggested that the Scorpion was at the center of a web of intelligence gathering and surveillance and a possible Cold War military activity that resulted in an alleged agreement by both the USA and the former USSR to cover up the full accounting of what happened.

A scenario dramatically different from the official Navy version was reported alleging that the Scorpion was not on a routine crossing of the Atlantic, but had been diverted to a top-secret mission to spy on a group of Soviet ships, including a nuclear submarine. Although the Navy's official explanation was of a mechanical malfunction, this countered an earlier conclusion by a panel of senior Navy officials that the Scorpion was sunk by a torpedo. The panel concluded it was one of the Scorpion's own torpedoes that went errant. Experts still disagree about whether it could have been a USSR torpedo.

An allegation was that even though the Scorpion believed it was operating in secret, Navy warrant officer John Walker, the Navy's most notorious spy, had communicated to the USSR the codes they needed to track the USA submarine in the hours before it sank. The USSR had the ability to monitor all electronic transmissions to the Scorpion, including the encrypted orders sending it on its intelligence gathering mission.

Russian Navy admirals said that senior Navy officials in both the USA and the USSR agreed to never disclose details of the Scorpion incident and the loss of a Soviet missile sub in the Pacific two months earlier in 1968.

Two months before the Scorpion sank, a Soviet missile sub known as the K-129 sank thousands of miles away, in the Pacific Ocean, also under mysterious conditions. There have been assertions by Russian submarine veterans over the years that the K-129 sank after an alleged collision with a USA attack submarine that allegedly had been shadowing it. USA military officials insisted the Golf-class submarine went down with its 98 man crew after an internal explosion, based on analysis of the sounds of the sinking captured on Navy hydrophones.

Retired Capt. Peter Hutchhausen was the USA Naval attaché in Moscow in the late 1980s, two decades after both incidents. He reported that he had several terse but pointed conversations with counterpart Soviet admirals about the two sinkings of the Scorpion and the K-K-129. One encounter was in June 1987 with Admiral Pitr Navoytsev, first deputy chief for operations of the Soviet Navy. When he asked Navoytsev about the Scorpion, Capt. Hutchhausen recalls his response: "Captain, you are very young and inexperienced, but you will learn that there are some things both sides have agreed not to address, and one is that event and our K-129 loss, for similar reasons." In another discussion in October 1989, Capt. Huchthausen said Vice Adm. B.M. Kamarov told him that a secret agreement had been reached between the USA and USSR in which both sides agreed not to press the other government on the loss of their submarines in 1968. The motivation, Capt. Huchthausen said, was to preserve the thaw in superpower relations.

A senior admiral in the Pentagon at the time of the Scorpion sinking said that USA intelligence agencies feared the submarine was headed into possible danger, based on intercepted Soviet naval communications in the Atlantic Ocean.

There was some communications analysis that the Scorpion had been detected by the group she had been shadowing and conceivably they had trailed her. There were some speculations that not only did they track her but attacked her as a tit-for-tat for the K-129 sinking. A further suggestion was that it was lured into a trap and ambushed. However, the intelligence of USSR hostility has never been confirmed.

The Navy mounted a secret search for the submarine within 24 hours of its sinking. The search was highly classified. The rest of the Navy, and even a Navy Court of Inquiry that investigated the sinking later in 1968, were never told about it.

The Court of Inquiry that probed the loss of the Scorpion in the summer and fall of 1968 described the Soviet presence as an undefined "hydro-acoustic" research operation involving two research vessels and a submarine rescue ship among others, implying the Soviets were merely engaging in research on oceanographic studies of sound effects in the ocean rather than a military mission. Pentagon officials had been concerned that the USSR was developing a way to support warships and submarines at sea without requiring access to foreign seaports for supplies.

What is known is that 15 hours after sending its final message, the Scorpion exploded at 6:44 pm on May 22, 1968, and sank in more than 2 miles of water depth about 400 miles southwest of the Azores. The Navy said it could not identify the “certain cause” of the loss of the Scorpion.

In late 1993, the Navy declassified most of the Court of Inquiry's 1968 conclusions that it had earlier classified. Headed by retired Vice Adm. Bernard Austin, the court had concluded that the best evidence pointed to an errant Scorpion own torpedo that circled around and exploded against the hull of the sub. The court's conclusion stemmed in part from records showing that the Scorpion has had a similar occurrence in 1967 with an unarmed training torpedo that suddenly started up and had to be jettisoned.

In its final 1,354-page report, the Court of Inquiry rejected two alternative theories for the loss: the contention by that an unspecified mechanical problem had set off a chain of events leading to massive flooding inside the submarine, and a scenario that an explosion inside the submarine touched off the sinking. The court also concluded that it was "improbable" the Scorpion sank as the result of "enemy action."

In 1970, a different Navy panel completed another classified report that disavowed the Court of Inquiry's conclusion. Instead of an accidental torpedo strike, the new group suggested a mechanical failure caused an irreparable leak that flooded the submarine. That report said the bulk of the evidence suggested an internal explosion in the submarine’s massive electrical battery caused the sub to flood and sink.

Two senior Navy officials involved in the initial Scorpion probe in the summer of 1968 suggested that the Court of Inquiry conclusion of an accidental torpedo strike remains the most realistic scenario because of the key acoustic recordings of the sinking. Underwater recordings retrieved from three locations in the Atlantic, the Canary Islands and two sites near Newfoundland, captured a single sharp noise followed by 91 seconds of silence, then a rapid series of sounds corresponding to the overall collapse of the submarine's various compartments and tanks. There was no way one can have the hull implode and then have 91 seconds of silence while the rest of the hull decides to try and hang itself together.

Retired Adm. Bernard Clarey, who in 1968 was the Navy's senior submariner, dismissed the battery explosion theory asserting that such a mishap could not have generated the blast and acoustic energy captured on the hydrophone recordings.

While several retired submariners over the years have speculated the Scorpion was ambushed and sunk by a Soviet submarine, no conclusive proof of a deliberate attack has appeared. The Navy concluded in 1968 probe there was "no evidence of any Soviet preparations for hostilities or a crisis situation as would be expected in the event of a premeditated attack on Scorpion."

The Court of Inquiry report was silent on whether an inadvertent clash may have resulted in the sinking. A Navy spokesperson said the Court of Inquiry had found the Scorpion was 200 miles away from the Soviet ships at the time it sank.

John S. Stennis, CVN-74 Loca Accident

On November 30, 1999 the nuclear aircraft carrier CVN-74 John S. Stennis ran aground in a shallow area adjacent to its turning basin as it attempted to maneuver off the California coast near Naval Air Station North Island, San Diego. This resulted into clogging by silt of the inlet coolant pipes to its two reactors and causing what would amount to a loss of cooling accident for a period of 45 minutes. One reactor was shut down by the automatic control system and the second was left running at low power to provide energy to the vessel and eventually taken offline by the operators until an alternate cooling supply was provided. The vessel was possibly lightened of its water and fuel supplies and towed by tugboat to its pier at high tide. The cleanup cost about $2 million.

San Francisco Underwater Collision

A January 8, 2005 incident occurred to the USS San Francisco nuclear submarine which sustained structural damage that shredded its bow and destroyed a water filled fiberglass sonar dome and forward ballast tanks when it hit in a glancing blow an underwater mountain 525 feet underwater that was not on its navigational charts.

Satellites images showed the presence of the mountain but were not incorporated into the navigational charts. The submarine was travelling at 30 knots when the accident occurred. The accident caused the death of one sailor and injured 60 others. The submarine crew took emergency measures to blast to the surface and keep the vessel afloat. An air blower was run for 30 hours to limit water seepage from holes in the forward ballast tanks keeping the vessel from sinking too low to maneuver.

The hull of a submarine is composed of two parts made of high strength steel such as HY-80 for the LA class submarines. The inner hull, that is much thicker and stronger than the outer hull and encloses the crew's living quarters and working spaces, held firm. The high yield steel can withstand pressure at depths greater than 800 feet and has a seamless rubberlike substance molded onto its surface. The ballast tanks are positioned between the two hulls. Two doors that shutter the torpedo hatches held tight and did not flood. The nuclear reactor was unaffected and powered the vessel back 360 miles northeast to its port at Guam.

The nose cone that is constructed of a composite material enabling sound to pass through it to a sonar sphere with active and passive sonar, was shattered. The sonar sphere is covered with hydrophones mounted on its surface and is isolated from sounds generated by the submarine by a baffle. In addition to the spherical array, the Virginia class of submarines is equipped with a chin, sail, three side mounted arrays on each side and a towed array that eliminates much of the blind area behind the submarine.

Nerpa, Akula Class Fire

An accident occurred on the Nerpa, an Akula Class Russian nuclear attack submarine on sea trials in the Pacific Ocean that was planned to be leased to the Indian Navy on November 8, 2008. The event claimed twenty deaths and 21 injuries to people who were not able to use the portable breathing gear issued to Russian submarine crews. The deaths were caused by the inhalation of the Freon toxic gas used as a fire suppressant in the vessel's fire extinguishing system that went off unexpectedly. Most of the injured were civilian workers from the Amur Ship Building Enterprise shipyard that built the submarine. Seventeen victims were civilian employees and three were sailors. Reportedly, 208 people or about 3 times the size of the usual crew were on board the submarine during its testing.

USS Houston Coolant Leak

In 2008, it was reported that the nuclear submarine USS Houston had a coolant leak. This was the first coolant leakage of its kind, and because of its small magnitude; it went undetected for two years.

HMS Vanguard, Le Triomphant Collision

While travelling at low speed, the ballistic missile submarine HMS Vanguard sustained dents and scratches on its hull when it collided in the Atlantic with the French ballistic missile submarine Le Triomphant in early 2009. The latter incurred damage to its sonar dome located under its bow. The sophisticated sonar equipment failed to detect the presence of the other submarine directly ahead of it.

The UK possesses four ballistic missiles submarines, as do the French, the USA has 14, the Russians 15, and the Chinese three. The 173 meter or 567 feet long Dimitry Donskoy is the world's largest strategic submarine with twice the displacement of the Kursk, which sank in the Barents Sea with 118 sailors in 2000. The hull of the Vanguard is as tall as a four story building and roughly 150 meters or 492 feet in length, and carries 16 ballistic missiles armed with nuclear warheads with a combined power more than about 6 Mt of TNT equivalent.

The methods used to detect submarines do not function reliably except for the passive and active sonars. Special magnetic detectors have been developed to detect the imprints a large steel vessel makes in the Earth's magnetic field, but many external factors can interfere with the devices. Infrared receivers can detect the heat wake generated by a nuclear reactor, but they also mistakenly identify the water being churned up behind a freighter as a submarine. Laser scanning beams cannot penetrate far enough beneath the ocean surface. Bioluminescence detectors detect the light emitted by microbes agitated by a submarine's propellers, but the same microbes also emit light for other reasons. The radioactive wake from neutron activation of the sodium in sea water salt is hard to detect.

Active sonar transmits “ping” noises into the water like whales, and the resulting echo enables the sonar device to compute the location and size of a submarine. However, sound travels far underwater, and a submarine that transmits sound will be revealing its location to a potential adversary. That is why strategic nuclear submarines use passive sonar which a system of highly sensitive hydrophones that uses computers to interpret underwater sounds. A problem is that submarines are extremely quiet; thanks to the use of special propellers and sound insulated engines, and their commanders usually driving them at no more than a walking pace making “less noise than a crab.”

In addition, the ocean is a structured labyrinth for submarine commanders. Layers of water with different salinity levels mimic horizontal ramps and the solid ocean floor, because the layers between them reflect and refract sound waves. Warm currents build vertical walls in the same way. This creates safe spots in the middle of the ocean into which strategic submarine commanders like to lurk and embed their vessels in, as well as to follow hidden paths that tend to be used by all submarines.

The UK and the USA coordinate the positions of their submarines with France expected to join the NATO military command structure. That leaves Russia and China out.

Hartford and New Orleans Accident

In the morning of March 20, 2009, the 2,899 ton nuclear submarine USS Hartford as part of the USA 5th fleet, was transiting into the Persian Gulf through the Hormuz Straits. It was accompanying an amphibious surface ship, the USS New Orleans, LPD-18, which was making her first extended deployment. The Hartford was submerged but near the surface at the time of the collision.

The two ships collided, and the submarine Hartford rolled 85 degrees to starboard. The impact and rolling caused injuries to 15 Sailors onboard. The bow planes and sail of the submerged Hartford ripped into the hull of the New Orleans.

The collision punched a 16-by-18 foot hole in the fuel tanks of the New Orleans. Two interior ballast tanks were also damaged. The New Orleans lost about 25,000 gallons of diesel fuel, which rapidly dissipated in the ocean and could not be tracked after a few days. There were no injuries to the New Orleans crew of 360 or the embarked unit of 700 USA Marines.

The nuclear powered submarine Hartford was severely damaged as its sail was torn from its mountings to the vessel’s pressure hull. The submarine’s communication masts and periscope were warped and became inoperable. The watertight integrity of the pressure hull became suspect, yet the Hartford transited on its own power on the surface to Bahrain, where it tied up to a military pier. The nuclear power plant was unaffected by the collision.

The Hartford ran aground in 2003 near La Maddalena, Italy damaging the bottom and rudder. Repairs involved the installment of equipment that was cannibalized from a decommissioned submarine.

M. Analysis of Nuclear Submarines

Overview

A nuclear submarine is a submarine powered by a nuclear reactor. The performance advantages of nuclear submarines over "conventional" (typically diesel-electric) submarines are considerable: nuclear propulsion, being completely independent of air, frees the submarine from the need to surface frequently, as is necessary for conventional submarines; the large amount of power generated by a nuclear reactor allows nuclear submarines to operate at high speed for long durations; and the long interval between refueling grants a range limited only by consumables such as food. Current generations of nuclear submarines never need to be refueled throughout their 25-year lifespans.

Conversely, the limited power stored in electric batteries means that even the most advanced conventional submarine can only remain submerged for a few days at slow speed, and only a few hours at top speed; recent advances in air-independent propulsion have eroded this disadvantage somewhat. The high cost of nuclear technology means that relatively few states have fielded nuclear submarines. Some of the most serious nuclear and radiation accidents in the world have involved nuclear submarine mishaps.

History of Nuclear Submarines

The idea for a nuclear-powered submarine was first proposed by the Naval Research Laboratory's Ross Gunn in 1939.

The United States launched the USS Nautilus, the first nuclear submarine, in 1954. Nautilus could remain underwater for up to four months without resurfacing.

Construction of the Nautilus was made possible by the successful development of a nuclear propulsion plant by a group of scientists and engineers at the Naval Reactors Branch of the Atomic Energy Commission. In July 1951, the U.S. Congress authorized construction of the world's first nuclear-powered submarine, under the leadership of Captain Hyman G. Rickover, USN.

The Westinghouse Corporation was assigned to build its reactor. After the submarine was completed, President Harry S. Truman broke the traditional bottle of champagne on Nautilus' bow. On January 17, 1955, it began its sea trials after leaving its dock in Groton, Connecticut. The submarine was 320 feet long, and cost about $55 million.

The Soviet Union soon followed the United States in developing nuclear-powered submarines in the 1950s. Stimulated by the U.S. development of the Nautilus, Soviet work on nuclear propulsion reactors began in the early 1950s at the Institute of Physics and Power Engineering, in Obninsk, under Anatoliy P. Alexandrov, later to become head of the Kurchatov Institute. In 1956, the first Soviet propulsion reactor designed by his team began operational testing. Meanwhile, a design team under Vladimir N. Peregudov worked on the vessel that would house the reactor.

After overcoming many obstacles, including steam generation problems, radiation leaks, and other difficulties, the first nuclear submarine based on these combined efforts entered service in the Soviet Navy in 1958.

At the height of the Cold War, approximately five to ten nuclear submarines were being commissioned from each of the four Soviet submarine yards (Sevmash in Severodvinsk, Admiralteyskiye Verfi in St. Petersburg, Krasnoye Sormovo in Nizhny Novgorod, and Amurskiy Zavod in Komsomolsk-on-Amur). From the late 1950s through the end of 1997, the Soviet Union, and later Russia, built a total of 245 nuclear submarines, more than all other nations combined.

Today, six countries deploy some form of nuclear-powered strategic submarines: the United States, Russia, France, the United Kingdom, People's Republic of China, and India. Several other countries, including Argentina and Brazil, have ongoing projects in different phases to build nuclear-powered submarines.

In the United Kingdom, all former and current nuclear submarines for the Royal Navy have been constructed in Barrow-in-Furness (at BAE Systems Submarine Solutions or its predecessor VSEL).

Technical Features

The main difference between conventional submarines and nuclear submarines is the power generation system. Nuclear submarines employ nuclear reactors for this task. They either generate electricity that powers electric motors connected to the propeller shaft or rely on the reactor heat to produce steam that drives steam turbines (cf. nuclear marine propulsion). Reactors used in submarines typically use highly enriched fuel (often greater than 20%) to enable them to deliver a large amount of power from a smaller reactor.

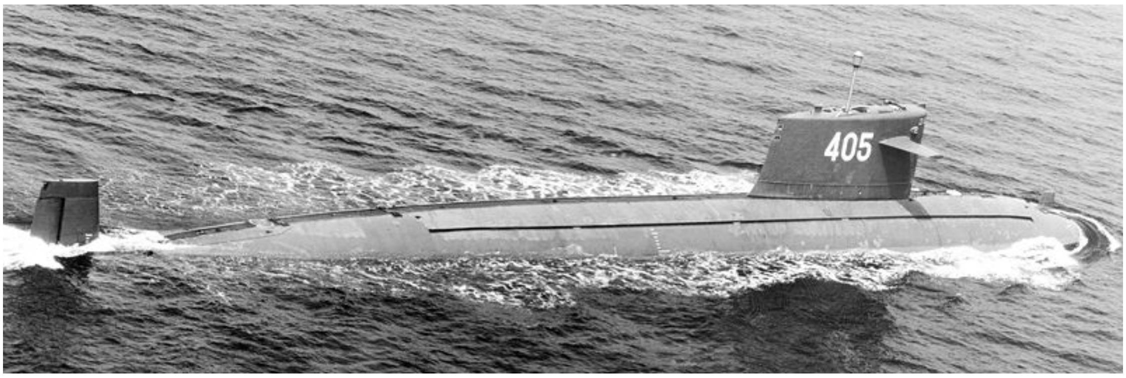
The nuclear reactor also supplies power to the submarine's other subsystems, such as for maintenance of air quality, fresh water production by distilling salt water from the ocean, temperature regulation, etc. All naval nuclear reactors currently in use are operated with diesel generators as a backup power system. These engines are able to provide emergency electrical power for reactor decay heat removal as well as enough electric power to supply an emergency propulsion mechanism. Submarines may carry nuclear fuel for up to 30 years of operation. The only resource that limits the time underwater is the food supply for the crew and maintenance of the vessel.

The stealth weakness of nuclear submarines is the need to cool the reactor even when the submarine is not moving; about 70% of the reactor output heat is coupled into the sea water. This leaves a "thermal wake", a plume of warm water of lower density which ascends to the sea surface and creates a "thermal scar" observable by thermal imaging systems, e.g. FLIR.

Operational Nuclear Submarines in China

Type 091 (Han) Attack Submarines

Figure 68: Type 091 (Han) Attack Submarines



The 4,500/5,500-ton Type 091 (US Department of Defense designation Han-class, Chinese designation 09-I) was the first nuclear-powered submarine (SSN) class deployed by the People's Liberation Army Navy. The first Chief Designer of the submarine was an engineer and scientist of nuclear propulsion engineering Mr. Peng Shilu, then in 1983 succeeded by Mr. Huang Xuhua. The first submarine in the class was commissioned in 1974 and the fifth and final boat of the class was commissioned in 1990. The Han-Class is among the first generation of nuclear-powered submarines in the People's Liberation Army Navy.

The Han-Class were developed with a backdrop of factional violence and in accordance with hunts for enemy agents. The Han-Class is well known for having a noisy reactor and poor radiation shielding. This causes health hazards for her crew as nuclear radiation levels are higher than they should be aboard the submarine. The submarine is also inhibited by the fact that it cannot launch missiles while submerged. This is a huge tactical drawback and makes a missile launch suicidal against most enemies.

The Han-class have gone through major upgrades and numerous refits since their commissionings. Their initial design and weapons appear to be inadequate for confronting modern warships. It is believed that long refits have often meant that these submarines have spent more time in port than out at sea, greatly affecting their operational capacity. The boats have six 533 mm torpedo tubes and carry 20 torpedoes. Alternatively, they can carry 36 mines in their tubes. The Han class is capable of firing sub-launched variants of the C-801 anti-ship missile as well as a range of indigenous and Russian torpedoes or mines.

Hull 401 (and possibly 402 as well in the near future) had been retired from active service by 2005. All remaining hulls however have been refitted with new sonars, with Type H/SQ2-262B sonar manufactured by No. 613 Factory replacing the original Type 603 sonar on board. Anechoic tiles were added later reduce noise levels. India's short term lease of a Charlie 1 Class SSGN in 1988 resulted in negotiations with Pakistan for a lease of a Han. Pakistan's request for one was withdrawn when India returned the Charlie 1 in 1991.

The Han has mostly operated in local waters. Since the 1990s, Hans have been used more aggressively. A Han shadowed a U.S. carrier battle group in the mid-1990s. In November 2004, a Han made an incursion into Japanese territorial waters and prompted Japan's maritime forces to go on alert for only the second time since the end of World War II. The incursion was through the Ishigaki, Okinawa island group, a lightly populated group of islands very near Taiwan. China later apologized for the incursion saying for "technical reasons," it ventured into Japanese waters.

All 5 boats (Changzheng 1 to 5; # 401 to 405) of this class were deployed with the North Sea Fleet and are home ported at Qingdao.

Type 092 (Xia) Ballistic Missile Submarines

The 6,500-ton Type 092 Daqingyu (US Department of Defense designation Xia-class, Chinese designation 09-II) submarine was the first ballistic missile-carrying, nuclear-powered submarine class (SSBN) deployed by the Chinese People's Liberation Army Navy, and the first SSBN designed and built in Asia. She was designed by Peng Shilu and Huang Xuhua, and derived from the Han-Class SSNs, with an extended hull to accommodate four missile tubes.

The first Changzheng 6 (# 406) of its class was laid down in 1978 at Huludao 120 miles North-East of Beijing; she was completed in 1981. She then spent 6 years being fitted out and conducting tests with its 12 JL-1 (CSS-N-3) missiles, becoming active in 1987. Later, the submarine went through numerous upgrades in incremental step, including using Type H/SQ2-262B sonar manufactured by No. 613 Factory replacing the original Type 604 sonar on board.

The 092 has undergone numerous refits, currently featuring a new black paint, possible quieting technologies, French-designed sonar, and the improved longer ranged JL-1A SLBM. It is reported that the 092 has not sailed beyond Chinese regional waters. One of the two Xias built was reported lost during an accident.

The Xia is aging however and a new Ballistic Missile Submarine design is in the works for the People's Liberation Army Navy. The US Defense Intelligence Agency lists the Xia-Class as being "Not Operational." While its capability is still being questioned, Xia made its worldwide debut on April 23rd, 2009 celebrating the 60th anniversary of PLA Navy's founding.

The 092 class are homeported in Jianggezhuang near Qingdao.

Type 093 (Shang) Attack Submarines

The Type 093 (NATO reporting name: Shang, Chinese designation: 09-III) is a nuclear powered attack submarine class deployed by the Chinese People's Liberation Army Navy. These boats are expected to replace the older Type 091 (NATO: Han class) SSNs currently in service. The Type 093 will be armed with various torpedoes and anti-ship missiles.

The lead boat in this class was launched in 2002. It is thought to have a seven-blade asymmetric propeller. Construction of the Type 093 submarines is being conducted at the Bohai Shipyard in Huludao. Six to eight boats are expected to be built.

China’s new generation nuclear submarine program can be dated back to the early 1980s, when the PLA Navy issued the requirement for a new nuclear attack submarine (SSN) as the successor to its first-generation Type 091 (NATO codename: Han class) nuclear attack submarine. The submarine development program, codenamed Type 093, was officially approved by the PLA leaders in July 1983. However, the development program only made very limited progress in its early stage due to enormous technical difficulties, especially the nuclear reactor and onboard weapon systems.

Rumors were that the original Type 093 design was inferior to existing Western and Soviet nuclear submarines even before its blueprint could be finished. As a result, the submarine design team had to give up the original design to meet the revised requirements from the PLA Navy. Development was speculated to have been suspended until the mid-1990s, when St. Petersburg-based Rubin Central Design Bureau for Marine Engineering began to assist the Chinese design team in the Type 093 development. Supposed Russian involvement in the program has played an important role in reviving the Type 093 project, which finally commenced construction in the late 1990s. Exactly how much help the Chinese design team received from Rubin Design Bureau is unknown, but could have included assistance in some critical areas such as overall hull design, engine and machinery quieting, combat system design, and weapon system and countermeasures outfit.

This rumored Russian-assisted new Type 093 design was speculated to have general performance comparable to that of Russian Victor-III class, SSNs originally introduced in the late 1970s by the Soviet navy, as well as early versions of the American Los Angeles class. Some have gone as far as saying it is comparable to early Akula class SSN's.

However, Russian involvement in the 093 project cannot be confirmed by any source, the extended re-fits to the 091 Han-class SSNs appeared to be the reason of delaying the development of the Type 093, not the rumored cause of encountering massive technical difficulty nor waiting for the supposed Russian involvement. In a matter of fact, during a visit to China in early 2000s, the Russian chief designer of the Kilo class submarine (also designed by Rubin Central Design Bureau, which China bought 12 of in total) was reported to have been denied the request to even visit either the Song class or the 093 class submarine program, and later according to interview made by Pinkov of Kanwa Defense Review, the Rubin Design Bureau denied that they had any kind of involvement with the Chinese nuclear sub program. Recently released photos have put the theory of relation to the Victor class and Russian design help of the 093 class in doubt as the Type 093 does not seem to be influenced by the Victor design.

The U.S. Navy intelligence and Pentagon predicted that the PLA Navy would have around 3~4 Type 093 submarines by 2010, other sources suggested that eventual production could reach 6 to 8 units. The exact number to be built may well depend on the results of the ongoing sea trial for the first hull, which has been carried out at the PLA Navy’s Huludao submarine base since 2003.

The Type 093 is estimated to be roughly 7000t displacement when dived. The Type 093 is estimated to be 110 meters (360 ft) long with a beam of 11m and can dive to a maximum depth of 400 meters (1,300 ft). It is estimated to have a noise level of 110db and have an endurance of 80 days. This submarine is the first to incorporate flank linear array sonars designated as H/SQG-207 in its design, and this linear flank array was designed by the 715th Institute, with deputy chief designer Mr. Li Qihu, who was the chief designer of H/SQ-2 262/262A/262B/262C/H-SQG-4 sonars used to upgrade Type 035, 033, both 091 and 092, 035G, and 039 submarines.

The Type 093 is expected to be armed with six 533 mm and/or 650 mm torpedo tubes that will launch Russian or indigenous wire-, acoustic, and wake-homing torpedoes as well as anti-ship and land attack cruise missiles. This could include the submarine launched version of YJ-83 anti-ship missile. Currently YJ-83 is not believed to be nuclear tipped. Nuclear deterrence missions are delegated to the 092 Xia class and 094 Jin class SSBN.

Type 094 (Jin) Ballistic Missile Submarines

The Type 094 (NATO reporting name: Jin-class) is a class of ballistic missile submarine developed by the Chinese People's Liberation Army Navy. The first-of-class was constructed at Huludao Shipyard in Huludao, Liaoning and launched in July 2004. Five submarines are believed to have been constructed.

The Type 094 submarine is capable of carrying 12-16 of the more modern JL-2s[5] with a range of approximately 8,000-12,000 km, and is capable of targeting some of the Western Hemisphere from close to the Chinese coast. The Type 094 is believed to replace the Type 092 submarine (NATO reporting name: Xia class) for the People's Liberation Army Navy.

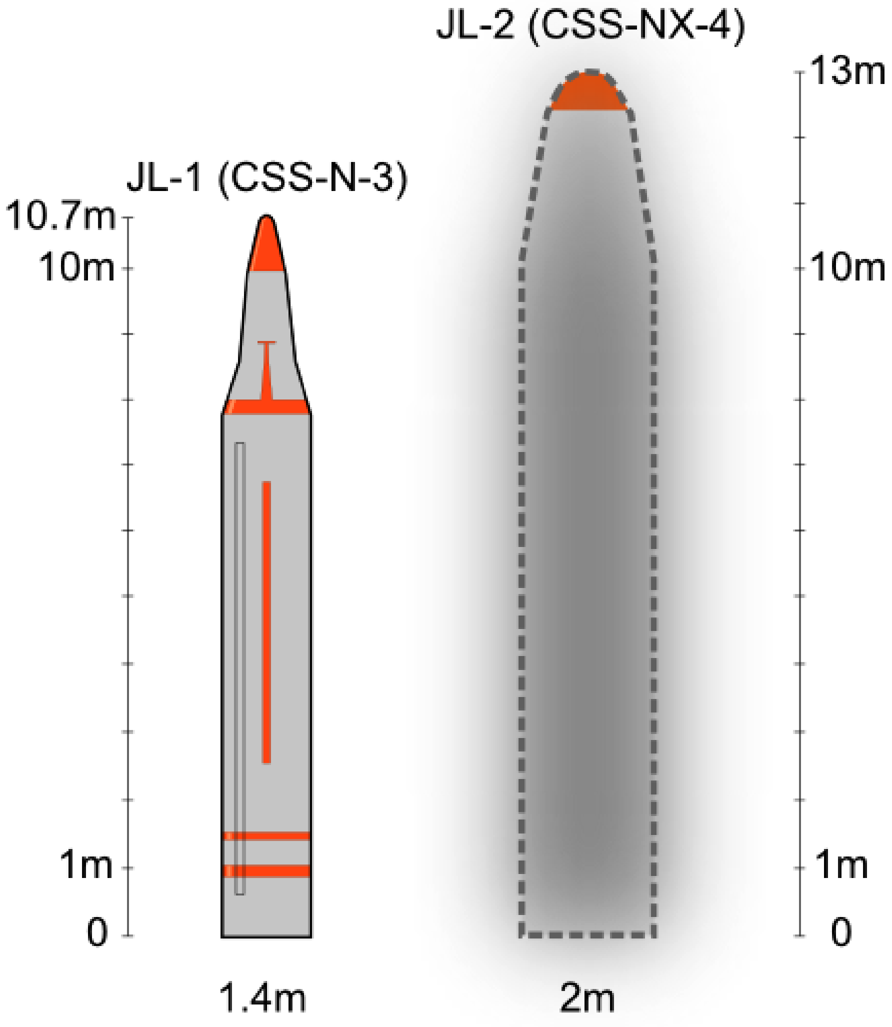
In its 2008 assessment of China's military, the United States Department of Defense estimated that one Type 094 "may soon enter service", and that "up to five" would be in service by 2010. The United States government has expressed concern over these submarines, saying that the Chinese government has not been transparent enough about the program.[6] Chinese SSBN will begin official sea patrol starting in 2014.

A new improved variant, carrying 16 missile tubes, was also spotted.

In late 2006, a commercial satellite photographed what is believed to be the new Jin-class submarine moored in Xiaopingdao Submarine Base. In comparison with the older Type 092-class submarine, it has been elongated from 122m to 133m in order to house the missile tubes and part of the reactor.

A Google Earth picture from May 2007 has been discovered that appears to show two more Jin Class submarines docked at the Bohai shipyard at Huludao. It is not clear whether one of these is the vessel that was first spotted at Xiaopingdao in 2006 or whether these are two additional vessels, bringing the total to 3 vessels. The pictured subs appear to have 12 missile tubes.

Figure 69: JL-1 and JL-2 Missiles



Nuclear Submarines under Development in China

Type 095 Attack Submarines

The Type 095 (Chinese designation: 09-V) is a proposed class of third generation nuclear-powered attack submarines for the People's Liberation Army Navy (PLAN) of the People's Republic of China. Two were rumored to be launched by the end of 2010 and they started their sea trials around the summer of 2011.

It is anticipated that Type 095 submarines will have a substantially reduced acoustic signature, within an improved hull type. Compared to the Type 093, the Type 095 will have a more advanced nuclear reactor, VLS tubes and greater number of advanced sensors such as new active/passive flank array sonar and low and high frequency towed sonar array. Additionally, it is also speculated that Type 095 submarines may act as a potential undersea escort for any future PLAN aircraft carrier task forces.

Type 096 (Tang) Ballistic Missile Submarines

The Type 096 (Tang class) submarine is a SSBN rumored to be in development for the Chinese People's Liberation Army Navy (PLAN). The Type 096 may carry 24 SLBMs, compared to the 12 of the previous Type 094 SSBN. According to analysts, it could also feature a hull similar to Western SSBNs. U.S. defense officials have stated that it might begin its first sea patrol in 2014.

Operational Nuclear Submarines in France

Rubis Class Attack Submarines

Figure 70: The Casabianca

The Rubis type is a class of first-generation nuclear attack submarines of the French Navy. They are the most compact nuclear attack submarines to date.

All submarines of the class (except for Casabianca) are named after gemstones.

Although the Rubis belonged to the same generation as the Redoutable class, due to President Charles De Gaulle's insistence on acquiring a nuclear deterrent for France, the Rubis program was started only in 1974, after the ballistic missile submarine program. The first Rubis hull was laid down in December 1976 and launched in 1979.

In 1987, the Canadian White Paper on Defense recommended the purchase of 10 to 12 Rubis or Trafalgar class submarines under technology transfer. with the choice of the type of submarine due to be confirmed before Summer 1988. The goal was to build up a three-ocean navy and to assert Canadian sovereignty over Arctic waters. The purchase was finally abandoned in April 1989.

The initial design of the Rubis proved to be problematic with unexpectedly high noise levels. This led to the Améthyste silencing program (AMÉlioration Tactique HYdrodynamique Silence Transmission Ecoute) which was applied to the fifth (S605 Améthyste) and sixth (S606 Perle) hulls.

The Améthyste and Perle were both longer that the original Rubis, 73.6 meters as compared with 72 meters and the program included upgrades to the sonar, reshaping of the hull form and bow to improve silencing and additional upgrades of the electronics. With the upgrades tested and proven, the original 4 boats were rebuilt to the same standards between 1989 to 1995.

During the Péan inter-allied maneuvers of 1998, Casabianca managed to "sink" the USS Eisenhower and her Ticonderoga class escort cruiser.

They have a central computer system for submarine detection, processing of information, and firing of weapons. The hull is made of 80 HLES high elasticity steel. The sonar dome and the conning tower are made of composite materials. The submarines have two crews, "Blue" and "Red", who man the ships every three months in turn.

They will be succeeded by the 2nd-generation Barracuda class.

Triomphant Class Ballistic Missile Submarines

The Triomphant class of ballistic missile submarines of the French Navy is the active class of four boats that entered service in 1997, 1999, 2004, and 2010. These four supersede the older Redoutable-class, and they provide the ocean-based component (the Force Océanique Stratégique in French) of the French Force de Frappe - its nuclear deterrent strike force.

The first three boats are all armed with the French-produced and armed M45 intermediate-range missile, and the fourth vessel Terrible, has tested and is equipped with the more advanced M51 missile. Each of the first three boats are to be retrofitted to the M51 missile standard, starting with Vigilant in Winter 2010, then Triomphant and ending with Téméraire in 2018.

In French, these are called Sous-Marin Nucléaire Lanceur d'Engins de Nouvelle Génération ("SNLE-NG, literally "Device-launching nuclear-powered submarine of the new generation"). They have replaced all of the Redoutable-class boats, with the last of those six boats being decommissioned in 2008. These submarines carry 16 Intermediate Range Ballistic Missile launching tubes apiece.

This class reportedly produces approximately 1/1000 of the detectable noise of the Redoutable-class boats (submarines), and they are ten times more sensitive in detecting other submarines. Initially armed with the M45 Missile, they are designed to carry the new M51 missile, which entered active service in 2010. As of October 2010, an M51 has been test-fired from one of these submarines across the Atlantic Ocean from near France to the west, and is equipped on the Terrible.

These boats were all constructed by the DCNS, and they carry an armament of 16 M45 SLBM or M51 SLBM missiles manufactured by the Aerospatiale company (now EADS Astrium Space Transportation.), plus conventional torpedoes and Exocet anti-ship missiles.

The French Navy's goal is to operate a force of four ballistic missile submarines (comparable with the Royal Navy's Vanguard-class submarines, of which two of the French boats are expected to be on patrol at any given time.

- Triomphant: Construction began on 9 June 1989; she was launched on 26 March 1994, and entered active service on 21 March 1997.

- Téméraire: Construction began on 18 December 1993; she was launched on 21 January 1998, and entered active service on 23 December 1999.

- Vigilant: Construction began in 1997; she was launched on 19 September 2003, and entered active service on 26 November 2004.

- Terrible: Construction began on 24 October 2000; she was launched on 21 March 2008, and entered active service on 20 September 2010.

Nuclear Submarines under Development in France

Barracuda Class Attack Submarines

The Barracuda class is a planned nuclear attack submarine class of the French Navy, designed by the French shipbuilder DCNS to replace the Rubis class submarines.

Barracudas will use technology from the Triomphant class, including pump jet propulsion. This class reportedly produces approximately 1/1000 of the detectable noise of the Redoutable-class boats (submarines), and they are ten times more sensitive in detecting other submarines. They will be fitted with torpedo-tube-launch cruise missiles MDCN SCALP Naval for long-range (1000 km) strikes against land strategic targets. Their missions will include anti-surface and anti-submarine warfare, land attack, intelligence gathering, crisis management and special operations. The Barracuda will use X-shaped stern planes.

The Barracuda class nuclear reactor incorporates several improvements over that of the preceding Rubis. Notably, it extends the time between refueling and complex overhauls (RCOHs) from 7 to 10 years, enabling higher at-sea availability.

In support of special operations missions, Barracudas may also accommodate up to 12 commandos, while carrying their equipment in a mobile pod attached aft of the sail.

On 22 December 2006 the French government placed a €7.9 billion order for six Barracuda submarines with DCN and their nuclear power plants with Areva-Technicatome. According to the DGA “Competition at the subcontractor level will be open to foreign companies for the first time.” The first submarine will be delivered in 2016. Alain Aupetit, DCN's Barracuda program director, said “The gap between the delivery of boats one and two will be two-and-a-half years. After that, we will deliver one boat every two years through to the delivery of the last submarine in 2026.”

Operational Nuclear Submarines in India

INS Chakra

The K-152 Nerpa is a 8,140-tonne (8,010-long-ton) Project 971 Shchuka-B (NATO: Akula II) type nuclear-powered attack submarine. Construction was started in 1993, but suspended due to lack of funding. K-152 Nerpa was launched in October 2008 and entered service with the Russian Navy in late 2009. The submarine will eventually be leased to the Indian Navy in 2010 and recommissioned as the INS Chakra.

While K-152 Nerpa was undergoing sea trials in the Sea of Japan on 8 November 2008, an accident caused the deaths of some twenty sailors and injury to twenty-one others. A fire suppression system discharged gas in the bow of the sub, suffocating civilian specialists and navy crew members.

The Nerpa was laid down at the Komsomolsk-on-Amur shipyard in 1993, but its completion was delayed for nearly a decade due to a lack of funds caused by the economic crisis of the early 1990s. The partly-constructed vessel was mothballed until 2004, when Rosprom (the Federal Agency for Industry) signed an agreement with the Indian government to complete the submarine and lease it to the Indian Navy. The vessel was intended to be completed by 2007, but underwent further delays. In 2007, it was transferred to the Vostok shipyard in the closed city of Bolshoy Kamen, Primorsky Krai, for fitting-out. It was launched in October 2008 for sea trials, following which it was due to be handed over to the Russian Defense Ministry. Reports in the Indian media suggest that the resumption of construction was underwritten with Indian funding.

The standards of the vessel's construction were criticized by several commentators. Alexander Golts, defense editor of the Yezhednevny Zhurnal newspaper, said that in the 1980s, the Amur shipyard turned out submarines "one after another, like pancakes," but from 1993 to 2008 had produced just one. "The old specialists had left, and the new ones lacked professionalism." An unnamed worker at the Amur shipyard told Komsomolskaya Pravda that there were "questions about the quality of the metal that was used in building the nuclear submarine", some of which had been bought from China, and alleged that "when the first trials of the submarine were carried out water was leaking in between the seams! So it is not surprising that the work dragged on."

During May 2009, the repairs were reported to be almost complete and new sea trials were planned for June 15–20. However, by October 2009, the work had still not been completed due to the shipyard's electrical supply having been disconnected. Nikolai Povzyk, the head of the shipyard, complained they had not been paid the 1.9 billion rubles (63.8 million dollars) owed for the work carried out on the Nerpa.

As of 2008, Russia had an agreement pending with India worth US$2 billion for the lease of Nerpa and another Project 971 Shchuka-B class submarine. Of this, K-152 Nerpa will be leased for 10 years to India at an estimated cost of US$650 million. After being handed over to the Indian Navy, it would be commissioned as INS Chakra. Nerpa is the Russian word for the Baikal seal, and Chakra is a weapon.

Indian naval crews earlier trained to operate the submarine near St. Petersburg and another group of sailors was expected to arrive in Vladivostok in late 2008 for joining sea trials. The training of the crew was viewed as crucial to India's own nuclear submarine program, known as the Advanced Technology Vessel (ATV).

After the 2008 accident, there were conflicting reports over the status of the lease. A Russian defense industry official denied that talks had been held with India on the delivery of the nuclear submarine. "Russia did not launch talks on a contract to supply India with the Nerpa nuclear-powered submarine." General of the Army Nikolai Marakov stated that Russia would commission the Nerpa and that it would join seven other Akula class submarines in Russia's Pacific Fleet. "The sum of $650-780 million, which Rosoboronexport and the Amur Shipbuilding Plant had negotiated over a long period of time with the Indian Ministry of Defense, will now be found in Russia," he said.

However, in May 2009, both Russian and Indian defense officials confirmed that the Nerpa would be joining the Indian Navy by the end of 2009, after Russian President Vladimir Putin visited the yard and announced an immediate release of 1.2 billion roubles, for the submarine construction.

On December 28, 2009, Nerpa was commissioned and joined the Russian Navy. The submarine underwent further adjustments in February 2010. As of August 2010 Russia was training a crew from the Indian Navy to sail the ship to India in fulfillment of the lease agreement.

Nuclear Submarines under Development in India

Arihant Class Ballistic Missile Submarines

The Arihant class submarines are nuclear-powered ballistic missile submarines being developed for the Indian Navy. The INS Arihant was introduced to the public on July 26, 2009 at a symbolic launch ceremony, which consisted of floating it by flooding the dry dock. The lead vessel of the class, INS Arihant, has been launched for sea trials by August 2013. Four vessels are being built and are expected to be in commission by 2023. The Arihant class is India's first indigenously designed and built submarine. The class is expected to consist of four vessels to be in commission with the Indian Navy by 2015, with a further four vessels planned to follow on. The Arihant class vessels were designed as a part of India's US$2.9 billion project to design and build nuclear-powered submarines.

The Arihant class submarines were designed and constructed as a part of the Indian Navy's Advanced Technology Vessel (ATV) Project. The first confirmation on the project came in 1998 from then defense minister of India, George Fernandes. The ATV project started with the intent to design nuclear-powered fast attack submarines, though over time the project was re-aligned towards the design of a ballistic missile submarine in order to complete India's nuclear triad. The project faced many challenges including design and miniaturization of the nuclear reactor.

The vessels are to be powered by an 85 MW pressurized water reactor (PWR) with enriched uranium fuel. The initial design of the miniaturized naval-version of the reactor developed by the Bhabha Atomic Research Centre (BARC) had technical challenges, after which Russian help was sought to resolve the design glitches. The final production version of the reactor was built by the BARC at the Indira Gandhi Centre for Atomic Research (IGCAR) at Kalpakkam. A land-based prototype of the marine PWR was first built at Kalpakkam and made operational in September 2006. The prototype included a 42-meter section of the submarine's pressure hull containing the shielding tank with water and the reactor, a control room, as well as an auxiliary control room for monitoring safety parameters. Successful operation of the prototype for three years yielded the data that enabled the production version for Arihant. The reactors are fueled by high fissile fuel requiring lesser refuels for the submarine.

The hulls for this class are built by L&T's Hazira shipbuilding facility. Tata Power SED built the control systems for the submarine. The systems for the steam turbine integrated with the PWR are supplied by Walchandnagar Industries.

The program has been shrouded in mystery and reports on the current status of the vessel have differed. It has been reported first by Defro.com that the nuclear reactor and other key systems including its surveillance equipment, sensors, weapons, and ordinance were still in the process of being installed.

Other reports have stated that the reactor is on board the submarine. India Today provided details of the nuclear reactor on-board. After the initial harbor trials are over, the steam turbines will be tested using a secondary power option. After successfully completing the turbine test, the nuclear reactor on-board the submarine will be activated. This is done by slowly raising the Zirconium rods which will make the nuclear reactor critical. Once the reactor is critical, the sea trial of the submarine is carried out. In 2010, the lead vessel of the class, INS Arihant was reported to have begun sea trials and the submarine is expected to formally join the Indian Navy by 2011. systems were not included in the submarine's launch and that it was only a ceremonious float-out. Although it has been reported that the new submarine already conducting sea trials, Navy chief Admiral Nirmal Verma said in December 2009, "Work is in progress to make INS Arihant operational for sea-trials...it should be inducted in two years or so."

In these two years the submarine will undergo harbor acceptance trials(HATs) where the submarine's nuclear reactor will be 'fired' and all the on board systems will be tested on the power generated by the submarine, which will be followed by sea acceptance trials (SATs) where the submarine will be operated at different speeds and different depths, the final phase will be the weapon trials where the submarine will fire its SLBMs (Submarine launched ballistic missiles) and torpedoes. Before working together all the systems installed in the submarine have to be tested one after the another (this process is called setting-to-work), the HATs and SATs are reported to last for one and a half year.

Full integration of key systems and Sea trials are expected to be extensive. The submarine is not expected to formally join the Indian Navy earlier than 2011. The INS Arihant will be more of "a technology demonstrator", rather than a fully-operational SSBN according to Admiral Verma. Two more submarines in the class are under construction and the hull sections of these has been completed at L&T facility in Hazira and is expected to be transported to Vishakhapatnam for assembling. INS Arihant is undergoing extensive sea trials before it's induction into service, and is said to be inducted prior to the induction of Akula class submarine.

The submarine is reported to be similar to the Russian Charlie-II class submarine, which India leased from the Soviet Union between 1988 and 1991. Personnel will have the opportunity to train on a Akula-II class nuclear attack submarine it will lease from Russia sometime in the second quarter of 2010. It is conjectured that India may have struck deal for the supply of two of these submarines with an option to purchase them in the future.

The Arihant class may possibly be armed with the existing 750 km K-15 Sagarika SLBM or the under-development K-4, an SLBM version of Agni-III.

Although it was widely speculated, the submarine does not sport either a "bulb" like towed array sonar, or a low blended sail. The glimpses of the submarine provided to the media seems to indicate a design with a blended hump behind the sail for the vertical launchers.

The Arihant class hull features twin flank-array sonars and Rafael broadband expendable anti-torpedo countermeasures. The UPA government's report card carried an image of INS Arihant, which provided the first glimpse of the complete sub.

Project Varsha

The Indian Navy is developing a new top-secret naval base for its nuclear submarines, code-named Project Varsha, located within a radius of approximately 200 kilometers (124.27 statute miles) from Visakhapatnam. Previous news reports suggested that Gangavaram had been the initial site for the new base. The new base is designed to support all 8-12 Arihant -class submarines to be built for the Indian Navy, and it will include state-of-the-art nuclear engineering support facilities and extensive crew accommodations. The Indian Navy is seeking foreign technical assistance pertaining to nuclear safety features for the base. While designed principally as a nuclear submarine support facility, the new base can accommodate other naval vessels because of the Indian Navy's expansion. This facility has been compared to the top-secret Hainan nuclear submarine base for the Chinese PLA Navy. This east coast base expansion program by the Indian Navy is in direct response to Chinese naval expansion into the region.

In addition to Project Varsha, in late 2009, the Hindustan Shipyard Limited (HSL), located at Visakhapatnam, was transferred from the Ministry of Shipping to the Ministry of Defense in order to support the Arihant -class nuclear submarine construction program.

Operational Nuclear Submarines in Russia

Project 941 (Typhoon) Ballistic Missile Submarines

Figure 71: Typhoon Class Submarine

The Project 941 or Akula class submarine (NATO reporting name: Typhoon) is a type of nuclear-powered ballistic missile submarine deployed by the Soviet Navy in the 1980s. With a maximum displacement of 33,800 tons, the Typhoons are the largest class of submarine ever built, large enough to accommodate decent living facilities for the crew when submerged for months on end. The source of the NATO reporting name remains unclear, although it is often claimed to be related to the use of the word "Typhoon" by Leonid Brezhnev in a 1974 speech while describing a new type of nuclear ballistic missile submarine. Soviet doctrine for these vessels was to have them launch SLBMs while submerged under the arctic ice, avoiding the traversal of the GIUK gap to remain safe from the enemy attack submarines and anti-submarine forces. Technically Typhoons were also able to successfully deploy their long-range nuclear missiles while moored at their docks.

Typhoon submarines are among the quietest Russian sea vessels in operation, being quieter and yet more maneuverable than their predecessors. Besides their missile armament, the Typhoon class features six torpedo tubes; four are designed to handle RPK-2 (SS-N-15) missiles or Type 53 torpedoes, and the other two are designed to launch RPK-7 (SS-N-16) missiles, Type 65 torpedoes, or mines. A Typhoon class submarine can stay submerged for periods up to 180 days in normal conditions, and potentially more if deemed necessary (e.g., in the case of a nuclear war). Their primary weapons system is composed of 20 R-39 (NATO: SS-N-20) ballistic missiles (SLBM) with a maximum of 10 MIRV nuclear warheads each.

Typhoon class submarines feature multiple pressure hulls that simplify internal design while making the vessel much wider than a normal submarine. In the main body of the sub, two Delta class pressure hulls lie parallel with a third, smaller pressure hull above them (which protrudes just below the sail), and two other pressure hulls for torpedoes and steering gear. This also greatly increases their survivability - even if one pressure hull is breached, the crew members in the other are safe and there is less potential for flooding.

Project 945 (Sierra) Attack Submarines

The Sierra I class (NATO reporting name) or Project 945 nuclear submarine was the Soviet Union's successor class to the partly successful Project 705 Lira (Alfa) class submarine. The Sierra class has a light and strong titanium pressure hull which enables the class to dive to greater depths, reduce the level of radiated noise and increase resistance to torpedo attacks.

The Sierra II class (NATO reporting name) or Project 945A nuclear submarine was a high tensile strength steel design.

Sierra I

The first hull, Karp, was laid down in May 1982 at the Gorky shipyard and was launched in August 1983 before being transferred to Severodvinsk for fitting out. It was laid up in 1987. The next hull to be built was the Kostroma, which was launched in July 1986 and was commissioned in September 1987. K-276 Kostroma was remained in a drydock since its February 11, 1992 collision with USS Baton Rouge (SSN-689).. Submarine was repaired on 29 June 1992 and was renamed to Krab, but in 1996 was renamed to its original name and is still in service with the Russian Northern fleet. The Sierra I type was also fitted with a releasable escape pod for the crew. The pod is covered by a V shaped casing on the port side of the sail.

Soviet titanium technology was far in advance of the West's, requiring fewer passes to achieve weld at the disadvantage of the cost of each hull which limits numbers built despite the advantages of greater depths and underwater speed. This was clearly shown in the Sierra class.

Submarines in class:

- B-239 Carp - commissioned 1987, removed from service
- B-276 Kostroma - commissioned Sep 1987, active

Sierra II

The Sierra II (Project 945.A) type has a considerably larger sail which is 16.5 ft (5.0 m) longer than the Sierra I type. The sail also has a curious flat, square leading edge which must impact hydrodynamic quietening. The masts are offset on the starboard side to make way for two escape pods in the sail. The starboard side also has a 10-point environment sensor fitted at right angles to the front end of the sail. Also, the Sierra II type has a much larger pod on its after fin. The pod houses the Skat 3 passive very low frequency towed array.

Submarines in class:

- B-534 Nizhniy Novgorod - commissioned Dec 1990, active
- B-336 Pskov - commissioned 1993, active

Sierra III (provisional)

The sole Sierra III/Project 945AB (Mars), was laid down in March 1990 but was scrapped in November 1993 before completion. Cited authoritative reference has no mention of additional hulls, with the second and third cancelled before their keels were laid.

While only one is considered to be completely operational, the first hull of the series was due to be brought for repair at the Zvezdochka Shipyard, Severodvinsk in 2007.

Project 949 (Oscar) Cruise Missile Submarines

The Project 949 (Granit) and Project 949A (Antey) Soviet Navy/Russian Navy cruise missile submarines are known in the West by their NATO reporting names, the Oscar-I and Oscar-II classes, respectively.

Project 949 submarines were the largest cruise missile submarines in service, until the Ohio class SSGN cruise missile submarine converted from SSBN and returned to service on October 15, 2007, and the third largest submarines in terms of displacement and length. Only the Typhoon class Soviet/Russian submarines, the American Ohio class ballistic missile submarines and the Russian Borei class submarines are larger.

Figure 72: Oscar Class Submarine

Project 949 Granit

Two Project 949 Granit submarines were built at Severodvinsk and assigned to the Soviet Northern Fleet:

- K-525 Arkhangelsk, laid down July 25, 1975; launched May 3, 1980; commissioned December 30, 1980, decommissioned July 31, 1996, scrapped at Sevmash 2001

- K-206 Murmansk (ex-Minskiy Komsomolets), laid down April 22, 1979; launched December 10, 1982; commissioned November 30, 1983, renamed Murmansk on April 6, 1993, decommissioned April 16, 1996, scrapped at Zvezdochka 2004

Project 949A Antey

Eleven Project 949A Antey submarines were completed at Severodvinsk. Five were assigned to the Soviet Northern Fleet:

- K-148 Krasnodar, laid down July 22, 1982; launched March 3, 1985; commissioned September 30, 1986; named Krasnodar" June 3, 1992, removed from active service, status unclear

- K-119 Voronezh, laid down February 25, 1986; launched December 16, 1988; commissioned December 29, 1989; named Voronezh April 6, 1993, 01.2009-05.2009 overhaul at Zvezochka, active

- K-410 Smolensk, laid down December 9, 1986; launched January 20, 1990; commissioned December 22, 1990; named Smolensk April 6, 1993, inactive, from 2007 waiting at Zvezdochka for overhaul

- K-266 Orel, (ex-Severodvinsk), laid down January 19, 1989; launched May 22, 1992; commissioned December 30, 1992; named Severodvinsk December 1991; renamed Orel April 6, 1993, active

- K-141 Kursk, laid down March 22, 1992; launched May 16, 1994; commissioned December 30, 1994; lost August 12, 2000; raised September–October 2001

Six were assigned to the Soviet Pacific Fleet, all originally commissioned in the Northern Fleet before transfer to the Pacific:

- K-173 Krasnoyarsk, laid down August 4, 1983; March 27, 1986; commissioned December 31, 1986, removed from active service, status unclear

- K-132 Irkutsk, laid down May 8, 1985; launched December 27, 1987; commissioned December 30, 1988; transferred to the Pacific Fleet August–September 1990 inactive reserve 1997

- K-442 Chelyabinsk, laid down May 21, 1987; launched June 18, 1990; commissioned December 28, 1990; transferred to the Pacific Fleet August–September 1991, inactive reserve 1998

- K-456 Vilyuchinsk (ex-Kasatka), laid down February 9, 1988; launched June 28, 1991; commissioned August 18, 1992; transferred to the Pacific Fleet August–September 1993, removed from active service, status unclear

- K-186 Omsk, laid down July 13, 1989; launched May 10, 1993, commissioned December 10, 1993; transferred to the Pacific Fleet August–September 1994, submarine was in overhaul 2007-2008

- K-150 Tomsk, laid down August 27, 1991; launched July 20, 1996; commissioned December 30, 1996; transferred to the Pacific Fleet September 1998, removed from active service for some time, since November 2008 undergoing repair at Bolshoy Kamen Zvezda shipyard to replace its steam generator

Three more Project 949A Antey submarines were planned.

- K-139 Belgorod, laid down July 24, 1992, is currently still on the building ways at the SEVMASH Shipyard in Severodvinsk. Its construction was frozen several times due to lack of funds. Finally, on July 20, 2006, Russian Minister of Defense Sergey Ivanov announced, "The Ministry of Defense does not need Belgorod... therefore, it will not finance its further construction." If the submarine is going to be finished, it is not clear who will pay for it. Construction halted at approximately 75%.

- K-135 Volgograd, laid down September 2, 1993; construction stopped January 22, 1998; incomplete

- K-160 Barnaul, laid down April 1994; construction stopped; incomplete

At one stage it had been planned to develop a new fourth-generation follow-on to the Project 949A, but this plan was later scrapped.

Like other Soviet submarine designs, the Project 949 not only has a bridge open to the elements on top of the sail but, for use in inclement weather, an enclosed bridge forward of this station in the sail.

A distinguishing mark is a slight bulge at the top of the fin. A large door on either side of the fin reaches this bulge. These are wider at the top than on the bottom, and are hinged on the bottom. The Federation of American Scientists reports that this submarine carries an emergency crew escape capsule; it is possible that these doors cover it.

The Oscar Class is commonly referred to as Mongo by crews of U.S. patrol aircraft in reference to their massive size.

Project 667BDR, Kalmar (Delta III) Ballistic Missile Submarines

The Delta class (Project 667B) is a class of submarines which formed the backbone of the Soviet and Russian strategic submarine fleet since its introduction in 1973. They carry nuclear ballistic missiles of the R-29 Vysota family, with the Delta I, II, III and IV carrying the R-29 (NATO reporting name: SS-N-8 'Sawfly'), R-29D (SS-N-8 'Sawfly'), R-29R (SS-N-18 'Stingray') and R-29RM (SS-N-23 'Skiff') respectively. The Delta I carried 12 missiles, the Delta II was a "stretched" Delta I that could carry 16 missiles; the Delta III and IV carry 16 missiles with multiple warheads and the submarines have improved electronics and noise reduction.

The R-27 Zyb missile carried by the Project 667s of the late 1960s had a range of just 2,500–3,000 km (1,600–1,900 mi), so the earlier subs were forced to patrol close to the North American coast, whereas the Deltas could launch the >7,700 km (4,780 mi)-range R-29s from the relative safety of the Arctic Ocean. In turn the Deltas were superseded by the larger Typhoon class submarines. The early Deltas remained in service until 1990s with treaties such as START I. High running costs and the retirement of the Typhoons' R-39 missiles meant that some Delta III's were reactivated in the early 2000s to replace the Typhoons.

As of July 2008, the Center for Arms Control Studies estimated the strength of the Russian strategic submarine fleet at one Typhoon class submarine (used to test the R-30 Bulava missile), six Delta III and six Delta IV subs. Of these two Delta III boats were decommissioning, with the rest expected to follow in the next few years. They will ultimately be replaced by the new Borei class submarines (also known as the Dolgorukiy class), of which the first is undergoing sea trials without its missiles and is not due to enter service until 2011. Five Delta IV boats have been overhauled in recent years, with work continuing on the last one. The third Delta IV, K-64 Vladimir, has been converted for use by Special Forces.

The 667BDR Kal'mar (Squid) Delta-III class submarine was a large ballistic missile submarine. Like the earlier Delta class submarines the Delta III is a double hulled design with a thin low magnetic steel outer hull wrapped around a thicker inner pressure hull. Development began in 1972 at the Rubin Central Design Bureau for Marine Engineering. The submarine was the first that could launch any number of missiles in a single salvo, also the first submarine capable of carrying ballistic missiles with multiple independently targetable reentry vehicles. The submarine carried 16 of the R-29R missiles each carrying 3 to 7 MIRVs, with a range of 6,500 to 8,000 km, depending on the number of re-entry vehicles.

The Delta III was also equipped with a new battle management system the Almaz-BDR for the fire control of torpedoes in deep-water, also a new inertial navigation system Tobol-M-1, and later the Tobol-M-2. A hydroacoustic navigational system called Shmel' (Bumblebee) allows the submarine to determine its position from hydroacoustic buoys. Finally a new sonar system called Rubikon was fitted.

On September 30, 2008 a Russian Navy spokesman reported that Ryazan had successfully completed a 30-day transit from a base in northern Russia under the Arctic ice cap to a base on the Kamchatka Peninsula. The Navy added that Ryazan will soon be assigned to regularly patrol the Pacific Ocean. As of July 2008, six Delta III boats were active, of which two were believed to be in the process of decommissioning.

Project 667BDRM, Delfin (Delta IV) Ballistic Missile Submarines

The Delta IV is a class of Russian SSBN submarine. Seven were built from 1985 to 1992; all are still in service in the Russian navy today. The submarines, based at the Sayda Guba Naval Base, operate in the Northern Fleet. The Severodvinsk Shipyard built these vessels between 1981 and 1992. The last vessel was the Novomoskovsk.

The design of the Delta IV resembles that of the Delta III and constitutes a double-hulled configuration with missile silos housed in the inner hull.

The submarine has an operational diving depth of 320 meters, with a maximum depth of 400 meters. The propulsion system allows speeds of 24 knots (44 km/h) surfaced or submerged using two VM-4 pressure water reactors rated at 180 MW. It features two turbines of type GT3A-365 rated at 27.5 MW. The propulsion system drives two shafts with seven-bladed fixed-pitch propellers.

The submarine design is similar to that of Delta III (Project 667 BDR). The submarine constitutes a double-hulled configuration with missile silos housed in the inner hull. The forward horizontal hydroplanes are arranged on the sail. They can rotate to the vertical for breaking through the ice cover. The operational diving depth of the submarine is 320 m with a maximum depth of 400 m. The propulsion system provides a run speed of 24 knots surfaced and 24 knots submerged. The submarine carries supplies for an endurance of 80 days. The surface of the submarine has an acoustic coating to reduce the acoustic signature.

During the development of the 667BDRM SSBN several measures were included to reduce its noise level. The gears and equipment are located on a common base isolated from the pressure hull, and the power compartments are also isolated. The efficiency of the anti-hydroacoustic coatings of the light outer hull and inner pressure hulls have been increased. Newly designed five-bladed propellers with improved hydroacoustic characteristics are employed.

The Delta IV submarines employs the D-9RM launch system and carries 16 R-29RMU Sineva liquid-fueled missiles which each carry four independently targetable reentry vehicles (MIRVs). Unlike previous modifications, the Delta IV submarine is able to fire missiles in any direction from a constant course in a circular sector. The underwater firing of the ballistic missiles can be conducted at a depth of 55 meters while cruising at a speed of 6-7 knots. All the missiles can be fired in a single salvo.

The 667BDRM Delphin submarines are equipped with the TRV-671 RTM missile-torpedo system that has four torpedo tubes with a caliber of 533 mm. Unlike the Delta III, it is capable of using all types of torpedoes, antisubmarine torpedo-missiles and anti-hydroacoustic devices. The battle management system Omnibus-BDRM controls all combat activities, processing data and commanding the torpedo and missile-torpedo weapons. The Shlyuz navigation system provides for the improved accuracy of the missiles and is capable of stellar navigation at periscope depths. The navigational system also employs two floating antenna buoys to receive radio-messages, target destination data and satellite navigation signals at great depth. The submarine is also equipped with the Skat-VDRM hydroacoustic system.

The Delta IV submarines are strategic nuclear missile submarines designed to carry out strikes on military and industrial installations and naval bases. The submarine carries the RSM-5 Makeyev missile (NATO reporting name: SS-N-23 Skiff) submarine-launched ballistic missile (SLBM). The RSM-54 is a three-stage liquid-propellant ballistic missile with a range of 8,300 km. The warhead consists of four to ten multiple, independently targeted re-entry vehicles (MIRVs) each rated at 100 kt. The missile uses stellar inertial guidance to provide a circular error probable (CEP) of 500 m. The CEP value is a measure of the accuracy of strike on the target and is the radius of the circle within which half the strikes will impact.

The submarine is also capable of launching the Novator SS-N-15 Starfish anti-ship missile or Mk 40 anti-ship torpedoes. Starfish is armed with a 200 kt nuclear warhead and has a range of up to 45 km. The submarine has four 533 mm torpedo tubes capable of launching all types of torpedoes, including anti-submarine torpedoes and anti-hydroacoustic devices. The system is fitted with a rapid reloading torpedo system. The submarine can carry up to 18 missiles or torpedoes. All torpedoes are accommodated in the bow section of the hull.

Project 971 (Akula) Attack Submarines

Project 971 (Shchuka-B, 'Shchuka' meaning pike, NATO reporting name "Akula"), is a nuclear-powered attack submarine (SSN) first deployed by the Soviet Navy in 1986. There are three sub-classes or flights of Shchuka, consisting of the original seven "Akula I" submarines which were built between 1982 and 1986, five "Improved Akula" submarines built between 1986 and 1991, and two "Akula II" submarines built from 1991. The distinction between the Improved Akula and the Akula II class is debated by authoritative sources. The Russians call all of the submarines Schuka-B, regardless of modifications.

Note that the name Akula ("shark") is the Soviet designation of the ballistic missile submarine class designated by NATO as the Typhoon class submarine.

As with many Soviet/Russian craft, information on the status of the Akula Class submarines is sparse, at best. Information provided by several internet sites varies widely.

Akula-I Submarines

Of the seven original Akula-I submarines, only three are known to still be in service. These boats are equipped with MGK-500 Skat sonar system (with NATO reporting name Shark Gill). The lead boat of the class, K-284 'Akula' was decommissioned in 2001, apparently to help save money in the cash-strapped Russian Navy. K-322 'Kashalot' and K-480 'Bars' [Currently Ak Bars] are in reserve. K-480 'Bars' was put into reserve in 1998, and is being dismantled in February 2010. 'Pantera' was due to return to service in March–April 2008 after a comprehensive overhaul.

Akula-I Improved Submarines

The five Akulas of this class are all thought to be in service. There is some debate about the hull number of the 5th submarine. Some sources report it as K-267, while others say K-295. Most however agree on the name 'Drakon', which is K-295 now named Samara. The original MGK-500 Skat sonar system on Akula-I is upgraded to the MGK-501 Skat-MS. Sources also disagree as to whether construction of this class has been suspended, or if there are a further two units planned. Improved Akula-I Hulls: K-461 Volk, K-154 Tigr, K-331 Narval.

Akula-II Submarines

The Akula II is approximately 230 tons larger in displacement and 2.5m greater in LOA compared to that of the Akula I's. The added space was used for an active noise reduction system. The MGK-501 Skat sonar system on Akula-I is replaced to a new MGK-540 Skat-3 sonar system, which is considered by its designers as the same class of American AN/BQQ-5/6. The K-157 Vepr (The first ship of this type) became the first Soviet submarine that was quieter than the latest U.S. attack submarines of that time, which was the Improved Los Angeles class (SSN 751 and later) The K-335 Gepard is the second unit.

The Soviet advances in sound quieting were of considerable concern to the West, for acoustics was long considered the most significant advantage in U.S. submarine technology compared to the Soviets.

In 1983-1984 the Japanese firm Toshiba sold sophisticated, nine axis milling equipment to the Soviets along with the computer control systems, which were developed by Norwegian firm Kongsberg Vaapenfabrik. U.S Navy officials and Congressmen announced that this technology enabled the Soviet submarine builders to produce more accurate and quieter propellers.

The command and control methods and also weapons for this later variant were centralized, with a high degree of automation, similar to the Project 705 Alfa SSN. This automation reduced crew numbers.

Due to the breakup of the Soviet Union in 1991, production of all Akulas slowed.

The 1999-2000 edition of Jane's Fighting Ships incorrectly listed the first Akula-II as Viper (The actual name is "Vepr", wild boar in Russian), commissioned November 25, 1995, Gepard (Cheetah), launched 1999 and commissioned December 5, 2001, and Nerpa, laid down in 1993 began sea trials in October, 2008 and was expected to be commissioned and leased to the Indian Navy as INS Chakra in late 2009. Nerpa will be delivered to the Indian Navy in early 2011.

The Gepard is known to have a slightly smaller and streamlined towed array dispenser than the other submarines of the class. It also appears to have a longer sail than other Akula class submarines. President Vladimir Putin was on board Gepard after the Kursk incident.

Project 671RTM Shchuka (Victor III) Attack Submarines

The Victor class is the NATO reporting name for a type of nuclear-powered submarine that was originally put into service by the Soviet Union around 1967. In the USSR, they were produced as Project 671. Victor-class subs featured a teardrop shape, which allowed them to travel at high speed. These vessels were primarily designed to protect Soviet surface fleets and to attack American ballistic missile subs, should the need ever arise.

Victor I

Victor I - Soviet designation Project 671 Yorzh (Ruffe) - was the initial type that entered service in 1967; 16 were produced. Each had 6 tubes for launching Type 53 torpedoes and SS-N-15 cruise missiles, and mines could also be released. Subs had a capacity of 24 tube-launched weapons or 48 mines (a combination would require less of each).

Victor II

Victor II - Soviet Designation Project 671RT Syomga (Atlantic Salmon)- entered service in 1972; 7 were produced in the 1970s. These were originally designated Uniform class by NATO. They had similar armament to Victor I. The Soviet Union discovered through its spy network that Americans could easily track Victor II-class subs and subsequently halted production of this type to design the Victor III class.

Victor III

Victor III - Soviet Designation Project 671RTM Shchuka (Pike) - entered service in 1979; 25 were produced until 1991. Quieter than previous Soviet submarines, these ships had 2 tubes for launching SS-N-21 or SS-N-15 missiles and Type 53 torpedoes, plus another 4 tubes for launching SS-N-16 missiles and Type 65 torpedoes. 24 tube-launched weapons or 36 mines could be on-board. The Victor-III caused a minor furor in NATO intelligence agencies at its introduction because of the distinctive pod on the vertical stern-plane. Speculation immediately mounted that the pod was the housing for some sort of exotic silent propulsion system, possibly a magnetohydrodynamic drive unit. Another theory proposed that it was some sort of weapon system. In the end, the Victor-III's pod was identified as a hydrodynamic housing for a reelable towed passive sonar array; the system was subsequently incorporated into the Sierra-class and Akula-class SSNs.

Borei-class Submarine

The Borei class (also known as the Dolgorukiy class after the name of the lead vessel, the Yuriy Dolgorukiy) is a class of nuclear-powered ballistic missile submarine produced by Russia and operated by the Russian Navy. The class is intended to replace the Delta III, Delta IV and Typhoon classes now in Russian Navy service. The class is named after Boreas, the North wind.

The first design work was laid down in mid-1980s but and the build of the first unit of the Borei class (officially designated "Project 955") started in 1996.(A short-lived, smaller parallel design appeared in the mid-1980s was designated Project 935 Borei II[5]) A new submarine-launched ballistic missile was developed in parallel, called the R-39UTTH "Bark". However, the work on this missile was abandoned, and a new missile called the Bulava was designed.

The submarine needed to be redesigned to accommodate the new missile, and the project name was changed to Project 955. The vessels are being built at the Northern Machinebuilding Enterprise (Sevmash) in Severodvinsk, and were designed by the Rubin Marine Equipment Design Bureau (Rubin). Because of the repeated failures during Bulava test launches, some experts have suggested that the Borei submarine could instead be armed with R-29RMU Sineva missiles. The Sineva is already in active duty on the Delta IV class submarine.

Advances include a compact and integrated hydrodynamically efficient hull for reduced broadband noise and the first ever use of pump-jet propulsion on a Russian nuclear submarine. Borei is approximately 170 meters (560 ft) long, (some claimed the Borei is 574 ft long) 13 meters (43 ft) in diameter, and has a maximum submerged speed of at least 46 kilometers per hour (25 kn; 29 mph). They are equipped with a floating rescue chamber designed to fit in the whole crew. Smaller than the Typhoon class, the Borei was initially slated to carry 12 missiles but was able to carry 4 more due to the decrease in mass of the 45-ton Bulava SLBM (a modified version of the Topol-M ICBM) over the originally proposed R-39UTTH Bark. Cost is some 23 bln RUR ($890 million USD), in comparison the cost of an Ohio-class SSBN was around 2 billion USD per boat (1997 prices).

A fifth generation successor/supplement is already in development.

The launch of the first submarine of the class, the Yuriy Dolgorukiy, was scheduled for 2002 but was delayed because of budget constraints. The vessel was eventually rolled out of its construction hall on 15 April 2007 in a ceremony attended by many senior military and industrial personnel. The Yuriy Dolgorukiy was the first Russian strategic missile submarine to be launched in seventeen years since the end of the Soviet era. Currently, there are three more Borei-class submarines under construction, named Aleksandr Nevskiy, Vladimir Monomakh and Knyaz Vladimir. The planned contingent of eight strategic submarines is expected to be commissioned within the next decade (five Project 955 are planned for purchase through 2015).

On 2 December 2010 the second Borei-class submarine, Alexander Nevsky, was moved to a floating dock in Sevmash shipyard. There the final preparations took place before the submarine was launched. Submarine was launched on 6 December 2010 and began sea trials on 24 October 2011.

On 28 June 2011 a Bulava missile was launched for the first time from the Borei-class submarine Yury Dolgorukiy. The test was announced as a success. After long delays finally the lead vessel Yury Dolgoruky joined the Russian Navy on 10 January 2013.

Nuclear Submarines under development in Russia

Project 885 (Graney) Attack Submarines

The Yasen class submarine, also known in the literature as the Graney class and Severodvinsk class, is a new Russian nuclear multipurpose attack submarine class. The submarine is based on the Akula-class submarine and the Alfa-class submarines and are projected to replace Russia's Soviet-era class attack submarines both Akula class and Oscar class.

The ship's design is claimed to be state-of-the-art. Larger than the older Akula class attack submarines, the Yasen class will have significantly more firepower. The submarine is presumed to be armed with 32 cruise missiles, with several types suggested, including the 3M51 Alfa SLCM, the P-800 Oniks SLCM or the RK-55 Granat SLCM. It will also have 8 torpedo tubes as well as mines and anti-ship missiles like the RPK-7.

This class is the first Russian submarines to be equipped with a spherical sonar, designated as Irytysh-Amfora. Due to the large size of this spherical array, the torpedo tubes are slanted. The submarine has a crew of about 90, suggesting a moderate degree of automation in the submarine's different systems. The newest U.S. attack sub, the Virginia-class submarine, has a crew of 134 in comparison.

Operational Nuclear Submarines in the UK

Trafalgar Class Attack Submarines

The Trafalgar-class submarines were, until the introduction of the Astute class, the Royal Navy's most advanced nuclear fleet submarines. Torbay, Trenchant, Talent, and Triumph have been fitted with Sonar 2076, which the Royal Navy describes as the most advanced sonar in service with any navy in the world.

The Trafalgar class is a refinement of the Swiftsure class and designed six years later than its predecessor. The design included a new reactor core and Type 2020 sonar. Internal layout is almost identical to the Swiftsure, and it is only 2.5 meters longer. The Trafalgar class have strengthened fins and retractable hydroplanes, allowing them to surface through thick ice. The hull is also covered in anechoic tiles which are designed to absorb sound rather than reflect it, making the boats more difficult to detect with active sonar.

The first Trafalgar-class submarine was ordered on 7 April 1977 and completed in 1983. Turbulent was ordered on 28 July 1978; Tireless on 5 July 1979; Torbay on 26 June 1981; Trenchant on 22 March 1983; Talent on 10 September 1984; and finally Triumph on 3 July 1986.

In 1993 Triumph sailed to Australia, covering a distance of 41,000 miles whilst submerged and without any forward support. This marked the longest solo deployment by any British nuclear submarine.

The Trafalgar class was to be replaced by the Future Attack Submarine (FASM), however this project was effectively cancelled in 2001 and replaced by the Maritime Underwater Future Capability. The Astute class will eventually replace the Trafalgar class as well as the now-retired Swiftsure. As of 2008 it is planned that the last Trafalgar-class submarines will remain in service until 2022. The name Trafalgar refers to the Battle of Trafalgar fought between the Royal Navy and the combined fleets of France and Spain.

The Trafalgar class have suffered from a number of technical difficulties. In 1998, Trenchant experienced a steam leak, forcing the crew to shut down the nuclear reactor. In 2000, a leak in the reactor primary cooling circuit was discovered on Tireless, forcing her to proceed to Gibraltar on diesel power. The fault was found to be due to thermal fatigue cracks, requiring the other Trafalgar-class boats, and some of the remaining Swiftsure-class boats, to be urgently inspected and if necessary modified. In August 2000 it was revealed that with Tireless still at Gibraltar, Torbay, Turbulent, Trenchant and Talent were at Devonport for refit or repair and with Trafalgar undergoing sea trials, only one boat, Triumph, was fully operational. By 2005, refits had reportedly corrected these problems.

In 2002, Trafalgar ran aground off Skye during Operation Cockfight.

In 2007, a small explosion aboard HMS Tireless resulted in the death of two sailors and injury of another. The accident took place while the submarine was submerged under the Arctic icecap during a joint British-American exercise. An oxygen candle in the forward section of the submarine was thought to be responsible for the accident.

The first of the submarines to be taken out of active service was Trafalgar, which was decommissioned on 4 December 2009.

Figure 73: HMS Tireless S-88

Vanguard Class Ballistic Missile Submarines

The Vanguard class are the Royal Navy's current nuclear ballistic missile submarines (Ship Submersible Ballistic Nuclear or SSBN), each armed with up to 16 Trident II Submarine-launched ballistic missiles (SLBMs). The class was introduced in 1994 as part of the UK government's Trident nuclear weapons program.

The class includes four boats: Vanguard, Victorious, Vigilant, and Vengeance, all built at Barrow-in-Furness by Vickers Shipbuilding and Engineering Ltd between 1986 and 1999.

All four boats are based at HM Naval Base Clyde (HMS Neptune), 40 km (25 miles) west of Glasgow, Scotland. Since the decommissioning of all WE.177 free-fall nuclear bombs in 1998, and the removal of all nuclear weapons from the British Army, the Royal Air Force, and all surface ships of the Royal Navy, the Vanguard submarines' Trident SLBM system is the sole holder of the United Kingdom's nuclear weapons.

The Vanguards were designed from the outset as an unlimited-range nuclear powered ballistic missile submarine, unlike the previous Resolution class which was adapted from the then existing Valiant class and the American Lafayette class of nuclear powered fleet ballistic missile submarines (SSBN in US terms). At 149.9 meters (492 ft) long and 15,980 tons (15,730 long tons) submerged displacement the Vanguards are roughly twice the size of the Resolutions, and are the third largest submarines ever built, by displacement when surfaced, after the Soviet Typhoon and American Ohio classes. The great increase in size is largely related to the much larger size of the Trident D-5 missile as compared to Polaris.

The Vanguards were designed and built at Barrow-in-Furness by Vickers Shipbuilding and Engineering Limited (VSEL), now BAE Systems Submarine Solutions. The Devonshire Dock Hall was built specifically to build these submarines. The missile compartment is based on the system used on the Ohio class, though only 16 missiles are carried rather than the 24 of the Ohio.

In addition to the missile tubes the Vanguard class is fitted with four 21-inch (53 cm) torpedo tubes and carries the Spearfish heavyweight torpedo, allowing it to engage submerged or surface targets at ranges up to 65 kilometers (40 mi; 35 nmi). Two SSE Mark 10 launchers are also fitted to allow the boats to deploy Type 2066 and Type 2071 decoys, and a UAP Mark 3 electronic support measures (ESM) intercept system is fitted.

HMS Vanguard, Victorious, Vigilant and Vengeance were commissioned in 1993, 1995, 1996 and 2000 respectively.

Vanguard carries the Thales Underwater Systems Type 2054 composite sonar. The Type 2054 is a multi-mode, multi-frequency system, which incorporates the 2046, 2043 and 2082 sonars. The fleet is in the process of having their sonars refitted to include open architecture processing using commercial off the shelf technology.

A Type 2043 hull-mounted active/passive search sonar is also carried, as is a Type 2082 passive intercept and ranging sonar. Finally a Type 2046 towed array is carried. This operates at very low frequency, giving a passive search capability.

Two periscopes are carried, a CK51 search model and a CH91 attack model. Both have a TV camera and thermal imaging camera as well as conventional optics.

A Type 1007 I-band navigation radar is also carried.

A new pressurized water reactor, the PWR 2, was designed for the Vanguard class. This has double the service life of previous models, and it is estimated that a Vanguard class submarine could circumnavigate the world 40 times without refueling. This should allow the class to carry out their entire service life without the need for expensive refueling. The reactor drives two GEC turbines linked to a single shaft pump jet propulsor. This propulsion system gives the Vanguards a maximum submerged speed of 25 knots (46 km/h; 29 mph). Auxiliary power requirements are provided by a pair of 6MW Steam-turbine generators supplied by WH Allen, (later known as NEI Allen, Allen Power & Rolls-Royce) with two Paxman diesel alternators for provision of backup power supply.

A decision on the replacement of Trident was made on the 4 December, 2006. Then-Prime Minister Tony Blair told MPs it would be "unwise and dangerous" for the UK to give up its nuclear weapons. He outlined plans to spend up to £20 billion on a new generation of submarines for Trident missiles. He said submarine numbers may be cut from four to three, while the number of nuclear warheads would be cut by 20 percent to 160. Blair said although the Cold War had ended, the UK needed nuclear weapons, as no-one could be sure another nuclear threat would not emerge in the future.

The 2006 white paper stated that the option of reducing the Trident carrying submarine fleet from four to three submarines, as part of plans to cut costs and to promote nuclear disarmament, would be considered. On 23 September, 2009, Prime Minister Gordon Brown confirmed that this reduction to three submarines was still under consideration.

Astute Class Attack Submarines

The Astute-class submarines are the next-generation nuclear fleet submarines of the UK Royal Navy. The class sets a new standard for the Royal Navy in terms of weapons load, communication facilities, stealth and crew comfort. The boats are being constructed by BAE Systems Submarine Solutions at Barrow-in-Furness.

Seven boats will be constructed. The first of class, Astute, was launched in 2007 and commissioned in 2010, and the second, Ambush, was launched on 6 January 2011.

Astute-class boats are powered by a Rolls-Royce PWR2 (Core H) reactor and fitted with a pump-jet propulsor. The PWR2 reactor was developed for the Vanguard-class ballistic missile submarines. As a result Astute-class boats are about 30 per cent larger than previous British attack submarines, which were powered by smaller diameter reactors. It is the first Royal Navy submarine class to have a bunk for each member of the ship's company, ending the practice of 'hot bunking', whereby two sailors on opposite watches shared the same bunk.

Like all Royal Navy submarines, the bridge fin of the Astute-class boats is specially reinforced to allow surfacing through ice caps. They can fire Tomahawk cruise missiles from their launch tubes, including the new "tactical Tomahawk" currently under development. More than 39,000 acoustic tiles mask the vessel's sonar signature, giving the Astute class a better stealth quality than any other submarine previously operated by the Royal Navy. The vessel is equipped with the advanced Sonar 2076, which is an integrated passive/active search and attack sonar suite with bow, intercept, flank and towed arrays.

The Astute Combat Management System is an evolved version of the Submarine Command System used on other classes of submarine. The system receives data from the boat's sensors and displays real time imagery on all command consoles. The submarines also have DESO 25 high-precision echo sounders, two CM010 non-hull-penetrating optronic masts which carry thermal imaging and low-light TV and color CCD TV sensors.

The Astute-class submarines can be fitted with a dry deck shelter which allows special forces (e.g. SBS and SAS) soldiers to deploy whilst the submarine is submerged.

BAE Systems issued a profit warning on 11 December 2002 as a result of the cost overruns and delays it was experiencing with the Astute class and also the Nimrod MRA4 maritime reconnaissance/attack aircraft. The delay was caused primarily by the problems of using 3D CAD; Armed Forces Minister Adam Ingram said in 2006 that "due to the complexity of the program, the benefits that CAD was envisaged to provide were more difficult to realize than either MoD or the contractor had assumed." Other issues were the insufficient capabilities within GEC-Marconi which became evident after contract-award and poor program management. BAE and the Ministry of Defense reached an agreement in February 2003 whereby they would invest £250 million and £430 million respectively to address the program's difficulties.

A major element of this was the enlisting of advice and expertise from General Dynamics Electric Boat. The MoD also signed a design and production drawing work contract through the U.S. Navy which ran from 2004 to 2007.

Work on the second and third submarines, Ambush and Artful, proceeded well with major milestones such as the closure of Ambush's reactor compartment, demonstrating significant schedule advance compared with Astute. BAE Systems and the MoD have made efforts to reduce costs and achieved significant cost-cutting and productivity gains. A £580 million cost increase was agreed in 2007 due to maturing of the design requiring more materials, inflationary costs, and "some program throughput assumptions at the Barrow site not being borne out."

First-of-class HMS Astute was launched by Camilla, Duchess of Cornwall on 8 June 2007.

As of March 2008 the program was 48% (or £1.2 billion) over-budget and 47 months late. Further delays due to a range of technical and program issues brought the program to a position of 57 months late and 53% (or £1.35 billion) over-budget by November 2009, with a forecast cost of £3.9 billion for the first three Astute boats.

As of August 2006 BAE Systems was negotiating for a contract to build another four Astute-class submarines (boats 4 to 7). The fourth boat was ordered on 21 May 2007, to be called Audacious, and the names of boats 5, 6, and 7 have been agreed as Agamemnon, Anson, and Ajax.

Upon the beginning of sea trials of Astute in November 2009, it was reported that long-lead items for boats 5 and 6 have been ordered, including their nuclear reactor cores, and that the stated intention of the MoD was for a total of seven Astute-class submarines.

On 25 March 2010, BAE Systems were given the go-ahead by the government to begin construction on boats 5 and 6, being given a £300 million contract for the "initial build" of boat 5 and "long lead procurement activities" for boat 6. In the same week the government re-affirmed their commitment to the construction of seven Astute-class submarines.

The order of 7 Astute-class boats was confirmed in the Strategic Defense and Security Review of October 2010. In December that year it was confirmed by the MoD that "early work" was under way on boats 5 and 6.

Figure 74: HMS Astute on a Shiplift

Operational Nuclear Submarines in the US

SCB-303: Los Angeles Class Attack Submarines

The Los Angeles class, sometimes called the LA class or the 688 class, is a class of nuclear-powered fast attack submarines (SSN) that forms the backbone of the United States submarine fleet. With 45 submarines on active duty and 17 retired, the Los Angeles class is the most numerous nuclear powered submarine class in the world. The class was preceded by the Sturgeon class and followed by the Seawolf and Virginia classes. Except for USS Hyman G. Rickover (SSN-709), submarines of this class are named after U.S. cities, breaking a long-standing Navy tradition of naming attack submarines after sea creatures.

The final 23 boats in the series, referred to as "688i" boats, are quieter than their predecessors and incorporate a more advanced combat system. These 688i boats are also designed for under-ice operations: their diving planes are on the bow rather than on the sail, and they have reinforced sails.

According to the U.S. government, the top speed of Los Angeles-class submarines is over 25 knots (46 km/h, 29 mph), although the precise maximum is classified. Some estimates put the top speed at 30–33 knots. Tom Clancy, in his book Submarine: A Guided Tour Inside a Nuclear Warship, puts the top speed of a Los Angeles class submarine at 37 knots.

Government sources give the maximum operating depth as 650 feet (200 m), while Patrick Tyler, in his book Running Critical, suggests a maximum operating depth of 950 feet (290 m). Although Tyler cites the 688-class design committee for this figure, the government has not commented on it. The maximum diving depth is 1,475 feet (450 m) according to Jane's Fighting Ships, 2004-2005 Edition, edited by Commodore Stephen Saunders of Royal Navy.

Los Angeles class submarines carry about 25 torpedo-tube-launched weapons and all boats of the class are capable of launching Tomahawk cruise missiles horizontally (from the torpedo tubes). The last 31 boats of this class also have 12 dedicated vertical launching system (VLS) tubes for launching Tomahawks.

There are two watertight compartments in the Los Angeles class of submarines. The forward compartment contains crew living spaces, weapons handling spaces and control spaces not critical to recovering propulsion. The aft compartment contains the bulk of the ship's engineering systems, power generation turbines and water making equipment. Some submarines in the class are capable of delivering SEALs through either the Dry Deck Shelter (DDS) system or the Advanced SEAL Delivery System (ASDS). A variety of atmospheric control devices are used to remain submerged for long periods of time without ventilating, including an Electrolytic Oxygen Generator (EOG) nicknamed "the bomb".

While on the surface or at snorkel depth the submarine may use the ship's auxiliary or emergency diesel generator for power or ventilation (e.g., following a fire). The diesel engine in a 688 class can be quickly started by compressed air during emergencies or to evacuate noxious (non-volatile) gases from the boat, although 'ventilation' requires raising of a snorkel mast. During non-emergency situations, design constraints require operators to allow the engine to reach normal operating temperatures before it is capable of producing full power, a process that may take from 20 to 30 minutes. However, the diesel generator can be immediately loaded to 100% power output, despite design criteria cautions, at the discretion of the submarine commander via the recommendation of the ship's Engineer, if necessity dictates such actions to a) restore electrical power to the ship, b) prevent a reactor incident from occurring or escalating, or c) to protect the lives of the crew or others as determined necessary by the commanding officer.

Normally, steam power is generated by the ship's nuclear reactor delivering pressurized hot water to the steam generator, which generates steam to drive the steam driven turbines and generators. While the emergency diesel generator is starting up, power can be provided from the ship's battery through the Ship Service Motor Generators (SSMGs). Likewise, propulsion is normally delivered through the ship's steam driven main turbines that drive the ship's propeller through a reduction gear system. The ship has no main shaft conventional engines.

Figure 75: USS Key West off the Coast of Honolulu, Hawaii with masts and Antennae Raised at Periscope Depth

SCB-304: Ohio Class Ballistic Missile Submarines

The Ohio class is a class of nuclear-powered submarines used by the United States Navy. The United States has 18 Ohio-class submarines:

- 14 nuclear-powered SSBNs (ballistic missile submarines), each armed with up to 24 Trident II SLBMs; they are also known as "Trident" submarines, and provide the sea-based leg of the nuclear triad of the United States strategic nuclear weapons arsenal
- 4 nuclear-powered SSGNs (cruise missile submarines), each capable of carrying 154 Tomahawk cruise missiles with either conventional or nuclear warheads.

The Ohio class is named after the lead submarine of this class, the USS Ohio (SSGN-726) formerly designated SSBN-726. The 14 Trident II SSBNs together carry approximately fifty percent of the total US strategic warhead inventory. The exact number varies in an unpredictable and classified manner, at or below a maximum set by various strategic arms limitation treaties. Although the missiles have no pre-set targets when the submarine goes on patrol, the platform, when required, is capable of rapid targeting using secure and constant at-sea communications links. The Ohio class is the largest type of submarine ever constructed for the U.S. Navy. Two Russian classes of submarines have larger total displacements: the Soviet-designed Typhoon class, which has more than twice the total displacement, and the Russian Federation's newest class of ballistic missile submarines, the highly advanced Borei class, which has roughly a 25% greater total displacement, but is shorter by 3 feet.

Ohios were specifically designed for extended deterrence patrols. Each submarine is complemented by two crews, Blue and Gold (standard practice for US FBMs), with each crew typically serving 70-90 day patrols. To decrease the time in port for crew turnover and replenishment, three large logistics hatches are fitted to provide large diameter resupply and repair openings. These hatches allow sailors to rapidly transfer supply pallets, equipment replacement modules, and machinery components, significantly reducing the time required for replenishment and maintenance. The class design allows the vessel to operate for over fifteen years between major overhauls. The boats are purported to be as quiet at their cruising speed of 20 knots (37 km/h; 23 mph) or more as previous subs were at a dead crawl of 6 knots (11 km/h; 6.9 mph), although exact information remains classified.

Ohios were constructed from sections of hull, each 42 ft (13 m) in diameter, each divided into four decks. The sections were produced at Quonset Point, Rhode Island, and assembled by Electric Boat at Groton. Fire control for the Mark 48 torpedoes is by Mark 118 Mod 2 system, while the Missile Fire Control (MFC) system is a Mark 98.

Except for USS Henry M. Jackson (SSBN-730), the Ohio class submarines are named after states in the United States.

The Department of Defense anticipates a continued need for a sea-based strategic nuclear force. The current Ohio SSBNs are expected to retire its first vessel by 2029, meaning that a platform must already be seaworthy by that time. A replacement may cost over $4 billion per unit compared to Ohio's $2 billion. The Navy is exploring two options. The first is a variant of the Virginia-class nuclear attack submarines. The second is a dedicated SSBN, either with a new hull or based on an overhaul of the current Ohio.

With the cooperation of both Electric Boat and Newport News Shipbuilding, in 2007 the Navy had already begun a cost control study. Then in December 2008 the Navy awarded Electric Boat a contract for the missile compartment design of the Ohio class replacement, worth up to $592 million. Newport News is expected to receive close to 4% of that project. Though the Navy has yet to confirm an Ohio class replacement program, Defense Secretary Robert M. Gates, as of April 2009, confirms that the Navy should begin such a program in 2010. The new vessel is scheduled to enter the design phase by 2014. It is anticipated that if a new hull design is used the program must be initiated by 2016 in order to meet the 2029 deadline.

Rep. Gene Taylor of Mississippi had threatened to block the project unless the Navy shares with the Congress an internal Analysis of Alternatives.

Seawolf Class Attack Submarines

The Seawolf class attack submarine (SSN) was the intended successor to the Los Angeles class, ordered at the end of the Cold War in 1989. At one time, an intended fleet of 29 submarines was to be built over a ten-year period, later reduced to twelve submarines. The end of the Cold War and budget constraints led to the cancellation in 1995 of any further additions to the fleet, leaving the Seawolf class limited to just three boats. This, in turn, led to the design of the smaller Virginia class.

Compared to previous Los Angeles class submarines, Seawolf subs are larger, faster, and significantly quieter; they also carry more weapons and have twice as many torpedo tubes, for a total of 8. As a result of their advanced design, however, Seawolf subs were much more expensive. They were intended to combat the then-threat of large numbers of advanced Soviet ballistic missile submarines such as the Typhoon class and attack submarines such as the Akula class in a deep ocean environment.

Seawolf hulls were constructed from HY-100 steel, rather than the weaker HY-80 steel employed in previous classes, to better withstand water pressure at greater depths. The boats also have extensive equipment for shallow-water operations, including a floodable silo capable of simultaneously deploying eight combat swimmers and their equipment. The boats carry up to 50 UGM-109 Tomahawk cruise missiles for attacking land and sea surface targets.

The projected cost for twelve submarines of this class was $33.6 billion, but after the Cold War, construction was stopped at three boats.

The class uses the more advanced ARCI Modified AN/BSY-2 combat system, which includes a new, larger spherical sonar array, a wide aperture array (WAA), and a new towed-array sonar. Each boat is powered by a single S6W nuclear reactor, delivering 52,000 hp (39 MW) to a low-noise pump-jet.

The USS Jimmy Carter is roughly 100 feet (30 m) longer than the other two boats of her class due to the insertion of a section known as the Multi-Mission Platform (MMP), which allows launch and recovery of ROVs and Navy SEAL forces. The MMP may also be used as an underwater splicing chamber for tapping of undersea fiber optic cables. This role was formerly filled by the decommissioned USS Parche (SSN-683). The Jimmy Carter was modified for this role by Electric Boat at the cost of $887 million.

Jimmy Carter is currently homeported at Naval Base Kitsap. In 2006, the Navy announced that it would homeport all three of its Seawolf submarines in Bangor.

Virginia Class Attack Submarines

The Virginia class (or SSN-774 class) of attack submarines are U.S. submarines designed for a broad spectrum of open-ocean and littoral missions. They were designed as a less expensive alternative to the Cold War-era designed Seawolf class attack submarines, and they are slated to replace the aging Los Angeles class submarines, nineteen of which (from a total of 62) have already been decommissioned.

The Virginia-class incorporates several innovations not previously seen in other submarine classes.

Photonics Masts

Instead of a traditional periscope, the class utilizes a pair of telescoping photonics masts located outside the pressure hull. Each mast contains high-resolution cameras, along with light-intensification and infrared sensors, an infrared laser rangefinder, and an integrated Electronic Support Measures (ESM) array. Signals from the masts' sensors are transmitted through fiber optic data lines through signal processors to the control center. Visual feeds from the masts are displayed on LCD interfaces in the command center.

Propulsion

The class also makes use of pump-jet propulsors, which significantly reduces the risks of cavitation, allowing for quieter and faster operations.

Sonar

The Virginia class submarines are equipped with a bow-mounted spherical active/passive sonar array, a wide aperture lightweight fiber optic sonar array (three flat panels mounted low along either side of the hull), as well as two high frequency active sonars mounted in the sail and keel (under the bow). The submarines are also equipped with a low frequency towed sonar array and a high frequency towed sonar array.

USS California will be the first Virginia with the advanced electromagnetic signature reduction system built in, but this will be retrofitted into the other submarines of the class.

The Virginias were intended, in part, as a cheaper ($1.8 vs. $2.8 billion) alternative to the Seawolf class, whose production run was stopped after just three boats. To reduce costs, the Virginia class uses many "commercial off-the-shelf" (or COTS) components, especially in their computers and data networks. In practice they actually cost less than $1.8 billion (in fiscal year 2009 dollars) each, due to shipbuilding technology improvement.

In hearings before both House of Representatives and Senate committees, the Congressional Research Service and expert witnesses testified that the current procurement plans of the Virginia class—one per year at present, accelerating to two per year beginning in 2012—resulted in high unit costs and (according to some of the witnesses and some of the committee chairmen) an insufficient number of attack submarines. In a March 10, 2005 statement to the House Armed Services Committee, Ronald O'Rourke of the CRS testified that, assuming the production rate remains as planned, "production economies of scale for submarines would continue to remain limited or poor."

The Virginia class is built through an industrial arrangement designed to keep both GD Electric Boat and Northrop Grumman Newport News (the only two U.S. shipyards capable of building nuclear-powered vessels) in the submarine-building business. Under the present arrangement, the Newport News facility builds the stern, habitability and machinery spaces, torpedo room, sail and bow, while Electric Boat builds the engine room and control room. The facilities alternate work on the reactor plant as well as the final assembly, test, outfit and delivery.

In order to get the submarine's price down to $2 billion per submarine in FY-05 dollars, the Navy instituted a cost-reduction program to shave off approximately $400 million in costs off each submarine's price tag. The project was dubbed "2 for 4 in 12," referring to the Navy's desire to buy two boats for $4 billion in FY-12. Under pressure from Congress, the Navy opted to start buying two boats a year earlier, in FY-11, meaning that officials would not be able to get the $2 billion price tag before the service started buying two submarines per year. However, program manager Dave Johnson said at a conference on March 19, 2008, that the program was only $30 million away from achieving the $2 billion price goal, and would reach that target on schedule.

In December 2008, the Navy signed a $14 billion contract with General Dynamics and Northrop Grumman to supply eight submarines. The contractors will deliver one submarine in each of fiscal 2009 and 2010, and two submarines on each of fiscal 2011, 2012 and 2013. This contract will bring the Navy's Virginia-class fleet to 18 submarines. And in December 2010, the United States Congress passed a defense authorization bill that expanded production to two subs per year.

On 21 June 2008, the Navy christened the New Hampshire (SSN-778), the first Block II submarine. This boat was delivered eight months ahead of schedule and $54 million under budget. Block II boats are built in four sections, compared to the ten sections of the Block I boats. This enables a cost saving of about $300 million per boat, reducing the overall cost to $2 billion per boat and the construction of two new boats per year. Beginning in 2010, new submarines of this class will include a software system that can monitor and reduce their electromagnetic signatures when needed.

In September 2010, it was found that urethane tiles, applied to the hull to dampen internal sound and absorb rather than reflect sonar pulses, were falling off while the subs were at sea.

Ross Babbage has called on Australia to buy or lease a dozen Virginia class submarines from the United States.

Figure 76: USS Virginia

Argentina's Plans for Nuclear Submarines

During a meeting with the press, the Argentine Minister of Defense, Nilda Garré unexpectedly announced an initiative about developing nuclear propulsion for its Navy's vessels. Sources from the Argentine Government made clear that the Project is about propulsion and not about weapons of mass destruction.

The project would be based on a nuclear reactor developed by INVAP (the Argentine flagship high technology company) and such reactor could be operative by 2014. To install the reactor on a vessel could demand two more years.

Brazil has a current development of the same kind where the nuclear reactor is in charge of the Navy and the submarine's conventional part will be supplied by France. From the latter estimates that project is expected to be completed by 2020. If the Argentine project progresses according to the announcement, Argentina would count on nuclear propulsion five years in advance.

Daniel Gallo commented for La Nación that the Minister explained during the meeting that: "Nuclear propulsion on the Navy's units will start changing the energy matrix." La Nación reveals that the project would be carried out with the agreement of the Presidency and the Ministry of Foreign Affairs, and Ms. Garré only made public a venture already in progress.

The Minister pointed out that the Government seeks to restore country's former scientific, technological and industrial capabilities, and added that Argentina cannot stay away of such key technology.

The core of the development would be the CAREM, an advanced SMR [small-medium reactor] with outstanding properties which have been recognized worldwide. The INVAP's proposal would be to test and build the prototype for external sales, as a power reactor. Even so, following the sources, the CAREM would seem to have the adequate compatibility to become a naval reactor, able to power the engines of a TR1700 submarine. Parts of that submarine would be already available for assembly at a local shipyard.

La Nación cited that a reliable naval source confirmed yesterday that the Navy is already working on the Project. The same source highlighted that only nuclear armed states count on naval propulsion. Brazil aims at joining such selected group of naval reactors' possessors, taking into account that nuclear propulsion is a technology not forbidden by the NPT. Last year India joined the nuclear submarines' club. Other members are, so far, the United States, Russia, China, the UK, and France.

When Lula's Government boosted its naval project, several Ministers visited in Buenos Aires to explain the goals and scope of the operation, including the Brazilian wish to play as a first line international actor. Within such framework it was presented as natural that Brazil aimed at counting on last generation armament.

Argentina sought to participate on the Brazilian Project but it was not possible. There were conversations, mainly at the time of the February 2008's presidential agreement, with no positive result.

A source from the Argentine Navy pointed out that Argentina always had the technological capability, but only the political decision was missing.

According to the announced schedule, the CAREM prototype would be in operation by 2013, whilst naval tests could be completed by 2015, when the reactor would be installed on a TR1700 submarine.

The announcement generated diverse reactions at a local level, from support, to irony, and skepticism. The INVAP's skills and technological solvency is widely recognized. The firm won complex international tenders within the nuclear field such as the supply of the Australian OPAL research reactor, already in operation.

However, several members of the opposition questioned the opportunity, and others remarked the project's low priority versus the Armed Forces reality with much more urgent needs, and "with the absence of a clear plan for modernization which can contribute to their full operability."

The well-known analyst Rosendo Fraga stated that the project generates many doubts, as the Brazilian strategic situation is pretty different from the Argentine one. He added that, in this sense, the last SIPRI Yearbook shows a Brazilian military expenditure ten times higher, for a GDP five times higher, than in the case of Argentina. This could reflect strong budgetary limitations that could directly impact on the maintenance of present capability, in some ways obsolete.

In addition, a strategic contest which involves both countries would be nonsense, Fraga states. Finally, he notices the negative consequences in terms of credibility of an announcement not accomplished, or diluted with passage of time.

Irma Arguello remarked that Argentina has got enough technical skills to reach success with the Project and nobody doubts about the qualities of INVAP, but the country's technological efforts should be focused on innovative lines which could consolidate the nation as a first line nuclear supplier, and at the same time, that could be favorable to its global technological insertion, and to keep its excellent nonproliferation reputation.

"It would be preferable to focus current capabilities on the successful development of nuclear power plants for regional uses, based on the CAREM's remarkable features.

Another very attractive and relevant line would be the conversion from HEU to LEU of research and other civil reactors, a knowledge already available at a nation level that will be increasingly demanded worldwide, given the renewed nations' security commitments mainly derived from the last April Nuclear Security Presidential Summit in Washington."

Brazil’s Plans for Nuclear Submarines

Brazil's developing nuclear program shows its increasing global prominence.

The National Defense Strategy the government of Brazil released on 17 December 2008 provides little plausible military justification for the recently accelerated nuclear-powered submarine project. The document stresses that this traditionally peaceful country has no problems with its neighbors, acknowledging that it has been difficult, therefore, to find a rationale for building forces and training for defense. Brazil had not previously attempted to elaborate an explicit national defense strategy, so why does it need nuclear submarines? The answer is apparently more related to political and economic factors associated with grand strategy than to requirements of naval strategy.

Brazil's new national-defense concept lays out three maritime goals—sea denial, control of maritime areas, and power projection—and includes several references to the development of nuclear submarines. But it does nothing to provide an adequate naval justification of the enormous investment the project will require. President Luiz Inacio Lula da Silva has argued that Brazil "will have a nuclear submarine because it is a necessity for a country that not only has the maritime coast that we have but also has the petroleum riches that were recently discovered in the deep sea pre-salt layer."

On 10 July 2007, the president announced plans to fund the construction of a nuclear-powered attack submarine. This project promised to fulfill a longstanding Brazilian aspiration for which considerable investments had already been made. The navy had begun a program in 1979 to build a dual-use nuclear reactor suitable to propel a submarine and generate electricity for civilian consumers. At the same time, the service undertook a fuel cycle project to give Brazil autonomy in the enrichment of uranium, which it produces domestically.

South Korea's Nuclear Submarines

The Republic of Korea Navy (ROKN) currently operates a submarine flotilla of nine diesel-electric Chang Bogo-class (Type 209/1200) vessels based at Chinhae. Four Type 214 hybrid diesel-electric/fuel cell AIP vessels are in the process of being built at Hyundai Heavy Industries shipyards under cooperation with Germany's Howaldtswerke-Deutsche Werft (HDW).

With North Korean submarines posing a significant threat to the ROK's sea lines of communication and frequently intruding into its territorial waters, ROKN submarines can be expected to play a significant role in sea denial to hostile forces and anti-submarine warfare. In addition to the naval aspect of the existing tension on the Korean Peninsula, there are unresolved territorial disputes between Japan and the ROK over the Liancourt Rocks (Takeshima or Tok-do).

Type 214	
Displacement, tons:	1,700 surfaced 1,860 submerged
Dimensions, ft (m):	213.3 x 20.7 x 19.7 (65 x 6.3 x 6)
Main machinery:	hybrid diesel-electric/fuel cell AIP (9)
Speed, knots:	12 surfaced 20 submerged
Range, miles:	12,000 at 6 knots surfaced; 420 at 8 knots submerged; 1,248 at 4 knots on fuel cells
Complement:	27 (5 officers)
Diving depth, ft (m):	1,300 (400)
Endurance:	50 days
Weapons:	16 SSMs and torpedoes; eight 21" (533 mm) tubes, four of which can launch SSMs

Chang Bogo (Type 209/1200)	
Displacement, tons:	1,100 surfaced 1,285 submerged
Dimensions, ft (m):	183.7 x 20.3 x 18 (56 x 6.2 x 5.5)
Main machinery:	diesel-electric
Speed, knots:	11 surfaced/snorting 22 submerged
Range, miles:	7,500 at 8 knots surfaced
Complement:	33 (6 officers)
Diving depth, ft (m):	820 (250)
Endurance:	50 days
Weapons:	14 torpedoes; eight 21" (533 mm) tubes; 28 mines in lieu of torpedoes

Active Duty Submarines

Name (Number)	Class	Base	Builder	Laid down	Launched	Commissioned
Chang Bogo (061)	Chang Bogo	Chinhae	HDW, Kiel	1989	1992	1993
Yi Chon (062)	Chang Bogo	Chinhae	Daewoo, Okpo	1990	1992	1994
Choi Muson (063)	Chang Bogo	Chinhae	Daewoo, Okpo	1991	1993	1995
Park Wi (065)	Chang Bogo	Chinhae	Daewoo, Okpo	1992	1994	1996
Lee Jongmu (066)	Chang Bogo	Chinhae	Daewoo, Okpo	1993	1995	1996
Jung Woon (067)	Chang Bogo	Chinhae	Daewoo, Okpo	1994	1996	1997
Lee Sunsin (068)	Chang Bogo	Chinhae	Daewoo, Okpo	1995	1998	1999
Na Daeyong (069)	Chang Bogo	Chinhae	Daewoo, Okpo	1996	1999	2000
Lee Eokgi (071)	Chang Bogo	Chinhae	Daewoo, Okpo	1997	2000	2001

Nuclear Submarine Accidents

Some of the most serious nuclear and radiation accidents in the world have involved nuclear submarine mishaps. Notable nuclear submarine accidents include:

- K-19, 4 July 1961, the reactor almost had a meltdown and exploded, resulting in 8 deaths and more than 30 other people being over-exposed to radiation. The events on board the submarine are dramatized by the film K-19: The Widowmaker.

- USS Thresher (SSN-593), 1963, was lost during deep diving tests and later investigation concluded that failure of a brazed pipe joint and ice formation in the ballast blow valves prevented surfacing. The accident motivated a number of safety changes to the US fleet.

- USS Scorpion (SSN-589), 1968, lost.

- K-27, 24 May 1968, experienced a near meltdown of one of its liquid metal (lead-bismuth) cooled VT-1 reactors, resulting in 9 fatalities and 83 other injuries. The ship was deactivated by 20 July 1968.

- K-431 reactor accident on 10 August 1985 resulted in 10 fatalities and 49 other people suffered radiation injuries.

- K-219, 1986, the reactor almost had a meltdown. Sergei Preminin died after he manually lowered the control rods, and stopped the explosion. The submarine sank three days later.

- K-278 Komsomolets, 1989, Soviet submarine sank in Barents Sea due to a fire.

- K-141 Kursk, 2000, the generally accepted theory is that a leak of hydrogen peroxide in the forward torpedo room led to the detonation of a torpedo warhead, which in turn triggered the explosion of half a dozen other warheads about two minutes later.

- Ehime Maru & USS Greeneville, February 2001, the American submarine surfaced underneath the Japanese fishing vessel. Nine Japanese were killed when their ship sank as a result of the collision.

- USS San Francisco (SSN-711), 2005, collided with a seamount in the Pacific Ocean. A crew member was killed and 23 others were injured.

- HMS Vanguard & Le Triomphant, February 2009, the French and British submarines collided in the Atlantic while on routine patrols. There were no injuries among the crews, but both ships were damaged during the collision.

N. Analysis of Nuclear Submarines Worldwide

USS Alabama, SSBN-731

Figure 77: USS Alabama

USS Alabama (SSBN-731) is the sixth Ohio-class nuclear-powered fleet ballistic missile submarine, and the sixth United States ship to be named after the state of Alabama. The ship's motto mimics the state's motto, Audemus Jura Nostra Defendere ("We dare to defend our rights").

The contract for Alabama's construction was awarded on 27 February 1978 and her keel was laid down on 14 October 1980 at Groton, Connecticut, by the Electric Boat Division of General Dynamics. She was launched on 19 May 1984, sponsored by Mrs. Barbara E. Dickinson, wife of William Louis Dickinson, Representative from Alabama, and commissioned at Naval Submarine Base New London at New London, Connecticut, on 25 May 1985.

After commissioning, Alabama departed Connecticut to conduct her shakedown cruise off the coast of Florida. After several domestic maneuvers and crew changes, Alabama visited Mobile, Alabama, before heading for the Panama Canal and from there to Bangor, Washington. Alabama operated out of Bangor until mid-May 1986, when she embarked on her first strategic deterrent patrol. Operating from the Pacific Northwest, Alabama carried out four deterrent patrols between June and December 1986.

In May 1988, Alabama conducted a successful test ballistic missile firing, launching two Trident I C4 ballistic missiles.

On 1 September 1988, Alabama moored at Bangor to complete her ninth deterrent patrol and the 100th strategic deterrent patrol by a Trident-armed submarine. An official ceremony commemorating the event was held pier side with then-Undersecretary of the Navy H. Lawrence Garrett III heading the official greeting party.

Alabama conducted another test ballistic missile firing in August 1989, launching four Trident I C4 ballistic missiles.

In the 1990's Alabama conducted routine refit operations out of Bangor Washington, post-refit sea trials operations in Dabob Bay, and patrol operations in the Pacific Ocean. Ports-of-call included Seattle, Washington, San Diego and Long Beach, CA, and Pearl Harbor, HI.

In February 1991, Alabama was selected as the change of command platform for the Commander-in-Chief Pacific Fleet (CINCPACFLT) in Pearl Harbor, HI. August of 1992, Alabama embarked Commander-in-Chief, United States Strategic Command (CINCSTRATCOM) and his entourage of senior U.S. Air Force and Navy Officers for an at-sea submerged orientation tour concerning SSBN strategic deterrent operations. In January 1996, the ship was awarded the Battle Efficiency E and the Strategic Operations S by the Commander of Submarine Squadron Seventeen. In March, she was awarded the U. S. Strategic Command's Omaha Trophy for ballistic missile unit excellence. March 1999, Alabama conducted exercises with the USS Constellation battle group and the USS Topeka. In September, she conducted underway operations for the Defense Advisory Council on Women in the Services.

After completing 47 strategic deterrent patrols, Alabama underwent a refit in 1999 and returned to service with numerous tactical and survivability upgrades. In the spring of 2000, Alabama completed her 50th strategic deterrent patrol and celebrated her 15th birthday. February 2000, conducted exercises with the USS Abraham Lincoln battle group. In April, she conducted a VIP cruise in Dabob bay, Washington to host the Chief of Defense of Japan and members of his staff. In August, she again conducted exercises with the USS Abraham Lincoln battle group.

Alabama entered the Bremerton Annex of Naval Base Kitsap at Bangor in 2005 to undergo a nuclear reactor refueling overhaul and conversion of her ballistic missile systems to fire the Trident II D5 ballistic missiles, which replaced her Trident I C4 ballistic missiles and launchers; Alabama was the last of Trident C4-equipped submarine to be refitted with the Trident D5 missile system. The refueling overhaul and Trident D5 conversion was completed in February 2009.

Alabama is currently part of Submarine Group 9 and her home port is at Naval Base Kitsap in Bangor.

USS Alaska, SSBN-732

Figure 78: USS Alaska

USS Alaska (SSBN-732), is a United States Navy Ohio-class ballistic missile submarine which has been in commission since 1986. She is the fourth U.S. Navy ship to be named for the Territory of Alaska or the State of Alaska.

The contract to build Alaska was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut, on 27 February 1978 and her keel was laid down there on 9 March 1983. She was launched on 12 January 1985, sponsored by Mrs. Catherine Stevens, and commissioned on 25 January 1986, with Captain Paul L. Callahan in command of the Blue Crew and Captain Charles J. Chotvacs in command of the Gold Crew.

USS Albany, SSN-753

Figure 79: USS Albany

USS Albany (SSN-753), a Los Angeles-class submarine, was the fifth ship of the United States Navy to be named for Albany, New York. The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia on 29 November 1983 and her keel was laid down on 22 April 1985. She was launched on 13 June 1987 sponsored by Nancy M. Kissinger, wife of Henry Kissinger, and was commissioned on 7 April 1990 with Commander Darl R. Anderson in command.

Albany was the last US submarine built via the traditional "keel up" ship construction method. Thus, it was the last submarine to "launch" down the shipway.

The Albany and her successor, the USS Topeka, form a unique sub-class among Los Angeles class submarines. The pressure hulls of both ships were partially manufactured using stronger HY-100, instead of the HY-80 steel used in the manufacturing of all other Los Angeles class submarines. This was done to test construction methods using this steel, which would later be employed in the assembly of the new Seawolf-class submarines. In theory, this permits the Albany and Topeka to dive to a slightly greater depth than any other member of the Los Angeles class, though it remains unclear if this ability has ever been tested by either vessel.

On 30 July 2004 Albany returned to Norfolk, Virginia, after a six-month deployment that began in the Persian Gulf and Gulf of Oman, then proceeded to the Mediterranean Sea for a NATO exercise, Operation "MEDSHARK/Majestic Eagle."

USS Albuquerque, SSN-706

Figure 80: USS Albuquerque

USS Albuquerque (SSN-706), a Los Angeles-class attack submarine, was the second ship of the United States Navy to be named for Albuquerque, New Mexico. The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 31 October 1973 and her keel was laid down on 27 December 1979. She was launched on 13 March 1982 sponsored by Mrs. Nancy L. Domenici, and commissioned on 21 May 1983 with Captain Richard H. Hartman in command.

On 6 August 2009, Albuquerque completed her change of homeport from Groton, Conn., to Naval Base Point Loma in order to maintain 60 percent of the submarine force in the Pacific in line with the 2006 QDR.

USS Alexandria, SSN-757

Figure 81: USS Alexandria

USS Alexandria (SSN-757), a Los Angeles-class nuclear-powered attack submarine, is the third ship of the United States Navy to be named for both Alexandria, Virginia, and Alexandria, Louisiana.

The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on November 26, 1984. Her keel was laid down on June 19, 1987.

The history of the Alexandria as a U.S. Navy warship begins with the staffing of what is known as the Pre-commissioning Unit (PCU) Alexandria. CDR Wilbur Cooke was the Commanding Officer of the Unit. Construction delays necessitated the detachment of CDR Cooke on October 6, 1989, and the assignment of Commander Paul E. Normand in his place on December 11, 1989.

Alexandria, together with the guided-missile cruiser USS Cowpens (CG-63), the frigate USS Gary (FFG-51), and P-3C Orion maritime patrol and reconnaissance aircraft, participated in Exercise Malabar 2004, a training exercise with the Indian Navy off the southwest coast of India that ended October 11, 2004.

In March 2007, Alexandria was participating in the Joint U.S. Navy/Royal Navy Ice Exercise 2007 (ICEX-2007), conducted in the Arctic Ocean with the Trafalgar-class submarine HMS Tireless (S88). The exercise took place on and under a drifting ice floe, about 180 nmi (333 km; 207 mi) off the north coast of Alaska. The two submarines were taking part in joint testing of submarine operability and tactical development in Arctic waters. On March 21, Tireless experienced an explosion of a self-contained oxygen generation candle. Tireless suffered only superficial damage, but two crew members were killed and one injured.

HMS Ambush, S120

HMS Ambush is an Astute-class nuclear fleet submarine of the Royal Navy, at present fitting out. Ambush was ordered from GEC's Marconi Marine (now BAE Systems Submarine Solutions) on 17 March 1997. She was laid down at Barrow-in-Furness on 22 October 2003, officially named on 16 December 2010, launched on 6 January 2011 and began sea trials by 2012.

The Astute class's nuclear reactor will not need to be refueled during the boat's 25 year service. Since the submarine can purify water and air, she will be able to circumnavigate the planet without resurfacing. The main limit is that the submarine will only be able to carry three months' supply of food for 98 officers and ratings.

The Astute class SSNs are designed as the stealthiest Royal Navy submarines in history. Using advanced stealth technology Astute "makes less noise than a baby dolphin, making her as good as undetectable by enemy ships."

Astute class carries a mix of 38 weapons in six 21-inch (533 mm) torpedo tubes:

- BGM-109 Tomahawk Block IV cruise missiles. Range of 1,350 nautical miles (2,500 km).
- Spearfish torpedoes.

S605 Améthyste, SNA (SSN)

The Améthyste is an attack nuclear submarine of the French Navy, the fifth of the Rubis type. Her name is an acronym for AMElioration Tactique, HydrodYnamique, Silence, Transmission, Ecoute ("Tactical, hydrodynamics, silence and transmission improvements"). She is the first vessel to serve in the French Navy under that name.

She is a major upgrade upon the initial design of the Rubis type, and earlier units have since been refitted to meet her standards.

The Améthyste also took part in Operation Allied Force, the 1999 bombing campaign over Yugoslavia, by protecting the NATO aeronaval group. Along with the Rubis, she was one of the two submarines that interdicted the Kotor straits to the Serbian Navy, thus effectively forbidding their use. She also gathered information for the coalition.

The submarine Améthyste was part of the French naval task group led by the Charles de Gaulle that departed Toulon on 30 October 2010 for a four-month deployment to the Mediterranean Sea, Red Sea, Indian Ocean and Persian Gulf.

Once on station, the Charles de Gaulle carrier task group joined two U.S. Navy carrier strike groups led by the Nimitz class aircraft carrier aircraft carriers USS Abraham Lincoln (CVN-72) and USS Harry S. Truman (CVN-75) operating in the Persian Gulf. Subsequently, between 7–14 January 2011, the French carrier task group led by the Charles de Gaulle participated with bilateral naval exercise, code named Varuna 10, with the Indian Navy. Indian naval units participating in Varuna 10 included the aircraft carrier Viraat, the frigates Godavari and Ganga; and the diesel-electric submarine Shalki. Varuna 10 was a two-phase naval exercise, with the harbor phase taking place between 7–11 January and the sea phase between 11–14 January in the Arabian Sea.

Figure 82: Améthyste Entering Portsmouth Naval Base, UK

USS Annapolis, SSN-760

Figure 83: USS Annapolis

USS Annapolis (SSN-760) is the tenth "improved" Los Angeles-class submarines, and is sister-ship to the USS Springfield (SSN-761). Homeported in Groton, CT, she is assigned to Submarine Development Squadron 12. USS Annapolis is the fourth ship of the United States Navy to be named for Annapolis, Maryland, site of the United States Naval Academy.

The contract to build USS Annapolis (SSN-760) was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 21 March 1986 and her keel was laid down on 15 June 1988. She was launched on 18 May 1991 sponsored by Mrs. Myra F. Kauderer, and commissioned on 11 April 1992, with Commander Richard Severinghaus in command.

Completing sea trials in April 1993, the ship had her first port visit to her namesake city, Annapolis, MD. She then entered Post Shakedown Availability in January 1993 after completing PSA in July 1993 the ship had her first port visit to Bermuda.

November 1993, USS Annapolis deployed on its first mission to the North Atlantic. Later that year it was awarded the Submarine Group Two Silver Anchor Award for enlisted retention. Annapolis returned to Groton, CT for the Christmas holidays and then continued on deployment in the Northern Atlantic in January 1994. During this time the boat made her first visit to Bergen, Norway where some members of the crew had an opportunity to attend a few of the 1994 Winter Olympic events, including the Men's Gold Medal Hockey Match, before returning to Groton in March. During this deployment the boat and crew earned the Navy Arctic Service Ribbon. Following an in-port refit period, Annapolis participated in a six month pre-deployment workup with USS Dwight D. Eisenhower (CVN-69), and on October 20, 1994, began her first six-month Mediterranean Deployment with the Eisenhower Battle Group. During the deployment, the crew had a chance to make port calls in places as diverse as Gibraltar; Toulon, France; La Maddalena, Italy; Limasol, Cypress; and Haifa, Israel. During this deployment Annapolis earned her first Sea Service Ribbon, Navy Expeditionary Medal and Meritorious Unit Commendation. Upon the boat's return, Annapolis was "adopted" by the town of Montville, Connecticut in an effort to strengthen community relations.

The boat's next deployment was not until October 1997, when it returned to the Mediterranean Sea with the George Washington Battle Group. In November 1997, in response to an emergent political and military crisis in the Persian Gulf, Annapolis transited the Suez Canal en route to the Middle East. While on station, Annapolis played a key role as a Tomahawk strike platform as well as serving as a public affairs platform by hosting news crews from both ABC and CBS networks.

Port calls were limited but the crew did get ashore in Abu Dhabi, United Arab Emirates and Bahrain. While in the Gulf, the boat earned its second Sea Service Ribbon and a Naval Unit Commendation. In March 1998 Annapolis was relieved of her duties by the USS Providence (SSN-719) and began the long voyage home.

After more than two years of local operations and extensive upkeep, Annapolis transited back to the Mediterranean in the summer of 2000 for a six-month independent submarine deployment. While in the Mediterranean, the boat had a chance to participate in several multi-national exercises as well as in real-world operations in the Adriatic. Crew members had significant liberty in Gibraltar; Rota, Spain; Toulon, France; and La Maddalena, Italy, and earned its third Sea Service Ribbon and second Naval Expeditionary Medal. The boat returned from this deployment in January 2001.

Annapolis entered Portsmouth Navy Yard for an extended overhaul on 23 April 2003. She set sail 16 May 2004, after completing a Depot Modernization Period one month ahead of schedule.

On 28 February 2008, Annapolis returned to homeport Groton from a six-month deployment. The deployment included visits to Rota, Spain; Toulon and Brest, France; Praia, Cape Verde; and Ghana. Annapolis was the first U.S. submarine to make a port visit to Africa (Cape Verde) outside of the Mediterranean. In addition to functions supporting national security, Annapolis participated in the African Partnership Station (APS) 2007, an initiative with regional maritime services in West and Central Africa.

In March 2009 Annapolis took part in Ice Exercise 2009.

INS Arihant, (ATV-1), SSBN-S02

INS Arihant (S-73) is the lead ship of India's Arihant class of nuclear-powered submarines. The 5,000–6,000 ton vessel was built under the Advanced Technology Vessel (ATV) project at the Ship Building Centre in Visakhapatnam.

The symbolic launch ceremony for the Arihant was held on 26th July 2009, the anniversary of Vijay Diwas (Kargil War Victory Day). The name of the vessel, Arihant is in Sanskrit and literally translates into destroyer of enemies. The completion of the INS Arihant will make India one of six countries in the world with the ability to design, build, and operate its own nuclear submarines.

The INS Arihant is to be the first of the expected five in the class of submarines designed and constructed as a part of the Indian Navy's secretive Advanced Technology Vessel (ATV) Project. The submarine is reported to be similar to the Russian Charlie-II class submarine, which India leased from the Soviet Union between 1988 and 1991. Arihant will be more of "a technology demonstrator", rather than a fully-operational SSBN according to Admiral Verma.

The vessel will be powered by an 85 MW pressurized water reactor with enriched uranium fuel. A land-based prototype of the reactor was first built at Kalpakkam and made operational in September 2006. Successful operation over a period of three years yielded the data that enabled the production version for Arihant. It was reported that a 80MW nuclear reactor was integrated into the hull of the ATV in January 2008.

The hull for the vessel was built by L&T's Hazira shipbuilding facility. Tata Power built the control systems for the submarine. The systems for the steam turbine integrated with the reactor are supplied by Walchandnagar Industries.

The INS Arihant, was introduced to the public on July 26, 2009 at a symbolic launch ceremony. The launch coincided with the tenth anniversary of the conclusion of the Kargil War and consisted of floating the vessel by flooding the dry dock. It was reported that the Arihant was launched without key systems including its nuclear reactor, surveillance equipment, and ordinance. Per naval tradition, Gursharan Kaur cracked a coconut on the hull to mark the launch of the submarine at the secret naval base 'Matsya' in Visakhapatnam. Photography was prohibited and photos showing the complete vessel are not available. The launch of INS Arihant strengthens India's endeavor to build a credible nuclear triad — the capability to fire nuclear weapons from air, land and sea.

On the condition of anonymity, a nuclear scientist familiar with the project echoed this report in response to the media coverage that India had successfully launched a completed nuclear submarine. It was also expected that the duplication of India's land based reactor, integration of systems, and sea trials is expected to take three to five years.

It was reported that the nuclear reactor and other systems were not included at the time of the submarine's launch. Navy chief Admiral Nirmal Verma said in December 2009, "Work is in progress to make INS Arihant operational for sea-trials...it should be inducted in two years or so." In 2010, the submarine was reported to have begun its sea trials with the submarine to be formally inducted into the Indian Navy by 2011. Full integration of key systems and Sea trials are expected to be extensive.

HMS Artful, S121

HMS Artful is the third Astute-class nuclear-powered fleet submarine of the Royal Navy. Artful was ordered from GEC's Marconi Marine (now BAE Systems Submarine Solutions) on 17 March 1997, and is under construction at Barrow in Furness.

Artful's nuclear reactor will not need to be refueled during the boat's 25 year service. Since the submarine can replenish her air supply and purify water underway and while submerged, she will be able to circumnavigate the planet without resurfacing. The submarine's main limitation will be from the three months' supply of food carried for the 98 officers and ratings.

The Astute class SSNs are designed as the most stealthy Royal Navy submarines in history. Using advanced stealth technology Astute "makes less noise than a baby dolphin, making her as good as undetectable by enemy ships."

Astute class submarines carry a mix of 38 weapons in six 21-inch (533 mm) torpedo tubes;

- BGM-109 Tomahawk Block IV cruise missiles. Range of 1,350 nautical miles (2,500 km).
- Spearfish torpedoes.

USS Asheville, SSN-758

USS Asheville (SSN-758) is a Los Angeles-class submarine. She is the fourth ship of the United States Navy to be named for Asheville, North Carolina. The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia on 26 November 1984 and her keel was laid down on 9 January 1987. She was launched on 24 February 1990, sponsored by Mrs. Dorothy Helms, and commissioned on 28 September 1991, with Commander Patrick Casey in command and the best initial manning crew the Navy has ever seen.

Asheville was fitted with a developmental Advanced Mine Detection System (AMDS) high-frequency active sonar array with transmitters and receivers in the sail and in a disc-shaped chin sonar dome beneath the hull at the bow. The system is used for target detection, mine avoidance, and bottom navigation. After a highly successful testing period the system was removed during overhaul in 2003.

Asheville is home ported in San Diego, CA where she is assigned to Submarine Squadron 11. She is currently commanded by CDR Gerald Miranda.

In December 1996, Asheville served as a trials platform for the Northrop Grumman Sea Ferret reconnaissance drone. After Asheville simulated an underwater launch, a Cessna 206 test aircraft flew over the area of operations with the Sea Ferret attached to its underside. Technicians aboard Asheville transmitted commands to the Sea Ferret, which were received and responded to by the Cessna pilot. Control of the drone was then passed back and forth among the Asheville team, USMC First Force RECON, and an United States Army Aviation team, all three teams continuing to receive a continuous flow of sensor data.

In August 1998 Asheville returned from a six month Western Pacific Deployment (WESTPAC). After a 30 day stand down, she entered an extended maintenance period at Pearl Harbor Naval Shipyard in Dry Dock #4. On 14 December 1998, she was floated off the blocks, but remained tied up inside the flooded dock, until after the New Year.

Almost immediately after the maintenance period Asheville began a work-up for another six month deployment to the Western Pacific. This work-up included various underway periods, for weekly operations. At the end of May 1999, Asheville conducted two family day cruises.

On 11 January 2000, Asheville departed Pearl Harbor for a six-month Western Pacific Deployment (WESTPAC). She was part of the John C. Stennis Carrier Strike Group.

On 1 April 2005 Asheville returned to San Diego, California, after a six-month deployment to the Western Pacific. While deployed she performed National Security Missions, and took part in two international exercises. During the deployment, she made port calls at Guam, Singapore, Japan, Saipan, and Hawaii.

On 1 August 2006, Asheville departed San Diego to return to the Western Pacific, for another six-month deployment. While deployed, she made port calls at Yokosuka, Japan, Hong Kong, Saipan, & Guam. She returned to her home port of San Diego, California, on 3 February 2007.

On 27 April 2007, Asheville entered Floating Dry Dock USS Arco (ARDM-5), at Naval Base Point Loma, for a scheduled maintenance period.

On 16 August 2007 Asheville, exited USS Arco, having completed a highly successful upkeep.

Figure 84: USS Asheville

HMS Astute, S119

HMS Astute is the lead ship of her class of nuclear-powered submarines. Astute was ordered from GEC's Marconi Marine (now BAE Systems Submarine Solutions) on 17 March 1997. She was laid down on 31 January 2001, 100 years to the day since the keel was laid down for HMS Holland 1, the first Royal Navy submarine. The vessel was built at BAE's submarine facility in Barrow-in-Furness and was launched on 8 June 2007 by HRH The Duchess of Cornwall.

Astute is the second submarine of the Royal Navy to be named for the characteristic of shrewdness and discernment. The first was the World War II Amphion-class Astute. Now that she has been commissioned, Astute is one of the most 'advanced submarines in the world'.

The 7,400-tonne Astute's nuclear reactor will not need to be refueled during the boat's 25 year service. Since the submarine can purify water and air, she will be able to circumnavigate the planet without resurfacing. The main limit is that the submarine will only be able to carry three months' supply of food for 98 crew. Astute will carry Tomahawk cruise missiles.

HMS Astute was launched at BAE's submarine facility in Barrow-in-Furness on 8 June 2007 by HRH The Duchess of Cornwall. The launch attracted more than 10,000 spectators. She is the first submarine built in the UK since HMS Vengeance, which was launched in 1998.

Astute left Barrow on 15 November 2009 and on 20 November 2009, arrived at her home port of HMNB Clyde at Faslane. On 16 February 2010 Astute left Faslane for sea trials and dived for the first time on 18 February and was commissioned on 27 August 2010, when she was given her HMS prefix, in a ceremony watched over by her patron, HRH The Duchess of Cornwall.

The launching of Astute was 43 months behind schedule, and the Astute class were £900 million over budget. This was due in part to outdated construction practices. Many of these were corrected when Murray Easton became construction boss. Among the changes to accelerate the project, psychologists were consulted to improve communication and management effectiveness. Murray also reduced manpower requirements by using US construction methods, specifically those of the Electric Boat company. For example, submarine sections were built vertically so that gravity could assist assembly.

On 22 October 2010, the Ministry of Defense confirmed that Astute had "run into difficulties" off the Isle of Skye while on trials after eye-witnesses reported the submarine had run aground a few miles from the Skye Bridge. There were no reports of injuries. The captain of the vessel elected to wait for tug assistance, rather than use the submarine's own power to clear the stern from the obstruction, to minimize the damage to the hull's anechoic tiles. A Royal Navy spokesperson said the vessel had been grounded on silt, and was re-floated at high tide. The Maritime and Coastguard Agency-chartered emergency tow vessel Anglian Prince was dispatched to the scene from Stornoway.

During the operation to tow Astute clear, there was a collision between the rescue tug and the submarine, which resulted in damage to her starboard foreplane. The submarine returned under its own power to Faslane, where the damage incurred in the grounding and afterwards was described as "minor".

On 27 October 2010, the Royal Navy announced that the captain of Astute, Commander Andy Coles, had been relieved of his command. It was subsequently decided that he would not face a court martial. In December 2010 it was announced that Commander Iain Breckenridge would take over command.

On 11 December 2010, on her first day back at sea after the grounding incident, Astute had to return to port after a problem with the steam plant.

HMS Audacious, S122

HMS Audacious is the fourth Astute-class nuclear-powered fleet submarine of the Royal Navy. Long lead items for its construction were ordered on 28 August 2006, however the actual order was not placed until 21 May 2007. It is currently under construction.

Some aspects of A-04 will be different from Boats 1-3. Changes include the External Communication System (ECS) which will be upgraded.

Audacious's nuclear reactor will not need to be refueled during the boat's 25 year service. Since the submarine can replenish her air supply and purify water underway and while submerged, she will be able to circumnavigate the planet without resurfacing. The submarine's main limitation will be from the three months' supply of food carried for the 98 officers and ratings.

The Astute class SSNs are designed as the most stealthy. Royal Navy submarines in history. Using advanced stealth technology Astute "makes less noise than a baby dolphin, making her as good as undetectable by enemy ships."

Astute class submarines carry a mix of 38 weapons in six 21-inch (533 mm) torpedo tubes;

- BGM-109 Tomahawk Block IV cruise missiles. Range of 1,350 nautical miles (2,500 km).
- Spearfish torpedoes.

USS Augusta, SSN-710

Figure 85: USS Augusta

USS Augusta (SSN-710), a Los Angeles-class submarine, was the second ship of the United States Navy to be named for Augusta, Maine. (There were three other ships named USS Augusta that were named for Augusta, Georgia). The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 31 October 1973 and her keel was laid down on 1 April 1983. She was launched on 21 January 1984 sponsored by Mrs. Diana D. Cohen, and commissioned on 19 January 1985, with Commander Thomas W. Turner in command.

The Soviet Navy claims that on 3 October 1986, Augusta, commanded by James von Suskil, collided with the 667AU Nalim (Yankee-I) class ballistic missile submarine K-219, commanded by Igor Britanov, off the coast of Bermuda. The United States Navy states that K-219 was disabled by an internal explosion.

On 20 October 1986, shortly after K-219 sank and Augusta had returned to patrol, she collided with something, and was forced to return to Groton for about US$3 million in repairs to her bow and sonar sphere. What she collided with is officially unknown. If not the K-219, it is suggested that she had been trailing a Delta-I ballistic missile submarine, and, unknown to Augusta, being trailed in turn by a Victor class submarine. If abrupt maneuvers were made, Augusta could have collided with the Delta. Photographs exist of a Delta submarine with a large dent in its starboard bow, which the Soviet Navy identified as K-279. In Russian version of book the soviet submarine is identified as K-457.

Beginning in July 1987, shortly after that repair work completed, Augusta began service as trials boat for the BQG-5D Wide Aperture Array (WAA) passive sonar system and carrying the prototype BQQ-10 ARCI sonars, which incorporate off-the-shelf computer components, allowing easy introduction of modular upgrades.

In 2003, the USS Augusta was one of a handful of submarines participating in Tomahawk Strikes against Iraq in the opening of Operation Iraqi Freedom. The boat successfully launched missiles against all assigned missions leaving the theater with 100% completion.

The USS Augusta underwent extensive maintenance during 2006 to prepare for six month deployment in 2007, which began in March and completed in September. Augusta is currently preparing to change its homeport to Norfolk Naval Shipyard where it will begin decommissioning.

USS Augusta began decommissioning in January 2008, and completed the disassembly of her reactor on 24 November 2008.

USS Boise, SSN-764

USS Boise (SSN-764), a Los Angeles-class submarine, was the second ship of the United States Navy to be named for Boise, Idaho. The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia on 6 February 1987 and her keel was laid down on 25 August 1988. She was launched on 23 March 1991 sponsored by Mrs. Louis McClure, and commissioned on 7 November 1992 with Commander D. Mericle in command.

In 2002 Boise was assigned to the John F. Kennedy carrier battle group when the group took part in Operation Enduring Freedom.

In March 2003, Boise delivered some of the opening shots of Operation Iraqi Freedom when she launched a full load of Tomahawk missiles in support of the initial invasion. The ship and crew were later awarded the Navy Unit Commendation for their distinguished service in action.

USS Bremerton, SSN-698

USS Bremerton (SSN-698), a Los Angeles-class submarine, was the second ship of the United States Navy to be named for Bremerton, Washington. The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 24 January 1972 and her keel was laid down on 8 May 1976. She was launched on 22 July 1978 sponsored by Mrs. Henry M. Jackson, and commissioned on 28 March 1981 with Captain Thomas H. Anderson in command.

On 11 March 1999, Bremerton used one torpedo to sink the derelict forebody of the merchant ship New Carissa off the Oregon coast. The USS David R. Ray also participated in the sinking.

After a successful Western Pacific deployment, in September 2003 Bremerton changed its homeport to Pearl Harbor, Hawaii. Bremerton spent two months in drydock at Pearl Harbor ending 21 January 2010.

When USS Los Angeles (SSN-688) was decommissioned on 23 January 2010, Bremerton became the oldest commissioned submarine in the US fleet. On that day, Richard O'Kane's cribbage board was transferred from Los Angeles to Bremerton, a tradition that dates back to World War II.

USS Buffalo, SSN-715

Figure 86: USS Buffalo

USS Buffalo (SSN-715), a Los Angeles-class submarine, was the second ship of the United States Navy to be named for Buffalo, New York (another USS Buffalo was named for the animal). The contract to build it was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia on 23 February 1976 and its keel was laid down on 25 January 1980. It was launched on 8 May 1982 sponsored by Mrs. Joanne Kemp, and commissioned on 5 November 1983, with Commander G. Michael Hewitt in command.

In 1999, Buffalo was modified to carry a Dry Deck Shelter (DDS). In 2002, the Buffalo entered drydock in Pearl Harbor, Hawaii and became the first ship to undergo nuclear refueling in Hawaii. In late November 2005, the DDS was used to launch an underwater glider capable of gathering and storing information to be later transmitted by means of a built-in satellite phone.

Russian Submarine K-117 Bryansk

K-117 Bryansk is a Russian Project 667BDRM Delfin class (NATO reporting name: Delta IV) nuclear-powered ballistic missile submarine. The submarine was laid down in April 1985 in the Russian Northern Machinebuilding Enterprise, Sevmash. In September 1988 the submarine was commissioned in the Soviet navy. When launched the submarine became the 1000th Russian/Soviet submarine constructed. After the collapse of the Soviet Union the submarine continued to serve in the Russian navy. In July 2002 the submarine went into overhaul and didn't return until early 2008. As of 2010 the submarine is on active duty with the Russian Northern Fleet.

On 28 October, 2010, the submarine conducted a successful SLBM launch.

S603 Casabianca (ex-Bourgogne), SNA (SSN)

Figure 87: Casabianca

The Casabianca (ex-Bourgogne) is a first-generation nuclear attack submarine of the French Navy. She is named in honor of the famous submarine of the Free French Naval Forces Casabianca.

She is the third of the Rubis series. Between 1993 and June 1994, she undertook a major refitting which upgraded her to the level of the Améthyste.

During the Péan inter-allied maneuvers of 1998, Casabianca managed to "sink" USS Eisenhower and her Ticonderoga class escort cruiser.

USS Charlotte, SSN-766

USS Charlotte (SSN-766), a Los Angeles-class submarine, is the fourth ship of the United States Navy to be named for Charlotte, North Carolina. The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia on 6 February 1987 and her keel was laid down on 17 August 1990. She was launched on 3 October 1992 sponsored by Mrs. Mary McComack, and commissioned on 16 September 1994, with Commander Michael Matthews in command. The current commanding officer is Commander Richard Young.

Charlotte is a MOSUB (Mother Submarine) for the Deep Submergence Rescue Vehicle (DSRV) and is also capable of launching and recovering the Advanced SEAL Delivery System (ASDS).

On 29 November 2005, Charlotte arrived in Norfolk, Virginia, having taken the northern route from Pearl Harbor, under the Arctic ice cap. Along the way, she surfaced at the North Pole through 61 inches of ice, a record for a Los Angeles-class submarine.

On 24 October 2007, Charlotte returned to Pearl Harbor from Norfolk Naval Shipyard after nearly two years in a Depot Modernization Period.

Figure 88: USS Charlotte

USS Cheyenne, SSN-773

USS Cheyenne (SSN-773), the last Los Angeles-class submarine, was the third ship of the United States Navy to be named for Cheyenne, Wyoming. The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia on 28 November 1989 and her keel was laid down on 6 July 1992. She was launched on 16 April 1995 sponsored by Mrs. Ann Simpson, wife of Wyoming Senator Alan K. Simpson, and commissioned on 13 September 1996, with Commander Peter H. Ozimik in command.

Cheyenne transferred to her homeport of Pearl Harbor, Hawaii, in 1998.

Cheyenne has served as a trials platform for flat-screen, interoperative sonar displays based on commercially-available equipment.

Cheyenne was the first ship to launch Tomahawk missiles in Operation Iraqi Freedom under the command of CDR Charles Doty. Cheyenne would go on to successfully launch her entire complement of Tomahawks, earning a "clean sweep" for combat actions in the final three months of a nine-month deployment. This dubbed her "First To Strike".

USS Cheyenne was the final Los Angeles class submarine built by Newport News Shipyards. Following the construction of the USS Cheyenne, Newport News began preparation for construction of the Virginia-class submarine.

USS Chicago, SSN-721

Figure 89: USS Chicago

USS Chicago (SSN-721) is a Los Angeles-class submarine, the fourth ship of the United States Navy to be named for the city of Chicago, Illinois. The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia on 13 August 1981 and her keel was laid down on 5 January 1983. She was launched on 13 October 1984 sponsored by Mrs. Vicki Ann Paisley, wife of Melvyn R. Paisley assistant Secretary of the Navy, and commissioned on 27 September 1986, with Commander Robert Avery in command.

On March 15, 2010 the sub's Captain, Commander Jeff Cima, was relieved of command after facing a captain's mast. The mast found that Cima had been drunk and had acted in an "unbecoming" manner during a visit with NROTC midshipmen at Cornell University on March 10, 2010. Cima was temporarily replaced by Captain James Horten.

Churchill-class (SSN)

The three Improved-Valiant-class submarines, sometimes known as the Churchill-class, were nuclear powered fleet submarines which served with the Royal Navy from the 1970s until the early 1990s. The lead ship was named after the former British Prime Minister and First Lord of the Admiralty Winston Churchill. The Churchill class was based on the older Valiant class, but featured many internal improvements.

The Churchills carried a crew of 103 and had a full load displacement of 4,900 tons whilst dived. They were 86.9 meters long, had a beam of 10.1 meters and a draught of 8.2 meters. Their single pressurized water-cooled reactor supplied steam to two English Electric geared turbines, producing a total of 20,000 shp (15,000 kW) for the single shaft and resulting in a maximum of 28 knots submerged. One Kelvin Type 1006 surface-search radar was fitted. The ships were built with a Type 2001 sonar array, but this was replaced in the late 1970s with a Type 2020 array and a Type 2026 towed array. Weapons included Mark 8 torpedoes, Mark 24 Tigerfish torpedoes, and Sub-Harpoon anti-ship missiles. Six 21-inch (533 mm) torpedo tubes fired from the bow.

Like all nuclear-powered submarines the Churchill class could remain submerged almost indefinitely, with supplies of food being the only limiting factor.

HMS Churchill evaluated both the American Mark 48 torpedo and the UGM-84 Harpoon missile, though only the latter was adopted by the Royal Navy. She was decommissioned in 1990 and is laid up at Rosyth awaiting disposal.

In 1981 HMS Courageous became the first British submarine to carry the Sub-Harpoon missile. She was decommissioned in 1992 and is at Devonport Dockyard serving as a museum ship.

HMS Conqueror was the most famous of the class, sinking the Argentinean cruiser ARA General Belgrano during the 1982 Falklands War. She did not fire again during the war, but provided valuable help to the British task force by using her monitoring equipment to track Argentine aircraft departing the mainland. After the war Conqueror returned to Faslane; the sinking of the Belgrano had provoked controversy in Britain and Conqueror was criticized for flying the Jolly Roger on returning to port, as Royal Navy submarines customarily did on returning after scoring a kill. She was decommissioned in 1990 and as of 2010 is laid up at Devonport awaiting disposal. Conqueror's periscope can be viewed at the Royal Navy's museum in Portsmouth.

HMS Churchill, S46

HMS Churchill was the first of three Churchill-class submarine nuclear fleet submarines that served with the British Royal Navy.

USS City of Corpus Christi, SSN-705

Figure 90: USS City Of Corpus Christi

USS City Of Corpus Christi (SSN-705), a Los Angeles-class submarine, was the second ship of the United States Navy to be named for Corpus Christi, Texas, though she is the only one required to bear the "City of" prefix (added to placate protesters who claimed that it was improper to name a warship "the body of Christ", the meaning of the Latin phrase "Corpus Christi").

The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 31 October 1973 and her keel was laid down on 4 September 1979. She was launched on 25 April 1981 sponsored by Mrs. John Tower, and commissioned on 8 January 1983 with Commander W.G. "Jerry" Ellis in command.

The ship's patch was chosen by the crew based on entries to an art contest sponsored by the Corpus Christi, TX city government.

USS Columbia, SSN-771

Figure 91: USS Columbia

USS Columbia (SSN-771), a Los Angeles-class submarine, was the eighth ship of the United States Navy to bear that name. The earlier Columbia's were given their names for differing reasons; SSN-771 was specifically named in honor of Columbia, South Carolina, Columbia, Missouri, and Columbia, Illinois.

The contract to build Columbia was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 14 December 1988 and her keel was laid down on 21 April 1993. She was launched on 24 September 1994 with the traditional slide down a 1300-foot wooden ramp, the last American submarine expected to be launched in this dramatic fashion. Future submarines built in the United States will be launched by flooding the dry dock where they are built. Columbia was sponsored by Hillary Rodham Clinton, and commissioned on 9 October 1995, with Commander Dale Govan in command. Currently, USS Columbia is under the command of Commander Dennis J. Klein, with Lt. Commander Melvyn Naidas as his Executive Officer, and Master Chief Donald Williams Jr. as its Chief of the Boat (COB).

USS Columbus, SSN-762

Figure 92: USS Columbus

USS Columbus (SSN-762), a Los Angeles-class submarine, was the fourth ship of the United States Navy to be named for Columbus, Ohio. The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 21 March 1986 and her keel was laid down on 9 January 1991. She was launched on 1 August 1992 sponsored by Mrs. Margaret DeMars, and commissioned on 24 July 1993 with Commander Carl M. Smeigh, Jr. in command.

Columbus completed a Post Shipyard Availability in June 1994 in Groton, Connecticut after initial construction and shakedown operations. In September 1994, the ship conducted an interfleet transfer to Pearl Harbor, Hawaii and joined the U.S. Pacific Fleet Submarine Force. Columbus deployed to the Western Pacific in late 1995 through early 1996 and conducted a variety of operations as a unit of the U.S. 7th Fleet along the way making port visits in Hong Kong, Subic Bay, Guam, and Yokosuka, Japan.

Columbus was the first Submarine equipped with the BYG-1 Fire Control System in December 2002. Two successful test launches of Tactical Tomahawk (Block IV) cruise missiles were conducted in late May 2003 from USS Columbus (SSN 762), underway in the Pacific Ocean off the coast of Southern California. Columbus departed Pearl Harbor for another western pacific deployment in late 2003 and visited Chinhae, South Korea, Singapore, and Japan while taking part in Annual-Ex 2003(exercise) with various units of the Japanese Navy Defense force.

In mid-April 2006 seven Columbus crewmen were charged with a variety of offenses, including assault, dereliction of duty, and hazing, for alleged attacks on two of their shipmates. The accused range from a petty officer third class (E-4) to a senior chief (E-8). A complete report on the situation was completed on 30 May. On 13 June, the Navy announced the dismissal of Columbus's commanding officer, Commander Charles Marquez because of concerns about his "ability to establish and maintain appropriate standards of professional conduct, provide the crew a safe, positive, professional environment in which to work, and maintain good order and discipline". Captain Brian McIlvaine, former commanding officer of USS Ohio (SSGN-726), replaced Marquez temporarily. After about one month CAPT McIlvaine was replaced with CDR James Doody on July 14, 2006. At the end of a DMP (depot modernization period) In Bremerton, Washington, Columbus relocated back to Pearl Harbor on December 22, 2006.

Columbus departed Pearl Harbor in March 2008 for a regularly scheduled six-month deployment, during which they supported theater security cooperation efforts and conducted port visits to Saipan, Guam, Okinawa, Sasebo, and Yokosuka, Japan. In January 2009 Columbus won the Submarine Squadron 7 Battle Efficiency (Battle "E") award, given to the submarine crew that best demonstrates technical proficiency and continual mission readiness throughout the year. CDR David Minyard relieved CDR Doody as Commanding Officer on May 8, 2009. In July 2009, the Chief of Naval Operations announced that the ship was the Pacific Fleet winner of the Calendar Year 2008 Arleigh Burke Fleet Trophy.

USS Connecticut, SSN-22

Figure 93: USS Connecticut

USS Connecticut (SSN-22), a Seawolf-class submarine, is the fifth ship of the United States Navy to be named for the fifth state.

The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 3 May 1991 and her keel was laid down on 14 September 1992. She was launched on 1 September 1997 sponsored by Patricia L. Rowland, wife of the Governor of Connecticut, John G. Rowland, and commissioned on 11 December 1998 with Captain Larry Davis in command.

1999 was spent conducting shakedown operations that evaluated Connecticut's weapons systems, sensors, stealth and engineering proficiency. She participated in Joint Task Force Exercise 2-99 as an opposing force asset, and completed acoustic trials, a shallow water exercise, and an anti-submarine warfare exercise.

In September 1999 Connecticut began a Post-Shakedown Availability (PSA) at the Electric Boat shipyard. Despite 100 percent growth in the amount of PSA work, making this the submarine force's most demanding PSA, Connecticut completed all work ahead of schedule. Additionally, this PSA concluded as the safest in the 100-year history of Electric Boat.

In April 2003, Connecticut surfaced through the Arctic ice at the University of Washington's Applied Physics Laboratory Ice Station (APLIS). While there, she came under attack by a polar bear, which gnawed on her rudder for a while before disengaging. Connecticut was able to complete her mission and return to base under her own power.

On 31 March 2004 Connecticut put to sea in support of the War on Terrorism as part of the Wasp Expeditionary Strike Group (ESG), returning to NSB New London on 2 September with a pier side band blasting Thin Lizzy's "The Boys Are Back in Town". For the next three years, the Connecticut was largely confined to port as she underwent a prolonged maintenance cycle.

In early 2007, it was announced that the Connecticut would be transferred to Naval Base Kitsap-Bremerton, in Washington's Puget Sound, following a six-month deployment commencing on 25 July 2007. She would be the last of the Navy's three Seawolf-class submarines to be transferred from New London to Kitsap as part of a larger U.S. Navy realignment shifting 60 percent of the fleet's submarines to the Pacific. Upon arrival at Kitsap on 30 January 2008, the Connecticut joined her Seawolf sisters in Submarine Development Squadron Five.

HMS Conqueror, S48

Figure 94: HMS Conqueror

HMS Conqueror (nickname "Conks") was a Churchill-class nuclear-powered fleet submarine that served in the Royal Navy from 1971 to 1990. She was built by Cammell Laird in Birkenhead.

Conqueror was the third of the class, the other two being Churchill and Courageous. The main aim of these submarines was to face the Soviet threat at sea by attacking other ships and submarines, and spying on Soviet nuclear-armed submarine movements.

Conqueror, commanded by Commander Chris Wreford-Brown, was most famously deployed during the Falklands War, setting sail from Faslane Naval Base on the Gare Loch in Scotland on 3 April 1982, one day after the Argentine invasion. Conqueror arrived in the exclusion zone around the Falklands twenty-one days later. She was ordered to scan the area for Argentine shipping, particularly the aircraft carrier ARA Veinticinco de Mayo (the "25th of May"). On 30 April, she spotted Argentine light cruiser ARA General Belgrano. Belgrano was sailing southwest of the Falklands, just outside the exclusion zone imposed by the British on all shipping, and approaching the Task Force, while ARA Veinticinco de Mayo was approaching from the north. British admiral J. F. Woodward requested permission from the British government to sink Belgrano. After some debate he was allowed to proceed, though while this was going on the Belgrano retired from its attack position since ARA Veinticinco de Mayo was not ready. Finally, the message to engage Belgrano was sent from the Royal Navy's fleet command center in Northwood in the United Kingdom to Conqueror.

The reason given was that the Royal Navy feared a pincer attack, with Belgrano attacking from the south and Veinticinco de Mayo from the north. Also Belgrano could have escaped from Conqueror by sailing across nearby shallow waters, and could then have attacked the British Task Force. It has been suggested that the decision for the attack was political, to forestall diplomatic negotiations which might have resulted in an outcome unfavorable for Britain, but Belgrano's captain and the Argentine government later acknowledged that the attack was legitimate.

The scene was now set and, on 2 May Conqueror became the first nuclear-powered submarine to fire in anger when she launched three Mark 8 torpedoes at Belgrano, two of which struck the ship and exploded. Twenty minutes later, the ship was sinking rapidly and was abandoned by her crew. General Belgrano was unable to issue a Mayday signal because of electrical failure; this and poor visibility meant the two escorting destroyers were unaware of the sinking until some hours later. A total of 323 men were killed.

Conqueror's war did not end there. The crew of the submarine had to face Argentine Air Force attempts to locate her in the days after the attack, which had shocked the Argentine people and ruling dictatorship. Conqueror did not fire again in anger throughout the war, but provided valuable help to the task force by using sophisticated monitoring equipment to track Argentine aircraft departing the mainland.

After the war, Conqueror returned to Faslane, flying the Jolly Roger, a customary act of Royal Navy submarines after a kill. When asked about the incident later, Commander Wreford-Brown responded, "The Royal Navy spent thirteen years preparing me for such an occasion. It would have been regarded as extremely dreary if I had fouled it up".

Conqueror did not take part in any other conflicts, and was decommissioned in 1990. The periscopes, captain's cabin and main control panel from the submarines maneuvering room can be viewed in the Royal Navy's museum in Gosport.

HMS Courageous, S50

Figure 95: HMS Courageous

HMS Courageous (S50) was a Churchill-class nuclear fleet submarine in service with the Royal Navy from 1971.

In 1982, the Courageous was sent with her sister ship, the HMS Conqueror, with the British task force to retake the Falkland Islands from the occupying Argentine forces. She returned home later in the year without damage.

The Courageous was retired from service in 1992. She is now a museum ship at Devonport Dockyard.

During the HMNB Devonport Navy Days 2006, one of the members of the team currently restoring HMS Courageous pointed out that HMS Valiant was one of the first Royal Navy submarines to have her reactor removed (hence the box-like structures, visible in the photograph on the HMS Valiant page, which penetrate deep into the pressure hull. Later attempts on other vessels didn't require these structures). As the Valiant had been cosmetically wrecked by this work, HMS Courageous was selected for the museum ship to represent the SSN fleet of the Royal Navy during the Cold War. Components were removed from HMS Valiant to restore Courageous.

HMS Courageous was due to be moved in 2007 from her current berth to a new berth, due to development of the HMNB Devonport area where she currently resides.

USS Dallas, SSN-700

USS Dallas (SSN-700) is a Los Angeles-class nuclear-powered attack submarine of the United States Navy. It is the Navy's second ship of that name, and the first to be named for the city of Dallas, Texas, although another two ships were scheduled but never completed.

Dallas recently completed an Engineered Refueling Overhaul (ERO) at the Portsmouth Naval Shipyard in Kittery, Maine. As a part of the overhaul, Dallas was fitted with a removable Dry Deck Shelter configuration. This large chamber, fitted aft of the sail, has an array of air, water and hydraulic systems that allow Dallas to employ the latest submarine arsenal: the Swimmer Delivery Vehicle — a highly mobile and virtually undetectable means of carrying out special forces missions.

Dallas has completed one deployment to the Indian Ocean, four Mediterranean Sea deployments, two Persian Gulf deployments, and seven deployments to the North Atlantic.

On 27 August 1981 Dallas damaged her lower rudder when she ran aground while approaching the Atlantic Underwater Test and Evaluation Center site at Andros Island, Bahamas. The submarine worked herself free after several hours and returned on the surface to New London, Connecticut, for repairs.

RFS Dmitriy Donskoy, TK-208 (SSBN)

RFS Dmitry Donskoy (TK-208) is a Russian Navy nuclear ballistic missile submarine, designated Project 941 Akula class (NATO reporting name Typhoon).

Hull number TK-208 was the lead vessel of the Soviet third generation Project 941 Akula class (NATO reporting name Typhoon) of ballistic missile submarines. She was laid down at the Severodvinsk shipyards on March 3, 1977 and launched on September 23, 1980. At 175 meters in length, she became the world's largest submarine, a record which she still holds today along with her five sister ships.

On December 9, 2009, the Dmitry Donskoy launched a Bulava missile which had a failed third stage and was visible in Norway making a glowing spiral in the sky.

On October 7, 2010, she launched another Bulava ballistic missile from the White Sea. Targets at the Kura Test Range in the Russian Far East were successfully hit.

The Dmitry Donskoy and the rest of the Akulas are to be replaced by the first "real" Russian fourth generation submarine class, the Borei.

Russian Submarine K-414 Daniil Moskovsky

B-414 Daniil Moskovsky is a Project 671RTM Schuka (NATO: Victor III) attack submarine of the Russian Northern Fleet.

The submarine was laid down in 1989, launched and commissioned in 1990. It was known as K-414 before renaming in 1992. In 1994 B-414 took part in joint combat service with SSBN K-18 of Delta-IV class. In 1996 the submarine was named after Prince Daniil Moskovsky, the youngest son of Alexander Nevsky.

On 6 September 2006, a fire broke out on board killing two sailors.

HMS Dreadnought, S101

The seventh HMS Dreadnought was the United Kingdom's first nuclear-powered submarine, built by Vickers Armstrongs at Barrow-in-Furness. Launched by Queen Elizabeth II on Trafalgar Day 1960 and commissioned into service with the Royal Navy in April 1963, she continued in service until 1980. The submarine was powered by a S3W reactor, a design made available as a direct result of the 1958 US–UK Mutual Defense Agreement.

The Royal Navy had been researching designs for nuclear propulsion plants since 1946, but this work was suspended indefinitely in October 1952. In 1955 the United States Navy completed USS Nautilus, the world's first nuclear-powered submarine. During subsequent exercises with the Royal Navy, Nautilus demonstrated the advantages of the nuclear submarine against British anti-submarine forces, which had developed extensive anti-submarine warfare techniques during the Second Battle of the Atlantic. The Admiralty appreciated the utility of such vessels and under the drive of the First Sea Lord, Admiral The Earl Mountbatten of Burma and the Flag Officer Submarines, Sir Wilfred Woods, plans were formed to build nuclear-powered submarines.

Although the plan was to build all-British nuclear submarines, much time would be saved by accepting the American technological lead and taking advantage of US nuclear technology. The excellent relations between Admiral Mountbatten and US Navy Chief of Naval Operations Arleigh Burke, expedited obtaining that help. This was despite Rear Admiral Hyman Rickover, in charge of the American naval nuclear power program, being set against any transfer of technology; indeed, Rickover prevented Mountbatten inspecting USS Nautilus. It was not until a visit to Britain in 1956 that Rickover changed his mind and withdrew his objections. Although Rickover wished to supply the third generation S3W reactor of the Skate class, Mountbatten exerted his influence and the entire machinery system for an American Skipjack-class submarine, with its fifth generation S5W reactor, was obtained. This was known as the "American Sector". The hull and combat systems of Dreadnought were of British design and construction, although British access to the Electric Boat Company influenced the hull form and construction practices.

Dreadnought was laid down on 12 June 1959, and launched by Queen Elizabeth II on Trafalgar Day, 21 October 1960. The reactor was embarked in 1962 and Dreadnought made her first dive, in Ramsden Dock, on 10 January 1963. She commissioned on 17 April 1963.

During Dreadnought's construction, Rolls-Royce, in collaboration with the United Kingdom Atomic Energy Authority at the Admiralty Research Station, HMS Vulcan, at Dounreay, developed a completely new British nuclear propulsion system. On 31 August 1960, the UK's second nuclear-powered submarine was ordered from Vickers Armstrong and, fitted with Rolls-Royce's PWR1 nuclear plant, Valiant was the first all-British nuclear submarine.

Due to machinery damage and the limited refit facilities then available for SSNs, Dreadnought was withdrawn from service in 1980. Dreadnought is now at Rosyth Naval Dockyard, laid up indefinitely while her radioactive contamination decays. Her nuclear fuel has been removed and she has been stripped of useful equipment.

S604 Émeraude, SNA (SSN)

The Émeraude is a nuclear submarine from the first-generation of attack submarines by the French Navy.

She is the fourth of the Rubis series. Between May 1994 and December 1995, she undertook a major refitting which upgraded her to the level of the Améthyste.

On the 30th of March 1994, an accidental explosion occurred in the engine compartment, while the boat was engaged in an anti-submarine exercise, killing ten men who were examining the turbo-alternator room.

In June 2009, the Émeraude was sent to the mid-Atlantic to aid in the search for the flight data recorder and cockpit voice recorder from the ill-fated Air France Flight 447.

USS Florida, SSGN-728

Figure 96: USS Florida

USS Florida (SSBN-728/SSGN-728), an Ohio-class ballistic missile submarine, was the sixth ship of the United States Navy to be named for the 27th state. She was commissioned with the hull designation of SSBN-728; with her conversion to a cruise missile submarine, she was re-designated SSGN-728.

The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 28 February 1975 and her keel was laid down on the bicentennial of the United States' independence, 4 July 1976. The boat was unnamed at the keel-laying ceremony.

The initial ship's crew formed the precommissioning unit on 8 July 1980. The first shipboard watches were stationed on 14 February 1981 to support the operational control transfer of engineering systems to ship's force control. The Secretary of the Navy finally named her on 19 January 1981.

Florida was launched on 14 November 1981 sponsored by Mrs. Jarcia M. Carlucci. Her reactor was initially taken critical on 13 November 1982 and she went into service and the crew moved onboard on 21 January 1983. Florida commenced initial builders' sea trials on 21 February 1983 and was subsequently delivered to the Navy on 17 May 1983 – 43 days ahead of schedule. She was commissioned on 18 June 1983, with Captain William L. Powell in command of the Blue Crew and Captain George R. Sterner in command of the Gold Crew.

Both crews successfully completed the demonstration and shakedown operations, each culminated by the successful launch of a Trident C-4 missile. Florida transited the Panama Canal in February and arrived in Bangor, Washington on 25 March 1984. She completed her first strategic deterrent patrol on 25 July 1984.

As of November 2002, Florida had successfully completed 61 strategic deterrent patrols. She won the Battle E in 1989, 1991, 1994, 1999, and 2002.

Florida entered Norfolk Naval Shipyard in July 2003 to undergo a refueling and conversion from an SSBN to an SSGN. Florida completed her conversion in April 2006 and is homeported in Naval Submarine Base Kings Bay, Georgia. On 25 May 2006 she had a return to service ceremony at Naval Station Mayport, Florida. Ms. Carlucci was the ship's sponsor for her recommissioning in Mayport, Florida in May 2006.

USS Georgia, SSGN-729

USS Georgia (SSBN-729/SSGN-729), a Ohio-class submarine, is the second ship of the United States Navy to be named for the fourth state. The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 20 February 1976 and her keel was laid down on 7 April 1979. She was launched on 6 November 1982 sponsored by Mrs. Sheila M. Watkins, and commissioned as a fleet ballistic missile submarine (SSBN) on 11 February 1984, with Captain A.W. Kuester commanding the Blue crew and Captain M.P. Gray commanding the Gold crew. This ship was later converted to a guided missile submarine (SSGN) for carrying guided cruise missiles instead of fleet ballistic missiles in its missile compartment.

From March to April, 1984 she went on her shakedown cruise and test-launched a Trident C-4 missile in the Eastern Test Range on 7 April 1986. In November 1984, she arrived in her home port of Bangor, Washington. In January 1985 she started her first strategic deterrence patrol. As an element of Task Unit 14.7.1 from September 1983 to May 1986, she was awarded a Meritorious Unit Commendation. She was awarded her second Meritorious Unit Commendation for Submarine Operations between February 1986 to August 1986.

On 22 March 1986, near Midway Island, USS Secota (YTM-415) had just completed a personnel transfer with the Georgia, when the Secota lost power and collided with the Georgia. Secota sank. Ten crewman were rescued, but two drowned. Georgia was undamaged.

Figure 97: USS Georgia

USS Greeneville, SSN-772

Figure 98: USS Greeneville

USS Greeneville (SSN-772), the penultimate Los Angeles-class submarine, is the only ship of the United States Navy to be named for Greeneville, Tennessee. The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia, on 14 December 1988, and her keel was laid down on 28 February 1992. She was launched on 17 September 1994, sponsored by Tipper Gore, and commissioned on 16 February 1996, with Commander Duane B. Hatch in command.

The ship was named for Greeneville, home of 17th United States President Andrew Johnson, after local residents, businesses such as Greeneville Metal Manufacturing, which built submarine components, and government officials began a campaign for a submarine to be named after their town, rather than a large metropolitan area.

The Greeneville is probably best known for colliding with a Japanese fishing vessel off the coast of Oahu in February 2001.

USS Hampton, SSN-767

Figure 99: USS Hampton at the North Pole

USS Hampton (SSN-767), a Los Angeles-class submarine, is the fourth ship of the United States Navy to bear this name. The earlier Hamptons were given their names for varying reasons, but SSN-767 was specifically named for four cities: Hampton, Virginia; Hampton, Iowa; Hampton, South Carolina; and Hampton, New Hampshire. There are 14 more "Hampton" towns in the United States.

The contract to build the Hampton was awarded to the Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia (adjacent to the aforementioned Hampton, Va.) on 6 February 1987, and her keel was laid down on 2 March 1990. She was launched on 3 April 1992, sponsored by Mrs. Laura Bateman, and she was commissioned on 16 November 1993, with Commander David Antanitus in command.

In late April 2004 Hampton along with HMS Tireless (S88) surfaced through the ice together at the North Pole.

In February 2007, Hampton left Norfolk, Virginia for a seven month Western Pacific (WESTPAC) deployment. She traveled through the Panama Canal and arrived in Yokosuka, Japan. She completed two missions of national importance, and participated in two major, multinational naval exercises. She made port visits in Apra Harbor, Guam, White Beach, Okinawa, and Brisbane, Australia, as well as a brief stop in Pearl Harbor, Hawaii, before arriving in San Diego, CA. She earned the Navy Expeditionary Medal during this time.

On 17 September 2007, the Hampton's homeport was changed from Norfolk to San Diego, in a change from the Atlantic Fleet to the Pacific Fleet.

In an isolated incident from her safe operational record, in October 2007, six naval personnel were disciplined for fraudulently documenting the chemistry records of the Hampton's nuclear propulsion plant. Shortly thereafter, the ship's commanding officer Commander Michael B. Portland was also relieved of his command because of a loss of confidence in his leadership, but he has not been charged with any offense. In March 2008, the US Navy revealed that a total of 11 officers and enlisted men had been disciplined in connection with the fraudulent documentation and for cheating on qualification tests. In addition to the Captain, the submarine's engineer officer, the engineering department master chief petty officer, and the entire reactor laboratory division were dismissed from Naval nuclear plant duty and submarine service. No damage was discovered in the reactor core and the submarine has returned to operational status.

USS Hampton completed a Western Pacific deployment from October 17, 2008 to April 17, 2009. She made port visits to Singapore, Yokosuka, Japan, Saipan, and Apra Harbor, Guam, before returning to home port in San Diego. She participated in the first submarine exercise between the United States and the Singapore Navy.

In 2010, the USS Hampton won the Submarine Squadron 11 Battle Efficiency award.

USS Hartford, SSN-768

Figure 100: USS Hartford

USS Hartford (SSN-768), a Los Angeles-class submarine, is the second ship of the Navy to be named for Hartford, Connecticut. The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 30 June 1988 and her keel was laid down on 22 February 1992. She was launched on 4 December 1993 sponsored by Laura O'Keefe, wife of former Secretary of the Navy Sean O'Keefe, and commissioned on 10 December 1994, with Commander George Kasten in command.

On 25 October 2003 Hartford ran aground near La Maddalena in Sardinia with such force that rudders, sonar and other electronic equipment were severely damaged. After the accident Commander Christopher R. Van Metre, captain of Hartford, and Captain Greg Parker, Commodore of Submarine Squadron 22, were relieved of command and sent back to the United States. Six other crewmen were also charged with dereliction of duty.

On 20 March 2009 Hartford collided with amphibious transport dock USS New Orleans (LPD-18) in the Strait of Hormuz, slightly injuring 15 sailors on board. Both vessels were able to proceed under their own power after the incident, although the New Orleans suffered a ruptured fuel tank, releasing 25,000 gallons of diesel fuel into the strait.

The Navy announced April 14, 2009 that the submarine's skipper, Commander Ryan Brookhart, had been relieved of duty by Rear Admiral Michael J. Connor because of a loss of confidence in Brookhart's ability to command. Brookhart was replaced by Commander Chris Harkins, deputy commander of Submarine Squadron Eight.

A repair contract has been awarded to General Dynamics. Repairs were initially expected to cost $37.4 million and be completed by January 2010. However, as of November 2009 repair costs had already exceeded $100 million.

USS Hawaii, SSN-776

USS Hawaii (SSN-776), a Virginia-class submarine, is the first commissioned warship of the United States Navy to be named for the 50th state. (A previous large cruiser, or battle cruiser Hawaii was launched, but never commissioned, and was named after the Territory of Hawaii in any case.) The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 30 September 1998 and her keel was laid down on 27 August 2004. She was christened on 17 June 2006 by her sponsor, Governor Linda Lingle of Hawaii. Electric Boat delivered Hawaii to the US Navy on 22 December 2006, ahead of schedule. She was commissioned on 5 May 2007 with Captain David A. Solms in command. In August 2007, Commander Edward Herrington assumed command. In July 2009, she changed home port from Groton, CT (Submarine Group Two, Submarine Squadron Two) to Pearl Harbor, HI (Submarine Squadron One).

USS Helena, SSN-725

Figure 101: USS Helena

USS Helena (SSN-725), a Los Angeles-class submarine, was the fourth ship of the United States Navy to be named for Helena, Montana. The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 19 April 1982 and her keel was laid down on 28 March 1985. She was launched on 28 June 1986 sponsored by Mrs. Jean Busey, and commissioned on 11 July 1987, with Commander Thomas Moore in command.

USS Henry M. Jackson, SSBN-730

Figure 102: USS Henry M. Jackson

USS Henry M. Jackson (SSBN-730), is a United States Navy Ohio-class ballistic missile submarine that has been in commission since 1984. She is the only U.S. Navy ship to have been named for United States Senator Henry M. "Scoop" Jackson (1912–1983) of Washington and the only Ohio-class submarine not named after a U.S. state.

Henry M. Jackson originally was to have been named USS Rhode Island. The contract to build Rhode Island was awarded to the Electric Boat Division of General Dynamics Corporation at Groton, Connecticut, on 6 June 1977 and her keel was laid down there on 19 January 1981. Shortly after Senator Jackson died in office suddenly on 1 September 1983, Rhode Island was renamed Henry M. Jackson, and the name Rhode Island was transferred to another Ohio-class submarine, USS Rhode Island (SSBN-740).

Henry M. Jackson was launched on 15 October 1983, sponsored by Senator Jackson's daughter, Ms. Anna Marie Jackson, and commissioned on 6 October 1984, with Captain R. Tindal in command of the Blue Crew and Captain M. A. Farmer in command of the Gold Crew.

The crew of Henry M. Jackson is very active in volunteer work, and has adopted a highway and donated time to the Salvation Army, among many other activities.

USS Honolulu, SSN-718

USS Honolulu (SSN-718), a Los Angeles-class submarine, was the third ship of the United States Navy to be named for Honolulu, Hawaii. The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia on 15 September 1977 and her keel was laid down on 10 November 1981. She was launched on 24 September 1983 sponsored by Mrs. Joan B. Clark, and commissioned on 6 July 1985, with Commander Robert M. Mitchell in command.

Honolulu featured unique split stern planes that operated from independent hydraulic systems. With this redundant configuration, the inboard and outboard planes could be operated independently, preventing a failure of one or the other from causing an uncontrolled dive.

Honolulu's patrols are commemorated by ten surfboards signed by the crews aboard her at the time. The latest three are kept on board the submarine; the other seven are stored at Pearl Harbor.

Honolulu held a farewell ceremony in Pearl Harbor on 15 April, 2006, that included remarks by Senator Daniel K. Inouye, Lieutenant Governor James Aiona, U.S. Pacific Fleet commander Admiral Gary Roughead and former Honolulu commanding officer Vice Admiral Jonathan Greenert. Honolulu put to sea in early May 2006 for her final patrol. Her last patrol ended at Puget Sound Naval Shipyard in October 2006 where she was placed on stand down, on her way to decommissioning.

Honolulu was decommissioned and stricken from the Naval Vessel Register on 2 November 2007. Ex-Honolulu entered the Nuclear Powered Ship and Submarine Recycling Program in Bremerton, Washington.

The forward section of ex-Honolulu was transferred to USS San Francisco (SSN-711), repairing extensive damage caused by a severe grounding San Francisco experienced in 2005. The "challenging, one-of-a-kind project" was completed on 20 October 2008.

USS Houston, SSN-713

Figure 103: USS Houston

USS Houston (SSN-713), a Los Angeles-class attack submarine, was the fourth ship of the United States Navy to be named for Houston, Texas. The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia on 1 August 1975 and her keel was laid down on 29 January 1979. She was launched on 21 March 1981 sponsored by Barbara Bush, wife of then Vice-President of the United States George H. W. Bush. Houston was commissioned on 25 September 1982, with Captain G. H. Mensch in command. Curiously, her hull number matches the area code for the interior portion (inside the Beltway/Sam Houston Tollway, as of 2000) of Metropolitan Houston, which is also 713, but at the time she was built 713 encompassed most of Metro Houston within Harris County.

Houston is an experienced actor, initially starring in a Navy recruiting film and then getting her "big break" in June 1989 with a part in The Hunt for Red October (where she played her sister ship Dallas). However, that summer and autumn were plagued with mishaps.

In May, before getting involved with the film, a broken valve caused a depth excursion. Then on 14 June, during the shoot, Houston snagged a tow cable, sinking the tugboat Barcona in the San Pedro Channel near Santa Catalina Island, and drowning a tugboat crewmember. Then, two days later, after filming wrapped, Houston was en route to San Diego, California when she was caught in the net of the fishing boat Fortuna. The nets were destroyed, but no injuries were reported.

On 1 August 2008 the Navy reported to CNN that the Houston was found to have been leaking radioactive water for months while on patrol and visiting stations in Japan, Guam and Hawaii. The problem was discovered the previous month during servicing at Pearl Harbor. One crewman was exposed to radioactive water but not injured. The Navy reported that the Houston's leak released only a "negligible" amount of radioactivity. The Navy later expanded the estimated time the leak existed to nearly two years, although they maintained the amount of radiation leaked was very small - "less than a smoke detector".

USS Hyman G. Rickover, SSN-709

USS Hyman G. Rickover (SSN-709), a Los Angeles-class submarine, was the only ship of the United States Navy to be named for Admiral Hyman G. Rickover and the only Los Angeles class submarine not named after a United States city. The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 10 December 1973 and her keel was laid down on 24 July 1981. She was launched on 27 August 1983. SSN-709 was commissioned on 21 July 1984 with Captain Fredrik Spruitenburg in command. A commemorative plaque honoring the ship's namesake was placed within the sub after commissioning with the poem "Admiral Rickover," an eight-line tribute by writer Ronald W. Bell.

During the months of January through April 1984 Rickover was nearing the completion of her construction. The initial manning was completed in January. Initial criticality of the ships S6G reactor was achieved on 10 March 1984. Berthing and messing areas were completed in April and on 23 April 1984 the crew moved aboard the ship. A special meal of rib eye steaks, baked potatoes, and corn on the cob was served to remember the occasion.

The ship was placed into service on 24 April 1984 and initial sea trials began on 16 May 1984 with Admiral Kinnaird R. McKee aboard. Admiral McKee served as Director of the Office of Naval Nuclear Propulsion, Department of Energy. The sea trials were completed smartly and in the shortest time ever for a 688 class submarine built at Electric Boat. Admiral McKee complimented the crew on their fine performance prior to his departure.

Rickover was inactivated on 14 December 2006 and will be transported to Portsmouth Naval Shipyard in Kittery, Maine, in early 2007 for the year-long inactivation process. She is scheduled to be decommissioned on 1 March 2007. While in Bremerton, ex-Rickover will go through a dismantling program overseen by the Navy. The submarine will remain moored at the shipyard until it is dry-docked for dismantlement and disposal, which is currently scheduled for 2016.

S615 L'Inflexible, SNLE (SSBN)

Figure 104: FS Inflexible

The Inflexible (S 615) is the sixth and final of the Redoutable class SNLE of the Force océanique stratégique (FOST), the submarine nuclear deterrent component of the French Navy.

Construction began on 27 March 1980. She was launched on 23 June 1982, commissioned on 1 April 1985 and decommissioned on 14 January 2008.

Inflexible uses basically the same design as the other Redoutable-class vessels, but has benefited from technological advances over its predecessors:

- She uses the M4 missile, which carries 6 independent 150 kiloton of TNT equivalent nuclear warheads. Range is reported to be over 4500 km.
- Miscellaneous improvements were made in electrical systems, nuclear systems (improving safety and stealth), rudder and engines (improving reliability and stealth).
- TIT (Traitement de l'Information Tactique, "Tactical Information Processor"), a cluster of French-designed computers and serial digital bus links for intersystem communication.
- DMUX21 sonar.
- Capability of launching the SM 39 Exocet anti-ship missile
- Improved inertial navigation system.
- Improved internal communication system—SNTI, Système Numérisé de Transmissions Intérieures (Digital Internal Communication System)

- Miscellaneous acoustical stealth improvements
- Improved hull profile

The other Redoutable-class submarines have been modified to meet the standards of the Inflexible ("Refonte M4"). The Inflexible was officially decommissioned on 14 January 2008.

USS Jacksonville, SSN-699

USS Jacksonville (SSN-699), a Los Angeles-class attack submarine, is the only ship of the United States Navy to be named for Jacksonville, Florida. The ship is nicknamed "The Bold One". The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 24 January 1972 and her keel was laid down on 21 February 1976. She was launched on 18 November 1978 using the pontoon system designed for the launching of the Ohio Class Trident Submarines. The Jacksonville was sponsored by Mrs. Charles E. Bennett, and commissioned on 16 May 1981, with Captain Robert B. Wilkinson in command.

Jacksonville’s operations have included a variety of fleet exercises and deployments including two around-the-world cruises in 1982 and 1985, deployments to the western Atlantic Ocean in 1983, 1986, 1993 and 1994, and deployments to the Mediterranean Sea in 1987 and 1993. In 1988, Jacksonville participated in a shock trials test program for Los Angeles class submarines, which was followed by a three-year major modernization overhaul in Norfolk Naval Shipyard.

Jacksonville was involved in a collision with a Saudi container ship near the mouth of the Chesapeake Bay in May 1996.

On 20 December 2004 a small fire broke out aboard Jacksonville while it was undergoing a refueling overhaul at the Portsmouth Naval Shipyard. The fire was immediately extinguished and the reactor was never in danger, though a shipyard firefighter and a sailor were treated at the scene for smoke inhalation.

USS Jefferson City, SSN-759

Figure 105: USS Jefferson City

USS Jefferson City (SSN-759), a Los Angeles-class submarine, was the only ship of the United States Navy to be named for Jefferson City, Missouri. The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia on 26 November 1984 and her keel was laid down on 21 September 1987. She was launched on 17 August 1990 sponsored by Mrs. Susan A. Skelton, and commissioned on 29 February 1992, with Commander Russell Harris in command.

Homeport is the Point Loma Sub Base in San Diego, CA.

USS Jimmy Carter, SSN-23

Figure 106: USS Jimmy Carter

USS Jimmy Carter (SSN-23), the third and last Seawolf-class submarine, is the first ship of the United States Navy to be named for former President Jimmy Carter, who served in the United States Navy as a Communications Officer, Sonar Officer, Electronics Officer, Weapons Officer, and Supply Officer while on board the USS Pomfret (SS-391). Jimmy Carter is one of the few ships of the United States Navy (and only the third submarine) to have been named for a person who was alive at the time of the ship's naming, and the first submarine to be named for a living former president; Jimmy Carter is the only U.S. President to qualify in submarines.

Carter is roughly 100 feet (30 m) longer than the other two ships of her class. This is due to the insertion of a plug (additional section) known as the Multi-Mission Platform (MMP), which allows launch and recovery of ROVs and Navy SEAL forces. The plug features a fairing over a wasp-waist shaped passageway allowing crew to pass between the fore and aft sections of the hull while providing a space to store ROVs and special equipment that may need to launch and recover from the submarine. According to figures published by Electric Boat, the MMP increased Carter's displacement by about 33%, her navigation draft by over a foot (300 mm), and made her louder by two dB at 20 knots (37 km/h). It reduced her speed by two knots (4 km/h).

Carter has additional maneuvering devices fitted fore and aft that will allow her to keep station over selected targets in odd currents. Past submarines outfitted this way were used to tap undersea cables, to intercept communications of foreign countries. Intelligence experts speculate that the MMP may find use in similar missions as an underwater splicing chamber for fiber optic cables.

USS Kentucky, SSBN-737

USS Kentucky (SSBN-737), is a United States Navy Ohio-class ballistic missile submarine which has been in commission since 1991. She is the third U.S. Navy ship to be named for Kentucky, the 15th state.

The contract to build Kentucky was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut, on 13 August 1985 and her keel was laid down there on 18 December 1987. She was launched on 11 August 1990, sponsored by Carolyn Pennebaker Hopkins, who used a custom blend of Kentucky bourbon whiskey, mixed for the occasion, rather than the traditional bottle of champagne to christen Kentucky. Kentucky was commissioned on 13 July 1991, with Captain Michael G. Riegel commanding the Blue Crew and Captain Joseph Henry commanding the Gold Crew. As of 2011, CDR Joe Nosse (GOLD) and CDR Ed Fernandez (BLUE) are commanding officers of their respective crews.

USS Key West, SSN-722

Figure 107: USS Key West

USS Key West (SSN-722), a Los Angeles-class submarine, was the third ship of the United States Navy to be named for Key West, Florida. The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia on 13 August 1981 and her keel was laid down on 6 July 1983. She was launched on 20 July 1985 sponsored by Mrs. Virginia Conn, and commissioned on 12 September 1987 with Commander Warren Lipscomb, Jr. in command. She is the fourth Los Angeles - class submarine equipped with the vertical launch system (VLS) capable of carrying 12 Tomahawk land attack cruise missiles (TLAM).

USS Key West was home ported at the Norfolk Naval Base, Norfolk, VA. She operated out of Norfolk, VA until 1995. During her Atlantic Fleet service, she completed numerous Cold War deployments and supported operations in the Caribbean, Western Atlantic and Mediterranean. USS Key West was awarded the "Hook-em" antisubmarine warfare (ASW) excellence award following her 1990 Mediterranean Cruise. She later was awarded the Meritorious Unit Commendation Award for her superior performance in Cold War operations during the 1989 and 1990 deployments. USS Key West won the "TOP TORP" Torpedo Shooting Competition in 1992 and was later awarded the Submarine Squadron Eight Battle "E" for that year.

The USS Key West deployed with the Theodore Roosevelt Carrier Battle Group in 1995. During that deployment she operated in the Mediterranean Sea and Persian Gulf and was awarded the Navy Unit Commendation, Armed Forces Service, and NATO Service medals.

The USS Key West visited her name sake city in 1987 for a weeklong celebration after commissioning, in 1992 and later in 1994. Since reassignment to the Pacific Fleet she has not been able to visit Key West, Florida again.

In 2007 USS Key West was named "Battle E" for COMSUBRON THREE, given to the best submarine in its squadron, awarded the Arleigh Burke Trophy for the most improved sea command in the Pacific, and awarded the Naval Unit Commendation for its outstanding accomplishments during the deployment.

Russian Submarine B-276 Kostroma

B-276 Kostroma is a Russian Sierra class submarine. She was launched in 1986, commissioned in 1987, and named K-276 Crab until 1992. The Kostroma was built at Gorky and later towed to Severodvinsk for completion. She is part of the Russian Northern Fleet.

On February 11, 1992, the Kostroma - then still named K-276 Crab - collided with the USS Baton Rouge (some sources state it was K-239 Carp that collided with the Baton Rouge). The Baton Rouge was damaged (as was the Crab/Kostroma), and the crew of the K-276 painted the number "1" bordered by a star on the sail, as did Soviet submarines during World War II to indicate the number of their victories.

USS La Jolla, SSN-701

Figure 108: USS La Jolla

USS La Jolla (SSN-701), a Los Angeles-class submarine, is named for La Jolla, California. The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 10 December 1973 and her keel was laid down on 16 October 1976. She was launched on 11 August 1979 sponsored by Mrs. Bob Wilson, and commissioned on 30 September 1981, with Captain James R. Lang in command.

During the sea trials for the La Jolla, an incident where there was a loss of ship control and subsequent depth excursion lead to the retirement of Admiral Hyman G. Rickover.

In late 1982, about 30 miles out of San Francisco, California, La Jolla, while at periscope depth, collided with Permit (SSN-594), operating on the surface. La Jolla suffered minor rudder damage, while putting a ten-foot (3 m) long, three-foot (1 m) wide scrape in the paint on Permit's keel.

La Jolla was the first to successfully test fire a Tomahawk cruise missile while submerged at the Pacific Missile Test Center on 29 April 1983.

On 11 February 1998, about 9 miles out of Chinhae, South Korea, La Jolla accidentally ran into and sank a 27-ton fishing trawler. The five crewmembers of the trawler were rescued by the crew of La Jolla.

In 2000, La Jolla was modified to carry a Dry Deck Shelter (DDS).

USS Los Angeles, SSN-688

Figure 109: USS Los Angeles

USS Los Angeles (SSN-688), lead ship of her class of submarines, is the fourth ship of the United States Navy to be named for Los Angeles, California. The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia on 8 January 1971 and her keel was laid down on 8 January 1972. She was launched on 6 April 1974 sponsored by Anne Armstrong, and commissioned on 13 November 1976 with Commander John E. Christensen in command. She hosted President Jimmy Carter and the First Lady on 27 May 1977 for an at-sea demonstration of her capabilities. In 2007 she was the oldest submarine in active service with the United States Navy. The Navy decommissioned the USS Los Angeles on 23 January 2010, in the Port of Los Angeles, Los Angeles, California, her namesake city.

Los Angeles made her first operational deployment to the Mediterranean Sea in 1977 and was awarded a Meritorious Unit Citation. In 1978, she transferred to the Pacific Fleet and was assigned to Submarine Squadron 7, homeported in Pearl Harbor. She conducted 17 Pacific deployments over the next 32 years and earned eight Meritorious Unit Citations and a Navy Unit Citation. Los Angeles participated in four multinational "Rim of the Pacific" (RIMPAC) exercises, and visited numerous foreign ports in Italy, Republic of the Philippines, Diego Garcia, Hong Kong, Mauritius, Australia, Japan, Republic of Korea, Canada and Singapore.

In 1999, while under the command of Mark D. Jenkins, Los Angeles was modified to carry a Dry Deck Shelter (DDS). Her capabilities included undersea warfare, surface warfare, strike warfare, mining operations, special forces delivery, reconnaissance, carrier battle group support and escort, and intelligence collection.

USS Louisiana, SSBN-743

The fourth commissioned USS Louisiana (SSBN-743) is the 18th and last ship of the United States Navy's Ohio class of nuclear-powered fleet ballistic missile submarines. She carries Trident ballistic missiles and has been in commission since 1997.

The contract for the construction of Louisiana was awarded on 19 December 1990 and her keel was laid down at the Electric Boat Division of General Dynamics in Groton, Connecticut, on 23 October 1992. She was launched on 27 July 1996, sponsored by Patricia O'Keefe, and commissioned on 6 September 1997 at Naval Submarine Base Kings Bay at Kings Bay, Georgia.

USS Louisville, SSN-724

USS Louisville (SSN-724), a Los Angeles-class submarine, was the fourth ship of the United States Navy to be named for Louisville, Kentucky. The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 11 February 1982 and her keel was laid down on 24 September 1984. She was launched on 14 December 1985 sponsored by Mrs. Kinnaird McKee, and commissioned on 8 November 1986 with Captain Charles E. Ellis in command.

Louisville serves as a trials platform for the prototype BQQ-10 ARCI sonars, which incorporate off-the-shelf computer components, allowing easy introduction of modular upgrades.

The Louisville transited the Panama Canal in January 1987 to make her home base at Naval Base Point Loma in San Diego as a part of COMSUBRON11.

During her stay at San Diego, Louisville conducted several WestPac tours. During her 1988-89 WestPac Louisville visited Korea, Japan, Thailand, the Philippines and Guam.

In January and February 1991, as Operation Desert Storm began, Louisville carried out the first war patrol conducted by an American submarine since World War II. The patrol began with a 14,000-mile submerged, high-speed transit across the Pacific Ocean and Indian Ocean to the Red Sea. Shortly after noon on 19 January, she launched Tomahawk cruise missiles against targets in Iraq, becoming the first submarine to launch Tomahawks in combat, as well as having fired the first warshot of Desert Storm. For this war patrol, Louisville was awarded the Navy Unit Commendation.

In July 1992 Louisville became the first attack submarine to work up and deploy with a carrier battle group in the Pacific.

The submarine is currently stationed at Pearl Harbor, Hawaii.

In 2003, Louisville participated in Operation Iraqi Freedom, launching 16 Tomahawk missiles from the Red Sea against targets in Iraq. Her deployment was extended to eight and a half months in support of the campaign. She was awarded the Navy Unit Commendation for her role in the operation.

Louisville completed an extensive overhaul in Portsmouth, NH at the end of 2008. She returned to her homeport of Pearl Harbor in the spring of 2009 as a part of CSS-3. The sub's chief of the boat, Senior Chief Petty Officer Savan Patel, was relieved and reassigned in January 2011 after being arrested near Pearl Harbor for allegedly driving under the influence.

Figure 110: USS Louisville with Crew

USS Maine, SSBN-741

USS Maine (SSBN-741) is a United States Navy Ohio-class ballistic missile submarine in commission since 1995. She is the fourth U.S. Navy ship authorized, and the third commissioned, to be named in honor of the state of Maine. She has the capability to carry 24 nuclear armed Trident ballistic missiles.

The contract to build Maine was awarded to the Electric Boat Division of the General Dynamics Corporation, Groton, Connecticut, on 5 October 1988, and her keel was laid there on 3 July 1990. Maine was launched on 16 July 1994, delivered to the U.S. Navy on 23 June 1995, and commissioned on 29 July 1995.

Maine has been homeported at Naval Base Kitsap, Bangor, Washington since 2006. Prior to this, she was homeported at Naval Submarine Base Kings Bay from August, 1995 until 2006.

Figure 111: USS Maine

USS Maryland, SSBN-738

Figure 112: USS Maryland

USS Maryland (SSBN-738) is the 13th of 18 United States Navy Ohio-class ballistic missile submarines, and has been commissioned since 1992. She is the fourth U.S. Navy ship to be named Maryland.

USS Maryland's mission is to provide the United States of America with an undetectable and unattackable nuclear launch platform in support of the national strategy of strategic deterrence.

The contract for the construction of Maryland was awarded on 14 March 1986. Her keel was laid down by the Electric Boat Division of the General Dynamics Corporation at Groton, Connecticut, on 22 April 1986.

On 13 June 1992, Maryland was formally commissioned into U.S. Naval service as USS Maryland, with Captain John W. Francis in command of the Blue crew and Captain Harold E. Marshall in command of the Gold crew. The principal speaker was Admiral Charles R. Larson, Commander-in-Chief U.S. Pacific Command.

At this point the Blue crew retained the ship for shakedown operations, while the Gold crew departed to King's Bay, Georgia to start their off crew training cycle.

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At this point the Blue crew retained the ship for shakedown operations, while the Gold crew departed to King's Bay, Georgia to start their off crew training cycle.

USS Maryland has been involved in several Follow-on Commander's Evaluation Tests (FCET) of its Trident D-5 missile system. The FCET launches a specially modified missile without a nuclear payload, and is used to test the performance of the Trident missile system.

- FCET 10, performed 3 January 1994. 4 missiles launched.
- FCET 14, performed 21 April 1996. 2 missiles launched.
- FCET 21, performed 26 April 1999. 2 missiles launched.
- FCET 30, performed 5 November 2003. 2 missiles launched.
- FCET 36, performed 21 November 2006. 2 missiles launched.
- FCET 42, performed 8 June 2010. 2 missiles launched.
- FCET 43, performed 9 June 2010. 2 missiles launched.

On 16 October 2001, USS Maryland joined the USS John F. Kennedy Battle Group in an exercise that resulted in the sinking of ex-USS Guam. Maryland fired one Mark 48 torpedo during the exercise, which finally sunk ex-USS Guam.

USS Maryland is currently part of both Submarine Squadron 20 (itself part of United States Fleet Forces Command) and the United States Strategic Command, with her home port at Naval Submarine Base Kings Bay, Georgia.

USS Memphis, SSN-691

USS Memphis (SSN-691), a Los Angeles-class submarine, was the sixth ship of the United States Navy to be named for Memphis, Tennessee. The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia on 4 February 1971 and her keel was laid down on 23 June 1973. She was launched on 3 April 1976 sponsored by Mrs. Cathy Beard, and commissioned on 17 December 1977, with Commander G. Dennis Hicks in command.

In March 1981, Memphis completed an around-the-world cruise via the Panama Canal, including operations with both the Sixth and Seventh Fleets.

Memphis was redesignated an experimental submarine during 1989 to test composite hull structures, unmanned underwater vehicles, advanced sonars, hull friction reduction, and other advanced technologies for the Los Angeles and Seawolf classes, but remains combat-capable.

During a mid-1990s refit, Memphis received numerous modifications, which added about 50 tons to her displacement, most of it aft.

- A glass-reinforced plastic (GRP) turtleback abaft the sail to accommodate remotely operated vehicles
- A towing winch and drum for experimental towed sonar arrays
- 4.27 m-high by 1.37 m-wide vertical surfaces at the ends of the stern stabilizers to accommodate sonar transducer arrays
- A 54 mm towed array dispenser in the port fin leading to the new winch abaft the sail
- Supports for the stern stabilizers
- New hydraulic systems
- A fiber-optic databus
- 58 standardized equipment racks to accommodate electronic test gear

Memphis was present, along with USS Toledo and the British submarine HMS Splendid, at the Russian war games during which the Russian submarine Kursk exploded and sank, resulting in the loss of that submarine and all 118 sailors and officers on board. Despite the conclusions of independent forensic inquiries and the eventual corroborating admission by the Russian Navy that the explosion was triggered by a faulty torpedo onboard the Kursk, various conspiracy theories posit that Kursk was actually sunk by one of the US subs. This may partly stem from the Russian Navy's initial attempts to shunt away criticism of its failed efforts to rescue the surviving crew members from the ocean floor and of the generally poor condition of its own equipment, which was eventually found to be the cause of both the sinking and the failure of the Russian rescue attempts. In the days immediately after the explosion, Russia suggested that the cause of the disaster was a collision with one of the US subs present. Though the accusation proved to be unfounded, conspiracy theorists have inevitably picked up on and elaborated it in various directions over time.

The USS Memphis scheduled to be decommissioned in April, 2011.

Figure 113: USS Memphis

USS Miami, SSN-755

USS Miami (SSN-755), a Los Angeles-class submarine, is the second ship of the United States Navy to be named for Miami, Florida. The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 28 November 1983 and her keel was laid down on 24 October 1986. She was launched on 12 November 1988 sponsored by Mrs. Jane P. Wilkinson, and commissioned on 30 June 1990 with Commander Thomas W. Mader in command.

USS Michigan, SSGN-727

USS Michigan (SSBN-727/SSGN-727) is the second Ohio-class nuclear-powered fleet ballistic missile submarine in the United States Navy. She is the third ship to bear the name of the state of Michigan.

Michigan was constructed at the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut and was commissioned on 11 September 1982. Michigan arrived in Bangor, Washington on 16 March 1983 and completed sixty-six Strategic Deterrent Patrols.

As of June 2007, Michigan has been converted to an SSGN at the Puget Sound Naval Shipyard. Her hull classification symbol then changed from SSBN-727 to SSGN-727. See the section on SSGN conversions of the Ohio class for more information.

Michigan is currently at sea in the Pacific, earning its certification before returning to active duty.

As of June 2008, Michigan has completed material and operational certifications for tactical strike and deployment of special forces. The officers and crew are currently training to meet her next milestone as a Pacific Fleet asset.

On December 12, 2009, Michigan returned to Naval Base Kitsap, her home base, completing her first deployment after the SSGN conversion. The deployment began November 10, 2008, and included numerous missions with Naval Special Warfare and experiments with unmanned aerial vehicles. The sub also completed several theater security cooperation engagements with Pacific Rim nations.

USS Minneapolis-Saint Paul, SSN-708

USS Minneapolis–Saint Paul (SSN-708), a Los Angeles-class submarine, was the first vessel of the United States Navy to be named for the metropolitan area of Minneapolis-Saint Paul, Minnesota, although each city had been honored twice before. The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 31 October 1973 and her keel was laid down on 20 January 1981. She was launched on 19 March 1983 sponsored by Mrs. Penny Durenberger (wife of Senator David Durenberger), and commissioned on 10 March 1984, with Commander Ralph Schlichter in command.

While Minneapolis-St. Paul was the first vessel named for the Twin Cities as a whole, she is the third ship to be named for Minneapolis as well as the third to be named for St. Paul. The previous St. Paul, CA-73, was the last big-gun heavy cruiser in the United States Navy, and held the distinction of having fired the final shot of World War II.

Minneapolis-St. Paul conducted inter-fleet transfer from Norfolk VA to Pearl Harbor HI in July 2007 for decommissioning. Custody of Minneapolis-Saint Paul was transferred to Pearl Harbor Naval Shipyard in August 2008.

USS Montpelier, SSN-765

Figure 114: USS Montpelier

USS Montpelier (SSN-765), a Los Angeles-class submarine, was the third ship of the United States Navy to be named for Montpelier, Vermont. The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia on 6 February 1987 and her keel was laid down on 19 May 1989. She was launched on 23 August 1991 sponsored by Mrs. Nancy Hayes Sununu, and commissioned on 13 March 1993 with Commander Victor Fiebig in command.

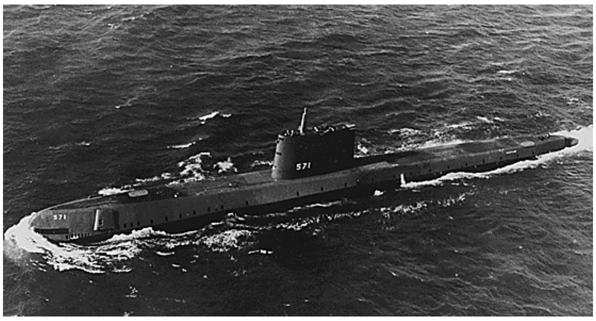
She was the first submarine to launch Tomahawk cruise missiles in Operation Iraqi Freedom. She would go on to fire all 20 missiles earning her a "clean sweep" under the command of CDR. William J. Frake.

The "Mighty Monty" is stationed in Norfolk, Virginia.

On May 27, 2004 the Montpelier went through an 18-month Depot Modernization Period (DMP) at Portsmouth Naval Shipyard in Kittery, Maine. The completed this period three months ahead of schedule and, after successfully completing sea trials returned to their home port in Virginia. The boat entered Norfolk Naval Shipyard on February 5, 2010 for modernization, maintenance, and upgrades, expected to cost around $35 million for 640,000 man hours, and included changing the submarine's buoyancy characteristics and upgrading its sonar capabilities. The work was completed and the sub returned to the fleet on July 26, 2010, eight days earlier than scheduled.

USS Nautilus SSN-571

Figure 115: USS Nautilus



USS Nautilus (SSN-571) is the world's first operational nuclear-powered submarine. She was also the first vessel to complete a submerged transit across the North Pole.

Named after the submarine in Jules Verne's Twenty Thousand Leagues Under the Sea, Nautilus was authorized in 1951 and launched in 1954. Because her nuclear propulsion allowed her to remain submerged for far longer than diesel-electric submarines, she broke many records in her first years of operation and was able to travel to locations previously beyond the limits of submarines. In operation, she revealed a number of limitations in her design and construction; this information was used to improve subsequent submarines.

The Nautilus was decommissioned in 1980 and designated a National Historic Landmark in 1982. She has been preserved as a museum of submarine history in Groton, Connecticut, where she receives some 250,000 visitors a year.

In July 1951 the US Congress authorized the construction of a nuclear-powered submarine for the U.S. Navy, which was planned and personally supervised by Admiral Hyman G. Rickover, known as the "Father of the Nuclear Navy." On 12 December 1951 the U.S. Department of the Navy announced that the submarine would be called Nautilus - the fourth U.S. Navy vessel officially so named - and would carry the hull number SSN-571.

Nautilus's keel was laid at General Dynamics' Electric Boat Division in Groton, Connecticut by Harry S. Truman, President of the United States, on 14 June 1952, and the ship was designed by John Burnham. She was christened on 21 January 1954 and launched into the Thames River, sponsored by Mamie Eisenhower, the wife of Truman's successor Dwight D. Eisenhower. Nautilus was commissioned on 30 September 1954, under the command of Commander Eugene P. Wilkinson, USN.

Nautilus was powered by the S2W naval reactor, a pressurized water reactor produced for the U.S. Navy by Westinghouse Electric Corporation. The prototype reactor was built at Idaho National Laboratory.

Following fleet exercises in early 1959, Nautilus entered the Portsmouth Naval Shipyard in Kittery, Maine, for her first complete overhaul (28 May 1959-15 August 1960). Overhaul was followed by refresher training and on 24 October she departed New London for her first deployment with the Sixth Fleet in the Mediterranean Sea, returning to her home-port 16 December.

Nautilus operated in the Atlantic, conducting evaluation tests for ASW improvements, participating in NATO exercises and, during October 1962, in the naval quarantine of Cuba, until she headed east again for a two month Mediterranean tour in August 1963. On her return she joined in fleet exercises until entering the Portsmouth Naval Shipyard for her second overhaul 17 January 1964.

On 2 May 1966, Nautilus returned to her home-port to resume operations with the Atlantic Fleet, and at some point around that month, logged her 300,000th mile (555,600 km) underway. For the next year and a quarter she conducted special operations for ComSubLant and then in August 1967, returned to Portsmouth, for another year's stay, following which she conducted exercises off the southeastern seaboard. She returned to New London in December 1968.

In the spring of 1979, Nautilus set out from Groton, Connecticut on her final voyage under the command of Richard A. Riddell. She reached Mare Island Naval Shipyard of Vallejo, California on 26 May 1979 — her last day underway. She was decommissioned and stricken from the Naval Vessel Register on 3 March 1980.

USS Nebraska, SSBN-739

USS Nebraska (SSBN-739) is the 14th Ohio-class ballistic missile submarine, and the second United States Navy ship to be named in honor of Nebraska, the 37th state. She carries Trident ballistic missiles.

The contract to build Nebraska was awarded on 26 May 1987 to the Electric Boat Division of the General Dynamics Corporation at Groton, Connecticut. Her keel was laid there on 6 July 1987 and she was launched on 15 August 1992, sponsored by Patricia Exon, the wife of United States Senator J. James Exon (1921–2005) of Nebraska. Nebraska was delivered to the U.S. Navy on 18 June 1993 and commissioned on 10 July 1993.

As of September 2010, the sub had completed 53 deterrent patrols during its 18 years of service. Each patrol was usually 77 days in duration followed by 35 days in port for maintenance.

Following Patrol 54 the USS Nebraska was awarded the "Battle E" for Submarine Squadron 17.

USS Nevada, SSBN-733

USS Nevada (SSBN-733) is a United States Navy Ohio-class ballistic missile submarine that has been in commission since 1986. She is the fourth ship of the U.S. Navy to be named for Nevada, the 36th state.

The contract to build Nevada was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut, on 7 January 1981 and her keel was laid down there on 8 August 1983. She was launched on 14 September 1985 sponsored by Mrs. Carol Laxalt, the wife of United States Senator Paul Laxalt of Nevada, and commissioned on 16 August 1986, with Captain F.W. Rohm in command of the Blue Crew and Captain William Stone in command of the Gold Crew.

USS New Hampshire, SSN-778

USS New Hampshire (SSN-778), a Virginia-class nuclear-powered attack submarine, is the fourth ship of the United States Navy to be named for the state of New Hampshire (though one of her predecessors, BB-70, existed only on paper — authorized, but cancelled before keel laying). The name was awarded to the submarine after a letter-writing campaign by the third-graders from Garrison Elementary School in Dover to their members of Congress, the state governor, and the Secretary of the Navy.

The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut, on 14 August 2003. Construction began in January 2004. A keel-laying ceremony for the submarine was held at Electric Boat's Quonset Point facility in North Kingstown, Rhode Island, on 30 April 2007. The ship's sponsor was Cheryl McGuinness of Portsmouth, New Hampshire, the widow of Thomas McGuinness, co-pilot of American Airlines Flight 11, who died in the September 11, 2001 attacks when the jet was flown into the North Tower of the World Trade Center.

The submarine was launched on 21 February 2008 and christened four months later, on 21 June 2008 in Groton, Connecticut, eight months ahead of schedule and $54 million under budget. New Hampshire finished sea trials and was delivered to the Navy on 28 August 2008. The ship was commissioned in a ceremony at the Portsmouth Naval Shipyard in Kittery, Maine, on 25 October 2008.

Figure 116: USS New Hampshire

USS Newport News, SSN-750

Figure 117: USS Newport News

USS Newport News (SSN-750), a Los Angeles-class submarine, was the third ship of the United States Navy to be named for Newport News, Virginia.

The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia on 19 April 1982 and her keel was laid down on 3 March 1984. She was launched on 15 March 1986.

Newport News returned to Norfolk, Virginia, following a six-month overseas deployment that included operations in the Middle East. In support of Operation Iraqi Freedom she launched 19 UGM-109C Tomahawk land Attack Missiles in March of 2003. She deployed in August 2004, first to take part in joint operations with allied navies in the North Atlantic, then to the U.S. Central Command area of operations "in support of national security interests and the global war on terrorism."

On 8 January 2007, Newport News was operating submerged in the Arabian Sea south of the Straits of Hormuz when it hit the Japanese tanker Mogamigawa. She had been operating as part of Carrier Strike Group 8 (CSG-8), organized around the aircraft carrier Dwight D. Eisenhower (CVN-69). The Carrier Strike Group was redeploying to the Indian Ocean to support a maritime cordon during the war in Somalia when the incident happened. The Newport News suffered damage to her bow, but there was no damage to the sail, mast or reactor, and she made for port in Bahrain under her own power. An official of the Kawasaki Kisen Company (or K Line), which owns the tanker, announced that Mogamigawa's hull and propellers were damaged.

According to a Navy spokesman, the collision occurred as a result of the venturi effect. The tanker drove over the area where the submarine was submerged and this created a sucking effect that forced the submarine upward to the surface. The incident was the third collision between a U.S. nuclear-powered submarine and a Japanese civilian ship.

On 29 January, after the boat returned to Bahrain for repairs, administrative personnel actions (Admiral's Mast) were taken against several members of her crew, which included relieving the boat's commanding officer, Commander Matthew A. Weingart, of command due to a lack of confidence in his ability to command.

On 10 April the Iranian Fars News Agency reported that the Newport News has been leaking radioactive and chemical pollution in the Persian Gulf and claimed that following this formal complaint, the ship departed the gulf for a complete overhaul. The US Navy Fifth Fleet denied this claim restating that damage was limited to the bow and that the sail, mast and reactors were not damaged. On 2 October 2007 the U.S. Navy agreed to pay Kawasaki Kisen Kaisha Ltd, the company that owns Mogamigawa an undisclosed amount in compensation for the collision.

USS Norfolk, SSN-714

USS Norfolk (SSN-714), a Los Angeles-class attack submarine, was the third ship of the United States Navy to be named for Norfolk, Virginia. The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia on 20 February 1976 and her keel was laid down on 1 August 1979. She was launched on 31 October 1981 sponsored by Mrs. Caspar Weinberger, and commissioned on 21 May 1983, with Commander Kenneth R. Karr in command (Commander Karr was promoted to the Pentagon later that year and retired from the NPEB as a Captain in 1988).

With the second Commanding Officer, Alfred Ponessa, Norfolk conducted extensive trials of the next-generation torpedo, ADCAP, as well as advanced and secret acoustic experiments. The ship also made an active deployment during one of the final spurts of activity from the declining Soviet navy. On July 23, 1988 the USS Norfolk fired the first ADCAP torpedo, sinking the USS Jonas Ingram (DD-938). Commander Ponessa was succeeded by Commander Harrop in 1988.

On January 17, 1989, Norfolk was involved in a collision with the combat stores ship USS San Diego (AFS-6) off Cape Charles Light, VA as both vessels were headed to sea. Norfolk was outbound for an engineering inspection, an event which occupied all of the ships most experienced officers. The Officer of the Deck was the ship's most junior officer, a non-nuclear-trained Lieutenant Junior-Grade, and the Commanding Officer himself was new to the ship, sick and hoarse that day. While trying to pass the San Diego in a turn in the channel, the current set Norfolk towards an outer buoy on the port side. Overcorrecting for this event, Norfolk delivered a glancing blow to the ship on her starboard side, San Diego. There were no injuries, and neither ship suffered significant structural damage. Upon returning to dockside later that day, Norfolk's commanding officer was relieved, and the sub proceeded on the surface to Kings Bay, Georgia, for inspection and repairs. As a result of this collision, COMSUBLANT issued orders limiting submarine speed and passing activities while in the restricted waters of the Hampton Roads channels.

On 25 August 2004, Norfolk returned to Norfolk, VA after a 22-month Engineering Refueling Overhaul (ERO) at Portsmouth Naval Shipyard in Kittery, Maine.

USS North Carolina, SSN-777

USS North Carolina (SSN-777), a Virginia-class attack submarine, is the fifth ship of the United States Navy named for the 12th state. It is currently the only nuclear submarine capable of performing full underwater "barrel-rolls".

The contract to build her was awarded to Northrop Grumman Newport News on 30 September 1998 and her keel was laid down on 24 May 2004. She was launched on 5 May 2007.

Virginia was commissioned on 3 May 2008. This class of submarine is unique in that it features a Photonics Mast Program (PMP) that freed ship designers to place the boat's control room in a lower, less geometrically-constrained space than would be required by a standard, optical tube periscope. It is additionally unique in the U.S. Navy for featuring all-digital ship and ballast control systems that are manned by relatively senior watchstanders and a pressure chamber to deploy SEAL divers while being submerged.

Commander, Submarine Force, U.S. Pacific Fleet announced that USS North Carolina SSN-777 will be changing homeports from Naval Submarine Base New London to Naval Station Pearl Harbor. North Carolina left Groton for Pearl Harbor on 22 July 2010. The USS North Carolina arrived at her new homeport, Joint Base Pearl Harbor-Hickam, on Monday, 15 November 2010 after her four month transfer activities. During the transfer, the officers and crew of SSN 777 conducted a series of exercises designed to test the boat's new combat systems and stealth capabilities. North Carolina is the third Virginia class attack submarine to be homeported at Joint Base Pearl Harbor-Hickam and is assigned to Commander, Submarine Squadron 3.

Russian Submarine K-407 Novomoskovsk

Novomoskovsk (K-407) is a Project 667BDRM Delfin-class ballistic missile submarine (NATO reporting name "Delta-IV") of the Russian Navy's Northern Fleet.

Construction of the nuclear submarine K-407 Novomoskovsk began at the Northern Machinebuilding Enterprise (Sevmash) in Severodvinsk on February 2, 1987, and it became part of the Soviet Navy on November 27, 1990. She was the last of seven 667BDRM Delfin submarines and the last SSBN submarine built in the USSR. This class of submarines was developed at the Rubin Design Bureau in 1975 and is considered one of the most successful Soviet submarine missile carrier designs.

The submarine has a submerged displacement of 18,200 tons and a surface displacement of 11,700 tons. It is 167 m long and 11.7 m wide. It is powered by two OK-700A nuclear reactors with a total power of 180 MW. The submarine's immersion depth is 400 m; its surface speed is 14 knots, and its underwater speed is 24 knots. It carries a crew of 135. Armaments include a D-9RM missile system (16 RSM-54 ballistic missiles) and four 533-mm torpedo tubes (18 torpedoes).

The RSM-54 missile (3M37, R-29RM, or SS-N-23 according to the NATO classification) is a liquid-propellant, three-stage missile with separable heads (it carries four or ten warheads depending on the modification). It has a range of 8300 km, a hit accuracy of 500 m, and a launching mass of 40.3 tons. It is 14.8 m long and 1.9 m in diameter.

At the moment, Novomoskovsk is worthy of the proud name of "the most shooting" submarine of the Russian Navy. The submarine is currently part of the 31st Order of the Red Banner underwater strategic missile cruiser division of the 12th submarine squadron of the Northern Fleet (Olenya Bay, Skalisty Naval Base). The submarine's commander is Captain Sergei Rachuk.

As a member of association of Russian regions and cities, patrons of Northern Fleet ships and units, the Tula Oblast patronages K-114 Tula and K-407 Novomoskovsk submarines and assists in patriotic education and preparation of young people for serving in the Armed Forces of the Russian Federation. Citizens of Novomoskovsk have preference to serve on K-407 Novomoskovsk. The submarine crew are regularly provided by humanitarian goods and visited by the city authorities.

Figure 118: Novomoskovsk, Russian Submarine

Russian Submarine K-152 Nerpa

The K-152 Nerpa is a 8,140-tonne (8,010-long-ton) Project 971 Shchuka-B (NATO: Akula II) type nuclear-powered attack submarine. Construction was started in 1993, but suspended due to lack of funding. K-152 Nerpa was launched in October 2008 and entered service with the Russian Navy in late 2009. The submarine will eventually be leased to the Indian Navy in 2010 and recommissioned as the INS Chakra.

While K-152 Nerpa was undergoing sea trials in the Sea of Japan on 8 November 2008, an accident caused the deaths of some twenty sailors and injury to twenty-one others. A fire suppression system discharged gas in the bow of the sub, suffocating civilian specialists and navy crew members.

The Nerpa was laid down at the Komsomolsk-on-Amur shipyard in 1993, but its completion was delayed for nearly a decade due to a lack of funds caused by the economic crisis of the early 1990s. The partly-constructed vessel was mothballed until 2004, when Rosprom (the Federal Agency for Industry) signed an agreement with the Indian government to complete the submarine and lease it to the Indian Navy. The vessel was intended to be completed by 2007, but underwent further delays. In 2007, it was transferred to the Vostok shipyard in the closed city of Bolshoy Kamen, Primorsky Krai, for fitting-out. It was launched in October 2008 for sea trials, following which it was due to be handed over to the Russian Defense Ministry. Reports in the Indian media suggest that the resumption of construction was underwritten with Indian funding.

The standards of the vessel's construction were criticized by several commentators.

During May 2009, the repairs were reported to be almost complete and new sea trials were planned for June 15–20. However, by October 2009, the work had still not been completed due to the shipyard's electrical supply having been disconnected. Nikolai Povzyk, the head of the shipyard, complained they had not been paid the 1.9 billion rubles (63.8 million dollars) owed for the work carried out on the Nerpa.

As of 2008, Russia had an agreement pending with India worth US$2 billion for the lease of Nerpa and another Project 971 Shchuka-B class submarine. Of this, K-152 Nerpa will be leased for 10 years to India at an estimated cost of US$650 million. After being handed over to the Indian Navy, it would be commissioned as INS Chakra. Nerpa is the Russian word for the Baikal seal, and Chakra is a weapon.

Indian naval crews earlier trained to operate the submarine near St. Petersburg and another group of sailors was expected to arrive in Vladivostok in late 2008 for joining sea trials. The training of the crew was viewed as crucial to India's own nuclear submarine program, known as the Advanced Technology Vessel (ATV).

After the 2008 accident, there were conflicting reports over the status of the lease. A Russian defense industry official denied that talks had been held with India on the delivery of the nuclear submarine. "Russia did not launch talks on a contract to supply India with the Nerpa nuclear-powered submarine." General of the Army Nikolai Marakov stated that Russia would commission the Nerpa and that it would join seven other Akula class submarines in Russia's Pacific Fleet. "The sum of $650-780 million, which Rosoboronexport and the Amur Shipbuilding Plant had negotiated over a long period of time with the Indian Ministry of Defense, will now be found in Russia," he said.

However, in May 2009, both Russian and Indian defense officials confirmed that the Nerpa would be joining the Indian Navy by the end of 2009, after Russian President Vladimir Putin visited the yard and announced an immediate release of 1.2 billion roubles, for the submarine construction.

On December 28, 2009, Nerpa was commissioned and joined the Russian Navy. The submarine underwent further adjustments in February 2010. As of August 2010 Russia was training a crew from the Indian Navy to sail the ship to India in fulfillment of the lease agreement.

Figure 119: Akula Class Submarine

USS Ohio, SSGN-726

USS Ohio (SSBN-726/SSGN-726), the lead ship of her class of nuclear-powered fleet ballistic missile submarines, was the fourth ship of the United States Navy to be named for the 17th state. She was commissioned with the hull designation of SSBN-726, and with her conversion to a guided missile submarine she was re-designated SSGN-726.

The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 1 July 1974 and her keel was laid down on 10 April 1976 by Mrs. Robert Taft, wife of Senator Taft. On 2 February 1978, the Precommissioning Unit was formed with Commander A. K. Thompson as its Commanding Officer. Ohio was launched on 7 April 1979 sponsored by Mrs. Annie Glenn, wife of Senator John H. Glenn.

In the summer of 1981, sea trials were held to test the equipment and systems, and the submarine was delivered to the U.S. Navy on 28 October 1981. On 11 November 1981, Ohio was commissioned. The principal speaker, Vice President George H. W. Bush, remarked to the 8000 assembled guests that the ship introduced a "new dimension in our nation's strategic deterrence," and Admiral Hyman G. Rickover noted that the Ohio should "strike fear in the hearts of our enemies." On that day, command of the two crews (designated Blue and Gold) of the USS Ohio was assumed by Captain A. K. Thompson (SSBN-726) (Blue) and Captain A. F. Campbell (SSBN-726) (Gold).

Following Post Shakedown Availability at Electric Boat Division, Ohio left the Atlantic and transited to her new home port, Bangor, Washington, by way of Cape Canaveral - where she tested her missile launch systems - and the Panama Canal, arriving on 12 August 1982. During August and September 1982, the first load out of Trident C-4 missiles and a predeployment refit were conducted. Ohio and her Blue Crew departed on the first Trident Submarine Strategic Deterrent Patrol in October 1982.

From June 1993 to June 1994 Ohio underwent overhaul at Puget Sound Naval Shipyard, Bremerton, Washington, receiving extensive upgrades to sonar, fire control, and navigation systems. Ohio resumed strategic deterrent patrols in January 1995 as part of Submarine Squadron Seventeen, Submarine Group Nine, Pacific Submarine Force.

Original plans called for Ohio to be retired in 2002. However, Ohio and three sister ships have been modified and remain in service as conventional missile submarines (SSGNs). (See the discussion of the entire Ohio class for details.) In November 2003 Ohio entered drydock, beginning a 36-month refueling and conversion overhaul. Electric Boat announced on 9 January 2006 that the conversion had been completed. Ohio rejoined the fleet on 7 February 2006. Ballistic submarines of Ohio's class employ two crews, Blue and Gold, in order to facilitate continuous operation at sea, called "forward-presence" in USN parlance. On 21 January 2007, the Gold Crew departed Naval Base Kitsap for Hawaii to conduct a forward-deployed crew exchange, the first such forward-deployed swap in approximately 20 years.

The Ohio left for her first mission on 15 October 2007. The Blue crew underwent several tests and inspections before completing a mission sometime in December. The Ohio is also the first one of the class to complete a mission.

Figure 120: USS Ohio

USS Oklahoma City, SSN-723

USS Oklahoma City (SSN-723), a Los Angeles-class submarine, is the second ship of the United States Navy to be named for Oklahoma City, Oklahoma. The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia on 13 August 1981 and her keel was laid down on 4 January 1984. She was launched on 2 November 1985 sponsored by Mrs. Linda M. Nickles, and commissioned on 9 July 1988, with Commander Kevin John Reardon in command.

In 1991, Oklahoma City won the Marjorie Sterrett Battleship Fund Award for the Atlantic Fleet.

On 13 November 2002, Oklahoma City collided with the Leif Hoegh liquefied natural gas tanker Norman Lady, east of the Strait of Gibraltar. No one on either vessel was hurt, and there were no leaks of oil from fuel tanks and no threat to the environment, but the submarine sustained damage to her periscope and sail area, and put into La Maddalena, Sardinia, for repairs. Her commanding officer, Commander Richard Voter, was relieved of his command on 30 November. One other officer and two enlisted crew members also were disciplined for alleged dereliction of duty.

On 20 January 2005 Oklahoma City returned to Norfolk, Virginia, after a six-month deployment in support of national security interests and the War on Terrorism. OKC transited to her patrol area in the Pacific Ocean via the Arctic Ocean, the first such transit for a first-flight Los Angeles-class submarine. After the patrol, she then completed a circumnavigation of North America by transiting back to the Atlantic Ocean through the Panama Canal and returning to her homeport in Norfolk.

In early 2007, Oklahoma City became the first submarine certified to exclusively use Digital Nautical Charts (DNCs), using the Voyage Management System (VMS). VMS is part of the Electronic Chart Display and Information System-Navy (ECDIS-N) system, which has been under development since 1990. The shift from traditional paper navigation to an all-electronic navigation suite marked the first significant shift in U.S. Navy navigation practices since the introduction of the Global Positioning System (GPS) in the 1990s.

From May to November 2007, Oklahoma City completed a deployment to the Persian Gulf in support of the War on Terror. She spent May to July 2008 in the Eastern Pacific in support of the War on Drugs, and was responsible for seizing more than 11 metric tons of cocaine valued at more than $1.5 billion (USD).

Oklahoma City was awarded the 2008 Squadron Eight Battle "E". On November 22, 2008, Commander Aaron M. Thieme relieved Commander Ed Mayer as commanding officer.

After a 26-month overhaul, in March 2011 the sub was forward deployed to Guam.

USS Olympia, SSN-717

USS Olympia (SSN-717), a Los Angeles-class submarine, was the second ship of the United States Navy to be named for Olympia, Washington. The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia on 15 September 1977 and her keel was laid down on 31 March 1981. She was launched on 30 April 1983 sponsored by Mrs. Dorothy Williams, and commissioned on 17 November 1984, with Captain William Hughes in command.

In 1998, Olympia became the first Pacific-based submarine to pass through the Suez Canal in over 35 years. She is currently captained by Cdr. Michael Coughlin.

USS Pasadena, SSN-752

USS Pasadena (SSN-752), a Los Angeles-class submarine, was the third ship of the United States Navy to be named for Pasadena, California.

Pasadena provides the Fleet Commander or Task Force Commander a multi-mission platform. This vessel has unlimited endurance due to the nuclear propulsion plant, advanced sonar, torpedo, cruise missile, and mine delivery systems, a combination of speed and stealth due to quieting and the capacity to fulfill numerous missions.

The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 30 November 1982 and her keel was laid down on 20 December 1985. She was launched on 12 September 1987 sponsored by Mrs. Pauline Trost, and commissioned on 11 February 1989 with Commander W. Fritchman in command.

USS Pennsylvania, SSBN-735

USS Pennsylvania (SSBN-735) is a United States Navy Ohio-class ballistic missile submarine which has been in commission since 1989. She is the fourth ship of the United States Navy to be named for Pennsylvania, the second state.

The contract to build Pennsylvania was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut, on 29 November 1982 and her keel was laid down there on 10 January 1984. She was launched on 23 April 1988, sponsored by Mrs. Marilyn Garrett, and commissioned on 9 September 1989, with Captain Richard M. Camp commanding the Blue Crew and Captain A. Lee Edwards commanding the Gold Crew.

S606 Perle, SNA (SSN)

Figure 121: FS Perle

The Perle is a first-generation nuclear attack submarines of the French Navy.

She is the sixth and last of the Rubis series.

She was deployed in the Royal Navy Auriga 2010 exercise along-side 7 Royal Navy war ships and 1 US navy destroyer.

USS Philadelphia, SSN-690

USS Philadelphia (SSN-690), a Los Angeles-class attack submarine, was the sixth ship of the United States Navy to be named for Philadelphia, Pennsylvania. The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 8 January 1971 and her keel was laid down on 12 August 1972. She was launched on 19 October 1974 sponsored by Mrs. Hugh Scott, and commissioned on 25 June 1977, with Commander Robert B. Osborne in command.

In 1988, Philadelphia became the first submarine to receive TLAM-D capability.

In 1994, Philadelphia completed the first refueling overhaul of a Los Angeles-class submarine. This was completed at Portsmouth Naval Shipyard in Kittery, Maine.

In 1998, Philadelphia was modified to carry a Dry Deck Shelter (DDS).

On 5 September 2005 Philadelphia was in the Persian Gulf about 30 nautical miles (60 km) northeast of Bahrain when it collided with a Turkish merchant ship, MV Yasa Aysen. No injuries were reported on either vessel. Damage to the submarine was described as "superficial." The Turkish ship suffered minor damage to its hull just above the water line, which the United States Coast Guard inspected and found still seaworthy.

In 2006, Philadelphia completed the first-ever Pre-Inactivation Restricted Availability (PIRA) conducted at Portsmouth Naval Shipyard in Kittery, Maine.

On July 20, 2009 the US Navy announced that the submarine would be inactivated on June 10, 2010 and decommissioned at an undetermined later date.

USS Pittsburgh, SSN-720

USS Pittsburgh (SSN-720), a Los Angeles-class submarine, was the fourth ship of the United States Navy to be named for Pittsburgh, Pennsylvania. The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 16 April 1979 and her keel was laid down on 15 April 1983. She was launched on 8 December 1984 sponsored by Mrs. George Sawyer, and commissioned on 23 November 1985, with Commander Raymond Setser in command.

On 2 April 1991, Pittsburgh and Louisville conducted submarine-launched Tomahawk missile attacks against Iraq.

Pittsburgh departed in October 2002 to deploy in the Mediterranean Sea. There, she again fired Tomahawk missiles into Iraq during Operation Iraqi Freedom. She returned from that deployment on 27 April 2003.

USS Portsmouth, SSN-707

Figure 122: USS Portsmouth

USS Portsmouth (SSN-707), a Los Angeles-class submarine, was the fourth ship of the United States Navy to be named for Portsmouth, New Hampshire, and Portsmouth, Virginia. The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 10 December 1973 and her keel was laid down on 8 May 1980. She was launched on 18 September 1982 sponsored by Mrs. Helen Poe Goodrich, and commissioned on 1 October 1983, with Commander Donald M. Olson in command.

Three weeks after commissioning Portsmouth began her first mission, supporting rescue operations in Grenada. She was awarded the Armed Forces Expeditionary Medal for that action.

In 1984 Portsmouth entered her homeport of San Diego, California.

She was the first American nuclear powered warship to make a liberty visit to communist Chinese reunified Hong Kong.

On 10 September 2004 Portsmouth decommissioned at Norfolk, Virginia. While the submarine was only halfway through her design lifespan, her reactor core required refueling. Decommissioning was chosen as a cost-saving measure.

USS Providence, SSN-719

USS Providence (SSN-719), a Los Angeles-class submarine, was the fifth ship of the United States Navy to be named for Providence, Rhode Island. The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 16 April 1979 and her keel was laid down on 14 October 1982. She was launched on 4 August 1984 sponsored by Mrs. William F. Smith, and commissioned on 27 July 1985, with Captain E. Morrow in command.

Providence is the first Los Angeles class submarine to be equipped with the Tomahawk missile Vertical Launch System (VLS). While others used test boxes and programs, Providence was the first submarine to launch a Tomahawk cruise missile from the VLS system using its combat system CCS MK1 and associated software C4.1.

Providence has been deployed several times to the Western Atlantic, the Mediterranean Sea, and the Persian Gulf. Some of the ports visited have included Port Canaveral (Cocoa Beach, Florida) and Port Everglades (Fort Lauderdale, Florida), Naval Station Roosevelt Roads in Puerto Rico, Tromsø in Norway, Halifax in Nova Scotia, Gibraltar, Toulon in France, Soudha Bay in Crete, La Maddalena in Italy, and Koper in Slovenia, in the Mediterranean, and al-Manama, Bahrain, and both Dubai and Jebel Ali in the United Arab Emirates in the Persian Gulf. The submarine has made transits of the Suez Canal in 1998, 2001, and 2003 and participated in Operation Southern Watch, Operation Enduring Freedom and Operation Iraqi Freedom, where she earned the nickname "Big dog of the Red Sea wolf pack."

She has since been retrofitted with numerous upgrades including the AN/BYG-1 Fire Control system and AN/BQQ-10 ARCI Sonar suite. Her astounding achievements continued in 2006-2007 as she has also completed an around-the-world deployment to the Western Pacific Ocean earning the coveted Order of Magellan certificate, participating in Exercise MALABAR 2006, and many other significant assignments. Port visits included Singapore, Yokosuka and Okinawa in Japan, Goa in India, as well as transits through both the Suez Canal and Panama Canal. In 2008, she completed yet another deployment to the Western Pacific Ocean, only this time taking a northern route, successfully transiting under the arctic ice cap.

The submarine is currently active and assigned to Submarine Squadron 2 at US Naval Submarine Base New London, Groton, Connecticut.

Figure 123: USS Providence

Russian Submarine K-336 Pskov

Russian submarine K-336 Pskov is a Sierra-class attack submarine of the Russian Navy. She is named after the Russian city Pskov.

This ship, originally named Okun (Perch), was laid down as the last Sierra-II class submarine in 1990 at the Krasnoye Soromovo factory in Nizhny Novgorod. After the hull was launched in 1992, it was towed to the Sevmash shipyard in Severodvinsk for completion and sea trials.

The boat was commissioned in 1993, serving in the Russian Northern Fleet and based in Ara Bay, Vidyaevo.

On March 5, 2003, the Pskov was being overhauled in a dry dock in Roslyakovo. The wood scaffolding surrounding the hull was ignited by the welding work that was done to the ship, and a fire broke out. After 90 minutes, the fire was put out, and the Pskov's outer soundproofing rubber coating was damaged. There were no casualties or radiation leakage. The submarine is believed to be operational since early 2007.

Russian Submarine K-211 Petropavlovsk-Kamchatskiy

K-211 Petropavlovsk-Kamchatskiy is an Project 667BDR Kalmar class (NATO reporting name: "Delta III") Russian nuclear ballistic missile submarine. The submarine was built by the Russian shipyard Sevmash in the late 1970s and joined the Soviet fleet in 1980. The submarine continued to serve in the Russian navy after the collapse of the Soviet Union and, as of 2009, is active in the Russian Pacific fleet.

The submarine is slated to be retired and replaced by the Borei class submarine in the next coming years.

Russian Submarine BS-64 Podmoskovye

Podmoskovye (BS-64) is a Project 667BDRM Delfin-class ballistic missile submarine (NATO reporting name "Delta-IV") of the Russian Navy. She was originally designated K-64.

K-64 was removed from active service in 1999 and was ordered to be refitted. It was planned for her to be reactivated in 2002 to replace the Yankee 'Stretch' class KS-411. KS-411 had been the mothership for the Paltus-class mini submarines, which are believed to be used for a combination of oceanographic research, search and rescue, and underwater intelligence-gathering. Due to lack of funds was this plan postponed, and the new recommissioning date is unknown. K-64 was renamed BS-64 Podmoskovye in 2002, and her central section containing 16 silos for ballistic missiles was removed to create space for the installation of scientific-experimental equipment, cabins for scientists and a rest room for the regular crew. The status of this work is unknown and as of 2008 the ship was still moored in Zvezdochka shipyard awaiting completion.

S611 Redoutable, SNLE (SSBN)

The Redoutable (S 611) was the lead ship of her class of ballistic missile submarine in the French Marine Nationale.

Commissioned on 1 December 1971, she was the first French SNLE ("Device-Launching Nuclear Submarine"). She was fitted with 16 M1 ballistic missiles, delivering 450 kt at 2000 kilometers. In 1974, she was refitted with the M2 missile, and later with the M20, each delivering a one-megaton warhead at a range over 3000 kilometers. The Redoutable ("formidable" or "fearsome" in French language) was the only ship of her class not to be refitted with the M4 missile.

The Redoutable had a 20-year duty history, with 51 patrols. She was decommissioned in 1991. In 2000, she was removed from the water in a purpose built dry dock, and over two years was made into an exhibition. This was a monumental task, the biggest of which was removing the Nuclear Reactor and replacing the mid-section with an empty steel tube. This opened in 2002, where she is used as a museum ship at the Cité de la Mer in Cherbourg, being now the largest submarine open to the public.

Figure 124: FS Redoutable

Resolution-class (SSBN)

The Resolution-class submarine armed with the Polaris missile was the United Kingdom's primary nuclear deterrent from the late 1960s to 1994, when they were replaced by the Vanguard-class submarine carrying the Trident II.

During the 1950s and early 1960s, the United Kingdom's nuclear deterrent was through the RAF's V-bombers. But developments in radar and surface-to-air missiles made it clear that bombers were becoming vulnerable, and would be unlikely to penetrate Soviet airspace by the early 1960s. Free-fall nuclear weapons would no longer be a credible deterrent.

To address this problem, in May 1960 Prime Minister Macmillan arranged a deal with President Eisenhower to equip the V-bombers with the US-designed AGM-48 Skybolt. The Skybolt was a 1,000-mile (1,600 km) range ballistic missile that allowed the launching bombers to remain well away from Soviet defenses and launch attacks that would be basically invulnerable. With this range, the V-bombers would have to fly only a few hundred miles from their bases before being in range of an attack on Moscow.

Under the agreement, the UK's contribution to the program was limited to developing suitable mounting points on the Avro Vulcan bomber, installing the required guidance systems that fed the missiles updated positioning information, and development of their own version of the US W47 warhead to arm it, the RE.179.

The incoming Kennedy administration expressed serious doubts with both Skybolt and the UK deterrent force in general. Robert McNamara was highly critical of the US bomber fleet, which he saw as obsolete in an age of ICBMs. Skybolt was seen simply as a way to continue the existence of a system he no longer considered credible, and given the rapidly improving capabilities of inertial guidance systems, their precision strike capability with free-fall bombs would no longer be needed. McNamara was equally concerned about the UK retaining an independent nuclear force, and worried that the US could be drawn into a war by the UK, or using the UK as a proxy hostage by the Soviets. He wanted to draw the UK into a dual-key arrangement.

McNamara first broached the idea of cancelling Skybolt with the British in November 1962. When this was reported in the House of Commons, a firestorm of protest broke out. A meeting was arranged to settle the issue, and Macmillan stated in no uncertain terms that the UK would be retaining their independent deterrent capability, no matter what the cost. With development of their Polaris-derived warheads well along, a suitable launch platform would be developed, if need be.

Faced with a clear failure in policy terms, Kennedy gave up on the idea of strong-arming Britain into accepting a dual-key arrangement. By the end of the series of meetings, the UK had gained the much more impressive Polaris system, and would start development of a new submarine to launch them. The SSBNs would then take over the nuclear deterrent role from the RAF's V-bombers from 1968 onwards.

Two pairs of the boats were ordered in May 1963 from Vickers Shipbuilding Ltd, Barrow in Furness and from Cammell Laird and Co. Ltd, Birkenhead. The option of buying a fifth unit, planned as Ramillies, was cancelled in February 1965. Traditional battleship names were used, signifying that they were the capital ships of the time.

Vickers Armstrong in Barrow-in-Furness constructed Resolution and Repulse and Cammell Laird in Birkenhead constructed Renown and Revenge. The construction was unusual in that the bow and stern were constructed separately before being assembled together with the American-designed missile compartment.

The design was a modification of the Valiant-class Fleet Submarine, but greatly extended to incorporate the missile compartment between the fin and the nuclear reactor. The length was 130 meters, breadth 10.1 meters, height 9 meters and the displacement 8,400 long tons (8,500 t) submerged and 7,600 long tons (7,700 t) surfaced. A Rolls-Royce pressurized water reactor and English Electric Company turbines gave them a speed of 25 knots (46 km/h) and they could dive to depths of 275 meters (902 ft). Sixteen Polaris A3 missiles were carried, in two rows of eight. For emergencies there was a diesel generator and six 21-inch (533 mm) torpedo tubes located at the bow, firing the Tigerfish wire-guided homing torpedoes. The submarines put to sea with a crew of 143.

According to former head of the Royal Corps of Naval Constructors R.J. Daniel, the Resolution class SSBNs possessed five features that were envied by the US Navy: the machinery loading hatch, automated hovering system, welded hull valves, standardized valves, and raft-mounted propulsion machinery.

The first to be completed was HMS Resolution, laid down in February 1964 and launched in September 1966. After commissioning in 1967 she underwent a long period of sea trials culminating in the test firing of a Polaris missile. Fired from the USAF Eastern Test Range off Cape Kennedy at 11:15 on 15 February 1968. Resolution commenced her first operational patrol on 15 June 1968, beginning 28 years of Polaris patrols. The class were part of the 10th Submarine Squadron, all based at Faslane Naval Base, Scotland.

All four of the class underwent conversion during the 1980s so that they could be fitted with the Polaris AT-K missile which was fitted with the British developed Chevaline MRV system.

As the newer Vanguard-class submarines entered service, the Resolution class was eventually retired and all boats laid up at Rosyth dockyard with their reactors removed.

New methods of project management were used in the refits of the Resolution class, including:

- The appointment of a senior officer of two star rank and with the title of Assistant Controller (Polaris), working under the joint superintendence of the Controller of the Navy and Chief of Fleet Support, whose responsibilities will include the oversight of the preparations for refits of Polaris boats, and their completion;
- The delegation to a designated officer (Director, Project Technical Submarines) of the responsibility for drawing up the "work package" for each refit, which will include full design information and documentation;
- The use of a fully integrated refit management team at Rosyth, and
- The full use of available management techniques and aids, including computers."

HMS Resolution, S22

HMS Resolution (S22) was the first of the Royal Navy's Resolution-class ballistic missile submarines.

Ordered in May 1963, she was built by Vickers Armstrong at a cost of £40.2m. The keel was laid down on 26 February 1964 by the Director General Ships, Sir Alfred Sims, and the launch was on 15 September 1966, attended by Queen Elizabeth the Queen Mother. The submarine was commissioned on 2 October 1967, and following extensive trials, including the firing of her first Polaris missile on 15 February 1968, commenced her first patrol on 15 June 1968.

Her Polaris system was updated in 1984 with the Chevaline IFE (Improved Front End) that included two new warheads and re-entry bodies and penaids, super-hardened to resist ABM attack, replacing the original three ET.317 warheads. Resolution conducted the longest Polaris patrol of 108 days in 1991.

Following the completion of the first Trident submarine in 1992, the Resolution class were gradually removed from service. Resolution was de-commissioned on 22 October 1994, after 69 patrols, and laid up at the Rosyth Dockyard.

HMS Repulse, S23

HMS Repulse (S23) was a Resolution-class ballistic missile submarine of the Royal Navy.

Launched on 4 November 1967, she was the last of her class remaining in service with the navy, decommissioning in 1996.

Repulse was the third Polaris Missile submarine of the Resolution class to be planned; HMS Renown was the second. Due to delays with Renown's build at Cammell Laird's Birkenhead shipyard, the Barrow-in-Furness Vickers built Repulse overtook Renown and was commissioned second of class. Repulse famously ran aground on launch, much to the delight of the CND protesters and was subsequently "blacked" by the shipyard unions. She survived all of these setbacks to become the longest-serving Polaris submarine.

A group called the "Committee of 100" were responsible for Repulse running aground. A group of about twelve protesters wedged themselves into the lock gates prior to launch. This action delayed the launch by some thirty minutes and caused the submarine to ground herself on the mudflats as there was insufficient clearance water in the sound. This fact was never reported by any national newspaper although early editions of a local Barrow paper did carry the story and even a photograph of the grounded submarine. Later editions of the same newspaper mysteriously made no mention of the event.

HMS Renown, S26

Figure 125: HMS Renown

HMS Renown (S26) was the third of the Royal Navy's Resolution-class ballistic missile submarines.

Built by Cammell Laird and launched on 25 February 1967, she was decommissioned in 1996.

HMS Revenge, S27

HMS Revenge (S27) was the fourth of the Royal Navy's Resolution-class ballistic missile submarines.

Built by Cammell Laird and launched on 15 March 1968, she was marked for disposal in 1992. She is currently being dismantled at Rosyth dockyard, near Edinburgh. Her old reactor core may end up being buried at Coulport.

USS Rhode Island, SSBN-740

Figure 126: USS Rhode Island

USS Rhode Island (SSBN-740) is a United States Navy Ohio-class ballistic missile submarine which has been in commission since 1994. She is the third U.S. Navy ship to be named for Rhode Island, the 13th state.

Originally, another Ohio-class submarine, SSBN-730, was to have been named USS Rhode Island; a contract was awarded in 1977 for SSBN-730's construction and her keel was laid in 1981 with this name planned for the completed submarine. However, shortly after United States Senator Henry M. Jackson of Washington died in office suddenly on 1 September 1983, SSBN-730 was renamed USS Henry M. Jackson (SSBN-730) while still under construction, and the name Rhode Island was transferred to SSBN-740, for which a construction contract had not yet been awarded.

The contract to build USS Rhode Island (SSBN-740) was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut, on 5 January 1988 and her keel was laid down there on 15 September 1988. She was launched on 17 July 1993, sponsored by Mrs. Kati Machthley, and commissioned on 9 July 1994, with Captain John K. Eldridge commanding the Blue Crew and Commander Michael Maxfield commanding the Gold Crew.

S601 Rubis (ex-Provence), SNA (SSN)

The Rubis (S 601 ; ex Provence) is a first-generation nuclear attack submarine of the French Navy, named after the French submarine Rubis which distinguished herself during the Second World War.

Originally named Provence, she was renamed to Rubis on 18 December 1980. Being the lead ship of the Rubis class, her fine-tuning was long, notably needing over 1000 hours of underwater testing before commissioning.

The Rubis is alleged to have entered the Pacific Ocean in 1985 to support the operation which lead to the Sinking of the Rainbow Warrior. It is claimed that the submarine recovered the crew of the yacht Ouvéa before they could be re-arrested by New Zealand police for their role in the bombing of the Rainbow Warrior.

The Rubis formed part of the French naval contribution to the Gulf War. Between September 1992 and July 1993, she undertook a major refitting which upgraded her to the level of the Améthyste. Soon after, on 17 July 1993, the Rubis collided with the tanker Lyria, as the Rubis was surfacing, causing minor damages and injuries.

The Rubis also took part in Operation Trident, the 1999 bombing campaign over Yugoslavia, by protecting the aeronaval group. Along with the Améthyste, she was one of the two submarines who interdicted the Kotor straits to the Serbian Navy, thus effectively forbidding its use. She also gathered information for the coalition.

In 2002, the Rubis protected Task Force 473 in the Indian Ocean, during operation Hercules, the naval part of the invasion of Afghanistan.

On 18 July 1996, the fourragère of the Ordre de la Libération was given to the submarine and her crew, as a legacy of the Rubis of the Second World War, which had been awarded the medal.

On 30 March 2007, while submerged, Rubis ran hit the bottom, damaging her bow and sonar. She returned to operations in July 2008.

Figure 127: S601 Rubis (ex-Provence), SNA (SSN)

USS Salt Lake City, SSN-716

USS Salt Lake City (SSN-716), a Los Angeles-class submarine, was the second ship of the United States Navy to be named for Salt Lake City, Utah. The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia on 15 September 1977 and her keel was laid down on 26 August 1980. She was launched on 16 October 1982 sponsored by Mrs. Kathleen Garn, and commissioned on 12 May 1984, with Commander Richard Itkin in command. Salt Lake City was featured in The History Channel's Mail Call when R. Lee Ermey answered viewer questions about life inside a submarine.

On 22 October 2004, Salt Lake City returned from a deployment with the Stennis carrier strike group in the western Pacific Ocean, after surging, over a month ahead of schedule, in support of Summer Pulse '04. Port calls during the deployment included Guam, Sasebo, Yokosuka, Singapore, and Oahu, Hawaii.

Salt Lake City earned numerous awards during her eight full deployments, including four Battle “E” Battle Efficiency Awards, three Navy Unit Commendations and two Meritorious Unit Commendations.

Salt Lake City conducted an inactivation ceremony in San Diego on 26 October 2005, then departed for a transit under the polar ice. On 15 January 2006 she was decommissioned at the Portsmouth Naval Shipyard. Over a year later, the hulk was taken under tow, arriving on 8 May 2007 at Puget Sound Naval Shipyard, where she will be recycled and scrapped.

USS San Francisco, SSN-711

USS San Francisco (SSN-711), a Los Angeles-class nuclear submarine, is the third ship or boat of the United States Navy to be named for San Francisco, California.

The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia, on 1 August 1975 and her keel was laid down on 26 May 1977. She was launched on 27 October 1979 sponsored by Mrs Robert Y. Kaufman, and commissioned on 24 April 1981, with Commander J. Allen Marshall in command.

On 8 January 2005 at about 02:00 GMT, San Francisco collided with an undersea mountain about 560 kilometers (350 statute miles) south of Guam while operating at flank (maximum) speed and more than 500 feet (150 m) deep. The collision was so serious that the vessel was almost lost — accounts detail a desperate struggle for positive buoyancy to surface after the forward ballast tanks were ruptured. Twenty-three crewmen were injured, and Machinist's Mate Second Class Joseph Allen Ashley, 24, of Akron, Ohio, died on 9 January from head injuries. Other injuries to the crew included broken bones, lacerations, and a back injury. The San Francisco's forward ballast tanks and her sonar dome were severely damaged, but her inner hull was not breached, and there was no damage to her nuclear reactor. She surfaced and, accompanied by the USCGC Galveston Island (WPB-1349), USNS GYSGT Fred W. Stockham (T-AK-3017), and USNS Kiska (T-AE-35), as well as MH-60S Knighthawks and P-3 Orion maritime patrol aircraft, arrived in Guam on 10 January. The U.S. Navy immediately stated that there was "absolutely no reason to believe that it struck another submarine or vessel." Later, an examination of the submarine in drydock showed unmistakably that the submarine had indeed struck an undersea mountain which had only vague references on the charts available to San Francisco.

The USS San Francisco now has her homeport at the Naval Base San Diego.

Figure 128: Los Angeles-class Fast-Attack Submarine USS San Francisco (SSN 711) in Dry Dock to Assess Damage Sustained after Running Aground 350 Miles South of Guam

USS San Juan, SSN-751

USS San Juan (SSN-751), a Los Angeles-class submarine, was the third ship of the United States Navy to be named for San Juan, Puerto Rico. The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 30 November 1982 and her keel was laid down on 9 August 1985. She was launched on 6 December 1986 sponsored by Mrs. Sherrill Hernandez, and commissioned on 6 August 1988, with Commander Charles Young in command.

San Juan was the first Los Angeles class (688-class) submarine to receive a number of significant improvements to the class's basic design, creating the 688I (for "improved 688"). San Juan and all following submarines in her class are quieter, incorporated an advanced AN/BSY-1 "busy one" combat control system/sonar suite, and have dedicated tubes for vertical launch of the Tomahawk cruise missile. The externally visible changes are also significant, as San Juan had her forward diving planes moved from the sail (fairwater planes) to the bow and made retractable. Together, the retractable bow planes, strengthening of the sail, and installation of additional depth control and support systems make it possible for San Juan to break through polar and near-polar ice as a part of 'normal' ship operations.

On 13 March 2007, San Juan was the subject of a search and rescue mission by elements of the Enterprise Carrier Strike Group when a red flare was spotted in her projected vicinity, suggesting an emergency. Communications were established by the early hours of the next day when San Juan surfaced, and no problems were indicated.

In early 2010, the San Juan changed homeport to Portsmouth, NH to undergo a routine Engineered Overhaul (EOH). In June 2010, the USS San Juan became the first submarine in PNSY history to perform Dual Media Discharge (DMD) as part of an EOH. "San Juan" holds the unofficial record for fastest 688 DMD at PSNY.

USS Santa Fe, SSN-763

USS Santa Fe (SSN-763), a Los Angeles-class submarine, was the second ship of the United States Navy to be named for Santa Fe, New Mexico. The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 21 March 1986 and her keel was laid down on 9 July 1991. She was launched on 12 December 1992 sponsored by Mrs. Joy Johnson, and commissioned on 8 January 1994, with Commander Rodger P. Krull in command.

Santa Fe deployed to the Western Pacific in September 2003 until March 2004. For this deployment she participated in ANNUALEX '03 with the Japanese Maritime Defense Force. The ship made port calls in Singapore, Guam, multiple times in Sasebo, Japan, and in Yokosuka, Japan in which she rode out a typhoon while in port. Santa Fe was awarded the Navy Unit Commendation, the second highest award given to a submarine, for actions completed on this deployment. She underwent a three-month Interim Drydocking in October 2004.

After the ship completed sea trials and other various workups she then completed a two-month Eastern Pacific Deployment that started in May 2005. After returning back to her homeport of Pearl Harbor in June 2005, she again deployed to the Western Pacific on 9 August 2005. During this deployment she participated in Exercise Malabar with the Indian Navy. Santa Fe was the second U.S. nuclear submarine to participate in the exercise and also to port in Goa, India. After Malabar, the ship made a brief stop in Phuket, Thailand. She was the first U.S. submarine to visit Phuket since 2001. The ship returned to Pearl Harbor in February 2006. She made the transit to the East Coast in July 2006, surfacing near the North Pole on the way.

USS Santa Fe recently completed a major repair period lasting 18 months at the Portsmouth Naval Shipyard in Kittery, Maine. After undergoing sea trials at Naval Submarine Base Kings Bay, Georgia and transiting through the Panama Canal, she has returned to her homeport of Pearl Harbor, HI.

She returned from her latest six month Western Pacific deployment in November 2009.

S601 Saphir (ex-Bretagne), SNA (SSN)

The Saphir (S 602) is a first-generation nuclear attack submarine of the French Navy. She was to be named Bretagne but was renamed Saphir in 1981.

She is the second of the Rubis series. Between October 1989 and May 1991, she undertook a major refit which upgraded her to the level of the Améthyste.

In September 2001, she torpedoed and sank the ex-destroyer D'Estrée expended as a target ship off Toulon.

HMS Sceptre, S104

The fifth HMS Sceptre is a Swiftsure-class submarine built by Vickers in Barrow-in-Furness. She was launched in 1976, with a bottle of cider against her hull. She was commissioned on 14 February 1978, by Lady Audrey White. She was the tenth nuclear fleet submarine to enter service with the Royal Navy. She was decommissioned on 10 December 2010, at which time she was the oldest commissioned vessel in the Royal Navy still available for service. In theory she is replaced by the first Astute-class submarine in service, HMS Astute.

Sceptre has suffered several accidents in her career. In the early 1980s she collided with a Russian submarine and her reactor's protection systems would have performed an automatic emergency shutdown (scrammed the reactor), but her captain ordered the safety mechanisms overridden (battleshort enabled). The crew were told to say that they had hit an iceberg. This incident was disclosed when David Forghan, Sceptre's former weapons officer, gave a television interview which was broadcast on 19 September 1991. The Soviet submarine collided with was probably K-211 of the Delta-III class, which on 23 May 1981 collided with an unknown submarine, identified at the time as an unknown Sturgeon-class American submarine.

On 3 February 2005 Sceptre put in at Gibraltar for repairs, expecting to leave within six days. British officials assured Spanish officials that damage is in the cooling system of the boat's diesel generator, not to the nuclear propulsion system. (Tireless spent much of 2000 at Gibraltar repairing a leak in her reactor coolant system.) Nonetheless Spain's Foreign Minister Miguel Angel Moratinos registered Spain’s "firm protest" with Jack Straw, and insisted that Sceptre be the last British submarine repaired at Gibraltar. In addition, Peter Caruana, Gibraltar's Chief Minister, claimed that he had been misinformed about the repairs by the British Ministry of Defense, and that he had learned the true extent of the problems from Spanish sources. Apparently London officials had told him that the repairs were all external, neglecting to mention the diesel generator's cooling system. On 7 February 2005, British military spokeswoman Katherine Purdhoe announced that repairs had been completed; the boat left Gibraltar on 9 February.

HMS Sceptre was sent to the Falkland Islands to beef up the British garrison in March 2010, during Desire Petroleum's exploratory oil-drillings. Sceptre returned to Devonport for the last time in May 2010 and was decommissioned on 10 December 2010 after 32 years of service.

USS Scranton, SSN-756

Figure 129: USS Scranton

USS Scranton (SSN-756), a Los Angeles-class submarine, was the second ship of the United States Navy to be named for Scranton, Pennsylvania.

The contract to build her was awarded to Newport News Shipbuilding and Drydock Company in Newport News, Virginia on 26 November 1984 and her keel was laid down on 29 August 1986. She was launched on 3 July 1989 sponsored by Mrs. Sarah McDade, and commissioned on 26 January 1991, with Commander J.G. Meyer in command.

Scranton was the first submarine at Newport News to be built via "modular construction". No keel was laid. In this method, the ship was almost fully built out in individual hull sections. Most of the internal structure, machinery, and piping were loaded in via open ends of the hull sections as each hull section was built out. The individual hull sections were later assembled with exact precision such that piping running between the sections was joined as the hull sections were welded together. The ship was later rolled into a floating drydock and "floated"

In January 2006, Scranton successfully demonstrated homing and docking of an AN/BLQ-11 Long-Term Mine Reconnaissance System (LMRS) unmanned undersea vehicle (UUV) system during at-sea testing under the leadership of Commanding Officer Michael J. Quinn.

USS Seahorse, SSN-669

USS Seahorse (SSN-669), a Sturgeon-class attack submarine, was the second submarine and third ship of the United States Navy to be named for the seahorse, a small fish whose head and upper body suggest the head and neck of a horse.

The contract to build Seahorse was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut, on 9 March 1965 and her keel was laid down there on 13 August 1966. She was launched on 15 June 1968, sponsored by Mrs. Paul Ignatius, and commissioned on 19 September 1969 with Commander George T. Harper, Jr., in command.

Seahorse was decommissioned on 17 August 1995 and stricken from the Naval Vessel Register the same day. Her scrapping via the Nuclear-Powered Ship and Submarine Recycling Program at Puget Sound Naval Shipyard in Bremerton, Washington, began on 1 March 1995 and was completed on 30 September 1996. One of her sail planes is on public display in memorial garden at the former Sand Point Naval Air Station (now Warren G. Magnuson Park) near seattle.

USS Seawolf, SSN-21

USS Seawolf (SSN-21), the lead ship of her class, is the fourth submarine of the United States Navy named for the seawolf, a solitary fish with strong, prominent teeth and projecting tusks that give it a savage look. The contract to build her was awarded to the Electric Boat Division of General Dynamics and Newport News Shipbuilding on 9 January 1989 and her keel was laid down on 25 October 1989. She was launched on 24 June 1995, sponsored by Mrs. Margaret Dalton, and commissioned on 19 July 1997 with Commander David M. McCall in command.

Seawolf was a product of the Cold War, designed as a replacement for the Los Angeles-class submarines and as a response to the Soviet Akula class. It is said that the Seawolf is quieter at its tactical speed of 25 knots than a Los Angeles submarine is pier side. Originally 29 were planned for production, but with the end of the Cold War, the cost was judged to be prohibitively high and only 3 were built in favor of the smaller Virginia-class submarines, which were expected to be about 10% cheaper.

On 22 July 2007, the submarine transferred from its previous homeport of Naval Submarine Base New London in Groton, Connecticut, to permanently reside at Naval Base Kitsap in Bremerton, Washington.

Adding support personnel as well as ship's crew, there are 140 personnel attached to the Seawolf.

HMS Sovereign, S108

HMS Sovereign (S108) is a nuclear powered fleet submarine of the Swiftsure class.

Construction of the boat began on 18 September 1970; she was launched on 17 February 1973, and commissioned on 11 July 1974.

In 1976, Sovereign played a role in Operation Brisk; the submarine surfaced at the geographical North Pole on 20 October 1976 as part of the exercise, testing navigational systems and equipment performance in low temperatures.

Sovereign underwent an extensive refit in the mid-1990s and was rededicated in January 1997. Cracks were discovered in the tail shaft during post-refit sea trials and she was sent to Rosyth for 14 weeks of emergency repairs in June 1998 before returning to Faslane.

Sovereign was used for the perisher submarine command course in June 1999 as well as other training cruises. She was part of the NATO exercise Linked Seas in May 2000, operating in the Bay of Biscay.

In the early 2000s, Sovereign was out of service for some time due to reactor problems, a fault she shared in common with others of her class. Although she was back in full service by July 2005, the submarine was decommissioned as of September 2006.

HMS Spartan, S105

HMS Spartan (S105) is a nuclear-powered fleet submarine of the Royal Navy's Swiftsure class. HMS Spartan was launched on April 7, 1978 by Lady Lygo, wife of Admiral Sir Raymond Lygo. The boat was built by Vickers-Armstrongs (now a division of BAE Systems) at Barrow-in-Furness in Cumbria, England. She was decommissioned in January 2006.

Spartan was ordered to sail south for the Falkland Islands two days before the Argentine invasion of the islands on March 30, 1982. Spartan was the first ship to arrive in the islands and began to enforce a 200-mile (370-km) maritime exclusion zone imposed by the British. Shortly after, Spartan sighted Argentine merchant shipping mining the harbor at Stanley, but was not ordered to attack. This was partly due to British concerns about escalating the war too early, but also to avoid scaring off more lucrative targets such as the Argentine aircraft carrier Veinticinco de Mayo. Unlike HMS Conqueror, Spartan did not fire in anger during the Falklands War, she did however provide valuable reconnaissance to the British Task Force on Argentine aircraft movements. Spartan's presence also ensured that the Argentine Navy would not dare leave its port.

In 1999, Spartan was fitted with Tomahawk cruise missiles.

HMS Splendid, S106

HMS Splendid was a Royal Navy nuclear powered fleet submarine of the Swiftsure class. HMS Splendid was launched at Barrow on 5 October 1979, by Lady Ann Eberle, wife of Admiral Sir James Eberle, then Commander-in-Chief Fleet. The boat was built by Vickers Shipbuilding Groups and was under the command of Commander R C Lane-Nott.

Since her launch in 1979, she has taken part in many conflicts involving British forces around the globe.

Her first major conflict came in 1982 when Argentinean forces invaded the British held Falkland Islands. Splendid was one of the first submarines to reach the islands, arriving mid-April, after sailing from Faslane. Unlike HMS Conqueror, Splendid did not directly engage Argentinian forces, she did however provide valuable reconnaissance to the British Task Force on Argentine aircraft movements. Splendid's presence along with HMS Conqueror effectively restricted the freedom of action of the Argentine Navy which spent most of the war confined to port.

In the late 1990s, HMS Splendid became the first British ship to be armed with American-built Tomahawk cruise missiles. In 1997 the BBC were allowed on board HMS Splendid to record one of the most important missions of her career. Splendid fired Tomahawks in battle against Yugoslav targets in Belgrade during the Kosovo War. She again fired these weapons against Iraqi targets in the 2003 invasion of Iraq.

In July 2003, HMS Splendid returned to her home at Faslane Naval Base on the River Clyde in Scotland. She was decommissioned in HMNB Devonport, Plymouth in 2004 due to defense cuts. Commander Burke was later awarded the OBE for his leadership of HMS Splendid in the Gulf.

HMS Splendid was present, along with the US Navy submarines the USS Memphis and the USS Toledo at the Russian war games during which the Russian submarine Kursk exploded and sank, resulting in the loss of that submarine and all 118 sailors and officers on board. Despite the conclusions of independent forensic inquiries and the eventual corroborating admission by the Russian Navy that the explosion was triggered by a faulty torpedo onboard the Kursk, various conspiracy theories posit that Kursk was actually sunk by one of the US or British submarines. This may partly stem from the Russian Navy's initial attempts to shunt away criticism of its failed efforts to rescue the surviving crew members from the ocean floor and of the generally poor condition of its own equipment, which was eventually found to be the cause of both the sinking and the failure of the Russian rescue attempts. In the days immediately after the explosion, Russia suggested that the cause of the disaster was a collision with one of the US or British submarines present. Though the accusation proved to be unfounded, conspiracy theorists have inevitably picked up on and elaborated it in various directions over time.

USS Springfield, SSN-761

Figure 130: USS Springfield

USS Springfield (SSN-761), a Los Angeles-class submarine, is the fourth ship of the United States Navy to bear that name. The earlier Springfield's were named for differing reasons; SSN-761 was specifically named for the cities of Springfield, Illinois and Springfield, Massachusetts.

The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 21 March 1986, and her keel was laid on 29 January 1990. She was launched on 4 January 1992 sponsored by the Honorable Lynn Martin, and commissioned on 9 January 1993 with Commander Richard K. Ford in command. Springfield is homeported at Naval Submarine Base New London in Groton.

In mid-2004, Springfield began an extensive overhaul, or Depot Modernization Period (DMP), at the Electric Boat shipyard in Groton. In addition to normal periodic maintenance and repairs, Springfield received extensive modernization in fire control systems, sonar processing, weapons launch systems, and communications outfit, a ring laser gyro inertial navigation system, as well as stealth improvements and engine room upgrades. The modernization was the first major overhaul and repair job for Electric Boat in almost 25 years. Originally awarded as a 12 month, $26.3 million depot modernization, Springfield was to be the test case for the possibility of awarding future repair and overhaul contracts to Electric Boat. The overhaul was plagued by cost and time overruns, and when finally completed in December 2005, it was several months late and well over budget. Electric Boat has not been awarded any DMP contracts since.

On 12 March 2009, Springfield returned from a regularly scheduled, six-month overseas deployment in support of the Global War on Terror.

HMS Superb, S109

HMS Superb (S109) was a nuclear powered fleet submarine of the Swiftsure class serving in the Royal Navy.

She was built by Vickers Shipbuilding Groups, now a division of BAE Systems Submarine Solutions. HMS Superb was launched on 30 November 1974 at Barrow-in-Furness, Cumbria and commissioned into the Royal Navy on 13 November 1976. After being damaged in May 2008 in the Red Sea, she returned to Devonport where she was decommissioned slightly ahead of schedule on 26 September 2008.

She was the first British submarine to visit the Arctic Ocean and sail under the polar ice caps.

During the Falklands War, Superb was spotted sailing from Gibraltar, which prompted press speculation that she was sailing to the South Atlantic to enforce a maritime exclusion zone. In fact, only HMS Spartan was sailing south at that time but the speculation was useful to promote the apparent threat of the Royal Navy in the South Atlantic and was not corrected by the Navy or MoD.

In support of the war against terror in 2001, HMS Superb operated in the Indian Ocean.

In 2007, Superb successfully completed training maneuvers off the Scottish coast, engaging with HMS Daring, a brand new Type 45 destroyer.

In January 2008 a sentry was found sleeping while on watch; the reprimand to the crew was caught on video.

On 26 May 2008, the Superb hit an underwater pinnacle in the Red Sea, 80 miles south of the Suez Canal. She remained watertight, and none of the 112 crew were injured; however, she was unable to resubmerge due to damage to her sonar. After undertaking initial repairs at the Souda Bay NATO base on Crete on 10 June 2008, she passed through the Mediterranean, with a pause (at night) some miles off Gibraltar to disembark some less critical crew. Superb then continued back to the UK, arriving at Devonport Dockyard on 28 June 2008. After surveying the damage, the Royal Navy decided to decommission the Superb slightly ahead of schedule on 26 September 2008.

Nearly two years after the grounding, in March 2010, three officers of the Superb were reprimanded for their roles in the incident. All three pleaded guilty to the charges of neglecting to perform their duty in failing to notice that the submarine was traveling towards the pinnacle. Despite the incident, all three officers still serve in the Royal Navy.

Russian Submarine K-433 Svyatoy Georgiy Pobedonosets

K-433 Svyatoy Georgiy Pobedonosets is a Russian Project 667BDR Kalmar class (NATO reporting name: Delta III) nuclear-powered ballistic missile submarine. The submarine was built for the Soviet Navy and has continued to serve in the Russian Navy. K-433 was put in reserve in 1997 and remained there until 2004 when it was recomissioned. As of 2010, it is on active duty.

The submarine is slated to be retired and replaced by the Borei class submarine in the coming years.

On October 28, 2010 the submarine carried out a successful R-29R missile test.

Swiftsure-class (SSN)

The Royal Navy's Swiftsure class of nuclear fleet submarines (SSN) until December 2010, was the oldest of the three classes of fleet submarine in service with the RN.

Six boats were built and commissioned. HMS Swiftsure was decommissioned in 1992 due to damage suffered to her pressure hull during trials. HMS Splendid followed in 2004 after defense cuts caused a reduction in the size of the RN SSN fleet. HMS Spartan was decommissioned in January 2006, with HMS Sovereign following on 12 September 2006. HMS Superb was decommissioned on 26 September 2008. The remaining boat in the class, HMS Sceptre, was decommissioned in December 2010. They are being replaced by the Astute-class submarine.

A few were upgraded to be able to use Tomahawk missiles in addition to their original armaments of torpedoes, mines and anti-ship missiles.

The Dreadnought, Valiant and Improved-Valiant classes all had a "whale-shaped hull", of "near-perfect streamlining giving maximum underwater efficiency". The hulls were of British design, "based on the pioneering work of the US Navy in Skipjack and Albacore." The hull of the Swiftsure was a different shape and maintained its diameter for a much greater length than previous classes. Compared with the Valiants the Swiftsures were 13 feet "shorter with a fuller form, with the fore-planes set further forward, with one less torpedo tube and with a deeper diving depth."

A second major change was in propulsion. Rather than the seven/nine-bladed propeller used by the previous classes, all but the first of the Swiftsure-class submarines used a shrouded pump-jet propulsor. The prototype propulsor had powered the Churchill. It is not clear why the Swiftsure was the only one of the class not fitted with a propulsor. The propulsor was perhaps as much as 50% more efficient than a propeller, producing the same speed at lower revolutions, thus reducing the noise signature. In addition all pipework connections to equipment on the main machinery raft had expansion/flexible coupling connections, which also reduced noise. The US Navy secured a license to copy the main shaft flexible coupling arrangement in US-built submarines.

On 28 May 2008, HMS Superb collided with a rock while submerged in the Red Sea. No injuries, or reactor damage resulted, yet the submarine had to surface and remain surfaced due to damage to the sonar equipment.

HMS Swiftsure, S126

HMS Swiftsure (S126) was the lead ship of her class of nuclear fleet submarines. HMS Swiftsure was decommissioned in 1992 due to damage suffered to the pressure hull during trials.

HMS Talent (S92)

HMS Talent is the sixth of seven Trafalgar-class submarine of the Royal Navy, and was built at Barrow-in-Furness.

Talent was launched by The Princess Royal in April 1988 and commissioned in May 1990. She was the last submarine to be launched down a slipway.

Talent has just undertaken a Long Overhaul Period (Refueling) at her base port in HMNB Devonport and in March 2007 rejoined the active fleet, following a £386 million upgrade. She has been given a new reactor core and has been equipped with a new sonar suite, the Sonar 2076. Sonar 2076 has the power equivalent to approximately 400 PCs and can precisely track the movement of small objects from hundreds of miles away. The Royal Navy describe SONAR 2076 as the most advanced Sonar in service with any navy in the world. She has also been given the ability to fire Tomahawk Land Attack Cruise Missile TLAM.

She is affiliated with Shrewsbury in Shropshire.

HMS Tireless (S88)

HMS Tireless, a Trafalgar-class submarine, is the second submarine of the Royal Navy to bear this name. She was launched in March 1984, sponsored by Mrs Sue Squires, wife of Admiral 'Tubby' Squires, and commissioned in October 1985.

Over the next six years, Tireless completed numerous exercises and visits around the world, including a trip to the Arctic in 1991. In early 1996, she entered refit and returned to sea in 1999.

In May 2000, Tireless developed a serious leak in the nuclear reactor primary cooling circuit, although there was no leak of radioactive material. The nuclear propulsion system was shut down and using backup diesel power Tireless made way to Gibraltar. The damage was found to be more extensive than first hoped, and the boat remained at Gibraltar, creating diplomatic tensions between Spain and Britain, until she left on 7 May 2001, nearly a year later following extensive repairs. During that year, all Trafalgar-class submarines were inspected for similar problems.

On 19 April 2004, Tireless and USS Hampton rendezvoused under the Arctic ice and surfaced together at the North Pole.

Tireless again angered Spain in 2004 when the boat put into Gibraltar from 9 July to 15 July for what was explained as "technical reasons." Britain assured Spain that the port call was unrelated to the British celebrations, on 21 July, of the 300th anniversary of the capture of Gibraltar from Spain.

In 2007 the Tireless ventured to the North Pole with USS Alexandria to participate in the Applied Physics Laboratory Ice Station.

On 21 March 2007, two Tireless crew members, Leading Operator Mechanic Paul McCann and Operator Maintainer (Weapons Submariner) 2 Anthony Huntrod, were killed in an explosion onboard, apparently caused by an oxygen generator candle in the forward section of the submarine. The submarine was in service near the North Pole under ICEX07 along with the USS Alexandria and had to make an emergency surface through the ice cap. A third crewmember suffered "non life-threatening" injuries and was airlifted to a military hospital at Elmendorf Air Force Base near Anchorage, Alaska. According to the Royal Navy, the accident did not affect the ship's nuclear reactor, and the ship sustained only superficial damage. Part of the exercise was being used to measure ice thickness by using sonar.

Figure 131: HMS Tireless

French Submarine Téméraire (S617)

The Téméraire is a strategic nuclear submarine of the French Navy.

USS Tennessee (SSBN-734)

USS Tennessee (SSBN-734) is a United States Navy Ohio-class ballistic missile submarine that has been in commission since 1988. She is the fourth ship and first submarine of the U.S. Navy to be named for Tennessee the 16th state.

Tennessee's construction was authorized in Fiscal year 1980, and the contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut, on 7 January 1982. Her keel was laid down there on 9 June 1986. She was launched on 13 December 1986, sponsored by Mrs. Landess Kelso, and commissioned on 17 December 1988, with Captain D. Witzenburg in command of the Blue Crew and Captain Kenneth D. Barker in command of the Gold Crew. She was the first submarine capable of firing the Trident II ballistic missile to be commissioned.

USS Texas (SSN-775)

USS Texas (SSN-775) is a Virginia-class submarine, and the fourth ship of the United States Navy to be named in honor of the state of Texas.

The contract to build her was awarded to the Northrop Grumman Newport News shipyard (then called Newport News Shipbuilding & Drydock Co.) in Newport News, Virginia on 30 September 1998 and her keel was laid down on 12 July 2002. She was christened on 31 July 2004 by Laura Bush, First Lady of the United States. She was launched into the James River on 9 April 2005.

Under the command of Captain John Litherland, Texas arrived at Galveston Bay on 4 September 2006 and was escorted into the harbor by Elissa. Texas was commissioned in Galveston, Texas, and joined the U.S. Atlantic Fleet on 9 September 2006.

The ship, under the command of Commander Robert Roncska, departed New London Naval Submarine Base at Groton for Pearl Harbor on September 16, 2009. On its way to Pearl Harbor, the sub traveled to the Arctic Ocean and surfaced near the North Pole's ice pack. Due to the thickness of the ice on the West Coast, the sub turned around and completed its westbound transit via the Panama Canal. The Texas arrived in her new home port on November 23, 2009.

The sub departed Pearl Harbor for her first three-month operational patrol on May 19, 2010. The location of the ship's first deployment was not disclosed by the Navy.

USS Toledo (SSN-769)

USS Toledo (SSN-769), a Los Angeles-class submarine, was the third ship of the United States Navy to be named for Toledo, Ohio. The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia on 10 June 1988 and her keel was laid down on 6 May 1991. She was launched on 28 August 1993 sponsored by Mrs. Sabra Smith, and commissioned on 24 February 1995, with Commander Jack Loye III in command. The submarine was a cover story of the 6 April 1998 issue US News & World Report.

The USS Toledo returned to the Naval Submarine Base New London in mid-April 2003 after having taken part in Operation Iraqi Freedom.

On 7 December 2004, Toledo returned to Groton, Connecticut, after a six-month deployment in the Persian Gulf with the John F. Kennedy carrier strike group that included port calls in Crete, Dubai, and Bahrain. Her route home from Bahrain was unusual, rounding the Cape of Good Hope rather than using the Suez Canal. Once back in the North Atlantic, she was diverted for a classified drug interdiction mission with the Joint Interagency Task Force–South in the Caribbean Sea.

On 31 January 2006, Toledo again departed for a six-month deployment to CENTCOM. Port calls included Augusta Bay, Dubai, the British island territory of Diego Garcia and La Maddalena. The ship returned from this deployment on 31 July 2006 and a change of command ceremony took place in 2009 where Commander Reckamp relieved Commander Goldman.

Toledo left for another six-month deployment on 22 January 2010.

In December 2010 Toledo did a port call in Haifa. Commander Reckamp was received by the Haifa City Major Yona Yahav in the City Hall as is customary for visiting commanders of war ships doing port calls in Haifa.

On 20 January 2011, Toledo returned to Groton, Connecticut after a six-month deployment that included port calls in Cyprus, Bahrain, and Haifa.

Northrop Grumman Corporation was awarded a contract from the U.S. Navy for maintenance work, known as a depot modernization period, on the nuclear-powered submarine USS Toledo (SSN 769). The initial planning contract was valued at approximately $34.7 million. The final value, including the actual execution, was $178.5 million. The ship arrived in December 2006 to Newport News, VA and the work was completed in March 2009. The project was delayed more than eight months because of more than 2,000 project changes. This was a competitive award under a Naval Sea Systems Command (NAVSEA) multiple award contract.

In July 2009 two hull cracks, including one in the pressure hull, were discovered during a routine inspection. The Navy has begun an investigation. Although the Navy and Northrop Grumman launched two investigations into welding practices at the yard while Toledo was under maintenance, the cracks do not appear to be related to welds.

USS Topeka (SSN-754)

USS Topeka (SSN-754), a Los Angeles-class submarine, was the third ship of the United States Navy to be named for Topeka, Kansas. The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 28 November 1983 and her keel was laid down on 13 May 1986. She was launched on 23 January 1988 sponsored by Elizabeth Dole and commissioned on 21 October 1989, with Commander Timothy Reichert in command.

The Topeka and USS Albany form a unique sub-class among Los Angeles class submarines. The pressure hulls of both ships were partially manufactured using stronger HY-100, instead of the HY-80 steel used in the manufacturing of all other Los Angeles class submarines. This was done to test construction methods using this steel, which would later be employed in the assembly of the new Seawolf-class submarines. In theory, this permits the Albany and Topeka to dive to a slightly greater depth than any other member of the Los Angeles class, though it remains unclear if this ability has ever been tested by either vessel.

HMS Torbay (S90)

Figure 132: HMS Torbay

HMS Torbay is a Trafalgar-class submarine (a fleet nuclear submarine) of the Royal Navy.

HMS Torbay was the first vessel to be fitted with the new command system SMCS-NG (derived from the earlier SMCS), which meant that she was also the first Royal Navy vessel to put to sea under the "command" of the Microsoft Windows operating system.

Torbay recently participated in an experiment in the use of color schemes to reduce the visibility of submarines from the air. In early 2006, the standard black paint of Royal Navy submarines was replaced by a carefully selected shade of blue. This was the result of research that found that black was the worst possible color for a submarine attempting to avoid detection from the air. This change is in part the result of the changing nature of Royal Navy commitments since the end of the Cold War, with Navy operations moving from the murky waters of the North Atlantic to the clearer waters of the Arabian Sea and the Indian Ocean.

Torbay completed a refuel and modernization process in February 2001.

HMS Trafalgar (S107)

Figure 133: HMS Trafalgar

HMS Trafalgar (S107) is a decommissioned Trafalgar class submarine of the Royal Navy.

After Operation Veritas, the attack on Al-Qaeda and Taliban forces following the 9/11 attacks in the United States, Trafalgar entered Plymouth Sound flying the Jolly Roger on 1 March 2002. She was welcomed back by Admiral Sir Alan West, Commander-in-Chief of the fleet and it emerged she was the first Royal Navy submarine to launch tomahawk cruise missiles against Afghanistan.

In November 2002, Trafalgar ran aground close to Skye, causing £5 million worth of damage to her hull and injuring three sailors. She was travelling 50 meters below the surface at more than 14 knots when Lieutenant-Commander Tim Green, a student in the "Perisher" course for new submarine commanders, ordered a course change that took her onto the rocks at Fladda-chuain, a small but well-charted islet. Commander Robert Fancy, responsible for navigation, and Commander Ian McGhie, an instructor, both pleaded guilty at court-martial to contributing to the accident. On 9 March 2004 the court reprimanded both for negligence. Green was not prosecuted, but received an administrative censure.

In May 2008 it was reported that the crash was caused by the chart being used in the exercise being covered with tracing paper, to prevent students marking it.

She was not launched with a pump jet propulsion system, but with a conventional propeller, unlike the rest of the Trafalgar Class boats that followed.

Trafalgar was decommissioned on the 4th December 2009 at Devonport.

HMS Trenchant (S91)

HMS Trenchant is a Trafalgar-class submarine built by Vickers Shipbuilding, Barrow-in-Furness. Trenchant is currently in service and is based at HMNB Devonport.

The submarine was ordered on 22 March 1983. She was laid down by Vickers Shipbuilding on 28 October 1985, was launched on 3 November 1986, and was commissioned into the Royal Navy on 14 January 1989.

On 22 November 1990, the nets of the fishing vessel Antares were snagged by Trenchant. Antares was pulled under with the loss of all four members of the crew.

In July 1997, the submarine ran aground off the western coast of Australia. While approaching Fremantle, Western Australia, the submarine remained at a depth of 200 meters (660 ft) and grounded when she made contact with the continental shelf, coming to rest on a sloping patch of seafloor. Trenchant was able to free herself, and an inspection by divers reported no significant damage.

Trenchant tested the non-hull-penetrating optronic mast in 1998. She also trialed a camouflage paint scheme comprising jagged shapes of various colors, including pale blue.

ON 21 June 2007, the submarine became the first Royal Navy vessel to fire the new Block IV Tomahawk cruise missile in a live firing trial in the Gulf of Mexico off the United States coast.

French Submarine Triomphant (S616)

The Triomphant is a strategic nuclear submarine of the French Navy; she is the lead boat of her class. She collided with a British nuclear submarine in 2009.
The first sheet of Triomphant was cut at DCN Cherbourg in October 1986, and her engine was shipped to her from DCN Indret five years later. The reactor was built into the vessel in August 1991, with the fore and aft sections being welded on in January and April 1992 respectively. She was armed and given a commander in May 1992 and moved from the assembly site to the completion basin in July 1993. Her launch in March 1994 was followed by her first dive that June and her trip from DCN Cherbourg to Ile Longue that July down the "free route" between Cherbourg and Brest, with a crew of 110 and engineers from DCN Cherbourg.

On 4 January 1995, during testing, she reached her maximum depth for the first time and made her first firing of a ballistic missile the following month. Photographs of her were exhibited to the Senate of France from 15 to 23 May 1995. In June she set off back to Cherbourg for Post-Testing Upgrades (Remises A Niveau Après Essais or RANAE), then set off for a second set of trials, making 1,300 hours of test dives in total and a five-week trip. She then spent five weeks in maintenance at Cherbourg and during her main weapons tests took on 11 torpedo models, five trial torpedoes and one Exocet SM39 exercise. As a deterrent system, a salvo of 15 models was successfully launched and, in the last round of development, she functioned successfully as a missile platform even if her engine did not achieve its best. She left Cherbourg on 7 March 1996 for her second round of trials, with the final tests of her nuclear boiler coming on 12 July and of her weapons systems on 26 August.

Triomphant entered active service in March 1997. On 18 October 2001, the fleet support service notified the DCN that Triomphant was about to take her first period of Unavailability for Maintenance and Repairs (IPER or Indisponibilité pour Entretien et Réparations). The 150 million Euro contract was granted to DCN, with the IPER starting at Ile Longue on 2 April 2002, scheduled for 29 months in all. In this, her first major refit, her missiles and the fuel elements of her nuclear boiler were disembarked. In August 2004 L'Humanité ran a piece with the headline "Pas si Triomphant que ça" reporting that Triomphant had suffered a nuclear leak from one of her nuclear warheads by the end of 1997 and from her reactor in 2004, though the FOST downplayed the incidents and stated no radiation had been released since the reactor had been nonoperational at the time. She carried out a test flight of a M45 strategic missile on 1 February 2005 in the Atlantic. In the night between 3–4 February 2009, Triomphant collided with the Royal Navy submarine HMS Vanguard. Triomphant was reported to have proceeded to Brest under her own power, submerged, but with extensive damage to her sonar dome.

The French originally claimed that Triomphant had "collided with an immersed object (probably a container)". After Vanguard returned to harbor, it was confirmed that the collision was in fact with her.

USS Triton (SSRN-586)

USS Triton (SSRN/SSN-586), a United States Navy nuclear-powered radar picket submarine, was the first vessel to execute a submerged circumnavigation of the Earth (Operation Sandblast) in early 1960. Triton accomplished this objective during her shakedown cruise while under the command of Captain Edward L. "Ned" Beach, Jr. The only member of her class, she also had the distinction of being the only non-Soviet submarine powered by two nuclear reactors.

Triton was the second submarine and the fifth ship of the United States Navy to be named for the Greek god Triton. At the time of her commissioning in 1959, Triton was the largest, most powerful, and most expensive submarine ever built, at $109 million excluding the cost of nuclear fuel and reactors.

After operating for only two years in her designed role, Triton's role as a radar picket submarine was made obsolete by the introduction of the carrier-based Grumman WF-2 Tracer airborne early warning aircraft. Converted to an attack submarine in 1962, she became the flagship for the Commander Submarine Forces U.S. Atlantic Fleet (COMSUBLANT) in 1964. She was decommissioned in 1969, the first U.S. nuclear submarine to be taken out of service.

Triton's hull was moored at the St. Julien's Creek Annex of Norfolk Naval Shipyard in Portsmouth, Virginia as part of the reserve fleet until 1993, though she was struck from the Naval Vessel Register in 1986. In 1993, she was towed to Puget Sound Naval Shipyard to await the Nuclear Powered Ship and Submarine Recycling Program. The former Triton landed on the keel resting blocks in the drydock basin on 1 October 2007 to begin this recycling process which was completed effective 30 November 2009.

Triton's main air search radar was the AN/SPS-26 electronically scanned, three-dimensional (3-D) radar system. The SPS-26 radar had a range of 65 nautical miles (120 km; 75 mi), and it was capable of tracking aircraft up to an altitude of 75,000 feet (23,000 m). Since it scanned electronically in elevation, it did not need a separate height-finding radar system. When not in use, the SPS-26 radar was lowered into its fairwater housing for stowage within Triton's massive sail. A submarine version of SPS-26, designated BPS-10, was under development at the time of Triton's construction, and it was slated for eventual installation on the Triton.

Triton's active/passive sonar detecting-ranging set was the AN/BQS-4, which had a listening range up to 20 nautical miles (37 km; 23 mi) for surfaced or snorkeling submarines, optimized to 35 nautical miles (65 km; 40 mi) with target tracking capability within 5 degrees of accuracy. The hull-mounted passive sonar AN/BQR-2 array supplemented the BQS-4 system, with a range up to 10 nautical miles (19 km; 12 mi) and a bearing accuracy of 1/10 of degree, allowing the BQR-2 to be used for fire control in torpedo attacks.

Triton's target fire-control system (TFCS) was the MK-101, a post-war development that incorporated target tracking and ranging data into a position keeper, with a pair of analyzers that automatically revised torpedo gyros and settings as the target position changed. This automation greatly simplified a targeting solution for a plotting party. Previously targeting solutions were manually estimated target bearings and then feed them into the Torpedo Data Computer (TDC) system initially introduced in fleet submarines prior to World War II. However, while entirely capable of providing efficient fire control solutions against post-war non-nuclear hunter-killer submarines, the MK-101 proved to be less responsive to the rapid changes associated with nuclear submarine operations.

Triton's torpedo system consisted of six Mark 60 torpedo tubes, four bow and two stern. The Mark 60 system was a 249.8 inches (6,340 mm) long hydraulic torpedo tube that did not have power handling capability. The standard torpedo carried by Triton was the Mark 37, with a weapon load of ten forward and five aft. Triton's first commanding officer, "Ned" Beach, noted the torpedo load in the forward torpedo room could have been doubled with the removal of a single support girder.

The number 2 periscope was Triton's navigational periscope, and it had a built-in sextant developed by the Kollmorgen Optical Company that allowed navigators to observe celestial bodies to order to obtain an accurate star fix to plot the ship's course and position.

Due to cutbacks in defense spending, as well as the expense of operating her twin nuclear reactors, Triton's scheduled 1967 overhaul was canceled, and the submarine—along with 60 other vessels—was slated for inactivation. While Triton's twin reactor plant was designed to be refueled by a submarine tender like other U.S. nuclear submarines, because of the complexity of her zirconium-clad fuel elements, Triton's previous re-fueling had been done in a shipyard during her 1962–1964 overhaul. Although new fuel elements were procured and available for installation, Triton's overhaul was canceled, a source of controversy. One speculation suggests that the cancellation of Triton's overhaul allowed funds to be redirected for the repairs to the supercarrier Forrestal which had been extensively damaged off Vietnam.

From October 1968 through May 1969, she underwent preservation and deactivation processes, and she was decommissioned on 3 May 1969. Triton became the U.S. Navy's first nuclear-powered submarine to be taken out of service, and second in the world, after the Soviet Navy's November-class submarine K-27 in 1968.

On 6 May 1969, Triton departed New London under tow and proceeded to Norfolk, Virginia, where she was placed in the reserve fleet. She remained berthed at Norfolk or at the St. Julien's Creek Annex of Norfolk Naval Shipyard in Portsmouth, Virginia, into 1993. She was stricken from the Naval Vessel Registry on 30 April 1986. In August 1993, the hulks of the ex-Triton and the ex-Ray were towed by the salvage tug Bolster to the Puget Sound Naval Shipyard (PNSY), in Bremerton, Washington, arriving on 3 September 1993, to await their turn in the Nuclear Powered Ship and Submarine Recycling Program (SRP). Effective 1 October 2007, ex-Triton landed on the keel resting blocks in the drydock basin to begin recycling. The long delay in the disposal of ex-Triton has been attributed to the complexity of her dual reactor plant. Final recycling was completed effective 30 November 2009.

Triton was the 2003 inductee into the Submarine Hall of Fame following her nomination by the Tidewater chapter and Hampton Roads Base of the United States Submarine Veterans, Inc. (USSVI). A shadow box filled with Triton memorabilia was placed in Alcorn Auditorium of Ramage Hall located at the U.S. Navy Submarine Learning Center, Naval Station Norfolk.

Figure 134: USS Triton

HMS Triumph (S93)

HMS Triumph is a Trafalgar-class submarine of the Royal Navy.

The boat was laid down in 1987 by Vickers Shipbuilding and Engineering Limited and launched in February 1991 by Mrs. Ann Hamilton, wife of the then Armed Forces Minister Archie Hamilton. She was commissioned in October that same year.

Triumph sailed to Australia in 1993, travelling 41,000 miles submerged without support -- the longest solo deployment so far by a Royal Navy nuclear submarine. In that same year, author Tom Clancy published a book called SUBMARINE: a Guided Tour Inside a Nuclear Warship which was centered around Triumph and USS Miami.

After the 9/11 attacks in the USA, Triumph, along with her sister-ship Trafalgar, formed part of a task group in 2001 as part of the American-led invasion of Afghanistan, Britain's contribution being known as Operation Veritas.

During Operation Veritas, Triumph launched Tomahawk missiles on targets inside Afghanistan. When Triumph returned home after operations had ended, the boat flew the Jolly Roger, the traditional way of showing a successful patrol.

In December 2001, Triumph experienced an accident when the boat was grounded off the Scottish coast while under the command of trainee officers; fortunately, she suffered only superficial damage.

Triumph is part of the Devonport Flotila based at Devonport.

She is currently affiliated with TS Exmouth SCC unit, Newton Abbot RNA.

USS Tucson (SSN-770)

USS Tucson (SSN-770), a Los Angeles-class submarine, was the second ship of the United States Navy to be named for Tucson, Arizona. The contract to build her was awarded to Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia on 10 June 1988 and her keel was laid down on 15 August 1991. She was launched on 20 March 1994 sponsored by Mrs. Diane C. Kent.

Tucson was supposed to be commissioned on 18 August 1995, however, Hurricane Felix threatened the Virginia coast, and the U.S. Navy decided to sortie the fleet, to prevent damage to ships in port if the hurricane made landfall. Tucson was the last ship to leave port, in case the prediction for landfall changed. As it turned out, the hurricane never did make landfall, but Tucson was at sea on 18 August. Upon returning to port, the commissioning ceremony was quickly rescheduled for 9 September 1995. At the new commissioning ceremony, the commanding officer, Commander Duane M. Baker, declared that for the next two hours, it was officially August 18.

In June 1996, Tucson was struck by the Military Sealift Command vehicle cargo ship USNS Gilliland (T-AKR-298) while moored in port at Newport News. A sudden windstorm caused Gilliland to break free from her mooring and cross the harbor, colliding with Tucson and a destroyer moored behind her. While the destroyer suffered the most damage. Tucson suffered minor damage to her AN/BRA-34 antenna.

Figure 135: USS Tucson

From September 1996 to October 1996, Tucson changed her home port. Tucson left Norfolk, Virginia, passed through the Panama Canal and stopped in San Diego, California for five days. VIPs from Tucson, Arizona, were allowed to ride on three separate short cruises, and then busloads of tourists from the city of Tucson came for tours of the submarine while in port. Following this port visit, Tucson continued on to arrive in Pearl Harbor, Hawaii.

Tucson left for her first Western Pacific deployment (maiden deployment) in February 1998. For historical context, note that prior to departure, tensions between the United Nations and Iraq had escalated drastically. In the 30 days leading up to departure, the government of Iraq had blocked access to the United Nations Special Commission (UNSCOM) and had withdrawn cooperation with the UNSCOM monitoring teams. The ship traveled as far west as the Persian Gulf before returning to Pearl Harbor in August 1998. It was during this period of time that the PBS series “Nova” filmed the episode “Battlegroups” aboard Tucson.

On 19 May 2004, Tucson departed for a Western Pacific deployment.

HMS Turbulent (S87)

HMS Turbulent is a Trafalgar-class submarine of the Royal Navy built by Vickers Shipbuilding, Barrow-in-Furness.

Turbulent went through her modernization and first nuclear refuel in 1997.

On 16 April 2003 HMS Turbulent was the first Royal Navy vessel to return home from the war against Iraq. She arrived in Plymouth flying the Jolly Roger after launching thirty Tomahawk cruise missiles.

HMS Turbulent is in service and is based at the naval base at HMNB Devonport.

The submarine has recently left Devonport Naval Base with some of the most advanced communications links in the Royal Navy’s fleet of submarines thanks to a Ministry of Defense update.

HMS Turbulent is set to be decommissioned in 2011.

A recent newspaper article states that an unnamed witness thought that HMS Turbulent may have been involved in the Bugaled Breizh's wreck.

Valiant Class Submarine

The Valiant class was the first fully British nuclear fleet submarine; the earlier HMS Dreadnought used an American nuclear reactor. There were only two boats of the class, the first, Valiant (the nameship) being commissioned three years after Dreadnought in 1966, and Warspite the following year. Both were built by Vickers at Barrow-in-Furness.

The class were based on Dreadnought, but were enlarged by twenty feet (6 m) and had a dived displacement of 4,900 tons compared to 4,000 tons. They were more polished than Dreadnought in the sense that they ran significantly quieter under main power, and also had a Paxman diesel-electric generator that could be used for silent running. In most other respects (outside the power plant), the Valiants were identical to Dreadnought.

According to former head of the Royal Corps of Naval Constructors R.J. Daniel, when US Admiral Hyman G. Rickover, widely regarded as the father of the nuclear submarine, initially learned of the proposed rafting system for the Valiant class he was dismissive of the concept, with the result that the Royal Navy gained an advantage in submarine silencing that the United States Navy did not introduce until considerably later.

The Valiants were primarily used in the anti-submarine role, important during the Cold War. In 1967 Valiant set a Royal Navy (RN) record of sailing 12,000 miles (19,312 km) submerged in twenty-eight days, from Singapore to the UK. Both boats received a number of refits, including the capability to use the Harpoon missile. HMS Valiant and other nuclear fleet submarines served in the Falklands War in 1982.

HMS Valiant (S102)

The sixth, and most recent HMS Valiant was the second of Britain's nuclear-powered submarines, and the first of the two-unit Valiant class. She was ordered on 31 August 1960, laid down 22 January 1962, launched on 3 December 1963 by Lady Thorneycroft, and finally entered service 18 July 1966.

She was refitted in 1970, 1977 and 1989, and participated in the Falklands War in 1982. Following the development of engine trouble in June 1994, she was paid off 12 August 1994.

Her hull and reactor are currently laid up afloat at Devonport Dockyard, Plymouth, Devon until facilities are available for the long term storage of her radioactive components.

During the HMNB Devonport Navy Days 2006, one of the members of the team currently restoring HMS Courageous pointed out that HMS Valiant was one of the first Royal Navy submarines to have her reactor removed (hence the box-like structures that are visible in the photograph below, which penetrate deep into the pressure hull, later attempts on other vessels didn't require these structures). As the Valiant had been cosmetically wrecked by this work, HMS Courageous was selected for the museum ship to represent the SSN fleet of the Royal Navy during the Cold War. Components were removed from HMS Valiant to restore Courageous. The fate of HMS Valiant now remains bleak.

Figure 136: HMS Valiant

HMS Vanguard (S28)

The eleventh HMS Vanguard (S28) of the Royal Navy is the lead boat of her class of Trident ballistic missile-armed submarines. The sub is based at HMNB Clyde, Faslane.

Vanguard was built at Barrow-in-Furness by Vickers Shipbuilding and Engineering Ltd (now BAE Systems Submarine Solutions), was launched on 4 March 1992, and commissioned on 14 August 1993.

The submarine's first commanding officer was Captain David Russell.

In February 2002, Vanguard began a two-year refit at HMNB Devonport. The refit was completed in June 2004 and in October 2005, Vanguard completed her return to service trials (Demonstration and Shakedown Operations) with the firing of an unarmed Trident missile. During this refit, Vanguard was illegally boarded by a pair of anti-nuclear protestors.

On 4 February 2009, Vanguard collided with the French submarine Triomphant in the Atlantic. She returned to Faslane in Scotland, under her own power arriving on 14 February 2009.

HMS Vengeance (S31)

HMS Vengeance (S31) is the fourth and final Vanguard class submarine of the Royal Navy. Vengeance carries the Trident ballistic missile, the UK's nuclear deterrent.

Vengeance was built at Barrow-in-Furness by Vickers Shipbuilding and Engineering Ltd (now BAE Systems Submarine Solutions), was launched in September 1998, and commissioned in November 1999.

Before she was commissioned, the British Government stated that once the Vanguard submarines became fully operational, they would only carry 200 warheads.

General Characteristics

- Displacement: 16,000 tons submerged
- Propulsion: Rolls-Royce PWR2 reactor, two GEC turbines, single shaft, pump jet propulsor

- Electrical Power: two Paxman diesel generators, two WH Allen turbogenerators
- Speed: 25 knots (46 km/h) submerged
- Complement: 14 officers, 121 men
- Strategic Armament: 16 Lockheed Trident II D5 ballistic missiles
- Defensive Armament: four 533 mm (21-inch) torpedo tubes, Spearfish torpedoes

Vengeance carries the unopened "last instructions" (Letters of last resort) of the current British Prime Minister that are to be used posthumously in the event of a national catastrophe or a nuclear strike.

Russian Submarine K-157 Vepr

Vepr (K-157) is a Project 971 Schuka-B (also known by the NATO reporting name "Akula-II") class nuclear powered attack submarine of the Russian Navy. Her keel was laid down on 16 June 1990 by Sevmash. She was launched on 10 December 1994, commissioned on 25 November 1995, and homeported in Gadzhievo.

Victor Class Submarine

The Victor class is the NATO reporting name for a type of nuclear-powered submarine that was originally put into service by the Soviet Union around 1967. In the USSR, they were produced as Project 671. Victor-class subs featured a teardrop shape, which allowed them to travel at high speed. These vessels were primarily designed to protect Soviet surface fleets and to attack American ballistic missile subs, should the need ever arise.

Figure 137: Victor III Class Submarine

HMS Victorious (S29)

HMS Victorious (S29) is the second Vanguard class submarine of the Royal Navy. Victorious carries the Trident ballistic missile, the UK's nuclear deterrent.

Victorious was built at Barrow-in-Furness by Vickers Shipbuilding and Engineering Ltd (now BAE Systems Submarine Solutions), was launched in September 1993, and commissioned in January 1995.

Victorious was involved in a minor collision with a United States Coast Guard ship in July 2001. The Coast Guard ship became tangled in the fiber optic cables of the submarine's sonar system which disabled its turbines. Victorious was not damaged in the incident.

She became the second of the class to refit. In 2008, she is undergoing sea trials pending resuming patrols in 2009.

General Characteristics

- Displacement: 16,000 tons submerged
- Propulsion: Rolls-Royce PWR2 reactor, two GEC turbines, single shaft, pump jet propulsor
- Electrical Power: two Paxman diesel generators, two WH Allen turbogenerators
- Speed: 25 knots (46 km/h) submerged
- Complement: 21 officers, 146 men
- Strategic Armament: 16 Lockheed Trident II D5 ballistic missiles
- Defensive Armament: four 533 mm (21-inch) torpedo tubes, Spearfish torpedoes

HMS Vigilant (S30)

HMS Vigilant (S30) is the third Vanguard class submarine of the Royal Navy. Vigilant carries the Trident ballistic missile, the UK's nuclear deterrent.

Vigilant was built at Barrow-in-Furness by Vickers Shipbuilding and Engineering Ltd (now BAE Systems Submarine Solutions), was launched in October 1995, and commissioned in November 1996.

In 2002, protestors from Trident Ploughshares breached security at Faslane Naval Base where the Vanguard submarines are based. Two protestors managed to spray-paint Vigilant with the CND symbol and the word "Vile".

Peter Hennessy reporting for the Today program on BBC radio 4, reported from the Vigilant on 28 December 2007. The Vigilant was one of four submarines that is the last line of defense for the United Kingdom. He also reported that there is a grey safe in the control room that has an inner safe that only the Commanding officer (Commander Pole) and Executive officer can open. In that safe is a letter from the current Prime Minister of the United Kingdom, the letter contains guidance and orders if the United Kingdom is attacked by nuclear weapons.

Vigilant arrived at Devonport on 11 October 2008 for a major refit. Vigilant is expected to return to the fleet in 2012 following her GBP 300 million refit.

The French Navy also have a SSBN in service called Vigilant.

French Submarine Vigilant (S618)

Figure 138: French Submarine Vigilant (S618)

The Vigilant is a strategic nuclear submarine of the French Navy.

The Royal Navy also have a SSBN in service called Vigilant.

Russian Submarine K-456 Vilyuchinsk

The K-456 Vilyuchinsk (ex Kasatka) is a Russian Oscar class SSGN of the Russian Navy. It was commissioned in 1991 as part of the Russian Northern Fleet and was transferred to the Russian Pacific Fleet in September 1993. The submarine is currently based at the Rybachiy Nuclear Submarine Base, in Vilyuchinsk, near Petropavlovsk-Kamchatsky.

USS Virginia (SSN-774)

Figure 139: USS Virginia (SSN-774)

USS Virginia (SSN-774) is a United States Navy attack submarine, the lead boat of her class and the tenth vessel of the Navy to be named for the Commonwealth of Virginia.

The contract to build her was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut on 30 September 1998 and her keel was laid down on 2 September 1999. She was launched on 16 August 2003 sponsored by Lynda Johnson Robb, the wife of former Virginia governor and senator Charles Robb, and daughter of President of the United States Lyndon B. Johnson and Lady Bird Johnson. On 10 March and 11 March, the prospective submarine shot 12 dummy torpedoes into the Thames River from each of the boat's four tubes.

Virginia was delivered to the Navy on 12 October 2004, the 104th anniversary of the commissioning of Holland, the Navy's second submarine. She was commissioned on 23 October 2004 under the command of David J. Kern. This class of submarine is unique in that it features a Photonics Mast Program (PMP) that freed ship designers to place the boat’s control room in a lower, less geometrically-constrained space than would be required by a standard, optical tube periscope. It is additionally unique in the U.S. Navy for featuring all-digital ship and ballast control systems that are manned by relatively senior watchstanders and a pressure chamber to deploy SEAL divers while being submerged.

On 23 November 2005, Virginia completed her first deployment in support of the Global War on Terrorism. On 12 January 2006, Virginia entered Electric Boat's shipyard for post-shakedown availability, which was expected to last for most of 2006.

HMS Warspite (S103)

The latest HMS Warspite was the third of Britain's nuclear-powered submarines, and the second (and final) of the Valiant class. She was launched on 25 September 1965 by Mary Wilson, the wife of the then British Prime Minister Harold Wilson, and entered service 18 April 1967.

She refitted for two years, which was nearing completion just as the Falklands War started. After the war ended she carried out a long patrol around the island and the Argentine coast.

The submarine was decommissioned in 1991. Mainly operated out of HMNB Clyde, at Faslane (the former Clyde Submarine Base) with the Third Submarine Squadron (SM3). Her hull and reactor are currently laid up afloat at Devonport Dockyard, Plymouth, Devon until facilities are available for the long term storage of her radioactive components.

Notable commanders of this vessel include the Falklands Conflict Battle Group Commander, Rear Admiral Sir John "Sandy" Woodward. Woodward went on to become the Commander-in-Chief Naval Home Command and rose to the rank of Admiral.

USS West Virginia (SSBN-736)

USS West Virginia (SSBN-736) is a United States Navy Ohio-class ballistic missile submarine which has been in commission since 1990. She is the third U.S. Navy ship to be named for West Virginia, the 35th state, and the 11th of 18 Ohio-class submarines.

The contract to build West Virginia was awarded to the Electric Boat Division of General Dynamics Corporation in Groton, Connecticut, on 21 November 1983 and her keel was laid down there on 24 December 1987. She was launched on 14 October 1989, sponsored by Mrs. Erma Byrd, wife of United States Senator Robert C. Byrd of West Virginia, and commissioned on 20 October 1990, with Captain J. R. Harvey in command of the Blue Crew and Captain Donald McDermott in command of the Gold Crew.

USS West Virginia (SSBN-736) is based at Naval Submarine Base Kings Bay, Georgia.

Figure 140: USS West Virginia

Russian Submarine Yury Dolgorukiy

K-535 Yuriy Dolgorukiy is the first SSBN submarine of the Borei class of the Project 955 that is being built for the Russian Navy. Named after the founder of Moscow Yuri Dolgoruki, it was laid down on 2 November 1996 and was first planned to enter service in 2001.

However, the SS-N-28 missile that the Borei class was supposed to carry was abandoned after several failed tests, and the submarine was redesigned for the Bulava missile. Bulava missile is smaller than the original SS-N-28, and in the 2007 START treaty data exchange it was reported that all Borei-class submarines would carry 16 missiles instead of 12, as originally intended.

The submarine was rolled out of its construction hall into a launch dock on 15 April 2007 in Severodvinsk, when it was about 82% complete. The Russian Government has allocated nearly 5 billion rubles, or 40% of the Navy's 2007 weapons budget, for the completion of the submarine.

Some doubts about the conditions in which the boat was launched were expressed to the Russian press by workers and managers at the Sevmash plant, where the construction was taking place. Specifically, workers noted that welding of the submarine's outer hull was in some places unfinished. There was some speculation that Yuriy Dolgorukiy would be rushed through the rest of its production and testing phases in order to be ready for the 2008 Russian presidential elections. Much of the ship's equipment remains as yet uninstalled and untested, a process that would normally take over a year to complete.

On 13 February 2008 Yuriy Dolgorukiy was finally launched from its floating dock in Severodvinsk where the final outfitting took place. The submarine's reactor was first activated on 21 November 2008. and the submarine began its sea trials on 19 June 2009.

In July 2010 ship passed one of company sea trial, in which navigation systems, buoyancy control system, and some other characteristics were tested at sea. Ship completed all company tests in end of September 2010 and now is preparing for state trials.

Initially was planned conduct the first torpedo launches during the ongoing state trials in December 2010 and then in same month conduct the first launch of the main weapon system, R-30 (RSM-56) Bulava missile. The plan was then postponed to mid-summer 2011 due to ice conditions in White Sea.

It was expected to be commissioned to Russian Pacific Fleet in 1st half 2011, but in December 2010 it was announced that the submarine had technical defects and would be laid up for repairs. The work will take at least six months, and after this the submarine will continue the Bulava missile tests and could be ready for active duty by the latter half of 2011.

Yasen Class Submarine

The Yasen class submarine, also known in the literature as the Graney class and Severodvinsk class, is a new Russian nuclear multipurpose attack submarine class. The submarine is based on the Akula-class submarine and the Alfa-class submarines and are projected to replace Russia's Soviet-era class attack submarines both Akula class and Oscar class.

Construction on the first submarine started on December 21, 1993. The submarine was slated for launch in 1998 but was delayed due to problems in financing the project. In 1996 work on the submarine appeared to have stopped completely. Some reports suggested that as of 1999 the submarine was less than 10 percent completed In 2003 the project received additional funding and the work of finishing the submarine continued.

In 2004 it was reported that the work on the submarine was moving forward, but due to the priority given to the new SSBN Borei-class submarine, Severodvinsk, the lead unit of the Yasen class would not be ready before 2010. In July 2006 the deputy chairman of the Military-Industrial Commission, Vladislav Putilin, stated that two Yasen class submarines were to join the Russian Navy before 2015.

On July 24, 2009 the work on a second Yasen submarine, named Kazan, was started. On July 26 the Russian navy command announced that one multipurpose submarine would be laid down every year, not necessarily of this class, starting in 2011.

An August 2009 report from the U.S. Office of Naval Intelligence rates the Yasen/Severodvinsk class submarines as the quietest, or least detectable, of contemporaneous Russian and Chinese nuclear submarines.

In April 2010 it was reported that the 7 May launch of the first boat had been postponed due to 'Technical Reasons'.

On June 15, 2010 the first submarine was rolled out of its building hall. Plans call for the submarine to be in service by late 2010 or early 2011.

It was speculated that the cost of the first Yasen class submarine was around 1 billion USD. Although another source claims that the price was actually 2 billion USD.

The ship's design is claimed to be state-of-the-art. Larger than the older Akula class attack submarines, the Yasen class will have significantly more firepower. The submarine is presumed to be armed with 32 cruise missiles, with several types suggested, including the 3M51 Alfa SLCM, the P-800 Oniks SLCM or the RK-55 Granat SLCM It will also have 8 torpedo tubes as well as mines and anti-ship missiles like the RPK-7.

This class is the first Russian submarines to be equipped with a spherical sonar, designated as Irytysh-Amfora. Due to the large size of this spherical array, the torpedo tubes are slanted. The submarine has a crew of about 90, suggesting a moderate degree of automation in the submarine's different systems. The newest U.S. attack sub, the Virginia-class submarine, has a crew of 134 in comparison.

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USS Wyoming (SSBN-742)

USS Wyoming (SSBN-742) is a United States Navy Ohio-class ballistic missile submarine which has been in commission since 1996. She is the fourth U.S. Navy ship to be named USS Wyoming, although it was only the third named for the state of Wyoming.

The contract to build Wyoming was awarded to the Electric Boat Division of the General Dynamics Corporation in Groton, Connecticut, on 18 October 1989 and her keel was laid down there on 8 August 1991. She was launched on 15 July 1995, sponsored by Mrs. Monika B. Owens, and commissioned on 13 July 1996, with Captain Randall D. Preston in command of the Blue Crew and Commander Seth F. Paradise in command of the Gold Crew.

O. Analysis of Russia's Nuclear-powered Naval Fleet

Military Vessel Classes and Generations

The start was a slow one. As early as 1948 the Russian director for Institute for Problems in Physics, Academician Anatoli Aleksandrov, wanted to see a nuclear-propulsion project established. However, Stalin's right-hand man, Beria, said that nothing was to be done, as described in Kotcher, until a nuclear bomb had been built. The bomb was finally ready, and on September 9, 1952, work on a submarine using a nuclear-propulsion reactor was officially initiated by the Council of Ministers of the Soviet Union. Six years later, the first Russian nuclear submarine was commissioned, and at 10.03 in the morning of July 4, 1958, the November-class attack submarine K-3 Leninsky Komsomol, containing two 70 MWt pressurized water reactors (PWR) initiated its first trip as part of the Russian Navy. This event was followed by a rapid build-up of the Russian nuclear fleet, which is based on Pavlov and IISS.

Russia's nuclear navy peaked in the late 1980s. There were several reasons for the ensuing reduction of the number of nuclear vessels. Some submarines had reached the end of their useful lifetime; disarmament agreements between the USA and Soviet Union/Russia required reductions in the number of ballistic missile submarines; the Cold War was coming to an end and a large nuclear navy was no longer needed; and economic difficulties developed in Russia. Reducing the number of operational nuclear vessels of the Russian Navy automatically created a need for decommissioning and dismantling the vessels no longer needed.

The Russian submarine fleet consists primarily of attack or multi-purpose submarines for attacks on enemy vessels, of cruise missile submarines for attacks on enemy convoys or coastal facilities, and of ballistic missile submarines for deterrence and – if need be – strategic attacks on enemy territory. In addition a few small deep-water nuclear submarines have been built. In the 1980s came the Kirov-class missile cruisers and a fleet command ship. NATO has given its own names to most of the classes of Russian nuclear naval vessels. Since these NATO names are often used also in Russian publications, they will primarily be used here. The first nuclear icebreaker came into operation in the late 1950s, later followed by eight more icebreaking ships.

In this report, the division between the generations has been made along the following lines, with only a few exceptions: The first generation was built from 1952 to 1968, the second from 1967 to 1992, and the third from 1980 (it remains an active design at Russian naval yards). Additionally, the Russian Navy has built three submarines of different designs of which only one vessel each was made. Therefore, they may be considered experimental submarines. Russia has also constructed three types of small, deep-water nuclear submarines, as well as four nuclear-powered missile cruisers and a nuclear-powered command ship.

Figure 141: Number of Russian Submarines Built and of Russian Nuclear Submarines in Operation as a Function of Time

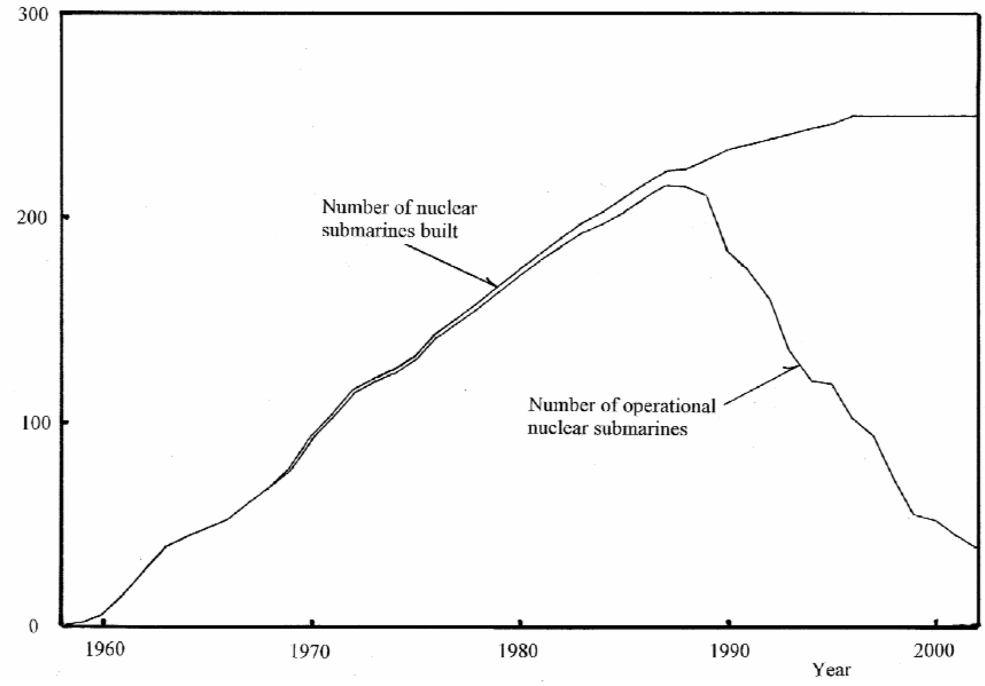
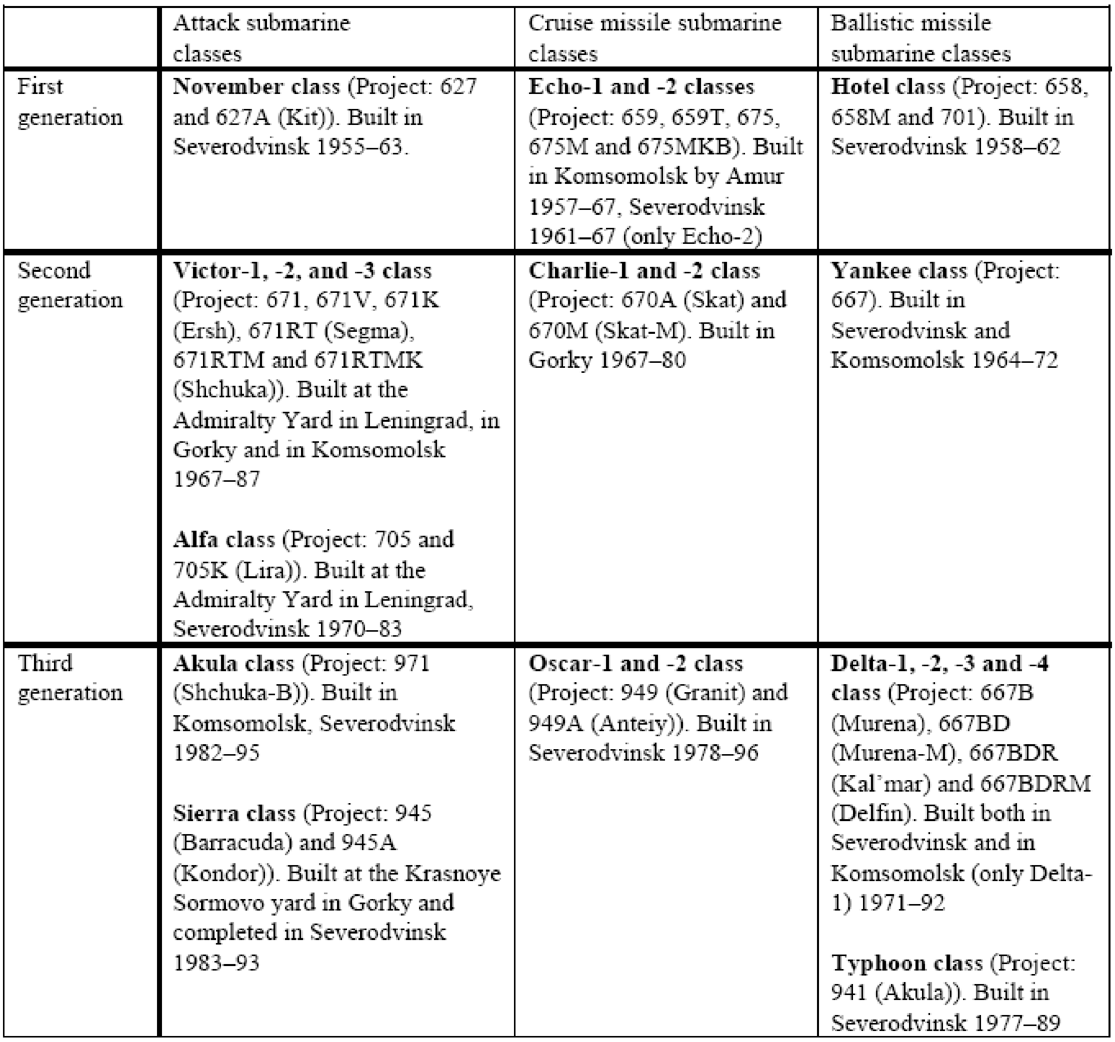


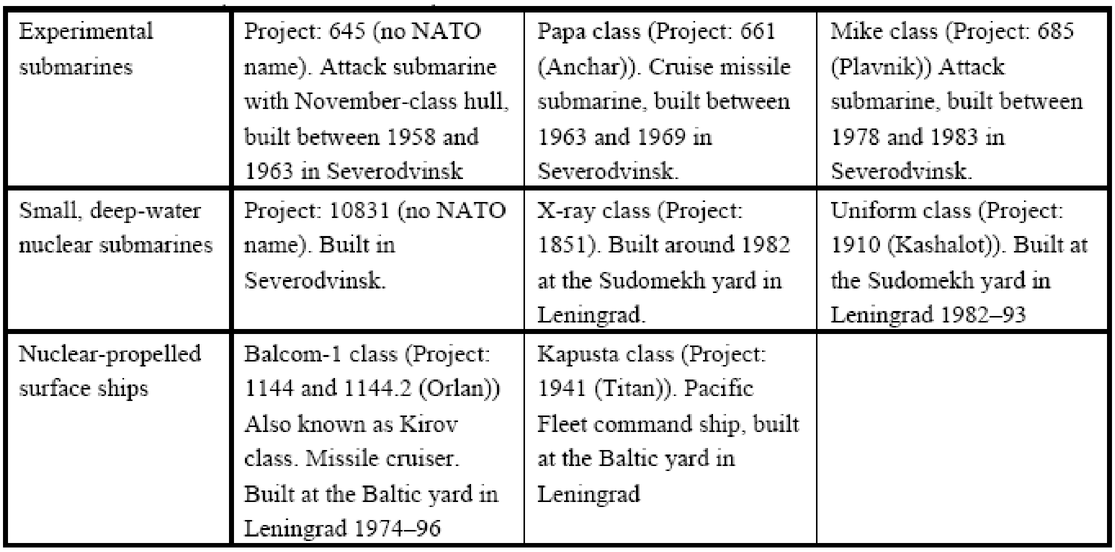
Table 9: Generations and Classes of Russian Nuclear Submarines



	Attack submarine classes	Cruise missile submarine classes	Ballistic missile submarine classes
First generation	**November class** (Project: 627 and 627A (Kit)). Built in Severodvinsk 1955–63.	**Echo-1 and -2 classes** (Project: 659, 659T, 675, 675M and 675MKB). Built in Komsomolsk by Amur 1957–67, Severodvinsk 1961–67 (only Echo-2)	**Hotel class** (Project: 658, 658M and 701). Built in Severodvinsk 1958–62
Second generation	**Victor-1, -2, and -3 class** (Project: 671, 671V, 671K (Ersh), 671RT (Segma), 671RTM and 671RTMK (Shchuka)). Built at the Admiralty Yard in Leningrad, in Gorky and in Komsomolsk 1967–87 **Alfa class** (Project: 705 and 705K (Lira)). Built at the Admiralty Yard in Leningrad, Severodvinsk 1970–83	**Charlie-1 and -2 class** (Project: 670A (Skat) and 670M (Skat-M). Built in Gorky 1967–80	**Yankee class** (Project: 667). Built in Severodvinsk and Komsomolsk 1964–72
Third generation	**Akula class** (Project: 971 (Shchuka-B)). Built in Komsomolsk, Severodvinsk 1982–95 **Sierra class** (Project: 945 (Barracuda) and 945A (Kondor)). Built at the Krasnoye Sormovo yard in Gorky and completed in Severodvinsk 1983–93	**Oscar-1 and -2 class** (Project: 949 (Granit) and 949A (Anteiy)). Built in Severodvinsk 1978–96	**Delta-1, -2, -3 and -4 class** (Project: 667B (Murena), 667BD (Murena-M), 667BDR (Kal'mar) and 667BDRM (Delfin). Built both in Severodvinsk and in Komsomolsk (only Delta-1) 1971–92 **Typhoon class** (Project: 941 (Akula)). Built in Severodvinsk 1977–89

Several systematic features for the development of the Russian military reactor can be noted. Russian nuclear submarines have in most cases a double hull, an outer hull and an inner pressure hull. The room between the two hulls is used for ballast tanks as well as equipment and weapon systems. Western nuclear submarines are in general provided with a pressure hull only. While the pressure hull is in most cases made of steel alloys, a few Russian nuclear submarines have been provided with a titanium pressure hull, as is the case for the Papa, the Mike, the Sierra and the Alfa classes. In addition to the main steam turbines which operate the shafts, the submarines are provided with turbo-generators for electric power supply. Should these generators fail, the submarines are provided with back-up diesel generators and batteries. These power sources can also be used for emergency propulsion. However, the diesel generators can operate only when the submarines are at or close to the sea surface.

Table 10: Experimental and Deep-Water Nuclear Submarines and Nuclear Surface Vessels



Experimental submarines	Project: 645 (no NATO name). Attack submarine with November-class hull, built between 1958 and 1963 in Severodvinsk	Papa class (Project: 661 (Anchar)). Cruise missile submarine, built between 1963 and 1969 in Severodvinsk.	Mike class (Project: 685 (Plavnik)) Attack submarine, built between 1978 and 1983 in Severodvinsk.
Small, deep-water nuclear submarines	Project: 10831 (no NATO name). Built in Severodvinsk.	X-ray class (Project: 1851). Built around 1982 at the Sudomekh yard in Leningrad.	Uniform class (Project: 1910 (Kashalot)). Built at the Sudomekh yard in Leningrad 1982–93
Nuclear-propelled surface ships	Balcom-1 class (Project: 1144 and 1144.2 (Orlan)) Also known as Kirov class. Missile cruiser. Built at the Baltic yard in Leningrad 1974–96	Kapusta class (Project: 1941 (Titan)). Pacific Fleet command ship, built at the Baltic yard in Leningrad	

Table 11: Number of Russian Nuclear Vessels Built

Project No.	NATO name	Submarine generation	Number built	Number in operation, 2003	Constr. period
627, 627A	November	First	13	0	1955–63
659,659T	Echo-1	First	5	0	1956–62
658,658M,658 S, 701	Hotel	First	8	0	1958–62
645	–		1	0	1958–63
675,675K, 675 MK,675MKB	Echo-2	First	29	0	1961–67
661	Papa		1	0	1963–69
667, 667 AO, 667 M, 667 AT,	Yankee	Second	34	1	1964–72
671, 671V,671K	Victor-1	Second	18	0	1965–74
670, 670A	Charlie-1	Second	11	0	1967–72
671RT	Victor-2	Second	7	0	1971–78
670M	Charlie-2	Second	6	0	1973–80
705,705A	Alfa		7	0	1977–83
685	Mike		1	0	1978–83
671RTM,671RTMK	Victor-3	Second	26	5	1978–91
945,945A	Sierra	Third	4	1	1983–93
971	Akula	Third	15	9	1982–
949,949A	Oscar	Third	10 (12?)	6	1978–
667B	Delta-1	Third	18	0	1971–77
667BD	Delta-2	Third	4	0	1973–75
667BDR	Delta-3	Third	14	5	1975–81
667BDRM	Delta-4	Third	7	6	1981–92
941	Typhoon	Third	6	2	1977–89
	Borei	Fourth			
	Granay	Fourth			
	Subtotal		246	36	
10831	–		1	1	
1851	X-ray		1	1	≈1982
1910	Uniform		2	2	1982–93
	Subtotal		250	40	
1144,1144.2	Balcom-1		4	2	1974–96
1941	Kapusta		1	0	
	Subtotal		255	42	
Icebreakers			8	6	
Icebreaker	Freighter		1	1	
	Total		264	49	

Most Russian submarines have two reactors. The exceptions are Charlie, Alfa, Mike, Sierra and Akula classes. For modern attack submarines, the trend is towards a single reactor unit. Western nuclear submarines are in almost all cases provided with one reactor only. The reason for two reactors in all early Russian nuclear submarines was presumably deliberate redundancy: even if one reactor stopped, the other could continue to operate. This might have been a consequence of the lack of time for testing these early versions. The head start enjoyed by the USA goes like a red thread through many Russian publications on submarine warfare and history.

The submerged displacement of the Russian nuclear submarines varies between 4,000 and 48,000 tons. Since vessels have to be able to operate at high speed when submerged, 25–45 knots – attack submarines are the fastest – propulsion power has to be considerable, from 20,000 to 100,000 shaft horsepower. Most of the earlier classes have two shafts, but the newer attack submarines have one shaft only. The early Russian submarines were quite “noisy” and therefore easy to detect – a major concern for Russia’s submarine designers. Much has been done to reduce the noise from the machinery of the submarines so as to avoid detection by passive sonar; in order to prevent detection by active sonar, the outer surface of submarines has been provided with a thick rubber layer.

Civilian Vessel Classes and Generations

The first icebreaker built by Russia was Lenin, which went in operation in 1959 and was decommissioned in 1989. The second generation of icebreakers consisted of Arktika (operational in 1975), Sibir (operational in 1977), Rossia (operational in 1985), Sovetskiy Soyus (operational in 1989) and Yamal (operational in 1992). Rossia, Sovetskiy Soyus and Yamal incorporate several improvements as compared to Arktika and Sibir. Sibir was decommissioned in 1992 due to too many pluggings of its steam-generator sections. The last icebreaker of this generation is Ural, the construction of which was started, but as far as is known never finished. Ural seems later on to have been renamed 50 let Pobedy (50 years of Victory), which was again renamed “60 let Pobedy (60 years of Victory)”. According to Nuclear Europe, the Russian government has decided to provide funds for the completion of 60 let Pobedy. According to Makarov, Arktika was to have been decommissioned in 2001, but the process has not been initiated yet.

The third generation consists of Taimyr (operational in 1989) and Vaigatch (operational in 1990). Both were built at the Wartsila shipyard in Finland, but provided with nuclear propulsion systems at the Baltiskiy shipyard in Saint Petersburg (Leningrad) in Russia. Finally, there is the icebreaking freighter Sevmorput, which became operational in 1988.

Several icebreaker projects are under way in Russia. One is a study of Yamal-2 to replace Arktika. Another is a "super icebreaker" intended to ensure all-year navigation between Europe and Japan along the Russian Arctic coast. A third is the Pevek icebreaker with restricted draught, to extend the applicability of the Taimyr type to operate in Arctic river estuaries. Finally, Russia has plans for constructing floating power plants. Due to the country's financial difficulties, the future of these projects and the completion of the icebreakers under construction are uncertain.

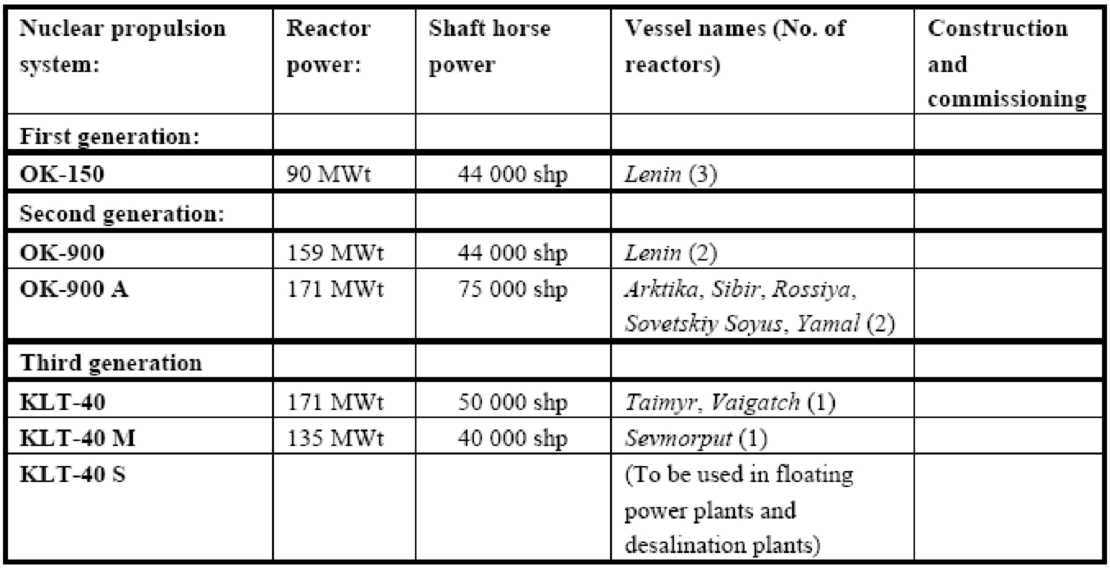
Civilian Marine Reactors in Russia

Overview

While only limited information is available about the design of the reactors used in Russian military naval vessels, the situation is different for the country's icebreakers.

The reactors are all pressurized water reactors. The development of a Russian marine reactor for civilian purposes started with the OK-150 power plant, which was the first plant used in the NS Lenin. Later on came the OK-900 and the KLT-40 plants. The OK-900 and the KLT-40 plants exist in various versions.

Table 12: Nuclear Power Plants for Civilian Vessels



Nuclear propulsion system:	**Reactor power:**	**Shaft horse power**	**Vessel names (No. of reactors)**	**Construction and commissioning**
First generation:				
OK-150	90 MWt	44 000 shp	*Lenin* (3)	
Second generation:				
OK-900	159 MWt	44 000 shp	*Lenin* (2)	
OK-900 A	171 MWt	75 000 shp	*Arktika, Sibir, Rossiya, Sovetskiy Soyus, Yamal* (2)	
Third generation				
KLT-40	171 MWt	50 000 shp	*Taimyr, Vaigatch* (1)	
KLT-40 M	135 MWt	40 000 shp	*Sevmorput* (1)	
KLT-40 S			(To be used in floating power plants and desalination plants)	

OK-150 Plant

Overview

The initial three reactor units of the icebreaker Lenin were OK-150 plants, each of which was provided with a pressurized water reactor with a power level of 90 MWt.

Reactor Analysis

The fuel elements were placed in a removable insert or “basket”, which hung from the top of the tank. The water coolant entered the reactor tank from the bottom and flowed up through the central part of the reactor core. At the top of the central fuel elements, the coolant moved out to the periphery of the tank and down through the reflector/thermal shield. At the bottom, the coolant flow was again reversed, and the coolant flowed up through the outer fuel elements and left for the steam generators at the top of the reactor tank. In Makarov, it is stated that the reason for locating the coolant inlet to the reactor vessel was to reduce the mass of the system. However, this design made repair of the main valves in the primary circuit difficult. The core of the first NS Lenin reactors was 1.58 m high and had an equivalent diameter of 1 m. This means that the power density was 72 kW/ liter.

Fuel Analysis

The core contained 219 technical fuel channels, arranged in a triangular lattice, with a pitch of 64 mm. Out of 219 channels, 189 contained 36 fuel rods, and, according to IIASAP, 30 contained 30 fuel rods. In total this gives 7,704 fuel rods in each core. The fuel elements were cluster-type elements with 36 fuel pins or rods (6.1 mm diameter), arranged in three rings and surrounded by a tubular shroud. The central rod was a steel rod, carrying the weight of the fuel rods. The fuels were UO2 pellets, with a diameter of 4.5mm. The first fuel load consisted of fuel enriched to 5% with a total of 80 kg. U--235 in each reactor, or 1.7 metric tons 5% enriched uranium. The gas gab between the fuel pellet and the cladding, 0.05 mm, was filled with helium. Initially the cladding material was zirconium.

Minimum clearance between the fuel pins was 1.5 mm. Fuel density has not been given. Burn-up was 18,000–20,000 MWd for the first loading. In practice this corresponds to a few years of operation. The first fuel loading lasted from 1959 to 1962.

Since several leaks developed in the cladding during the operation of the first core due to fuel cladding interaction, one of the reactors was at the first re-fueling provided with stainless steel clad fuel and the other two reactors with fuel with an improved zirconium alloy cladding. The fuel was still UO2 pellets. The fuel with stainless steel cladding (and presumably with higher enrichment) achieved an energy production 25% higher than planned.

During the re-fueling all fuel was replaced. The core was designed in such a way that the temperature coefficient was moderately negative at operation temperatures. For the second core load, these parameters were changed slightly, with a zirconium-niobium alloy introduced as cladding with a thickness of 0.75 mm. The amounts of fuel in the three reactors were 129 kg. in N1 and 75 kg. in N2 and N3. The density of this fuel has not been given. Bellona has claimed that approximately 320 fuel assemblies from the Lenin reactors have ended up in Lepse. In addition it has been claimed as part of the remediation of Andrejeva Bay that icebreaker fuel is also stored in the bay. It has not been confirmed whether this is fuel from any of the fuel batches from Lenin.

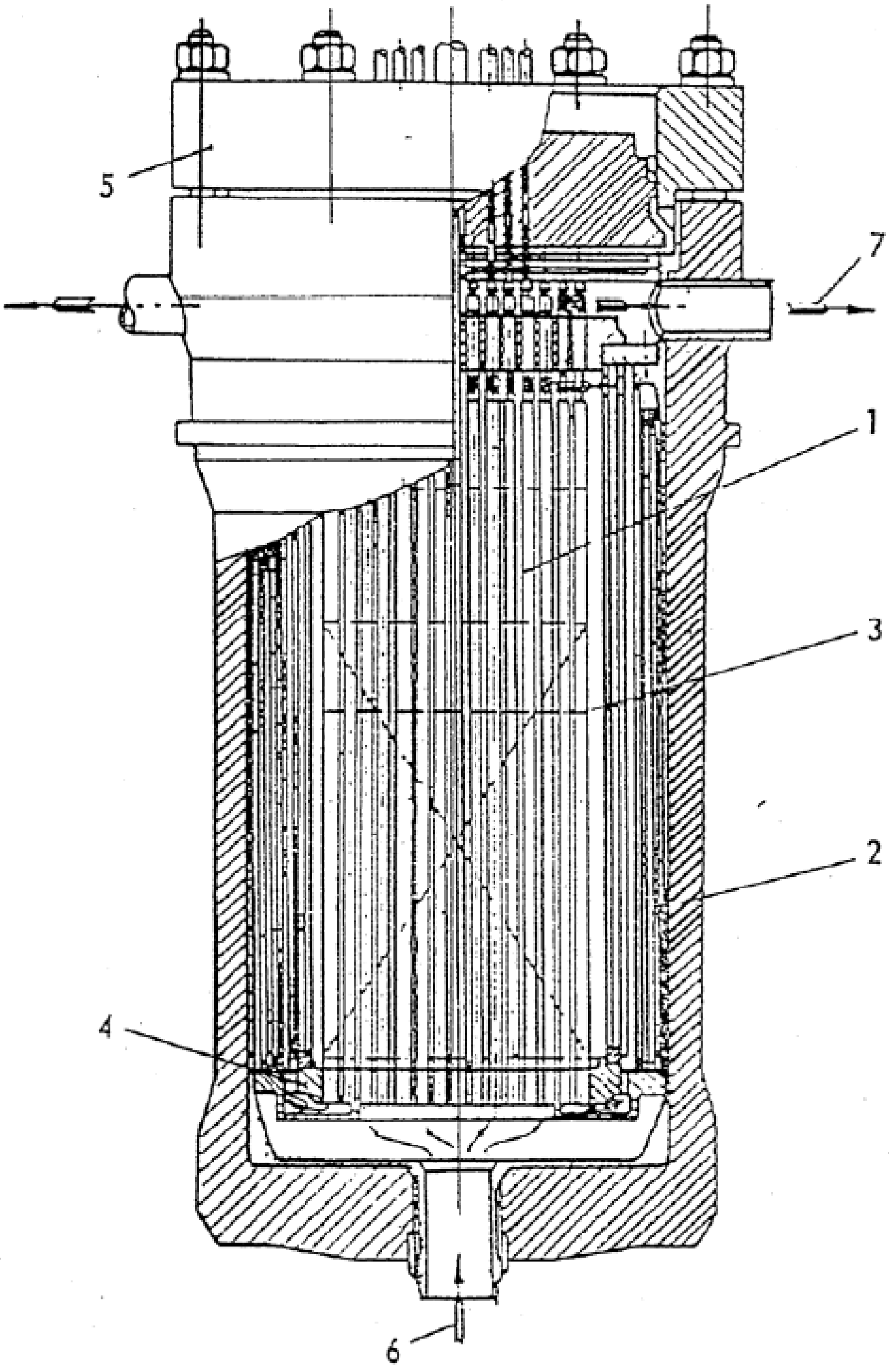
Reaction Control

Reactor power was, thanks to the negative temperature coefficient, regulated by changing the flow rate of the feed-water and by use of three regulation rods (one of them a reserve) with a rack-and-pinion drive. Reactor shutdown was accomplished by use of safety rods. All control rods were inserted from above. Burn-up was increased by the use of burnable poison (B-10). In the first core loading, the boron was situated in the shroud tubes of the central part of the core where it also helped to flatten the power distribution in a radial direction.

Pressure Vessel & Safety Radiation Shield

The pressure vessel had an outer diameter of about 2 m and a height of about 5 m. On the inside it was provided with a stainless steel layer. To protect the reactor vessel against radiation damage a thermal shield consisting of steel plates was placed between the core and the pressure vessel, and was cooled by the primary coolant.

Figure 142: Vertical Cross Section of the OK-150 Reactor



1, Channels; 2, pressure vessel; 3, shielding; 4, lower plate; 5, cover; 6, coolant inlet; 7, coolant outlet

Figure 143: Horizontal Cross Section of the OK-150 Reactor

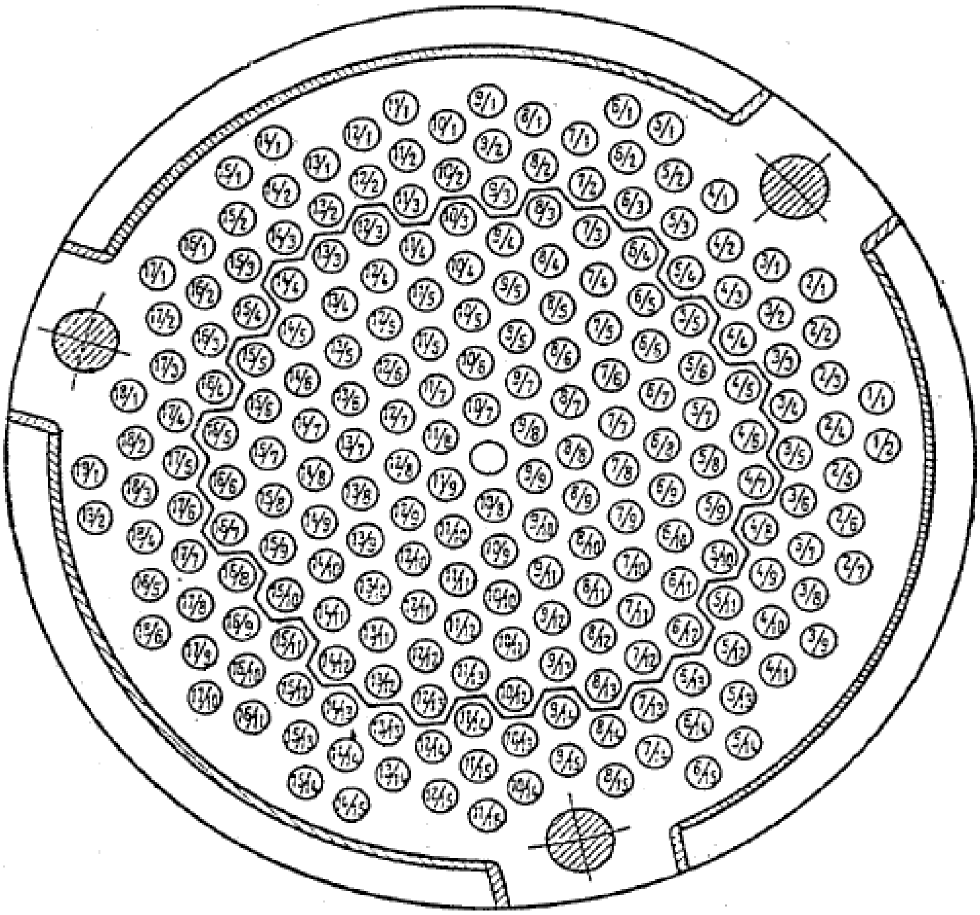


Figure 144: Fuel Element for the OK-150 Reactor

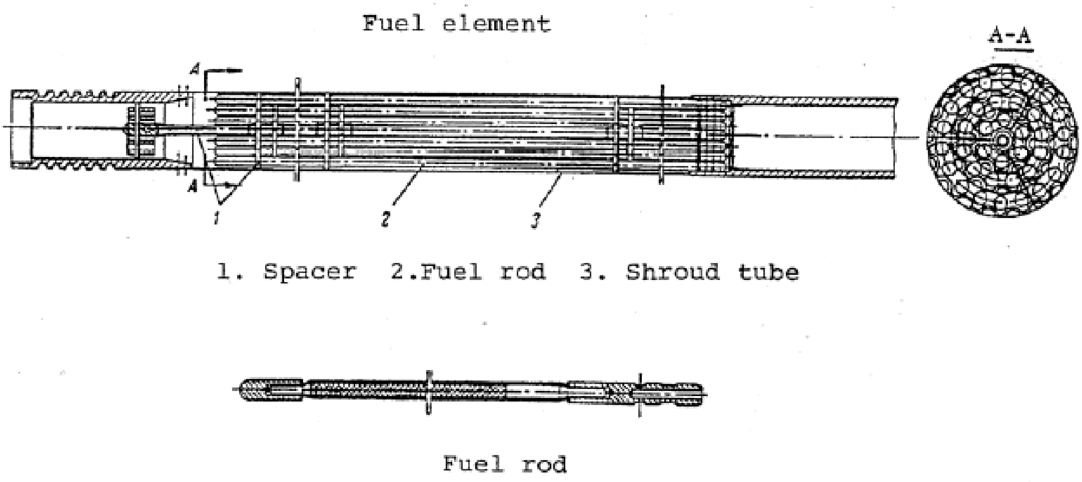
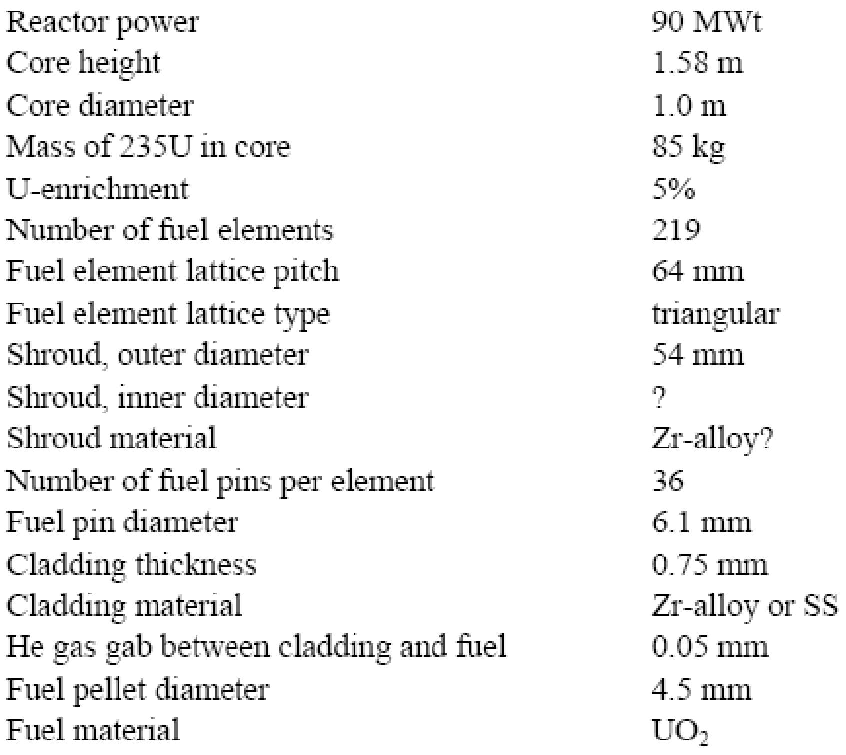


Table 13: Core and Fuel Data of OK-150, First Core Load (All Reactors)



Reactor power	90 MWt
Core height	1.58 m
Core diameter	1.0 m
Mass of 235U in core	85 kg
U-enrichment	5%
Number of fuel elements	219
Fuel element lattice pitch	64 mm
Fuel element lattice type	triangular
Shroud, outer diameter	54 mm
Shroud, inner diameter	?
Shroud material	Zr-alloy?
Number of fuel pins per element	36
Fuel pin diameter	6.1 mm
Cladding thickness	0.75 mm
Cladding material	Zr-alloy or SS
He gas gab between cladding and fuel	0.05 mm
Fuel pellet diameter	4.5 mm
Fuel material	UO_2

The reactor vessel was surrounded by a biological shield, primarily iron and water layers. The water was circulated through a heat exchanger, thereby removing the heat produced in the shield. Russian publications often refer to this circuit as the third circuit. At a few places, e.g. at the top of the reactor, heavy concrete shields were used.

Cooling Circuit

Each reactor had two coolant loops, each provided with a steam generator and two main circulation pumps (one of which was a reserve), an emergency pump and an ion exchange filter with an associated cooler. The primary circuit was provided with four pressurizers, which controlled the pressure of the system (in Russian terminology, pressurizers are called volume compensators). Pressure was increased by heating the water of the pressurizers by electric heating, thereby producing additional steam. Pressure was lowered by condensation of the steam. The pressurizers also accommodated changes in water volume due to temperature changes in the coolant during start-up and shut-down.

Thermal Features

According to Alexandrov, core coolant inlet temperature was 248o C, outlet temperature 325°C, operating pressure of the primary circuit was 200 bar, and the coolant flow was 1000 m3/hr. According to Makarov, inlet temperature was 261°C, outlet temperature 284°C, and operating pressure of the primary circuit 180 bar. According to Afrikantov, inlet temperature was 260°C, outlet temperature 311 to 313°C, and the coolant flow 435 to 467 tons/hr at a power output at 70–75%. These differences in thermal parameters probably reflect changes in optimal operating conditions, which may well have changed with time, experience and fuel design.

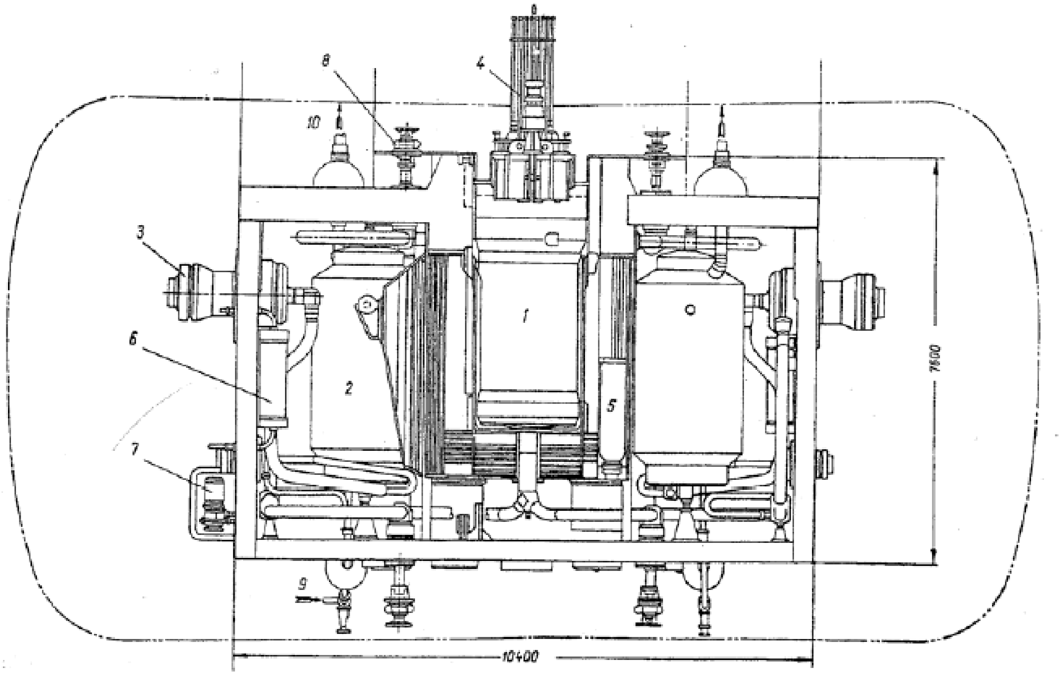
According to Alexandrov, steam output of the steam generators was at full power 360 t/hr at a pressure of 29 bar and a temperature of 310° C. According to Makarov, it was 360 t/hr at a pressure of 31 bar and a temperature of 290°C, whereas according to Afrikantov, it was 250 tons at a pressure of 29–31 bar and a temperature of 307 to 310o C at 70–75% of full power.

OK-900 Plant

Overview

From September 1967 to April 1970, the initial reactor compartment with the three OK-150 units, one of which had been damaged by the 1966 LOCA accident, was cut out of Lenin and replaced by a new compartment with two OK-900 units, each with a power level of 159 MWt. Later on a modified design, OK-900A with a power level of 171 MWt, was used in the icebreakers Arktika, Sibir, Rossia, Sovetskiy Soyus and Yamal. Each of these ships was provided with two OK-900A units. However, the plants of the three latter are not identical to those of the two former, since experience obtained from the operation of Arktika and Sibir was used to improve the plants of the last three. Most, but not necessarily all, of the improvements mentioned below will apply to both the OK-900 and the OK-900A unit.

Figure 145: General Layout of the OK-150 Plant



1. Reactor. 2. Steam generators. 3. Main Circulation Pumps. 4. Control Rod Drive Mechanism. 5. Filter. 6. Cooler. 8. Primary Circuit Valve. 9. Feed-Water Inlet. 10. Steam Outlet.

During the operation of the Lenin reactors, cracks had developed in the primary cooling system due to thermal cycling. Thus, in designing the OK-900, efforts were made to decrease the effect of thermal cycling and thereby increase the lifetime of the system from 25,000 to 50–60,000 hrs.

Reactor Analysis

In the OK-900 plant, the number of loops of the primary circuit was increased from two to four. Further the main cooling pumps and steam generators were connected to the reactor tank by a pipe-inside-pipe load-bearing connection, which greatly reduced the length of the pipes in each loop. New pressurizers were introduced in which the reactor pressure was regulated by varying the gas pressure above the water surface of the pressurizer, by use of an external compressed gas source.

Both the inlet tubes to and the outlet tubes from the reactor tank were connected to the tank at the top of the tank, making it impossible for the tank to be drained due to an operator error, as had been the case on NS Lenin in 1966.

Since water of the secondary circuit will become contaminated by seawater, stainless steel cannot be used for construction of the steam generator if corrosion leaks are to be avoided. For this reason, the tubing of the steam generators and of the secondary system were made of a corrosion resistant alloy. This should allow a service life of 50–60,000 hours. Should a rupture occur in the steam generator, the circulation loop is switched off from the secondary circuit, not from the primary one.

Fuel Analysis

It was found desirable to develop new fuel elements with a fuel material with much higher specific heat and thermal conductivity than UO2, e.g. a uranium-zirconium alloy with zirconium cladding. The gas gap between the fuel material and the cladding was removed. The first OK-900 cores had a burn-up of 29–38,000 MWtd, later increased to 88–96,000 MWtd. The use of the new fuel improved the reactor’s self-regulation properties. The increased burn-up was possibly a result of increased enrichment levels. The icebreaker fuel at RTP Atomflot in the icebreakers using OK 900 A has been reported to be up to 90%, and this has, according to Mærli, been used as a dimensional factor when establishing physical protection systems for the reactors and the ships themselves. However, representatives from the Murmansk Shipping Company have confirmed that not all icebreakers are using this high enrichment; 55–90% is the range that has been presented earlier.

Reaction Control

During the operation of the OK-900 plants, the force required to move the control rods increased. This led to the introduction of a new drive mechanism design to ensure “self-propulsion” in the case of power failure, as well as a manual drive system to lower the control rods if need be. In addition, injection into the reactor of a liquid absorber was introduced, in case the control rods should become stuck.

Safety System

The OK-900 plant was provided with a containment system, so that any release of radioactive material from the primary system would remain inside the containment. Should the vessel sink, valves in the wall of the containment would stay open as long as the outside pressure was higher than that inside, thereby flooding the containment and preventing its destruction and the release of radioactivity.

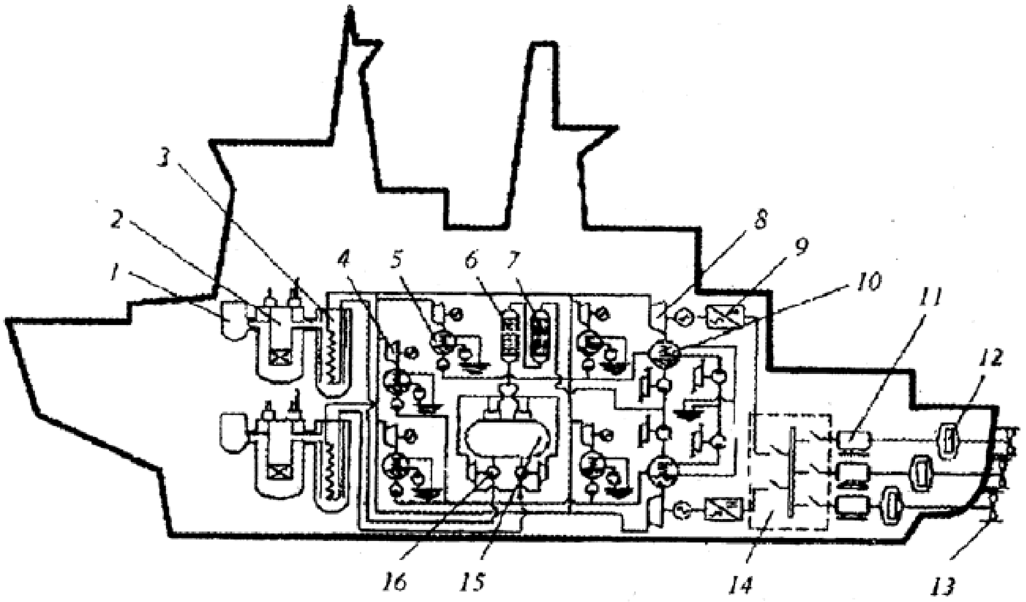
KLT-40 Plant

Overview

The latest version of Russian maritime reactor plants is the KLT-40. It has been installed in the icebreaking freighter Sevmorput and in two icebreakers, Taimyr and Vaigatch, all with one reactor only. Much is known about this plant, because the Russian government submitted the safety report for NS Sevmorput to the Norwegian safety authorities in 1991 before a visit of Sevmorput to Tromsø in 1991. This report has been the basis for many studies of Russian marine reactors. The KLT-40 plant contains a pressurized water reactor with power levels of 135 MWt (Sevmorput) and 171 MWt (Taimyr and Vaigatch).

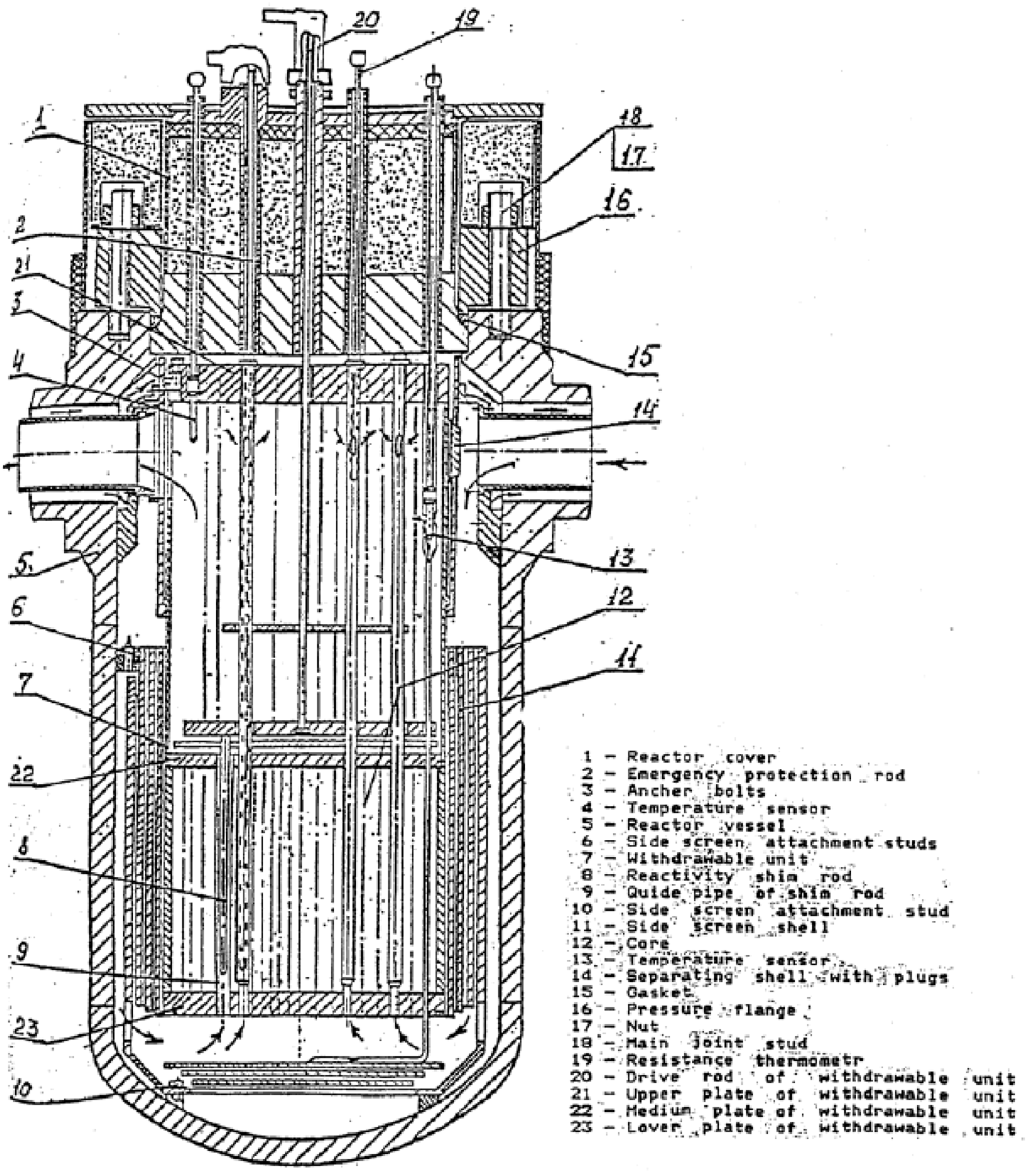
Reactor Analysis

Figure 146: Circuits of the Nuclear Icebreaker "Arktika"



1. Circulation pumps. 2. Reactor. 3. Steam generator. 4. Auxiliary turbo generator.
5. Condenser. 6 Ion-exchange filters. 7. Mechanical filter. 8. Main turbo generator.
9. Converter. 10. Main condenser. 11. Propeller motor (electric). 12. Intermediate bearing.
13. Screw propeller. 14. Circuit breaker for propeller motor 15. De-aerator. 16. Turbo-feed pump.

Figure 147: Vertical Cross-section of the KLT-40 Reactor



The coolant enters the reactor tank at the top, flows downwards through the reflector/thermal shield, up through the reactor core and from the top of the reactor tank to the steam generator. From here, the coolant flows through the canned circulation pump back to the reactor. The design is very compact, completely welded with a tube-inside-tube arrangement whereby the length of the piping and number of flanges etc. of the primary circuit is kept to a minimum, reducing the risk of leakage. The reactor tank is on the inside provided with a stainless steel layer. The thermal shield consists, in the radial direction, of steel-water layers and, at the top above the tank lid, of a concrete shield.

The core height is 1 m and the diameter 1.21 m. The 241 fuel elements are arranged in a triangular lattice with a spacing of 72 mm. The fuel elements are placed in a removable insert or basket inside the reactor tank, and movement is prevented by fixing them both at the bottom and at the top.

Fuel Analysis

The fuel elements are of the cluster type, with 53 fuel pins with an outer diameter of 5.8 mm. The number of fuel pins is not given, but since core height, pin diameter, number of pins per fuel element, number of fuel elements in the core and the heat transfer area of the core (233 m2) are all given, the number of fuel pins can be calculated. The spacing of the fuel pins in the element is 7 mm. The cluster of fuel pins is surrounded by a zirconium alloy shroud with an outer diameter of 60 mm. The fuel material is a uranium-zirconium alloy, and the uranium is 90% enriched. The total amount of uranium in the core is 167 kg (150.7 kg U-235). The cladding is a zirconium alloy. The fuel elements are also provided with burnable poison pins containing natural gadolinium.

Table 14: Core and Fuel Data for KLT-40 (Sevmorput)

Reactor power	*135 MWt*
Core height	*1 m*
Core diameter	*1.21 m*
Mass of U-235 in core	*150.7 kg*
U-enrichment	*90%*
Number of fuel elements	*241*
Fuel element lattice pitch	*72 mm*
Fuel element lattice type	*triangular*
Shroud, outer diameter	*60 mm*
Shroud, inner diameter	*?*
Shroud material	*Zr-alloy?*
Number of fuel pins	*53*
Fuel pin lattice pitch	*7.2 mm*
Fuel pin diameter	*5.8 mm*
Cladding thickness	*?*
Cladding material	*Zr-alloy*
Fuel material	*U-Zr-alloy*

The operating period for Sevmorput is 10,000 effective hours. This presumably means that the achievable burn-up is 56,000 MWd. According to Kuznesov, the operation period at full power for OK-900 and KTL-40 reactors is 460–500 days, which for Sevmorput yields burn-ups of 62,000 to 68,000 MWd.

Reaction Control

The power level of the reactor is controlled by regulating the amount of feed-water. This is possible due to the negative temperature coefficient of the reactor, which gives it its self-regulating property. The reactivity is controlled by a system of shim and scram rods. The scram system consists of four banks of scram rods, moving in sleeves in 16 fuel elements. The scram rods are provided with accelerating springs to ensure rapid injection of the rods in case of emergency. The shim system consists of five rod-banks. Further, to ensure reactor shutdown in case of emergency, an aqueous solution of cadmium nitrate may be injected into the coolant.

Safety System

The radial shield consists of consecutive steel-water layers. At the top the reactor tank is provided with a concrete shield.

Cooling Circuit

The reactor is provided with four cooling loops, each of which contains one steam generator and one circulation pump. Pressure in the primary system is controlled by a gas pressurizing system connected to the four pressurizers. This system is based on injection/discharge of gas. According to Kuznesov, coolant inlet temperature is 278°C and outlet temperature is 318°C. According to OKBM, inlet temperature is 78o C, outlet temperature 312°C and the pressure of the primary system is 130 bar. The temperature and 25 pressure of the steam leaving the steam generator is 290°C and 40 bar. There is an emergency cooling system, but in addition, the reactor can run by natural circulation at 25–30% full power.

Radioactivity Containment System

Ships using KLT-40 plants are provided with improved versions of the containment system, basically a pressure suppression system. With a release of steam inside the containment, pressure will increase. If the pressure rise exceeds about 0.5 bar, a valve will open and the air-steam mixture will be led down through a water pool whereby the steam is condensed and the pressure reduced.

Floating Nuclear Power Stations

Overview

Floating nuclear power stations are vessels projected by Rosatom that present self-contained, low-capacity, floating nuclear power plants. The stations are to be mass-built at shipbuilding facilities and then towed to the destination point in coastal waters near a city, a town or an industrial enterprise. Although the world's first floating nuclear power station was MH-1A, the Rosatom project represents the first mass production of that kind of vessel. By 2015, at least seven of the vessels are supposed to be built.

History

The project of Russian floating nuclear power stations started in early 2000s. In 2000, the Ministry for Atomic Energy of the Russian Federation (Rosatom) chose Severodvinsk in Arkhangelsk Oblast as the place for building the first floating power generating station. Sevmash was appointed as general contractor. Construction of the first floating nuclear power station, Akademik Lomonosov, started on 15 April 2007 at the Sevmash Submarine-Building Plant in Severodvinsk. However, in August 2008 construction works were transferred to the Baltic Shipyard in Saint Petersburg, which is responsible also for construction of the next vessels. Akademik Lomonosov was launched on 1 July 2010.

Technical Features

The floating nuclear power stations are non-self-propelled vessels with a length of 144.4 meters (474 ft), width of 30 meters (98 ft), height of 10 meters (33 ft), and draught of 5.6 meters (18 ft). The vessel has a displacement of 21,500 tons and a crew of 69 people.

Each vessel has two modified KLT-40 naval propulsion reactors together providing up to 70 MW of electricity or 300 MW of heat, enough for a city with a population of 200,000 people. It could also be modified as a desalination plant producing 240,000 cubic meters of fresh water a day. Another modification will be supplied by two ABV-6M reactors with a capacity of around 18 MWe (megawatts of electricity). Also, 325 MWe VBER-300 and 55 MWe RITM-200 reactors have been mentioned as potential reactors to use for the floating nuclear power station.

Fueling Features

The floating power stations need to be refueled every three years while saving up to 200,000 metric tons of coal and 100,000 tons of fuel oil a year. The reactors are supposed to have a lifespan of 40 years. Every 12 years, the whole plant will be towed home and overhauled at the wharf where it was constructed. The disposal of the nuclear waste will be organized by the manufacturer and supported by the infrastructure of the Russian nuclear industry. Thus, virtually no radiation traces are expected at the place where the power station produced its energy.

Developers of the Stations

The hull and sections of vessels to be built by the Baltic Shipyard in Saint Petersburg. Reactors are designed by OKBM Afrikantov and are assembled by Nizhniy Novgorod Research and Development Institute Atomenergoproekt (both part of Atomenergoprom). The reactor vessels are produced by Izhorskiye Zavody. Kaluga Turbine Plant supplies the turbo-generators.

Advantage of Location

Floating nuclear power stations are planned to be used mainly in the Russian Arctic. Five of these will be used by Gazprom for offshore oil and gas field development and for operations on the Kola and Yamal peninsulas. Other locations include Dudinka on the Taymyr Peninsula, Vilyuchinsk on the Kamchatka Peninsula and Pevek on the Chukchi Peninsula. In 2007, Rosatom signed an agreement with the Sakha Republic to build a floating plant for its northern parts, using smaller ABV reactors.

According to Rosatom, 15 countries, including China, Indonesia, Malaysia, Algeria, Namibia, Cape Verde and Argentina, have shown interest in hiring such a device.

Safety Issues

Environmental groups are concerned that floating plants will be more vulnerable to accidents and terrorism than land-based stations. They point to a history of naval and nuclear accidents in Russia and the former Soviet Union, including the Chernobyl disaster of 1986.

Russia does have 50 years of experience operating a fleet of nuclear powered icebreakers that are also used for scientific and Arctic tourism expeditions. The Russians have commented that a nuclear reactor that sinks, such as the similar reactor involved in the Kursk explosion, can be raised and probably put back into operation. At this time, it is not known what, if any, containment structure or associated missile shield will be built on the ship. The manufacturers believe that an airliner striking the ship would not destroy the reactor. According to MosNews, a Russian news outlet, there is no way an airliner striking the ship would destroy the reactor.

A 2004 book on Russian floating nuclear power stations was written by a number of authors, including "Vladimir Kuznetsov, formerly of the Russian Federal Inspectorate for Nuclear and Radiation Safety; Alexey Yablokov, a biologist, former environmental advisor to the Russian president and president of the Center for Russian Environmental Policy; Yevgeney Simonov, senior engineer at the Obninsk nuclear power plant; Vladimir Desyatov, an engineer who worked in nuclear submarine construction; and Alexander Nitikin." The book concludes that such stations are impossible to protect against terrorism, that safety cannot be guaranteed ("The only question is how serious the emergency and its consequences."), and that an accident would be uniquely difficult to contain. Besides that, the book argues that such stations would be uneconomic.

Military Marine Reactors in Russia

Overview

Russian military marine reactor systems may seem as confusing a subject as the submarines itself; several different notations and not very much open-source material.

VM-A Reactor System

The first generation of Russian submarines is usually understood to include the classes November, Hotel and Echo I and II. They were similar in size, both concerning the vessels themselves and the reactor systems, the latter limited to 70 MWt. A particular designation for the complete steam-generating system has not been registered for the first generation. The operational characteristics of the different vessels are similar, with slightly lower speed for the larger vessel Echo II than the others. The reactor systems are considered to be identical.

According to Gladkov, the choice of water-cooled and water-moderated reactor, i.e. reactor with high-purity water as moderator and coolant, marked the breakthrough for this technology in Russia. This reactor type has four interrelated circuits. The first circuit consists of the core which heats up the water in the reactor. In the second circuit, there is a steam turbine using steam with specific properties in its production of power. In order to get the steam with the required parameters in the second circuit, water of the primary circuit should have a temperature exceeding the temperature of the generated steam. In order to avoid boiling in the primary circuit, the pressure is increased considerably compared to normal atmospheric pressure. The equalizers, which regulate the pressure in the primary circuit system, are directly connected to the primary circuit. The third circuit is used to cool equipment in the steam-generating section.

An important part of a marine reactor, where weight is a fundamental consideration, is the biological shielding. Consisting of water, steel, lead, concrete and other materials, it protects against the penetration of neutrons and gamma radiation. This biological shielding is heavy: at one point it was approximately 50% of the plant weight.

Reactor Analysis

All first-generation vessels seem to have similar reactor systems, VM-A, and propulsion systems using two shafts of 17,500 HP each. The reactors of these submarines of the first generation – and presumably also of the later generations – have no connecting pipes, including tubes of large diameters, below the upper edge of the core. Thus it is not possible to drain part of the core by accident, as happened with the Lenin reactor in 1966. A reactor model – presumably of an early submarine reactor – at the town museum of Severodvinsk confirms this design feature, with both the inlet and the outlet pipes above the top of the core.

The construction of the reactor system was made on the basis of the properties expected of the vessel and then the necessary operational characteristics for the heat carrier. The vessel should be able to work down to depths of 200–300 meters, achieve an underwater speed of at least 20–25 knots and complete assignments lasting up to 60 days.

Figure 148: Design of First-Generation Submarine Reactor

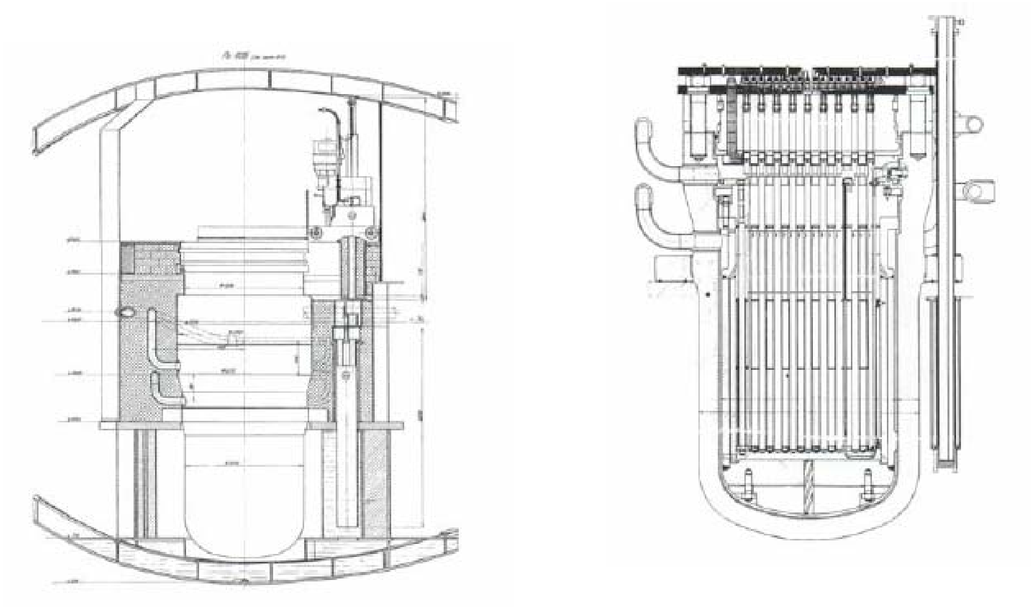


Table 15: Reactor and Coolant Characteristics, First PWR Submarine Reactor

Reactor power (MWt)	70
Water pressure in primary circuit (kg/cm^2)	200
Steam pressure (kg/cm^2)	36
Steam temperature (^{0}C)	355[6]

The first generation of Russian submarines operated in limited range from their home bases . Not until 1966, between February 2 and March 26, did the first Russian nuclear submarine cross the equator in the Atlantic; it then continued south of South America through the Drake Passage to the Pacific Ocean and joined the Russian Pacific Fleet.

Except for one vessel, a Yankee-class submarine, and a liquid metal reactor, all the reactors dumped in the Kara Sea were reactors of the first generation (November) that had experienced several accidents during the 1960s. We note that the Lenin reactor has been a useful tool for assessing the properties of Russian submarines. Therefore the basic fuel and reactor properties will be presented here and assessed in relation to calculations on the amounts of fuel and assessment of fuel geometry regarding the first-generation submarines as completed below.

Fuel Analysis

A minimum level of reliable information is essential for evaluating the safe and secure handling and protection of excessive stocks of naval fuel – which are often stored under highly unsatisfactory conditions. Among the most important is the enrichment level. The need for self-sufficiency, strong power-outputs and limited reactor sizes may require the use of highly enriched naval nuclear fuel.

However, for submarines of the first generation, the enrichment of the uranium of the fuel elements of the pressurized water reactors seems, in general, to have been about 20%, as suggested by Sivintsev in the IASAP report. This is consistent with the Russian prosecutor's article on the stolen HEU in 1994. The amount of U-235 is here said to be 283.3 grams out of overall uranium content of 1,448.9 grams, enriched to 19. 9% and corresponding to the fuel enrichment in the Russian naval training reactor in Paldiski, and data on earlier US submarines.

However, the overall figures presented as part of the IASAP report have been discussed and corrected by other Russian official sources. In the case of a reactor compartment with two reactors (without fuel) dumped near Novaya Zemlya in 1965, the fuel enrichment is presented as being 6%. This was K-3, the first Russian nuclear submarine, which got a new reactor compartment due to several design weaknesses. If this enrichment information is correct, the reactors of the first nuclear submarine, and possibly a few others, may have had a lower enrichment, more like that of the civilian icebreaker Lenin.

Table 16: Fuel data on Russian reactors dumped at Novaya Zemlya, as presented by Rubtsov et al. for the ISAP Source Term Working Group and in the Russian journal Nuclear Energy

Project no.										K-140
Plant no. – submarine	285		901		260		538	254		421
NATO class	November									Yankee
Thermal power (MWt)	70		70		70		70	70		90
Fuel com-position	U-Al alloy		U-Al alloy		U-Al alloy		U-Al Alloy	U-Al alloy		U-Al alloy
Enrichment (%)	9	21	20		20		20	6	5.45	21
Left (LB)/ right (RB)	RB	LB	RB	LB			?	RB	LB	LB
Amount of U-235 (kg)	50.4	55	30.6	40.7	40.7	40.7	50	46.3	45.3	116.3

From these data, it seems that the first generation of Russian submarine reactors could accommodate a flexible amount of material. The total amount of uranium in the plant number 254, left board reactor was, according to these data, initially 831.2 kg. At the opposite end we find right board reactor in plan number 901 with only 153 kg of uranium.

Several sources have used the average figures of 50 kg. U-235 enriched to 20% for fuel in the first generation of submarines. However, additional information indicates that this is insufficient for calculations regarding criticality, possible releases when considering a certain vessel or reactor. Take, for example, the impact assessment carried out by Norwegian authorities after the sinking of K-159. The Russian government then informed Norway that the submarine in its two reactors contained a total of 400 kg. of spent fuel. However, this was not specified further, which made it difficult to complete a realistic impact assessment. This information also underlined that submarine fuel, especially for this generation, is of less interest in the context of non-proliferation.

Concerning overall fuel density and geometry, very little open-source information has been noted, except from what has been discussed above. However, as part of the IAEA's IASAP effort, the configuration from Lenin was used in the source term modeling, indicating certain relevance for this circular tube design. The fuel elements used in early generations of Russian naval vessels may therefore also be of the rod cluster type. We know also that when the design of the first Russian submarine was worked out, each fuel assembly was constructed with "37, and not 23" fuel elements as originally planned.

The fuel material in the first generation of submarines has been suggested to be a U-Al alloy. This would have been a natural starting point at that time, in the mid-1950s, due to such attractive properties as good thermal conductivity and easy fabrication. Stainless steel was probably the preferred cladding material at that time.

The reactor was divided into two groups, the central part and the periphery. The central part should, without any more specification in the present sources, have 9 fuel groups, while the periphery should have 14. A similar division between an outer and an inner part of the reactor is seen in the Lenin reactor.

The number of fuel elements – or fuel assemblies in Russian terminology – has been claimed from 180 to 225 for the first generation of Russian military reactors. Together with the given amounts of U-235 above ranging from 30.6 to 55 kg. in one reactor, this yields a range of fissile material pr. fuel assembly of 0.136 to 0.306 kg. Similarly, the amount of uranium pr. Fuel assembly has a range of 0.680 to 4.618 kg.

According to the fuel data above for the Lenin reactor, overall fuel density in the Lenin reactor was 9.7 cm3, when using 881.74 cm3 as the volume of one fuel assembly. Using approximately the same fuel density for submarine fuel of first generation, 10 g/ cm3, we see that this equals a total volume pr. fuel assembly in the range of 68–461.8 cm3, the limits taken from the low and high ends of the possible amount of fuel in the reactor. When considering possible geometries giving this volume pr. fuel assembly based on the Lenin fuel geometry, we see that the volume and the fuel density might be reduced and still accommodate the required amount of fuel. This would confirm an assumption that the submarine reactor should be more compact than an icebreaker reactor: a core height of approximately 1 meter has been suggested.

However, assuming only small differences between the civilian and the military reactor, the latter should be able to accommodate many different fuel configurations.

Reactivity Control

Work on the VM-A started from scratch, and one of the early decisions was to use vertical rods for compensating excess reactivity. The control rods used in submarine reactors usually contain europium as the absorbing material. This results in very high activity of the control rods after the final reactor shutdown. In addition the Eu2O3 presumably used in the rods has a tendency to swell due to hydration, even if dispersed in a matrix.

The control rod system of the early submarines included an unusual design feature: apparently it was not possible or at least not easy to lift the lid of the reactor tank without lifting the control rods as well. This resulted in two criticality accidents with first-generation submarines – one on February 12, 1965, with K-11, a November-class submarine, and one on October 10, 1985, with K-431, an Echo-II-class submarine. Both accidents happened just after re-fueling, i.e. with new core in the reactors. In both cases, the lid had to be lifted slightly with the control rods connected to the lid, presumably due to incorrect alignment.

To avoid a criticality accident a beam was placed above the lid to prevent it from being lifted too high up. However, in one case the beam itself had been placed too high up, and in the other the beam had not been fixed properly. In both cases the lid and the control rods were lifted too far up and the reactors went critical. However, this was changed, and reactor design modifications on submarines of the second and third generations should not allow the control rods to be raised when the lid of the reactor vessel is lifted.

This element has been emphasized in another article also: “Electronic and mechanical circuits of higher reliability and with interlocking of failures were developed to greatly reduce the chance of improper lifting of the control members.”

The reason for this rather strange arrangement may be that it was difficult to connect the control rods to the drive mechanisms. Once they had been connected, it was tempting for the personnel to avoid a new connection process, even if this meant that the reactor lid had to be lifted a little.

VM-4/ VM-2 Reactor Systems

Overview

The second generation comprises in most cases Victor I-III, Yankee, Charlie 1 to 2 and Delta IIV. By this time, the Cold War and the positive experiences with nuclear propulsion had accelerated the construction of new models with increasing abilities of the submarines as flexible weapons platforms.

Reactor Analysis

All Delta submarines have the Yankee vessels as their construction base, and it is reasonable to expect similar propulsion systems in all these 77 submarines. Compared with the first generation, there are overall larger power levels and new propulsion systems, including the use of only one shaft. The use of one shaft and, at least in beginning, reduced displacement, served to improve propulsion by 30%. While the hull diameter increased, the second-generation vessel got more compact reactors than had been used in the first generation.

The most significant change regarding the propulsion system is the use of one reactor in the Charlie 1-class – a fundamental break with the redundancy found in the all earlier submarine classes, where there were two reactors. This change was possible due to a substantial reorganizing of the reactor system. The emphasis was put on lighter equipment, and, as dryly stated in one source, by giving the submarine the shape of a limo.

The reactor notations change, from VM-A to VM-4, and several different models are registered, possibly due to changes in configuration and continuous improvements. For example, one reactor core is able to accommodate longer and longer journeys, from 750 hours for the core type VMAB, to 2000 hours for the core type VM-1A used between 1961 and 1963 also in the first generation of submarines. However, the development continues to 2500 hours (VM-1 AM, in 1964 to 4000 hours (VM-2A), and, "at last, in 1969, core VM-2AG for 5000 hours". It seems as if there is a logical chain of letters in the different notations, starting with the letter "A" or "1" and continuing upwards as different configurations are established.

A new surface vessel, project 1941, with an atomic energy plant, was put into active service in the Navy in 1985; it had a steam-generating unit OK-900B that provided a shaft power of 2x23000 HP. The steam-generating unit of the surface vessel consisted of two self-contained sections, each with a water-cooled and water-moderated reactor with all the supporting systems and installations, and situated in the reactor compartment. The steam-turbine plant was divided into two self-contained parts located towards the stern and the bow directions from the steam generating unit, as in the icebreaker Lenin. Each main turbo-gear assembly, with a power of 70,000 HP, functioned along its own line of shafting.

Alongside with the main turbo-gear assemblies there was one standby boiler with a steam capacity of 115 tons per hour in each steam turbine compartment. Besides this vessel, this steam-generating system has been registered only in civilian icebreakers.

Fuel Analysis

In Table 15, data on the fuel of the Yankee vessel N-421 are presented; 116.3 kg of U-235 and 21% enrichment, which corresponds an overall amount of 553.8 kg. uranium. These figures represent a significant change compared to first generation of Russian submarines, at the same time the second generation submarines are said to have more compact reactors. These figures point towards an important breakthrough in the design and operation of naval reactors. In Sarkisov, enrichment is claimed to be around 40% for the second generation. This seems to be the case with the fuel in the third generation, as will be seen later, and this is not supported of other sources.

The number of assemblies in the second generation has been specified to approximately 280, but it must be kept in mind that the number of assemblies is linked with the submarine project in question. Watson and Sarkisov have suggested 225 to 270 per reactor, and for second-generation submarines about 250 cluster type fuel elements with 350 kg 20% enriched uranium, each element containing 54 fuel pins and each fuel pin containing 25.9 g 20% enriched uranium. This might be, however, an indication that the increased amount of fuel in reactors of the second generation has been achieved through a greater number of fuel assemblies in the reactor using the same level of enrichment, probably without increasing the size of the reactor. From the figures given for N421 and the number of fuel assemblies given in Aagaard, each fuel assembly then contains 1.97 kg uranium or 0.42 kg U-235.

Figure 149: Alternative Russian Submarine Fuel-Assembly Configurations

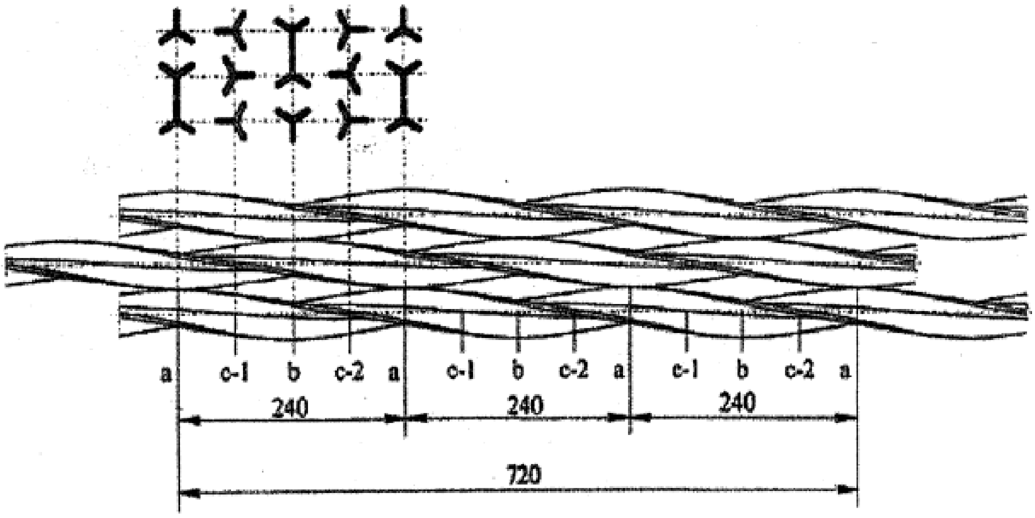
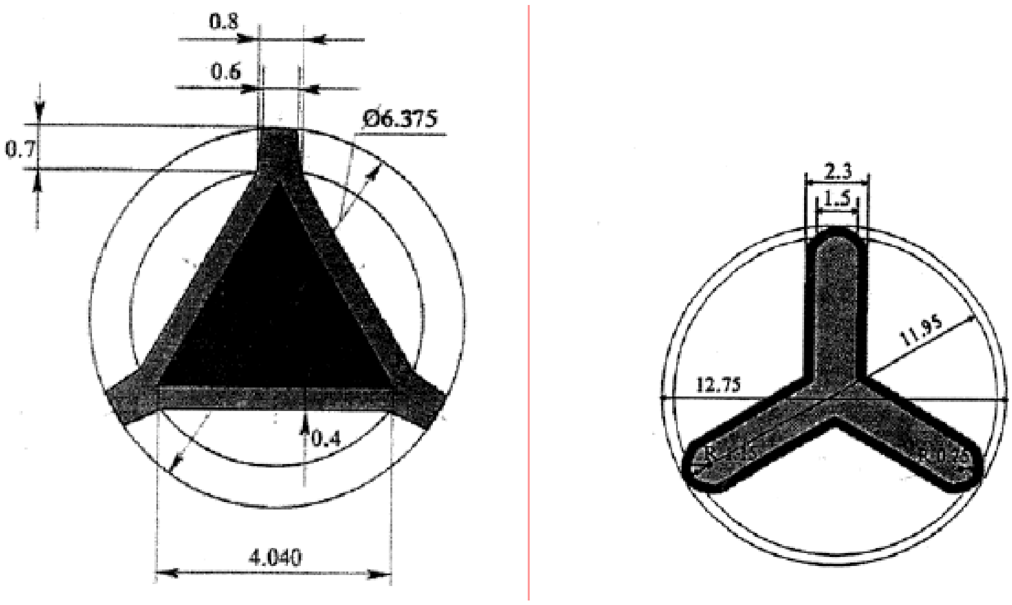


Figure 150: Alternative Russian Submarine Fuel-Element Geometry



In assessing the risk for spontaneous fission reactions in transportations casks, calculations have been performed at one occasion under the assumption that a second generation submarines core has about 250 cluster type fuel elements with 350 kg 20% enriched uranium, each element containing 54 fuel pins. Without specifying the basis for these speculations, this seems founded on a core configuration similar to that specified for the IASAP report, possibly using the confirmed data from the civilian icebreaker Sevmorput on number of assemblies.

Alternative Fuel Geometries

Due to the noise problems inherent in using circular fuel rods (and hence the increased turbulence in the reactor coolant), second- and later generations of submarines have presumably used other fuel types of different, less noisy, geometries. The United States today uses plate fuel, presumably also to reduce noise, but virtually no information has been published on possible fuel geometries in modern Russian military nuclear vessels.

When considering the need for less noise, for improved thermal properties and for accommodating more fuel material, we might assume a radical change in the submarine fuel geometry. The expected direction, considering the discussions above, would be a more compact design that would facilitate a higher power density, improved thermal characteristics and increased fuel mass in the reactor as a whole. If assuming circular fuel rods in the VM-A reactor type, the figures above, which has been said to be Russian submarine fuel design, might represent one version of “second generation” submarine fuel.

Reactivity Control

An unusual control system feature became apparent during an accident involving a Yankee-class submarine. Due to fire, the submarine was endangered and the reactors were shut down with the submarine at the sea surface. However, the control rods could not be fully inserted due to a short circuit in the electric system. To achieve full insertion, it was necessary to send two crewmembers into the reactor compartment to carry out a manual operation. One of the staff members perished during the operation.

Here the reason that the control rod could not be fully inserted was the short circuit of the electric system. But another reason for the manual system may possibly be that, as mentioned above, the control rods have a tendency to swell near the end of their lifetime, and at that time the electric drive mechanisms may not have power enough to drive the swollen control rods into the core. A third possibility is that if a submarine sinks it may not end up in its normal position. A significant deviation from that position may mean that the control rods are moved out of the core, and manual insertion could ensure that this does not happen.

A third feature heavily discussed, due to later accidents, is the mechanism for locking the control rods in case the submarine rolls over and remains in an upside-down position. During the investigations of possible accident scenarios for the raising the submarine Kursk in 2001, it was never confirmed that such a mechanism was in place to prevent the control rods from falling out of the reactor during the lifting operation.

According to Gladkov, “the redistribution of the regulating members made it possible to reduce the non-uniformity of energy liberation in the core by a factor of 1.2 – 1.3.”. As a result of further improvements, the core-life was improved more than threefold, and absorbers distributed heterogeneously in the fuel channels.

OK 650/ KN-3 Reactor Systems

Overview

The third generation was constructed due to the growing concern for Soviet capabilities of retaliation in case of a Western nuclear attack. Most of these vessels are still in active service, except those dismantled as part of the START treaties, and are therefore not the subject of the same broad international interest as the older vessels for cooperation on the dismantling of the vessels. A special feature of the Typhoon class is that it is provided with two parallel pressure hulls, each with a reactor and a shaft, with the missile launching tubes placed between the two hulls. The Sierra and Akula classes were provided with titanium hulls, with considerable effect on displacement.

Reactor Analysis

From 1952, the starting point of the first submarine project, until 40 years later with the construction of the third generation of Russian submarines, the development of the reactor systems involved more than a doubling of the energy density in the reactor. The increase in nominal power is apparent: from 90 MWt to 190 MWt in submarines, while a separate reactor system for the surface vessels, KN-3, seems to have developed. The relevant submarine classes are Typhoon, Sierra, Akula and Oscar, in addition to Mike. Extremely limited open-source information is available concerning third-generation reactor systems. However, OK-650 seems to be the reactor system in the vessels with titanium hull, hence only one reactor, four steam generators and one shaft with a little less than 50,000 HP. In the Typhoon and Oscar classes, two similar reactor systems were installed, however, using two shafts of 50,000 HP each.

Fuel Analysis

The increased power levels should be reflected in the amount of fissile material in the reactor. According to Sarkisov, for the subsequent generations, enrichment was later increased to around 40%. A similar figure, 36%, for third-generation submarine fuel has been put forward to a US Senate Committee. Also 21–45% has been proposed earlier Bukharin. This increase in enrichment should provide space for additional fissile material, and the total amount of U-235 has been claimed to be as high as 200 kg. If correct, this is in line with the amount in modern US submarines using 90% enriched fuel, however, with a lower enrichment. Komsomolets was of the Russian side said to have “modestly enriched fuel”, however no specification of the actual level of enrichment has ever been given in the literature.

Compared with the low enrichment levels in the first generation, ‘modest’ might very well be in the area around 20% or more.

Another discussion concerns the fuel material. While the starting point in 1958 was presumably U-Al alloy with stainless steel cladding as seen above, at some point the disadvantages of this technology compared to other fuel and cladding materials would have become obvious. As seen in the civilian program, the change from ceramic fuel to metal fuel was completed with the OK- 900, however, then using U-Zr in Zr-cladding. This development continued into the third generation of civilian marine reactors, building the KLT-40.

RM-1 and VM- 40 A Reactor Systems

Overview

During the construction of the first November-class submarine, Russia also initiated a program in 1954 for building liquid-metal cooled submarine propulsion systems. As mentioned above, liquid metal cooled submarine reactors have been used by the Russian Navy. The technology was developed at the Institute of Physics and Power Engineering (IPPE) in Obninsk and used in two submarine classes: Project 645, a class in itself, and the Alfa class.

Using liquid metal coolant was considered to have several advantages. It is more compact than pressurized water reactors, since it needs no moderator. No heavy pressure vessel is needed; it operates at higher temperatures and has therefore a higher thermal efficiency. The use of an intermediate reactor makes xenon poisoning less important. Refueling is faster, since the core is removed in a single operation. However, there are disadvantages: the melting point of the coolant is above room temperature, so the primary system must be kept heated at all times for the coolant to remain liquid. If not, the coolant will solidify and the cooling will be interrupted. The liquid metal coolant will gradually oxidize and the oxides must be removed regularly, to avoid blockage of the coolant flow through the core.

The LMC reactor was first used in 1962 in a special version of a November-class submarine (Project 645, K-27), which used two RM-1 reactors with capacity of 73 MWt each. The K-27 was re-fueled in 1967. However, it suffered a loss-of-coolant accident in 1968 in port when it was ordered to participate in a naval exercise at a time when the coolant needed to be cleaned of oxide impurities. During the exercise, these impurities blocked the entrance to the core of the port-side reactor and caused a LOCA, after which the submarine was laid up. In 1981 the free volume in the reactor and in the reactor compartment was filled with a conserving material and the submarine was sunk off Novaya Zemlya at 50 m.

The first Alfa-class submarine (K-377 or No. 900) became operational in 1970, but suffered a loss-of-coolant accident in 1972 when a leak developed between the secondary water-steam circuit and the primary liquid metal circuit, exposing the primary circuit to a pressure of 70 atm. As the pressure relief system failed to function, the high pressure caused a rupture of the piping of the primary circuit. Two tons of liquid metal coolant flowed out into the reactor compartment, where it solidified. Leakage of the coolant of the reactor tank was prevented by closing the isolation valves. The coolant in the tank later solidified.

At the time of the accident, the reactor had been in operation for only 10% of its lifetime. It was not possible to re-melt the coolant and remove the fuel. In 1986, the reactor compartment was cut out of the submarine, the reactor room was filled with furfural, the upper deck above the reactor was covered with bitumen and the compartment was prepared as a three-compartment unit, now in floating storage at Saida Bay of the Northern Fleet. It is not the intention to de-fuel this reactor. The first 705K Alfa submarine (No. 105) operated from 1977 to 1982, when it suffered a LOCA and leakage of coolant into the reactor compartment. The reactor compartment with fuel in the reactor and the coolant frozen was cut out, and is now in floating storage.

A new reactor compartment was inserted into the submarine (still No. 105), which was put in operation again from 1992 to 1996. The Alfa submarines were withdrawn from active service during the 1990s and were never re-fueled, since at the time of decommissioning maximum fuel burn-up had not been reached. Current burn-up of the reactor fuel varies between 10 and 100% of the design value.

The Alfa submarines were based at Gremikha on the Kola Peninsula. Fueling and de-fueling operations were performed by loading and unloading the whole core, including the control rods, the reflector (for Project 705K) and the upper biological shield, as one unit. Upon de-fueling, this unit was placed in a steel tank containing non-radioactive Pb-Bi coolant at 150–160o C. The steel tank was later transferred to a concrete well, to be cooled by natural circulation of air. As the decay heat gradually decreased, the liquid metal solidified. At present the decay heat is about 2 kW and the coolant is frozen. This form of storage was not intended for long-term use; it might be, in case of extended storage, that water will penetrate through the steel tank and into the core through porosity formed during the solidification of the Pb-Bi coolant. This might make the core critical. Six unloaded cores are currently stored in such wells in Gremikha. Three of the cores remain in the submarines.

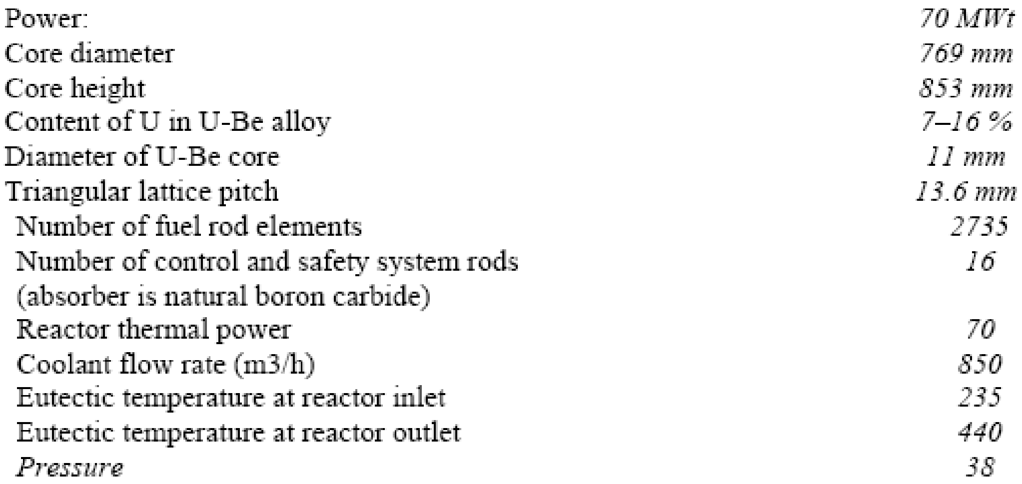
Two of the 705 Alfa submarines (No. 905, in operation from 1978 to 1986, and No. 915, in operation 1981–89) were de-fueled in 1989 and 1990. Two of the 705K Alfa submarines (No. 106, in operation 1978–90 with core burn-up of 96%, and No. 107, in operation 1981–90 with core burn-up of 87%) were de-fueled in 1991 and 1992. These four core units are stored in the storage facility at Gremikha. This facility has room for eight core units, of which six are in use, since it contains also the two cores from the de-fueling of Project 645. This means that, while the facility can take the core unit from No. 910 (burn-up 80%) and the second core unit of No. 105 (burn-up 15%), there is no room for the first core unit of No. 105 (burn-up 50%). Since the coolant is frozen in these three reactors, it will have to be re-melted before de-fueling can be performed.

The de-fueling of submarine No. 910 will present a special problem, since the top of the reactor has become contaminated with Eu-152 and Eu-154. This occurred when water condensate penetrated the control-rod gas system, resulting in boiling of the water and ejection of europium from the control rods into the drive mechanisms of the rods.

Reactor Analysis

Two land prototypes of this type of reactor plant have been made, one at Obninsk (27/ VT) and one at Sosnovy Bor (KM-1) near Saint Petersburg. Work on the 27/ VT facility started, as mentioned above, in 1953, the year after the beginning of the PWR submarine project. Technical specifications of the ground prototype 27/ VT facility are given in the table below. Several problems were noted concerning the operation of this reactor, such as coolant freezing problems in sections of the lead-bismuth circuits and leaks. However, work on a submarine reactor was initiated in 1957 at the Malakit Design Bureau (SKB-143) in Leningrad.

Table 17: Technical Data for the VT/ 27 Test Reactor



Power:	70 MWt
Core diameter	769 mm
Core height	853 mm
Content of U in U-Be alloy	7–16 %
Diameter of U-Be core	11 mm
Triangular lattice pitch	13.6 mm
Number of fuel rod elements	2735
Number of control and safety system rods (absorber is natural boron carbide)	16
Reactor thermal power	70
Coolant flow rate (m3/h)	850
Eutectic temperature at reactor inlet	235
Eutectic temperature at reactor outlet	440
Pressure	38

KM-1 was a prototype for the Alfa-class submarine with OK-550 steam supply system. The operation of the KM-1 started in 1978 and lasted until 1987. Then the core was unloaded and stored in the same type of storage block as at Gremikha. The experience gained with KM-1 is said to be used to solve the unloading problems at Gremikha.

The main propulsion plant of the project 645 submarine consisted of a double reactor steam generating unit with two RM-1 reactors and heat power of 2 x 73.5 MWt and a two-shaft steam turbine plant. Coolant pressure in reactor was 20 kg/cm2. The generated steam had the following parameters: pressure 36 kg/cm2, temperature 355^{0}C. Some overall technical data on the RM-1 are given in IASAP; among the dimensions – core diameter approx. 800 mm and core diameter 780 mm. The radial reflector consisted of "from the core surface on outward, 10 mm thick ss, 65 mm BeO, and 8 mm thick SS".

Two different models of the LMC-type reactor were developed for the Alfa-class submarines, VM-40 A reactor with two separate steam loops and circulating pumps, and the OK-550 steam system with branched first-loop lines and triple circulating loops and pumps. VM-40 A was used in the three Alfa-class submarines (Project 705). They had two primary loops and a fixed beryllium reflector. The remaining four submarines (Project 705K) were each provided with one OK-550 reactor with three primary loops and a beryllium reflector that was fixed to the core and removed together with the fuel. For both types, the power level was 155 MWt. These reactors were built by EDO "Gidropress" and OKBM under supervision of IPPE. This reactor type was run on intermediate energy neutrons. The core consisted of the fuel and the coolant, and was, as for RM-1, surrounded by a radial reflector of beryllium.

The core had a diameter of 85 cm and a height of 77 cm. The fuel pins had a diameter of 1.1 cm and were arranged in a triangular lattice with a pitch of 1.36 cm. The number of fuel rods was 2,735 and the number of control rods 16.

Fuel Analysis

The fuel for both the RM-1 and the VM-40A m had the form of rods containing an intermetallic compound of 90% enriched uranium and beryllium (U-Be13), dispersed in a beryllium matrix. The total amount of 235U in the RM-1 core was 90 kg at an enrichment of 90%. The fuel rod pellets were approximately 10 mm in diameter. The pellets were covered with a 0.1 mm thick layer of MG and clad in SS with 0.5 mm thickness, as a result the fuel rods were 11 mm outside diameter. These were subsequently arranged in a 13 mm triangular pitch as shown in the IASAP-report. In total, there were approximately 3000 fuel rods in each LMR core. For the larger VM-40A m reactor, the total amount of 235U is about 200 kg. For both reactor types, the coolant was a eutectic lead-bismuth alloy (44.5 wt% lead, 55.5 wt% bismuth) with a fairly low melting point (around 125°C).

Reactivity Control

The emergency protection rods (EPR), control rods (CCR) and emergency cooling tubes (ECT) passed through a special shield plug on the top of the core for the RM-1 reactor. The ten CCRs were approx. 17 mm in inside diameter and arranged with one at the center, three evenly spaced at a radius of 97.5 mm and six spaced within radii of 97.5 and 292.5 mm. Both EPRs and CCRs were made of europium hexaboride (EuB6). The content of europium has resulted in very high activity of the control rods. As described in IASAP, the 24 ECTs were 70 mm inside and 80 mm outside diameter and evenly spaced on a radius of 641.5 mm. total amount of U-235 in the RM-1 core was 90 kg at an enrichment of 90%. The fuel rod pellets were approximately 10 mm in diameter.

According to IASAP, the pellets were covered with a 0.1 mm thick layer of MG and clad in SS with 0.5 mm thickness, yielding an outside diameter of 11 mm. These were subsequently arranged in a 13 mm triangular pitch, as shown in the IASAP report. In total, there were approximately 3,000 fuel rods in each LMR core. For the larger VM-40A m reactor, the total amount of U-235 was about 200 kg. For both reactor types, the coolant was a eutectic lead bismuth alloy (44.5 wt% lead, 55.5 wt% bismuth) with a fairly low melting point (around 125° C).

Future of Russian Marine Nuclear Systems

Industry Forecast

In the development of Russian marine reactor systems, two specific avenues have been pursued: (1) civilian reactor systems with conventional designs and materials, (2) military reactor systems, much less transparent, but with more advanced technologies and materials. The development of military naval reactors soon branched into two separate tracks: water-cooled and water-moderated reactors vs. liquid-metal-cooled reactors (without moderations using intermediate neutrons).

From the very beginning, the main feature of both civilian and the military systems was the use of two identical reactors in each vessel – in contrast to US nuclear submarines, where one reactor was considered sufficient. Given the limited operation of the first generation of Russian submarines outside Russian coastal waters, the use of two reactors seems to be a measure of deliberate operational redundancy. This is a logical consequence when one recalls the many failures experienced in the first decades of submarine reactor operation, as also stated in Russian scientific sources. This in turn might have been a consequence of the lack of testing of these early versions of the military reactors.

Since the Kurchatov Institute has played an important role in the design of pressurized water reactors for both naval and icebreaking vessels, it seems reasonable to assume that the general designs were probably quite similar. On this basis the assumption was made that the design of fuel assemblies in the first generation of submarine reactors was similar in naval vessels and in icebreakers: however, the validity of this is hard to judge. However, the overall tendencies for the civilian program should apply to the military realm as well, even if there are distinct differences between important elements in the civilian and military technology.

Civilian Reactors

The first civilian marine propulsion system installed in the icebreaker Lenin was based on low enriched ceramic fuel, uranium dioxide, in Zr-cladding. Apparently, there was a need to improve the cladding, as several other types of cladding were introduced as part of the second fuel load for the reactor, at least stainless steel and Zr-Nb alloy. After the accident with Lenin in 1967, important developments were identified, and today the icebreakers use a uranium-zirconium alloy as fuel in Zr-cladding. The precise amount of fuel is not known except for the freighter Sevmorput, where the safety report specifies 150.7 kg. enriched to 90% as one fuel load. The changes can be summarized as follows:

- Increased amount of fuel in the core (from 80 kg to 150.7 kg. U-235) and increased enrichment levels (from 5% to 90%);

- Increased number of fuel pins pr. assembly (36 to 54) and increased number of assemblies in the core (219 to 241);

- Improved heat-transfer characteristics (from ceramic – UO-2 – to metal fuel – U-Zr alloy);

In total, this accounts for improved output with regard to reactor power, 90 to 171 MWt, and optimization of the operational characteristics, as the number of reactors was reduced from two to one, thereby removing the redundancy. As seen, safety provisions were also dramatically increased from OK-150 to OK-900.

Military Reactors

Russia started developing submarine reactors in 1952, about the same time as the civilian marine reactor program was initiated. For the PWR platform, an alumina-based metal fuel was developed. The use of two reactors compensated for the low-enriched uranium used in the fuel.

Changes here can be summarized in the same way as for the civilian sphere:

- Increased amount of fuel in the core (from 30 kg to possibly 200 kg. U-235) and increased enrichment levels (6% to 45%);

- Increased number of fuel pins pr. assembly and increased number of assemblies in the core (180–280 – presumably even higher for third-generation submarines);

- Different fuel compositions and cladding materials (U-Al with stainless steel cladding, unknown matrix with zirconium cladding)

As the composition and geometry of the submarine fuel are rarely made public, it is hard to evaluate whether and how the heat-transfer characteristics of submarine fuel have been improved. It is reasonable to assume, however, that considerable scientific effort has been devoted to this. The strategies have possibly been to improve heat production capabilities by increasing the amount of metal and the heat-producing area in the fuel matrix and . The latter implies employing other fuel shapes than rods, for example plate fuel as used in US submarines or advanced geometries based on the rod shape, e.g. hollow pins, extremely small pins, use of fins, etc.

A pertinent question when considering enrichment levels in Russian submarines is why higher levels have not been used in order to boost the operational properties of the submarines – improving overall economy by reducing re-fueling operations to zero, as the US Navy has achieved, and reducing the time the submarine is not operational at sea. The explanation might lie in the inherent inertia in the Russian military-industrial complex and the absence of financial constraints in military spending until fairly recently. Under conditions of the same societal laws as in the West, one might expect to see future Russian submarines consisting of one single reactor with highly enriched fuel.

Regarding the reactor systems, leaks in the reactor circuits seem to have been a major problem, and one that has limited the operation of submarines.

P. Case Study: China's Nuclear Submarine Force

In recent years, China has conducted many sea trials of its new nuclear-powered submarines armed with longer-range ballistic missiles. The sea trials have been a part of a broader push by China to check US naval power in the western Pacific with a more modern fleet of nuclear-powered ballistic missile and attack submarines.

China's first new nuclear ballistic missile submarines, designated the Type 094 SSBN, began operating in 2008.

It is be equipped with the JL-2 sea-launched ballistic missile with range of 8,000 kilometers (5,000 miles), a big gain over China's only other ballistic missile submarine.

The XIA SSBN, a 24-year-old nuclear powered vessel, is armed with the JL-1 missile, which has a range of only 1,7770 kilometers (1,000 miles).

Even at that shorter range, the XIA can target US military facilities in the region from launch points inside traditional Chinese operating areas.

China is likely to build five of the new ballistic missile submarines in order to provide more redundancy and capacity for a near-continuous at-sea SSBN presence.

China is also concluding sea trials of a new Type 093 nuclear powered attack submarine that is expected to be quieter and armed with more advanced weaponry than its predecessor, the HAN SSN class submarines.

It will have anti-ship cruise missiles and more modern torpedoes than the HAN.

China has built these features into the Type 093 in an effort to improve the PLA(N)'s (Peoples Liberation Army Navy) to conduct anti-surface warfare at greater ranges from the Chinese coast than its diesel submarine force offers.

China's navy currently has about 55 attacks submarines, most of them diesel electric.

It is a smaller but more technologically advanced force than the one China had in the 1980s.

Each of the attack submarines are armed with anti-ship cruise missiles and designed to be quiet enough to operate in the open ocean.

A key focus of China's maritime strategy is to keep outside powers beyond striking range in a Taiwan scenario.

Much of China's military modernization effort of the past five years, and particularly the modernization of the Chinese Navy, has been designed to improve China's anti-carrier capability.

China envisions an attack on a carrier strike group as incorporating submarine-launched ASCM (anti-ship cruise missile) strikes and ASBM (anti-ship ballistic missile) strikes.

China is equipping theater ballistic missiles with maneuvering reentry vehicles with radar and infrared seekers to attack a ship at sea.

China has also focused on submarines because its surface warfare ships are harder to defend against air or submarine attack.

China's maritime strategy is also aimed at protecting a growing sea trade crucial to its economy.

In order to protect oil and other trade routes, the PLA (N) is beginning to develop the foundations of a naval capability that can defend sea lines of communications.

Q. Case Study: India's Nuclear Navy

Introduction

Many decades ago, Chairman Mao Zedong reportedly told his naval commanders that they "must build a nuclear submarine in China even if it took ten thousand years". Indian leaders, not generally known for such earthy expressions of national political will, would have readily agreed with Mao.

India launched its first indigenously built nuclear-powered submarine at the end of July 2009. It is not difficult to see the parallel with China. The nuclear submarine, now christened INS Arihant, had been in the works for nearly three decades. Widely known as the Advanced Technology Vessel (ATV), the project suffered repeated technological, engineering and organizational setbacks. It is persistent political support and the navy's dogged pursuit that has now brought the project to its culmination. To be sure, there is a considerable distance to go before INS Arihant is declared operational.

However, there is no denying that unveiling the vessel marks a breakthrough for India on naval nuclear propulsion. It also sets the stage for India's eventual deployment of some nuclear weapons at sea. Until now, only the five nuclear weapon states have operational nuclear submarines. While the achievement is significant, India is fully aware that it is well behind China in the building of conventional submarines, developing marine nuclear reactors and mastering the technology of submarine-launched nuclear tipped ballistic missiles (SLBMs).

Meanwhile, China itself is decades behind the United States and Russia in operating a credible nuclear navy. This paper reviews the recent significant naval nuclear developments in India, puts them in a comparative perspective in relation to China, and speculates on their future evolution. The paper also offers a preliminary assessment of how India's emerging maritime nuclear capabilities might impact the Sino-Indian naval dynamic as well as the nuclear calculus of other great powers, especially the United States.

Maritime Nuclear Development in India

Not too soon after its first atomic test, India embarked on the development of three essential technologies needed for a nuclear submarine program – a marine reactor that can be integrated with a submarine platform, nuclear-tipped missiles that can be launched from underwater, and the operational skills to run a nuclear submarine. The program to build the platform, called the ATV, has been underway since the mid-1970s. The construction of a prototype has already taken more than three decades, highlighting the gap between India's nuclear strategic ambition and its industrial and technological capabilities. The difficult challenge in developing a nuclear reactor for the submarine lies in its small size. This involves a lot more than simply scaling down the design of a traditional land-based reactor. Producing a small reactor involves sophisticated engineering skills.

Although India's Department of Atomic Energy has been building power and research reactors since the 1960s, designing and building the reactor for the ATV was an entirely different ball game. For one, the design of the reactor must cope with very high power densities in a limited space. Reducing the size of the reactor core requires that it be run on enriched uranium. The higher the level of enrichment, the smaller the potential size. Unlike in the traditional reactors, the fuel for naval reactors is not made of uranium oxide, but a uranium-zirconium metal alloy. The design aims at a long life for the reactor without any need for a fuel recharge.

The long core life produces its own problems, when the fuel itself and the various materials at the heart of the reactor suffer radiation damage and become vulnerable to cracks. Accidents in naval nuclear reactors tend to be higher than in normal reactors. Therefore, building a small, mobile, safe and easy to use nuclear reactor has tested even the advanced countries. That India is about to launch the ATV implies that the Department of Atomic Energy (DAE) and its partners have overcome many of the troubles of designing the reactor and have become confident about their designs. There is no doubt that India's mastery of naval nuclear propulsion is some distance away. However, it is likely to improve as it tests and eventually operates the ATV.

Thanks to the extraordinary secrecy surrounding the project, there has been little official information available on the program. As it inched towards completion in recent years, the veil over the ATV program has been lifted a little. In early 2009, the Indian Defense Minister A. K. Antony announced that most bottlenecks to the ATV project have been overcome and that the vessel would be launched this year. According to a variety of unconfirmed reports, the Indian navy has the authorization to build at least five nuclear submarines based on the ATV.12 Based on media reports, the ATV will be powered by a 100 MW reactor, built by the DAE in collaboration with the Defense Research and Development Organization and the navy.

Reports claim that the ATV could be 124 meters long and have a displacement of 4,000 tons. The test bed reactor, apparently being built at the Kalpakkam Indira Gandhi Centre for Atomic Research in the DAE complex at Kalpakkam outside Chennai, went critical in 2004 and since then has been undergoing tests on mating it with the hull of the ATV. The enriched uranium fuel for the reactor has apparently been produced at the Rare Materials Project at Ratnahalli near Mysore in Karnataka. The delay in the supply of enriched uranium has reportedly been one of the many reasons that caused such long delays in the launch of the first ATV, now christened INS Arihant. The cost of the program until mid-2009 has been estimated at around US$3 billion. For India, it was probably never a question of cost but of mastering an important strategic technology. For New Delhi, it was also about the determination to catch up with China on the development of a sea-based deterrent.

While India has every reason to be pleased at the progress of the ATV project, there will be special satisfaction at the kind of organizational and technological innovations that facilitated forward movement. The ATV project not only brought together a number of governmental agencies, but also the private sector. Larsen & Toubro, which has emerged as a major player in India's domestic private sector shipbuilding industry, has been associated with the Indian nuclear and space programs, and appears to have contributed significantly to the success of the ATV.

While much of the work on ATV has been indigenous, it is quite clear that cooperation with Russia has played a rather critical role. The Russian decision to lease a Charlie I Class (named INS Chakra by India) nuclear submarine to India during 1988-91 was an important catalyst in the evolution of the ATV. Russian crew reportedly operated the reactor and gave the Indian naval and scientific personnel valuable training in the management of a nuclear submarine.

Besides the training function, the Chakra became a valuable test bed for developing indigenous capabilities in the design, maintenance and operation of naval reactors. Cooperation with Russia has been revived with the Indian decision to lease one or two Akula II class submarines from Russia. The deal first announced in the early years of this decade involved Indian financing of the building of the boats to be leased.

According to one report, the total cost of building two Akula class submarines for India and the training of the crew was to cost up to US$2 billion. Since then there were many difficulties in implementing the deal, and the vessel that was to be sent out to India had a major accident in November 2008.

Amidst a general political controversy in New Delhi over the reliability of Russia as an arms supplier, Moscow and Delhi have now agreed to speed up the implementation of the deal, that is reported to have been scaled down to the lease of just one boat. Displacing 12,000 tons, the Akula II class submarine is believed to be quieter and deadlier than any other nuclear attack submarine in the Russian fleet. Unlike the previous time, after the initial training in Russia, the Indian crew is expected to fully man the operations of the leased submarine. Until now the external cooperation on the nuclear submarine project has been limited to Russia. There are indications that India is also exploring the possibilities of such cooperation with France, which is building Scorpene advanced diesel submarines in India.

The third element of India's maritime nuclear project is the development of an appropriate nuclear tipped missile system for the ATV and its eventual nuclear submarine fleet. Some analysts suggest that India might originally have conceived the nuclear submarine as an attack boat rather than a platform to carry nuclear armed missiles. All reports now indicate that India is developing two naval nuclear systems for its sea-based deterrent.

One is the Dhanush, a ship-based surface to surface missile. A variant of the Indian Prithvi missile, the Dhanush, with its short range of 300 kilometers may not be of strategic value to the navy. It later has turned out that the Dhanush was a test bed for the development of other technologies, rather than the vehicle for the sea-borne deterrent. India's current hopes for underwater delivery of nuclear weapons rest on the Sagarika system that is also often referred to as the K-15 missile. In the media reports there has been considerable confusion on the name and the nature of the technology. While some have called it a ballistic missile, others have referred to it as a cruise missile. But the successful underwater test of a ballistic missile in 2008, with an estimated range of about 700 kilometers seemed to give the basic test bed for a long sought secure deterrent capability for India.

India is also reported to be developing a cruise missile, called Nirbhay, similar to the United States' Tomahawk SLCM. According to reports, Nirbhay might be capable of delivering nuclear warheads up to a range of 1,000 kilometers from a variety of platforms including submarines.

Sino-Indian Nuclear Dynamic

While the launch of the ATV marks India's arrival on the nuclear maritime domain, its sea-borne nuclear capability is a long distance away from becoming a credible force. As a prototype, the ATV itself needs many years of sea trials which will in turn allow the Indian naval and nuclear establishments to tweak the design and make it an effective delivery system for underwater nuclear weapons. The launch certainly stirs up nuclear nationalism, and mobilizes stronger political and financial support in favor of catching up with the nuclear naval capacities of Beijing. Meanwhile, it must be borne in mind that China itself is in the process of closing its long gap with the United States on underwater technologies. India will have to overcome many of the same difficulties China had to in the last few decades on the path to a credible underwater deterrent.

Given its international isolation immediately after the proclamation of the People's Republic, its conflict with the United States in the 1950s, the overwhelming superiority of the United States and Japanese navies in the Western pacific, and the variety of maritime territorial disputes with its neighbors in East Asia and Southeast Asia, China has always emphasized the importance of submarines. Even in the current phase of its naval modernization, building advanced conventional submarines in large numbers has remained an important priority for China.

As it declared itself a nuclear weapon power after the first test in 1964, China has given considerable emphasis to building both nuclear attack submarines (the SSNs) as well as ballistic missile carrying nuclear powered delivery systems (the SSBNs). The Chinese political leaders, naval commanders and the nuclear scientific establishment fully understood the significance of the twin development of SSNs and SSBNs. From 1965 to 1968, the People's Liberation Army Navy (PLAN) focused on the development of the experimental Type-091 Han class SSN. Although the turbulence of the Cultural Revolution had its impact on the program, the first Han class vessel was launched at the end of 1971. The same design was used to develop a separate SSBN (Type 092) of the Xia class. It is believed that not more than two operational Xia class SSBNs were built, given the serious difficulties with developing a safe and reliable reactor. The first of them was deployed in the early 1980s. On 15 October 1985, China launched its JL-1 submarine launched missile from the Xia class platform, but it was considered a failure.

With the Xia class falling below expectations, the Chinese intensified their efforts during the 1980s and 1990s to develop a credible SSBN equipped with a powerful SLBM. China was fortunate to have a strong naval commander, Admiral Liu Huaqing, who was determined to build a powerful nuclear force at sea. Admiral Liu, who is often called China's Mahan, was the head of the PLAN during 1992-98 and the powerful Vice Chairman of the Central Military Commission (1989-97). During his stewardship, Liu succeeded in laying the foundation for a new generation of the SSN as well as the SSBN. The Chinese political leaders fully backed this effort.

As a result of these efforts, China launched its second generation SSN called the Shang class, also called Type 093. Two Shang class vessels were launched in 2002 and 2003. The first pictures of this submarine came into public view in 2008. Faster, stealthier and exponentially lethal, the Shang class submarines have the capability to operate in the Indian Ocean. If the Shang class submarines give China a significantly improved capability to attack other naval vessels, it is the Jin class (Type 094) SSBNs that promise to showcase China's rise as a nuclear weapon power.

Western analysts assess that China may build five or six Jin class submarines in the coming years. Each of these will be equipped with 12 powerful long-range SLBMs. The JL-2 missiles have an estimated range of at least 7,200 kilometers and its warheads are believed to have sophisticated penetration aids. When inducting these into service, China would more than match Britain and France in terms of the technological sophistication of its nuclear arsenal and its credibility as a survivable second strike force.

The Indian navy has been closely monitoring the extraordinary scale and scope of the modernization of China's naval nuclear capabilities and their increased operational patrols. India is conscious of the huge nuclear gap that separates it from China. But after the launching of the indigenous nuclear submarine INS Arihant in July 2009 and the acquisition of the Russian Akula II class submarine, as well as INS Chakra by the end of 2009, the Indian maritime strategic community will be confident of its ambitious goal to narrow the nuclear gap with China. As Beijing and New Delhi take their nuclear weapons to sea, they begin to impact on the strategic calculus of the other great powers. The recent advances in the modernization of China's naval forces have begun to ring alarm bells in the United States.

Many United States analysts have begun to question the wisdom of America's naval force reductions at a time when China is improving its underwater war-fighting capabilities. Some argue that China might be able, in the not too distant future, to constrict the current absolute freedom of movement that the United States navy enjoys in the Western Pacific. In any case, the somewhat benign and condescending approach to Chinese naval and nuclear capabilities may be coming to an end in Washington.

The lower level of India's emerging maritime nuclear capabilities is clearly not seen as a threat to the United States or the West. To be sure, those who view India's nuclear arsenal from the perspective of non-proliferation will have anxieties about its emerging maritime dimension. In terms of official policy, the United States civil nuclear initiative towards India, unveiled by George W. Bush in July 2005, is premised on two very different propositions. One is that India does not pose a nuclear or political threat to the United States. The other is that while the United States will not help advance India's military nuclear capabilities, it will facilitate civilian nuclear cooperation with India and step up conventional defense cooperation.

Despite many reservations among the Democrats, the Obama Administration has chosen to persist with the Bush logic of the civilian nuclear deal. What we do not know at this stage, is whether the rapid expansion of the Chinese nuclear capability will eventually result in United States assistance towards India's maritime nuclear project. Although the current global non-proliferation regime bars the United States from assisting the nuclear weapons programs of other countries, it does not prohibit cooperation on military nuclear propulsion.

That is indeed the basis on which Russia has been cooperating with India on the non-explosive military uses of nuclear energy. There are no signs of this debate in Washington at this stage and nor is India seeking such cooperation. But as the Indian and American navies draw closer together in the Indian and Western Pacific oceans, the China factor is indeed an important driver.

It will be interesting to watch whether naval nuclear propulsion will emerge as a potential area of India's cooperation with the United States and other Western powers.

Meanwhile, the maturation of the Chinese maritime nuclear arsenal and successful inauguration of the India's naval nuclear project demand that Beijing and New Delhi begin a serious conversation of nuclear weapons issues. While China and India do discuss a range of contentious bilateral issues, the nuclear question is not one of them. China has tended to take a formalistic view that India is not a recognized nuclear weapon power and therefore Beijing has nothing to discuss except non-proliferation.

India has been deeply concerned about Chinese nuclear cooperation with Pakistan in the past and Beijing's opposition to the United States-India civil nuclear initiative. China, on the other hand, has seen the United States-India nuclear rapprochement as driven by a shared agenda of limiting, if not containing Chinese power in Asia. Given the danger of letting these negative perceptions fester, Beijing and New Delhi must launch a comprehensive nuclear dialogue that will touch on all relevant issues, including the developments on the maritime domain.

R. Case Study: Safety of US Nuclear Powered Warships

Introduction

U.S. Nuclear Powered Warships (NPWs) have safely operated for more than 50 years without experiencing any reactor accident or any release of radioactivity that hurt human health or had an adverse effect on marine life. Naval reactors have an outstanding record of over 134 million miles safely steamed on nuclear power, and they have amassed over 5700 reactor-years of safe operation.

Currently, the U.S. has 83 nuclear-powered ships: 72 submarines, 10 aircraft carriers and one research vessel. These NPWs make up about forty percent of major U.S. naval combatants, and they visit over 150 ports in over 50 countries, including approximately 70 ports in the U.S. and three in Japan.

Regarding the safety of NPWs visiting Japanese ports, the U.S. Government has made firm commitments including those in the Aide-Memoire of 1964; the Statement by the U.S. Government on Operation of Nuclear Powered Warships in Foreign Ports of 1964; the Aide-Memoire of 1967; and the Memorandum of Conversation of 1968. Since 1964 U.S. NPWs have visited Japanese ports (i.e., Yokosuka, Sasebo and White Beach) more than 1200 times.

The results of monitoring in these ports conducted by the Government of Japan and the U.S. Government, respectively, demonstrate that the operation of U.S. NPWs does not result in any increase in the general background radioactivity of the environment. The U.S. Government states that every single aspect of these commitments continues to be firmly in place. Particularly, the U.S. Government confirms that all safety precautions and procedures followed in connection with operations in U.S. ports will be strictly observed in foreign ports, including Japanese ports.

Also, the U.S. Government notes here that its commitments are supported by concrete measures that ensure the safety of U.S. NPWs and that are continuously being updated and strengthened.

Design of Naval Reactor Plant

All U.S. NPWs use pressurized water reactors (PWRs). PWRs have an established safety history, their operational behavior and risks are understood, and they are the basic design used for approximately 60% of the commercial nuclear power plants in the world. The mission that naval reactors support is different from the mission of commercial reactors. All NPWs are designed to survive wartime attack and to continue to fight while protecting their crews against hazards. They have well-developed damage control capabilities, redundancy, and backup in essential systems. In addition, to support the mission of a warship, naval reactors are designed and operated in such a way as to provide rapid power level changes for propulsion needs, ensure continuity of propulsion, and have long operational lifetimes (current naval reactor cores are designed such that aircraft carriers are refueled just once in the life of the ship and submarines never have to be refueled).

These are the significant differences between NPW and commercial reactor missions. Also, the fact that operators and crews have to live in close proximity to the nuclear reactor requires that the reactor have redundant systems and comprehensive shielding and be reliable and safe. For these reasons, naval reactor plant designs are different from commercial reactors, which results in enhanced capability of naval vessels to operate safely under harsh battle conditions, or even more safely during peacetime operations.

There are at least four barriers that work to keep radioactivity inside the ship, even in the highly unlikely event of a problem involving the reactor. These barriers are the fuel itself, the all-welded reactor primary system including the reactor pressure vessel containing the fuel, the reactor compartment, and the ship’s hull. Although commercial reactors have similar barriers, barriers in NPWs are far more robust, resilient and conservatively designed than those in civilian reactors due to the fundamental differences in mission.

U.S. naval nuclear fuel is solid metal. The fuel is designed for battle shock and can withstand combat shock loads greater than 50 times the force of gravity without releasing fission products produced inside the fuel. This is greater than 10 times the earthquake shock loads used for designing U.S. commercial nuclear power plants. With the high integrity fuel design, fission products inside the fuel are never released into the primary coolant. This is one of the outstanding differences from commercial reactors, which normally have a small amount of fission products released from the fuel into the primary coolant.

An all-welded primary system provides a second substantial metal barrier to the release of radioactivity. This system is formed by the reactor pressure vessel, which is a very robust and thick metal component containing the reactor core, and primary coolant loops. They are tightly and firmly welded to stringent standards to constitute a single structure that keeps pressurized high temperature water within the system. The primary system coolant pumps are canned motor pumps, which means they are completely contained within the all-welded primary system metal barrier. No breach in the primary boundary is needed to power the pump; the pump is operated from outside by the force of an electromagnetic field.

No rotating parts with associated packing seals penetrate the metal barrier. While the design ensures that no measurable leakage takes place from this primary system, it should be noted that there is only a very small amount of radioactivity within the primary coolant. As explained above, there are no fission products released from the fuel into coolant. The main sources of radioactivity in the primary coolant are trace amounts of corrosion and wear products that are carried by reactor cooling water and activated by neutrons when the corrosion products pass by the reactor fuel.

The concentration of radioactivity (Becquerels per gram, Bq/g) from such activated corrosion products is about the same as the concentration of naturally occurring radioactivity found in common garden fertilizer. The U.S. Navy monitors radioactivity levels in the reactor cooling water on a daily basis to ensure that any unexpected condition would be detected and dealt with promptly.

The third barrier is the reactor compartment. This is the specially designed and constructed high-strength compartment within which the all-welded primary system and nuclear reactor are located. The reactor compartment would hold back the release of any primary coolant system liquid or pressure leakage in the event a leak were to develop in the primary system The fourth barrier is the ship's hull. The hull is a high-integrity structure designed to withstand significant battle damage. Reactor compartments are located within the central, most protected section of the ship.

The U.S. Naval Nuclear Propulsion Program has a dual agency structure with direct access to the Secretaries of Energy and Navy. The Program is responsible for all aspects of U.S. naval nuclear propulsion, including research, design, construction, testing, operation, maintenance, and ultimate disposition of naval nuclear propulsion plants. None of these activities can be undertaken without the approval of the Program.

Furthermore, the U.S. Nuclear Regulatory Commission and the Advisory Committee on Reactor Safeguards independently review each of the Navy's reactor plant designs. These organizations have concluded that, in many areas, military requirements have led to features and practices that meet objectives that are more demanding than those necessary for commercial nuclear reactors. After rigorous reviews, the U.S. Nuclear Regulatory Commission and the Advisory Committee on Reactor Safeguards have concluded that U.S. NPWs can be operated without undue risk to the health and safety of the public.

Operation of the Naval Reactor

Operation of naval reactors is also different from that of commercial reactors because of the different purpose they serve. First, naval reactors are smaller and lower in power rating than typical civilian reactors. The largest naval reactors are rated at less than one-fifth of a large U.S. commercial reactor plant. Also, naval reactors do not normally operate at full power. The average power level of reactors on nuclear-powered aircraft carriers over the life of the ship is less than 15% of their full rated power. In contrast, commercial reactors normally operate near full power.

Second, the naval reactor power level is primarily set by propulsion needs, and not by the ship's other service needs, which are also powered by the reactor but require a small fraction of the power required for propulsion. Consequently, reactors are normally shut down shortly after mooring and they are normally started up only shortly before departure, since only very low power is required for propulsion in port. While in port, electric power for service needs is provided from shore power supplies. This has been and will continue to be the case for NPWs in Japanese ports where sufficient shore power is available.

From these two facts alone, it follows that the amount of radioactivity potentially available for release from a reactor core of a U.S. NPW moored in a port is less than about one percent of that for a typical commercial reactor. A large fraction of the fission products that are produced during the operation of the reactor, and are of concern for human health, decay away shortly after the reactor is shut down.

Issue of Radiation Exposure

With the four barriers to the release of radioactivity and comprehensive shielding, U.S. Navy reactors are so effectively shielded and radioactivity is so controlled that a typical NPW fleet crew member receives significantly less radiation exposure than a person would receive from background radiation at home in the U.S. in the same period. This is due to the comprehensive shielding built into the ships and the absence of radiation from the earth itself, most notably from radon, while the NPW is deployed.

The average exposure per person monitored in the Naval Nuclear Propulsion program has been on a downward trend for the last 24 years. For fleet personnel, the average exposure per person in 2004 is 0.038 rem (0.38 mSv), while the annual average over the 25 years since 1980 is about 0.044 rem (0.44 mSv),

For comparison, this average annual exposure of 0.044 rem (0.44mSv) since 1980 is:

- Less than 1 percent of the U.S. Federal annual worker limit: 5 rem (50 mSv)
- Approximately one-third the average annual exposure of commercial nuclear power plant personnel: 0.109 rem (1.09mSv).
- Approximately one-fourth of the average annual exposure received by U.S. commercial airline flight crew personnel due to cosmic radiation: 0.170 rem (1.7 mSv)
- Less than 15 percent of the average annual exposure to a member of the population in the U.S. from natural background radiation: approximately 0.3 rem (3.0 mSv).
- Less than the difference in the annual exposure due to natural background radiation between Denver, Colorado and Washington, DC: 0.070 rem (0.7mSv)

Disposal of Nuclear Waste

As is the case for commercial reactors, the operation of naval nuclear reactors involves creation of liquids containing low levels of radioactivity. In the case of commercial reactors, low-level radioactive liquids are routinely discharged as part of plant operation within limits established to ensure that there is no significant effect on the environment or on public health.

For U.S. NPW reactors, extensive efforts have been taken to control routine discharges strictly so as to minimize the amount of radioactivity released.

U.S. Navy stringently controls NPW effluent discharges in such a way that is wholly consistent with Japanese as well as established international standards, including those issued by the International Commission on Radiological Protection. Specifically, U.S. policy prohibits discharge of radioactive liquids, including primary coolant, from U.S. NPWs within 12 miles of shore, including in Japanese ports. Forty years of U.S. and Japanese environmental monitoring confirm that U.S. NPW operations have had no adverse effect on human health, marine life, or the quality of the environment. Solid wastes are properly packaged and transferred to U.S. shore or tender facilities for subsequent disposal in the U.S. in accordance with approved procedures. U.S. NPWs have not discharged demineralizer waste (i.e., ion exchange resins used for purification) into the sea for over 30 years.

The U.S. commitment expressed in the 1964 aide-memoire regarding fuel change and repair remains absolutely in place. Fuel change and reactor repairs are not performed in foreign countries. Fuel change can only be accomplished with proper specialized equipment and in facilities authorized by the U.S. Naval Nuclear Propulsion Program, which are only located in the United States.

Environmental Impact

The robust and redundant design, relatively low power operation history particularly in port (typically shut down), and very strict control of radioactive waste all contribute to the fact that there has never been a reactor accident nor any release of radioactivity that has had an adverse effect on human health, marine life, or the quality of the environment throughout the entire history of the U.S. Naval Nuclear Propulsion Program.

Since 1971, the total amount of long-lived gamma radioactivity released each year within 12 miles from shore from all U.S. naval nuclear-powered ships and their support facilities, combined, has been less than 0.002 curie (0.074 GBq); this includes all harbors, both U.S. and foreign, entered by these ships. As a measure of the significance of these data, this amount of radioactivity is less than the quantity of naturally occurring radioactivity in the volume of saline harbor water occupied by a single nuclear-powered submarine, and less than one tenth of the quantity of radioactivity naturally occurring in the volume of saline harbor water displaced by a single aircraft carrier. This means that a U.S. NPW releases far less radioactivity than exists naturally in the comparable volume of seawater. In addition, even exposure to the entire amount of radioactivity released into any harbor in any of the last 34 years would not exceed the annual radiation exposure permitted for an individual worker by the U.S. Nuclear Regulatory Commission.

One typical U.S. commercial nuclear power plant will, safely within its operational license limits, annually discharge over one hundred times the amount of long-lived gamma radioactivity released within 12 miles from shore by all of the U.S. NPWs and their support facilities. Further, as a measure of how stringently the Navy's policy is applied even on the high seas outside of 12 miles from shore, the entire fleet of U.S. NPWs collectively released less than 0.4 curie (14.8 GBq) of long-lived gamma radioactivity in each year since 1973. This total is still less than the amount of radioactivity a single typical U.S. commercial nuclear power plant is permitted to release in a year by the U.S. Nuclear Regulatory Commission. Such low levels of radioactivity released on the high seas have not had any adverse effect on human health, marine life, or the quality of the environment.

No national or international standard requires that the level of radioactivity released by nuclear facilities be as low as this level. The stringent efforts of the U.S. Navy to implement this policy have ensured that the operation and servicing of U.S. NPWs do not result in any increase in the general background radioactivity of the environment.

Preparations for Emergencies

Due to the four barriers in place in U.S. NPWs, it is extremely unlikely that radioactivity would ever be released from the reactor core into the environment. For additional assurance, however, U.S. NPWs have multiple safety systems to prevent problems from happening and expanding.

The all-welded primary system is designed with a zero-leakage design criterion that allows NPWs reactor operators to determine quickly if there were even a very small primary coolant leak and take prompt corrective action before it could lead to additional problems.

Further, U.S. NPWs have a failsafe reactor shutdown system, which brings about reactor shutdown very quickly, as well as other multiple reactor safety systems and design features, each of which has back-ups. Among these is a decay heat-removing capability, which depends only on the physical arrangement of the reactor plant and on the nature of water itself (natural convection driven by density differences), not on electrical power, to cool down the core. Also, naval reactors have ready access to an unlimited source of seawater that can, if ultimately necessary, be brought on board for emergency cooling and shielding and would remain on the ship. All reactors on U.S. NPWs are located in robust compartments and have multiple ways of adding water to cool the reactor.

These multiple safety systems ensure that, even in the highly unlikely event of multiple failures, naval reactors would not overheat and the fuel structure would not be damaged by heat produced in the reactor core. Thus, it would require virtually incredible accident conditions, where these safety systems and their back-ups all fail, to cause a release of fission products from the reactor core to the primary coolant.

The NPW crew is fully trained and fully capable to respond immediately to any emergency in the ship. Naval operating practices and emergency procedures are well defined and rigorously enforced; and the individuals are both trained for dealing with extraordinary situations and subject to high standards of accountability. Also, the fact that the crew lives in such close proximity to the reactor provides the best and earliest monitoring of even the smallest change in plant status. The operators become very attuned to the way the plant sounds, smells, and feels.

In the extremely unlikely event of a problem on board involving the reactor plant of a U.S. NPW visiting Japan, the U.S. Navy would initiate actions required to respond and could call on other U.S. national response assets if necessary. While the U.S. Government will keep the Government of Japan informed while the U.S. is responding, the U.S. Government will not require assistance from the Government of Japan to respond to an affected NPW. Because of the rugged design of the reactor plant, multiple safety systems, and fully trained and capable crew, the safety of U.S. NPWs is extremely high. In order for an accident that affects the operation of the ship or the crew to happen, the ship must simultaneously experience numerous unrealistic equipment and operator failures.

Even though such an accident scenario is very unrealistic, the U.S. NPWs and their support facilities are required to simulate such situations as they conduct meaningful training on highly unlikely reactor accident scenarios.

With such a defense-in-depth approach, even in the highly unlikely event of a problem involving the nuclear reactor of a U.S. NPW, all radioactivity from the fuel would be expected to remain inside the ship.

Possible Radiation Leakage

All of the above discussion leads to the conclusion that the likelihood of an accident resulting in radioactivity from the nuclear reactor core itself being released from the ship to the environment is extremely small. However, the U.S. Navy never dismisses such an accident scenario as something that does not deserve serious consideration. The U.S. Navy has made thorough studies on: what could bring about a release of radioactivity from the ship during highly unlikely accident scenarios, what effect such a release could have on the environment, and what emergency plans would be required for such a situation.

To get into the environment, fission products would have to pass through each of the four barriers: the fuel, the all-welded reactor primary system, the reactor compartment, and the ship’s hull. Also, it would require that all reactor safety systems and their back-ups malfunction. Further, it would require that the fully trained and very capable crew could not react to and control the situation. If all of these abnormalities took place simultaneously in a highly unlikely accident scenario, then a U.S. NPW could potentially release fission products to the environment. In other words, such an accident would be possible only in a very unrealistic situation of multifold and simultaneous errors and malfunctions.

Nevertheless, the U.S. Navy does prepare for and test its response to simulated highly unlikely accident scenarios. As was stated by the U.S. Government in the 1967 aide-memoire, based on a detailed and conservative safety analysis in which the maximum credible accidents resulting in the release of radioactivity are assumed, nuclear-powered warships do not represent unreasonable radiation or other nuclear hazards to the civilian population in the neighborhood of their mooring locations. Even in these highly unlikely events, the maximum possible effect of the predicted amount of radioactivity released would be localized and not severe: the effect would be so small that the area where protective actions, such as sheltering, would be considered at all would be very limited, and only in the immediate vicinity of the ship and well within the U.S. Navy bases in Japan.

This statement is based on existing thresholds for public protective actions set by the U.S. Federal Government, and is equivalent or more conservative than the existing guidelines set by the International Atomic Energy Agency (IAEA) for similar emergencies. A number of factors contribute to keep the effect of such a highly unlikely accident localized and not severe. First, fission products in the fuel would not be directly and immediately exposed to the atmosphere. The fission products would first have to pass through the four barriers. Even in a very unrealistic situation where radioactivity passed through all four barriers, the amount of radioactivity for potential release would be significantly reduced after passing through each successive barrier. This means that the amount of radioactivity eventually released from the ship during an accident would be only an extremely small portion of what could have been released into the primary coolant.

Second, the process through which radioactivity would be potentially released from the ship would not be a short-time event like an explosion. It would take a long time for radioactivity to pass through the four barriers. The high-strength reactor compartment and ship’s hull would restrict the movement of radioactivity such that the radioactivity could not be released in a short time period through an explosive-like force.

Third, since it would take a long time for radioactivity to pass through the four barriers, there would be sufficient time for the crew to respond to the problem and mitigate potential consequences before any radioactivity reached the outside of the ship. Also, a large fraction of the fission products that are produced during the operation of the reactor, and are of concern for human health, decay away shortly after the reactor is shut down and before they could pass through the four barriers.

The process described above is totally different from an atomic bomb explosion. It is physically impossible for this type of nuclear explosion to occur in a land-based commercial reactor or naval nuclear propulsion reactors.

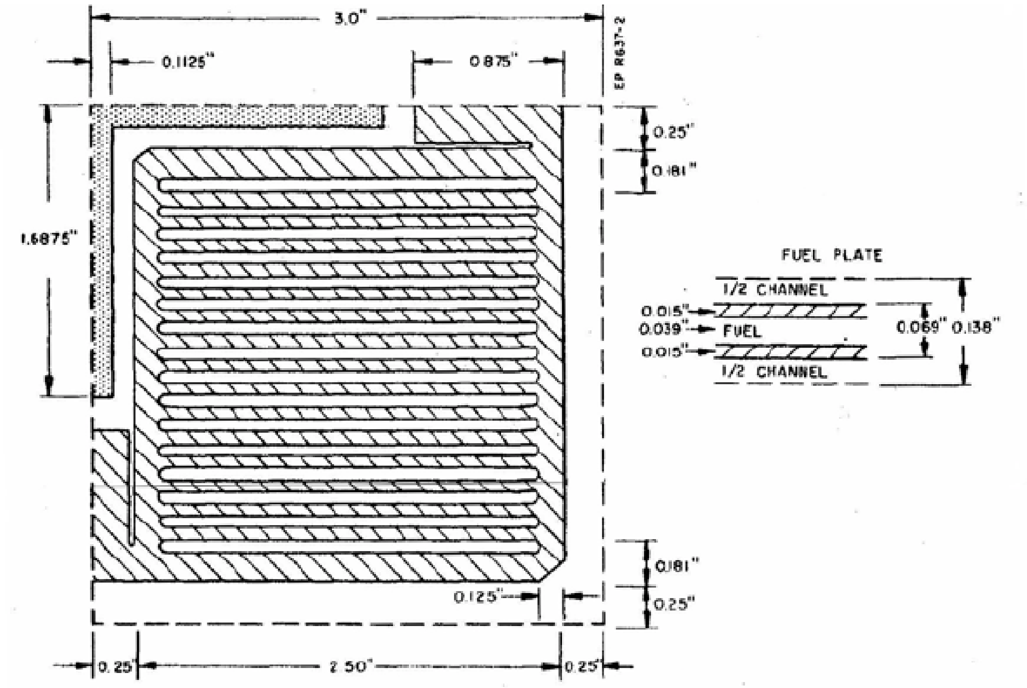
S. Appendix

Analysis of the Shippingport Pressurized Water Reactor and Light Water Breeder Reactor

The Shippingport power station, first operated in December 1957 and was the first USA's commercial nuclear power reactor operated by the Duquesne Light Company. It was a pressurized water reactor with the first two reactor cores as "seed and blanket" cores. The seed assemblies had highly enriched uranium plate fuel clad in zirconium, similar to submarine cores, and the blanket assemblies had natural uranium.

The first core, PWR-1, had 32 seed assemblies with each seed assembly including four subassemblies for a total of 128. Each subassembly contained 15 fuel elements for a total of 1920. The U235 loading for the first seed core 75 kgs and the subsequent seeds had 90 kgs loadings.

Figure 151: Shippingport Reactor PWR-1 seed subassembly showing the highly enriched zirconium clad fuel and coolant channels



Dimensions in inches.

The PWR-1 blanket fuel was made of natural uranium in the form of natural UO2 pellets clad with Zircaloy tubes. Each blanket assembly was made from seven stacked fuel bundles. Each fuel bundle was an array of short Zircaloy tubes with natural uranium oxide pellets in the tubes. PWR-1 had 113 blanket assemblies each containing seven fuel bundles for a total of 791, and each bundle contained 120 short fuel rods for a total of 94,920. The natural uranium loading for the blanket fuel was 12,850 kgs of natural uranium.

Subsequently, the Shippingport blanket was replaced by a thorium control assembly to introduce the light water breeder concept where U233 is bred from Th232 in a thermal neutron spectrum.

Figures & Tables

Figure 152: Icebreaker Yamal

Figure 153: Fuel Consumption per Soldier Over Time

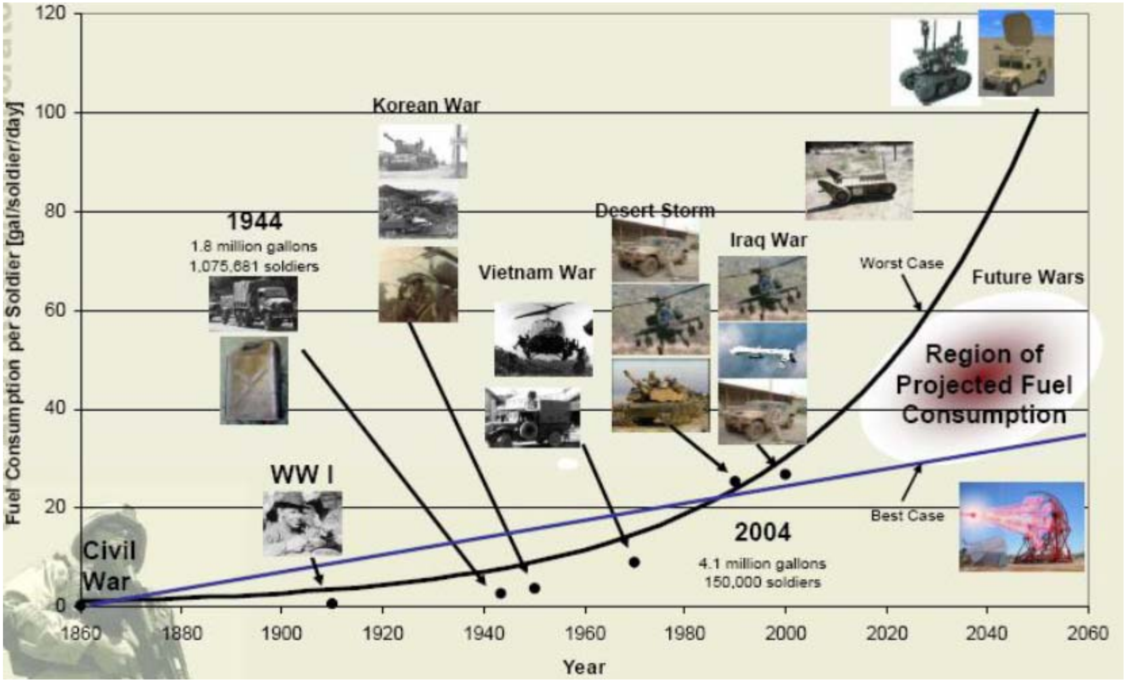


Figure 154: US Army Battlefield Supply Volume

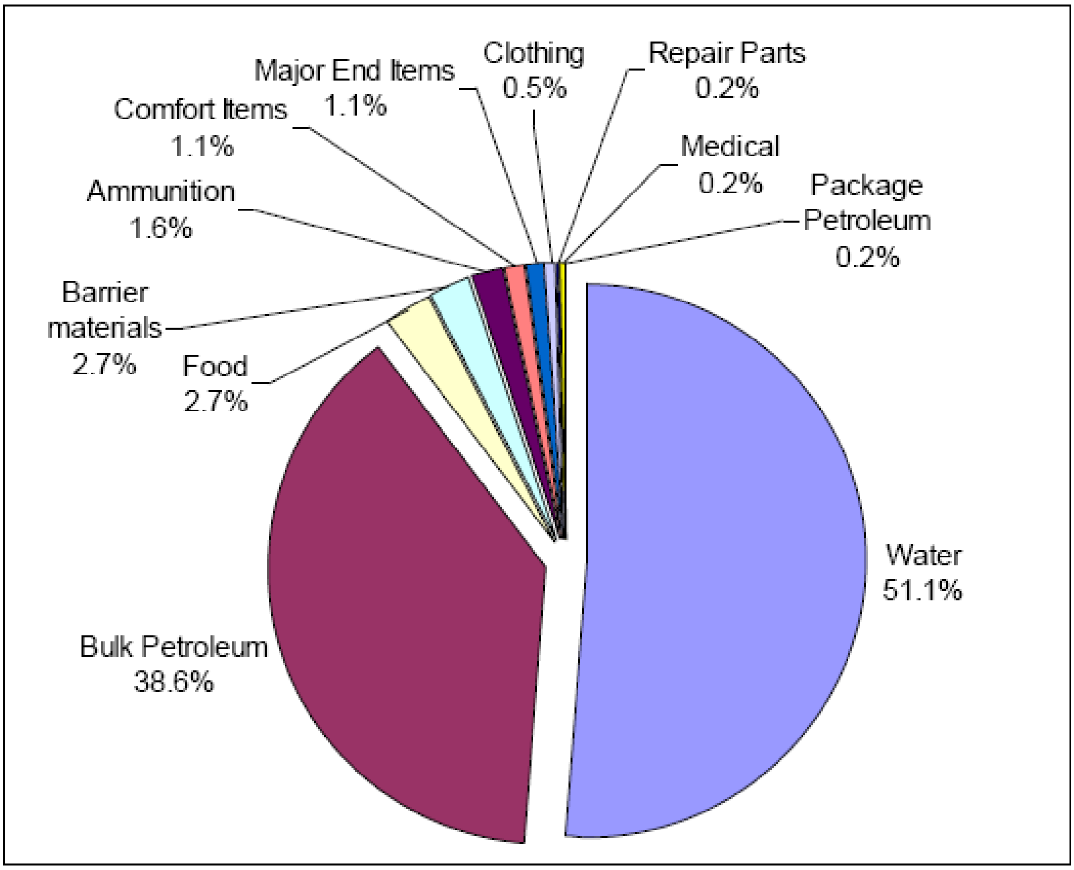


Figure 155: NS Savannah

Figure 156: Nuclear Icebreaker (Russian)

Figure 157: Nuclear Propulsion

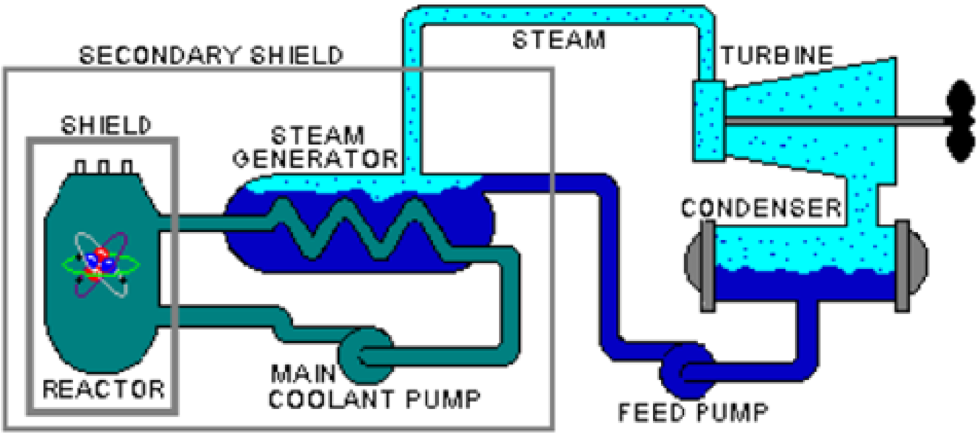


Figure 158: Nuclear Steam Supply from 3 Loop Pressurized Water Reactor

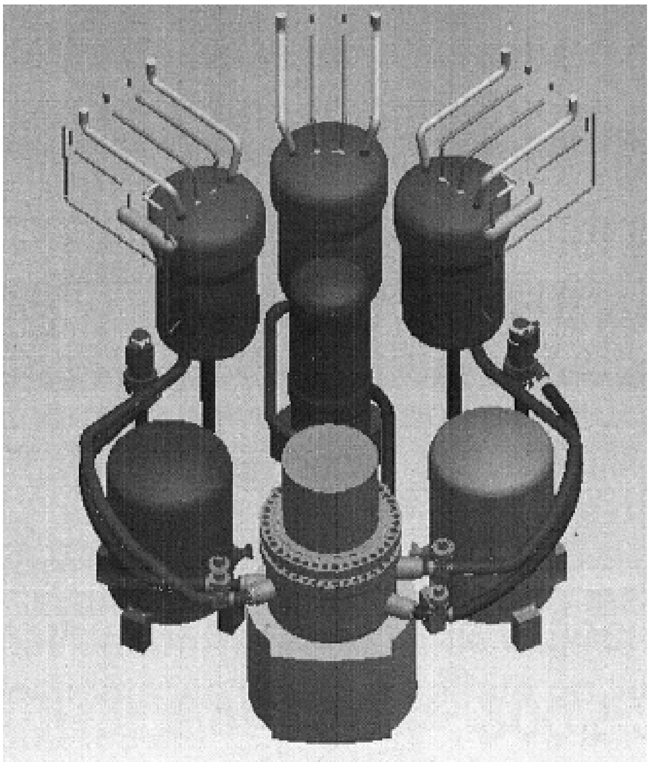
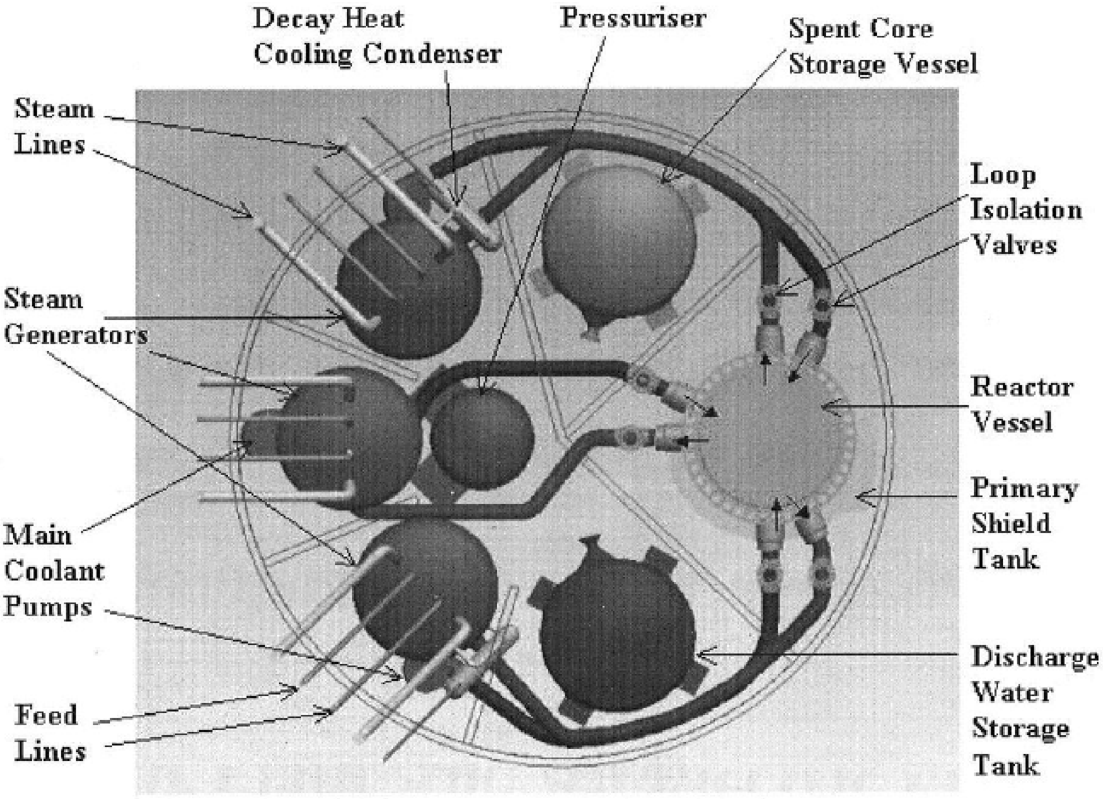


Figure 159: Nuclear Steam Supply



T. Glossary of Terms

Actinide: An element with atomic number of 89 (actinium) to 102. Usually applied to those above uranium - 93 up (also called transuranics). Actinides are radioactive and typically have long half-lives. They are therefore significant in wastes arising from nuclear fission, e.g. used fuel. They are fissionable in a fast reactor.

Activation Product: A radioactive isotope of an element (e.g. in the steel of a reactor core) which has been created by neutron bombardment.

Activity: The number of disintegrations per unit time inside a radioactive source. Expressed in becquerels.

ALARA: As Low As Reasonably Achievable, economic and social factors being taken into account. This is the optimization principle of radiation protection.

Alpha Particle: A positively-charged particle from the nucleus of an atom, emitted during radioactive decay. Alpha particles are helium nuclei, with 2 protons and 2 neutrons.

Atom: A particle of matter which cannot be broken up by chemical means. Atoms have a nucleus consisting of positively-charged protons and uncharged neutrons of the same mass. The positive charges on the protons are balanced by a number of negatively-charged electrons in motion around the nucleus.

Background Radiation: The naturally-occurring ionizing radiation which every person is exposed to, arising from the earth's crust (including radon) and from cosmic radiation.

Base Load: That part of electricity demand which is continuous, and does not vary over a 24-hour period. Approximately equivalent to the minimum daily load.

Becquerel: The SI unit of intrinsic radioactivity in a material. One Bq measures one disintegration per second and is thus the activity of a quantity of radioactive material which averages one decay per second. (In practice, GBq or TBq are the common units).

Beta Particle: A particle emitted from an atom during radioactive decay. Beta particles may be either electrons (with negative charge) or positrons.

Biological Shield: A mass of absorbing material (e.g. thick concrete walls) placed around a reactor or radioactive material to reduce the radiation (especially neutrons and gamma rays respectively) to a level safe for humans.

Boiling Water Reactor (BWR): A common type of light water reactor (LWR), where water is allowed to boil in the core thus generating steam directly in the reactor vessel. (cf PWR)

Breed: To form fissile nuclei, usually as a result of neutron capture, possibly followed by radioactive decay.

Burn: Cause to fission.

Burnable Poison: A neutron absorber included in the fuel which progressively disappears and compensates for the loss of reactivity as the fuel is consumed. Gadolinium is commonly used.

Burnup: Measure of thermal energy released by nuclear fuel relative to its mass, typically Gigawatt days per ton (GWd/tU).

Calandria: (in a CANDU reactor) a cylindrical reactor vessel which contains the heavy water moderator. It is penetrated from end to end by hundreds of calandria tubes which accommodate the pressure tubes containing the fuel and coolant.

CANDU: Canadian deuterium uranium reactor, moderated and (usually) cooled by heavy water.

Chain Reaction: A reaction that stimulates its own repetition, in particular where the neutrons originating from nuclear fission cause an ongoing series of fission reactions.

Cladding: The metal tubes containing oxide fuel pellets in a reactor core.

Concentrate: See Uranium oxide concentrate (U3O8).

Control rods: Devices to absorb neutrons so that the chain reaction in a reactor core may be slowed or stopped by inserting them further, or accelerated by withdrawing them.

Conversion: Chemical process turning U3O8 into UF6 preparatory to enrichment.

Coolant: The liquid or gas used to transfer heat from the reactor core to the steam generators or directly to the turbines.

Core: The central part of a nuclear reactor containing the fuel elements and any moderator.

Critical Mass: The smallest mass of fissile material that will support a self-sustaining chain reaction under specified conditions.

Criticality: Condition of being able to sustain a nuclear chain reaction.

Cross Section: A measure of the probability of an interaction between a particle and a target nucleus, expressed in barns (1 barn = 10-24 cm2).

Decay: Disintegration of atomic nuclei resulting in the emission of alpha or beta particles (usually with gamma radiation). Also the exponential decrease in radioactivity of a material as nuclear disintegrations take place and more stable nuclei are formed.

Decommissioning: Removal of a facility (e.g. reactor) from service, also the subsequent actions of safe storage, dismantling and making the site available for unrestricted use.

Delayed Neutrons: Neutrons released by fission products up to several seconds after fission. These enable control of the fission in a nuclear reactor.

Depleted Uranium: Uranium having less than the natural 0.7% U-235. As a by-product of enrichment in the fuel cycle it generally has 0.25-0.30% U-235, the rest being U-238. Can be blended with highly-enriched uranium (e.g. from weapons) to make reactor fuel.

Deuterium: "Heavy hydrogen", a stable isotope having one proton and one neutron in the nucleus. It occurs in nature as 1 atom to 6500 atoms of normal hydrogen, (Hydrogen atoms contain one proton and no neutrons).

Disintegration: Natural change in the nucleus of a radioactive isotope as particles are emitted (usually with gamma rays), making it a different element.

Dose: The energy absorbed by tissue from ionizing radiation. One gray is one joule per kg, but this is adjusted for the effect of different kinds of radiation, and thus the sievert is the unit of dose equivalent used in setting exposure standards.

Element: A chemical substance that cannot be divided into simple substances by chemical means; atomic species with same number of protons.

Enriched Uranium: Uranium in which the proportion of U-235 (to U-238) has been increased above the natural 0.7%. Reactor-grade uranium is usually enriched to about 3.5% U-235, weapons-grade uranium is more than 90% U-235.

Enrichment: Physical process of increasing the proportion of U-235 to U-238. See also SWU.

Fast Breeder Reactor (FBR): A fast neutron reactor (qv) configured to produce more fissile material than it consumes, using fertile material such as depleted uranium in a blanket around the core.

Fast Neutron: Neutron released during fission, traveling at very high velocity (20,000 km/s) and having high energy (c 2 MeV).

Fast Neutron Reactor: A reactor with no moderator and hence utilizing fast neutrons. It normally burns plutonium while producing fissile isotopes in fertile material such as depleted uranium (or thorium).

Fertile (of an isotope): Capable of becoming fissile, by capturing neutrons, possibly followed by radioactive decay; e.g. U-238, Pu-240.

Fissile (of an isotope): Capable of capturing a slow (thermal) neutron and undergoing nuclear fission, e.g. U-235, U-233, Pu-239.

Fission: The splitting of a heavy nucleus into two, accompanied by the release of a relatively large amount of energy and usually one or more neutrons. It may be spontaneous but usually is due to a nucleus absorbing a neutron and thus becoming unstable.

Fissionable (of an isotope): Capable of undergoing fission: If fissile, by slow neutrons; otherwise, by fast neutrons.

Fission Products: Daughter nuclei resulting either from the fission of heavy elements such as uranium, or the radioactive decay of those primary daughters. Usually highly radioactive.

Fossil Fuel: A fuel based on carbon presumed to be originally from living matter, e.g. coal, oil, gas. Burned with oxygen to yield energy.

Fuel Assembly: Structured collection of fuel rods or elements, the unit of fuel in a reactor.

Fuel Fabrication: Making reactor fuel assemblies, usually from sintered UO2 pellets which are inserted into zircalloy tubes, comprising the fuel rods or elements.

Gamma Rays: High energy electro-magnetic radiation from the atomic nucleus, virtually identical to X-rays.

Genetic Mutation: Sudden change in the chromosomal DNA of an individual gene. It may produce inherited changes in descendants. Mutation in some organisms can be made more frequent by irradiation (though this has never been demonstrated in humans).

Giga: One billion units (e.g. gigawatt = 109 watts or million kW).

Graphite: Crystalline carbon used in very pure form as a moderator, principally in gas-cooled reactors, but also in Soviet-designed RBMK reactors.

Gray: The SI unit of absorbed radiation dose, one joule per kilogram of tissue.

Greenhouse Gases: Radiative gases in the earth's atmosphere which absorb long-wave heat radiation from the earth's surface and re-radiate it, thereby warming the earth. Carbon dioxide and water vapor are the main ones.

Half-Life: The period required for half of the atoms of a particular radioactive isotope to decay and become an isotope of another element.

Heavy Water: Water containing an elevated concentration of molecules with deuterium ("heavy hydrogen") atoms.

Heavy Water Reactor (HWR): A reactor which uses heavy water as its moderator, e.g. Canadian CANDU (pressurized HWR or PHWR).

High-Level Wastes: Extremely radioactive fission products and transuranic elements (usually other than plutonium) in used nuclear fuel. They may be separated by reprocessing the used fuel, or the spent fuel containing them may be regarded as high-level waste.

Highly (or High)-Enriched Uranium (HEU): Uranium enriched to at least 20% U-235. (That in weapons is about 90% U-235.)

In Situ Leaching (ISL): The recovery by chemical leaching of minerals from porous ore bodies without physical excavation. Also known as solution mining.

Ion: An atom that is electrically-charged because of loss or gain of electrons.

Ionizing Radiation: Radiation (including alpha particles) capable of breaking chemical bonds, thus causing ionization of the matter through which it passes and damage to living tissue.

Irradiate: Subject material to ionizing radiation. Irradiated reactor fuel and components have been subject to neutron irradiation and hence become radioactive themselves.

Isotope: An atomic form of an element having a particular number of neutrons. Different isotopes of an element have the same number of protons but different numbers of neutrons and hence different atomic mass, e.g. U-235, U-238. Some isotopes are unstable and decay (qv) to form isotopes of other elements.

Light Water: Ordinary water (H20) as distinct from heavy water.

Light Water Reactor (LWR): A common nuclear reactor cooled and usually moderated by ordinary water.

Low-Enriched Uranium: Uranium enriched to less than 20% U-235. (That in power reactors is usually 3.5 - 5.0% U-235.)

Low-Level Wastes: Mildly radioactive material usually disposed of by incineration and burial.

Megawatt (MW): A unit of power, = 106 watts. MWe refers to electric output from a generator, MWt to thermal output from a reactor or heat source (e.g. the gross heat output of a reactor itself, typically three times the MWe figure).

Metal Fuels: Natural uranium metal as used in a gas-cooled reactor.

Micro: one millionth of a unit (e.g. microsievert is 10-6 Sv).

Milling: Process by which minerals are extracted from ore, usually at the mine site.

Mixed Oxide Fuel (MOX): Reactor fuel which consists of both uranium and plutonium oxides, usually about 5% Pu, which is the main fissile component.

Moderator: A material such as light or heavy water or graphite used in a reactor to slow down fast neutrons by collision with lighter nuclei so as to expedite further fission.

Natural Uranium: Uranium with an isotopic composition as found in nature, containing 99.3% U-238, 0.7% U-235 and a trace of U-234. Can be used as fuel in heavy water-moderated reactors.

Neutron: An uncharged elementary particle found in the nucleus of every atom except hydrogen. Solitary mobile neutrons traveling at various speeds originate from fission reactions. Slow (thermal) neutrons can in turn readily cause fission in nuclei of "fissile" isotopes, e.g. U-235, Pu-239, U-233; and fast neutrons can cause fission in nuclei of "fertile" isotopes such as U-238, Pu-239. Sometimes atomic nuclei simply capture neutrons.

Nuclear Reactor: A device in which a nuclear fission chain reaction occurs under controlled conditions so that the heat yield can be harnessed or the neutron beams utilized. All commercial reactors are thermal reactors, using a moderator to slow down the neutrons.

Nuclide: elemental matter made up of atoms with identical nuclei, therefore with the same atomic number and the same mass number (equal to the sum of the number of protons and neutrons).

Oxide Fuels: Enriched or natural uranium in the form of the oxide UO2, used in many types of reactor.

Plutonium: A transuranic element, formed in a nuclear reactor by neutron capture. It has several isotopes, some of which are fissile and some of which undergo spontaneous fission, releasing neutrons. Weapons-grade plutonium is produced in special reactors to give >90% Pu-239, reactor-grade plutonium contains about 30% non-fissile isotopes. About one third of the energy in a light water reactor comes from the fission of Pu-239, and this is the main isotope of value recovered from reprocessing used fuel.

Pressurized Water Reactor (PWR): The most common type of light water reactor (LWR), it uses water at very high pressure in a primary circuit and steam is formed in a secondary circuit.

Radiation: The emission and propagation of energy by means of electromagnetic waves or particles. (cf ionizing radiation)

Radioactivity: The spontaneous decay of an unstable atomic nucleus, giving rise to the emission of radiation.

Radionuclide: A radioactive isotope of an element.

Radiotoxicity: The adverse health effect of a radionuclide due to its radioactivity.

Radium: A radioactive decay product of uranium often found in uranium ore. It has several radioactive isotopes. Radium-226 decays to radon-222.

Radon (Rn): A heavy radioactive gas given off by rocks containing radium (or thorium). Rn-222 is the main isotope.

Radon Daughters: Short-lived decay products of radon-222 (Po-218, Pb-214, Bi-214, Po-214).

Reactor Pressure Vessel: The main steel vessel containing the reactor fuel, moderator and coolant under pressure.

Repository: A permanent disposal place for radioactive wastes.

Reprocessing: Chemical treatment of used reactor fuel to separate uranium and plutonium and possibly transuranic elements from the small quantity of fission product wastes, leaving a much reduced quantity of high-level waste (which today includes the transuarnic elements). (cf Waste, HLW).

Separative Work Unit (SWU): This is a complex unit which is a function of the amount of uranium processed and the degree to which it is enriched, i.e. the extent of increase in the concentration of the U-235 isotope relative to the remainder. The unit is strictly: Kilogram Separative Work Unit, and it measures the quantity of separative work (indicative of energy used in enrichment) when feed and product quantities are expressed in kilograms.

Sievert (Sv): Unit indicating the biological damage caused by radiation. One Joule of beta or gamma radiation absorbed per kilogram of tissue has 1 Sv of biological effect; 1 J/kg of alpha radiation has 20 Sv effect and 1 J/kg of neutrons has 10 Sv effect.

Spallation: the abrasion and removal of fragments of a target which is bombarded by protons in an accelerator. The fragments may be protons, neutrons or other light particles.

Spent Fuel: Used fuel assemblies removed from a reactor after several years use and treated as waste.

Stable: Incapable of spontaneous radioactive decay.

Tailings: Ground rock remaining after particular ore minerals (e.g. uranium oxides) are extracted.

Tails: Depleted uranium (cf. enriched uranium), with about 0.3% U-235.

Thermal Reactor: A reactor in which the fission chain reaction is sustained primarily by slow neutrons, and hence requiring a moderator (as distinct from Fast Neutron Reactor).

Transmutation: Changing atoms of one element into those of another by neutron bombardment, causing neutron capture and/or fission. In an ordinary reactor neutron capture is the main event, in a fast reactor fission is more common and therefore it is best for dealing with actinides. Fission product transmutation is by neutron capture.

Transuranic Element: A very heavy element formed artificially by neutron capture and possibly subsequent beta decay(s). Has a higher atomic number than uranium (92). All are radioactive. Neptunium, plutonium, americium and curium are the best-known.

Uranium (U): A mildly radioactive element with two isotopes which are fissile (U-235 and U-233) and two which are fertile (U-238 and U-234). Uranium is the basic fuel of nuclear energy.

Uranium Hexafluoride (UF6): A compound of uranium which is a gas above 56°C and is thus a suitable form in which to enrich the uranium.

Uranium Oxide Concentrate (U3O8): The mixture of uranium oxides produced after milling uranium ore from a mine. Sometimes loosely called yellowcake. It is khaki in color and is usually represented by the empirical formula U3O8. Uranium is sold in this form.

Vitrification: The incorporation of high-level wastes into borosilicate glass, to make up about 14% of it by mass. It is designed to immobilize radionuclides in an insoluble matrix ready for disposal.

Waste:

High-level waste (HLW) is highly radioactive material arising from nuclear fission. It can be what is left over from reprocessing used fuel, though some countries regard spent fuel itself as HLW. It requires very careful handling, storage and disposal.

Low-level waste (LLW) is mildly radioactive material usually disposed of by incineration and burial.

Yellowcake: Ammonium diuranate, the penultimate uranium compound in U3O8 production, but the form in which mine product was sold until about 1970. See also Uranium oxide concentrate.

Zircaloy: Zirconium alloy used as a tube to contain uranium oxide fuel pellets in a reactor fuel assembly.

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