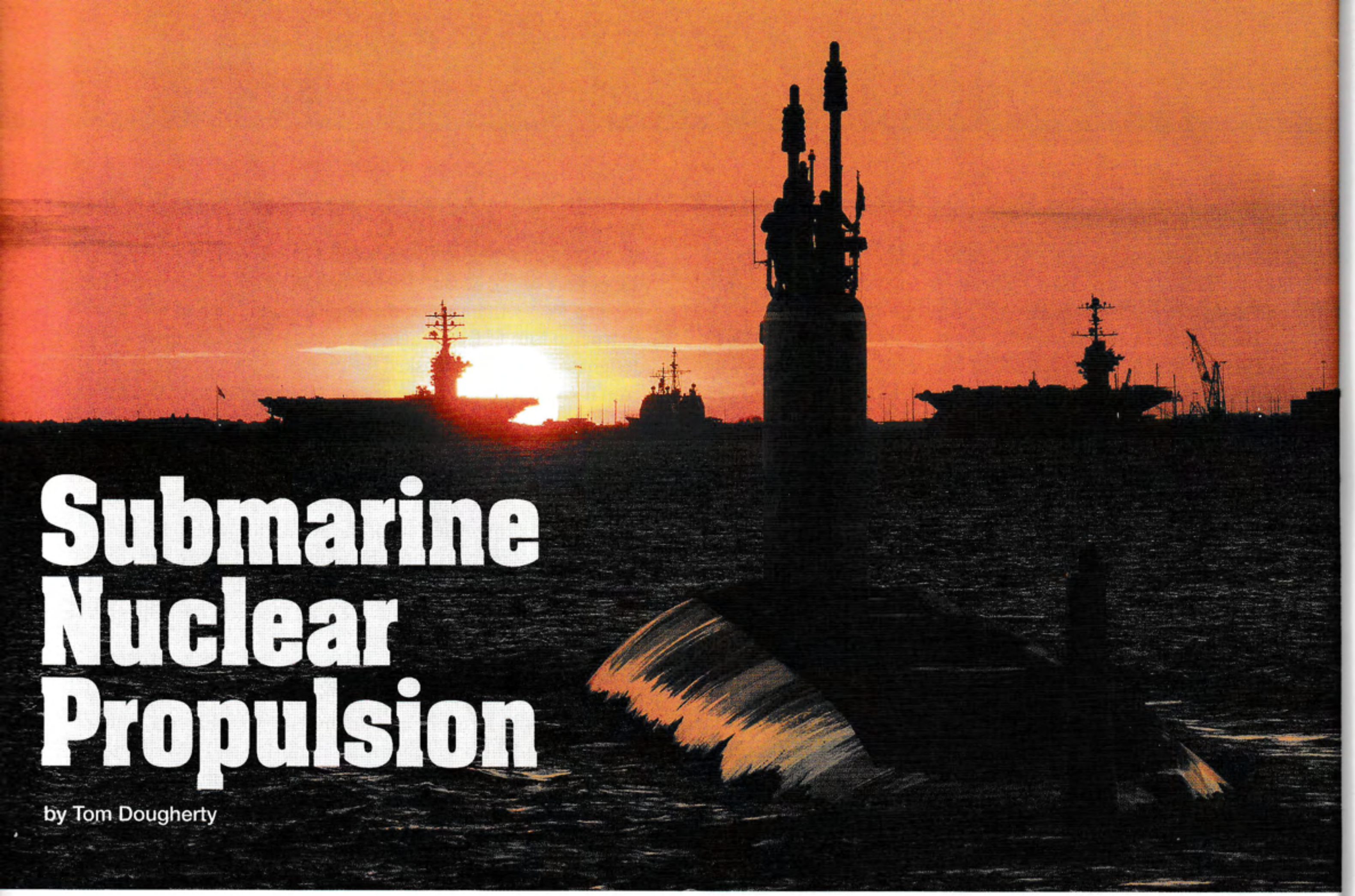


Submarine Nuclear Propulsion

by Tom Dougherty

Most people without firsthand knowledge still possess a general idea of the concept behind nuclear propulsion. Usually when you look up info on the subject, you get a diagram such as what's seen on page 22. If that's good enough for you, read no further. But if you'd appreciate more detail, that's the direction this article will take. I should state at the outset that everything discussed herein is in the public domain. But trying to find, assemble, and put it together in a coherent fashion required no little effort. If you do have an interest though, I believe you'll enjoy this deeper look into some of the more technical aspects of the subject. The additional graphics will serve as a good guide to the individual components to be discussed. Details of individual submarine reactors through the years are listed in the table on page 21.

The Critical Role of Water

With one notable exception, all U.S. Navy nuclear reactors have employed pressurized water to operate. Water serves two roles in the reactor: first, it functions as the working fluid (often termed the primary coolant) to transfer the heat from the nuclear reaction in the reactor to the steam generator system downstream. Second, water acts as a moderator of the reaction. In this function, the high-energy neutrons initially given off by the nuclear fission of uranium are inefficient at sustaining the nuclear chain reaction. These "fast" neutrons would escape the reactor core and not contribute to sustaining the ongoing fission reaction. But multiple collisions of high-energy neutrons with H (as in H_2O) causes them to lose energy and slow down in a process called thermalization. These neutrons can now productively collide with the highly enriched fuel, uranium (U235), sustaining the nuclear fission chain reaction in the reactor in a continuous manner. After collision with a thermalized neutron, U235 undergoes fission, splitting into smaller nuclei and releasing heat energy, neutrons, and gamma radiation. By its ability to both thermalize the neutrons and remove the heat energy generated by the uranium fission, water has become the selected basis of all U.S. naval reactor design.

Liquid metals such as sodium in the original *Seawolf* (SSN-575) S2G plant and lead bismuth in the Russian OK550 reactor were tested, but these metals act largely only as coolants and not as neutron moderators. Additional neutron moderation methods (e.g. beryllium reflectors) are necessary with this design. Liquid metal reactors can operate at much higher, more efficient temperatures and have much higher metal boiling points. Thus, they can be kept at lower operating pressures to be able to produce efficient, superheated steam. But several significant operational disadvantages of liquid metals make water a more desirable alternative. As we will see, the advantages of water as moderator are substantial as far as reactor control is concerned.

Reactor Design

Let's start with reactor basics. The U.S. Navy employs Pressurized Water Reactors (abbreviated PWR) to propel all its nuclear-powered vessels. These reactors are pressurized so that their water can be heated well above the atmospheric boiling point of 212°F (100°C). If you attempt to heat water in an open container at atmospheric pressure (14.7 psi) above 212°F (100°C), all you'll do is increase the rate at which steam is given off into the surrounding air; you will not raise the water temperature. In order to operate a PWR system at a much higher temperature and efficiency, the system is both closed and pressurized to 1750 psi, allowing liquid water operating temperatures of around 500°F. So, what components are required to carry this out?

The nuclear reactor itself is essentially a large steel cylinder of 6-inch thick magnesium-molybdenum alloy steel. Its bottom is hemispheric, penetrated by four large pipes: two inlets and two outlets. The top of the reactor features a "lid" bolted onto the reactor body, and it contains openings for the control rods. The entire reactor interior is coated with zirconium, which forms an oxide that retards corrosion of the steel alloy from the extremely hot water inside. Over time, the constant bombardment of the reactor metal with neutrons causes it to degrade. Another source of degradation is the slow reaction between water and zirconium at high operating temperatures. This generates hydrogen, also causing the reactor vessel's metal to become brittle. Both of these factors act to limit the lifespan of the reactor.

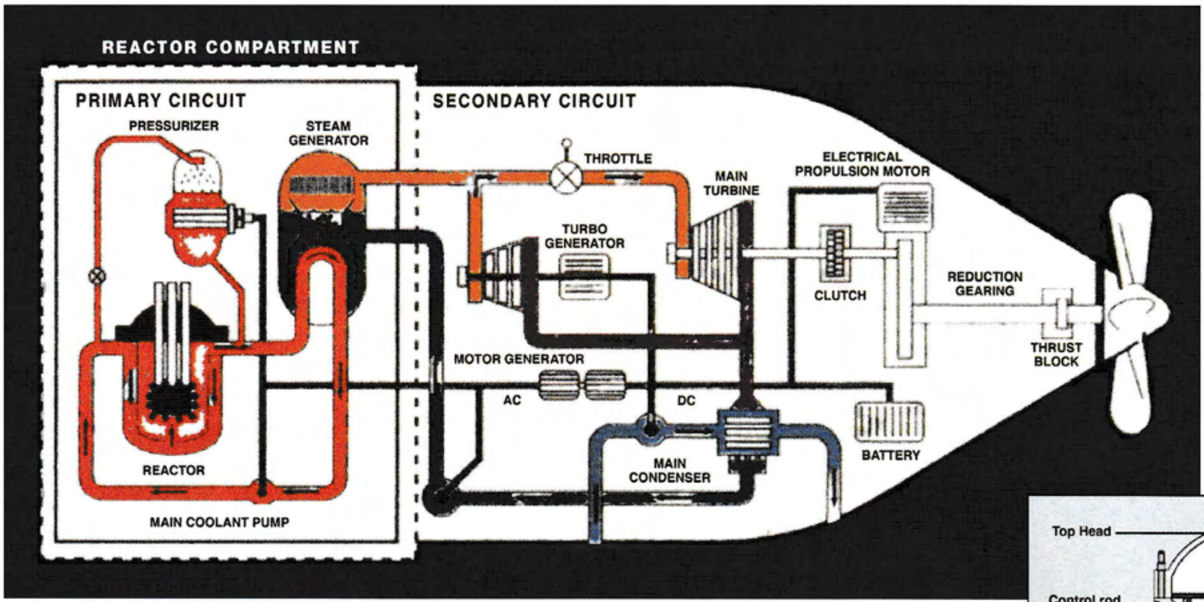
Uranium 235 Fuel

As mentioned above, naval nuclear reactors employ enriched, fissile U235. This isotope makes up only about 0.7% of natural uranium, which is mostly the non-fissile U238 isotope. Using several enrichment techniques, the U235 level is brought up to 93% for U.S. submarine reactors. In contrast, most land-based commercial power reactors are at around 7% enriched. The Navy's higher enrichment permits more compact reactor core designs and longer operation compared to commercial electrical power reactors. The reactor contains multiple fuel bundles or assemblies. These are arranged in a regular pattern consisting of hollow zirconium metal fuel rods and zirconium plates holding tiny ceramic-coated spheres or capsules of enriched U235 inside. The zirconium holder, called cladding, features multiple openings to allow for free passage of water through and around the U235 reactor fuel spheres. Pure zirconium is both transparent to neutrons (important in sustaining the chain reaction) and relatively resistant itself to hot water corrosion over a long term. Coolant water enters through the inlet pipes, flows in a channel down the vessel sides to the bottom of the reactor, then sluices through a zirconium plenum (a plate with multiple small passages to distribute the water evenly) into the reactor core. There it rises up through and around the fuel assembly bundles, picking up heat from the fissioning uranium. This water with increased thermal energy now enters a plenum feeding the exit through the outlet pipes atop the reactor. The reactor core itself is surprisingly compact; in fact, an illustration I've seen depicts it as about the size of a curbside garbage can. Another interesting fact is that the temperature difference between the relatively cold water entering from the steam generators (460°F; 237°C) and the heated water exiting the reactor (500°F; 260°C) is only around 40°F, or 23°C. But the water is pumped around the primary loop to the steam generators very quickly, passing through the reactor in less than a second. So, an enormous volume of water continuously cycles through the reactor, and in that short time quickly picks up that 40°F heat from the fission reaction. For water to be heated by 40°F in less than a second of exposure time means that core is generating a lot of heat! It's both the huge volume of water heated and its temperature difference which generates so much power.

Reactor	Estimated Reactor Power (MWt)	Estimated Propulsion Power (shp)	Initial ops	Application
S1W, S2W, S2Wa	70	13,400	1953	• S1W prototype, NFR Idaho • S2W on USS *Nautilus* (SSN-571) and S2Wa USS *Seawolf* (SSN-575) replacement power plant
S3W	38	7,300	1957	• USS *Halibut* (SSGN-587) • 2 of 4 *Skate*-class (SSGN-578) and USS *Sargo* (SSN-583)
S4W	38	7,300	1957	• S3W core in an S4W plant with an alternate arrangement of some equipment • 2 of 4 *Skate*-class: USS *Swordfish* (SSN-579 and USS *Seadragon* (SSN-584)
S5W	78	15,000	1958	• Used on 98 U.S. nuclear subs in 8 classes and on the first UK nuclear sub, HMS *Dreadnaught*, making S5W the most used Navy reactor plant design to date.
S6W	220	45,000	1994	• Core tested in the S8G prototype • Used on all SSN-21 *Seawolf*-class subs. Life-of-the-boat core. *Seawolf* SSN service life is 30 years
S1C, S2C	13	2,500	1959	• S1C prototype, Windsor, CT • S2C on USS *Tullibee* (SSN-597)
S1G S2G	78	15,000	1955	• S1G prototype, West Milton, NY (later became the D1G) prototype • USS *Seawolf* (SSN-575) original sodium-cooled reactor plant, which was removed and replaced by an S2Wa PWR
S3G S4G	78	15,000	1958	• S3G prototype, West Milton, NY • USS *Triton* (SSRN-586), which had 2 x S4G reactors. • An S3G core 3 installed in an S5W reactor plant was original equipment in many later *Sturgeon*-class SSNs, which required one mid-life refueling. This core was also used to refuel many S5W plants.
S5G	90	17,300	1965	• S5G natural circulation prototype, NRF Idaho • USS *Narwahl* (SSN-671)
S6G with D1G-2 core	150	30,000	1976	*Los Angeles*-class Flight I boats. One mid-life refueling was required for the original 30-year service life of the boat (extended to 33 years). Some Flight I boats were not refueled and were decommissioned early.
S6G with	160	33,500	1985	Original equipment in all *Los Angeles*-class Flight II and 688i D2W core boats. Designed as a life-of-the-boat core for an original 30-year service life (extended to 33 years). Also installed on *Los Angeles*-class Flight I boats that had a mid-life refueling.
S8G	185	35,500	1980	• S8G prototype, West Milton, NY • All *Ohio*-class SSBNs and SSGNs. One mid-life refueling was required. Original design life of the boats was 30 years; then increased to 42 years. S8G reactor core life is at least 20 years.
S9G	210	40,000	2004	All *Virginia*-class SSNs. Naval Reactors describes S9G as "the first core specifically designed to operate without refueling for the service life of the ship." (NR FY 2004 Congressional Budget). *Virginia* SSNs have a 33-year service life.

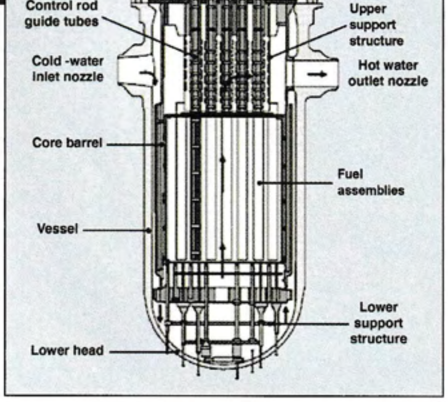
A list of U.S. submarine nuclear reactors, along with their estimated reactor and propulsion power (shaft horsepower) and the submarines in which they were or are deployed. Adapted from: *Marine Nuclear Power. Part 2A: United States Submarines.* Peter Lobner. Presentation to The Lyncean Group of San Diego.

The life of the reactor core's load of enriched uranium, U235, is measured in Effective Full Power Hours (EFPH), with the U.S. Navy employing this fuel at highly



Left: Block diagram of the main components involved in U.S. submarine nuclear propulsion. The reactor, steam generator, and primary steam loop are on the left, behind the shielding. At right is the secondary steam loop and the propulsion train.

Below: The reactor vessel with inlet, fuel assemblies, control rods and the outlet. Note that "cold" and "hot" water are relative terms, as described in the text.



enriched 93% levels, as we've noted. For nearly all of its operational life, the typical nuclear-powered submarine cruises at modest velocities while its reactor is run at a fraction (25-30%) of available maximum power; only when sprinting at high speed is more power really needed. In an average year, then, a submarine might use around 500-700 EFPH. Based on the starting EFPH value (12,000 in the older S5W reactors, much longer with the new *Virginia*-class S9G cores), the older S5W-equipped submarine could go for years between nuclear refuelings. The new, high-density cores in the *Virginia* class are intended for life of the boat usage however.

Control Rods

Interspersed with the zirconium-clad U235 fuel bundles in the reactor core are slots for the control rods. The U.S. Navy uses the transition metal element hafnium for these critical elements. When zirconium metal was first proposed as a structural material for the U235 fuel bundles, a serious problem was believed to be that in its natural state zirconium was not transparent to neutrons; neutrons being absorbed would not sustain the fission reaction. It was soon discovered that it was actually the hafnium contaminant within the natural zirconium which was absorbing neutrons, and so the hafnium was purified away from the zirconium. During this process, it was found that hafnium, like zirconium, was also highly resistant to hot water corrosion and was an excellent neutron absorber. So, the zirconium contaminant (hafnium) actually became the source of U.S. naval control rod material. Control rods have a "X"-shaped cross section, and slide into channels between the uranium fuel bundles of the reactor.

To start the reactor after a shutdown, subsets (groups) of control rods are pulled up from the core in small increments. These rods are divided into linked groups, with the center Group 1 being the "control" group in the middle. Groups 2 and 3 are positioned around the core: Group 2 in a ring around the center with Group 3 as the outermost ring. Groups 2 and 3 control the reactivity of their areas in order to spread out the use of the U235 (reactivity loss is called burning) evenly over the life of the core. As the core ages and fuel is "burned," Group 3 is pulled up, leaving Group 2 in the core and Group 1 controlling the core temperature. Later in core's life, Groups 2 and 3 will swap, with Group 3 staying at the core's bottom and Group 2 being pulled up. This evens out the rate of U235 use (or burn) across the core. Also helping are compounds in the fuel bundles along with the U235. These are called burnable poisons. Initially they generate neutron absorbers such as xenon-135. Xenon-135 is also produced by the fission reaction itself, having a significant dampening effect on reactor operation. Fortunately, xenon-135 absorbs neutrons from the fission process and in a relatively short time reduces to a non-absorbing decay product. Thus, xenon-135 production and decay reach a steady state during reactor operation. As the core ages and loses a percentage of reactivity due to U235 depletion, the burnable poisons are slowly used up and neutralized by the neutrons, converted to non-absorbers, and thus neutron absorption declines. The entire point of burnable poisons is to smooth out the reactivity of the core over longer periods while retaining sufficient reactivity near the end of the core's life to overcome the xenon-135 produced when the reactor needs to be rapidly restarted.

The amount a control rod must be removed from the core to achieve criticality is calculated before startup. This is termed the Estimated Critical Position, or ECP. It's calculated based on the amount of power used in the past, and the length of the shutdown. As the core ages, the rods must be withdrawn to a higher level to achieve criticality, which is the point where each fission event releases a sufficient number of neutrons to sustain an ongoing series of reactions. During startup, with the pumps running, the Group 1 rods are incrementally withdrawn over time until the power level reaches the self-sustaining point (critical) and no longer drops after each incremental pull. The distance withdrawn should closely match the calculated ECP. The reactor is then slowly heated up by withdrawing the rods in further increments to achieve actual operating temperature. This slow rise in heat is to prevent fracturing the reactor vessel from temperature differences too large or too sudden. During this process, the rate of temperature increase is about 5°F per minute. The entire procedure is monitored from the reactor control panel in the maneuvering room. Instruments measure the quantity of neutrons, temperature changes, startup rate, and other parameters of the reactor as it increases power.

The design of the rod system is truly ingenious in its failsafe feature. The rods themselves are held in the core both by their own weight and by strong coil springs. In order to be withdrawn to start the reaction, the rods are latched up in their groups as previously described. The tops of the rods are gripped by alligator clamp-like assemblies, which are closed by powerful electromagnets; they are literally grabbed and lifted. If power is lost, the electromagnetic clamps are deenergized; they open, and the springs (and their own weight) drive the rods back into the reactor, causing a scram—a sudden reactor shutdown. Big T-handles on the reactor control panel in the maneuvering room direct the rod latching process, as well as the amount of distance they are lifted out of the core.

ESSENTIAL ELEMENTS...

Generating the Power (Steam Generation)

During operation, once the primary loop water exits the reactor, it goes to one of two identical vertical steam generators. These also occupy space within the reactor compartment (on the radiation "hot" side). In the steam generator, water from the reactor at 500°F, designated the primary circuit or loop, is pumped into an inlet to a plenum which channels the primary water through a series of about 1800 inverted U-shaped tubes. Surrounding the outside of these tubes is the secondary loop water. This is the water which will be heated by the primary loop into steam which exits the reactor compartment to drive the turbines. By this arrangement, it never comes into any physical contact with the radioactive primary loop water. Further details of the secondary loop will be discussed later. In the process of generating steam, the secondary water cools down the primary loop water—which is then collected after passing through the U-tubes at an exit plenum and return-pumped into the primary circuit, back to the reactor. As such, only steam generated in the reactor compartment ever exits, having never come into direct contact with the radioactive primary loop water passing through the reactor. The primary loop water is treated with chemicals to reduce corrosion in the steam generator loop.

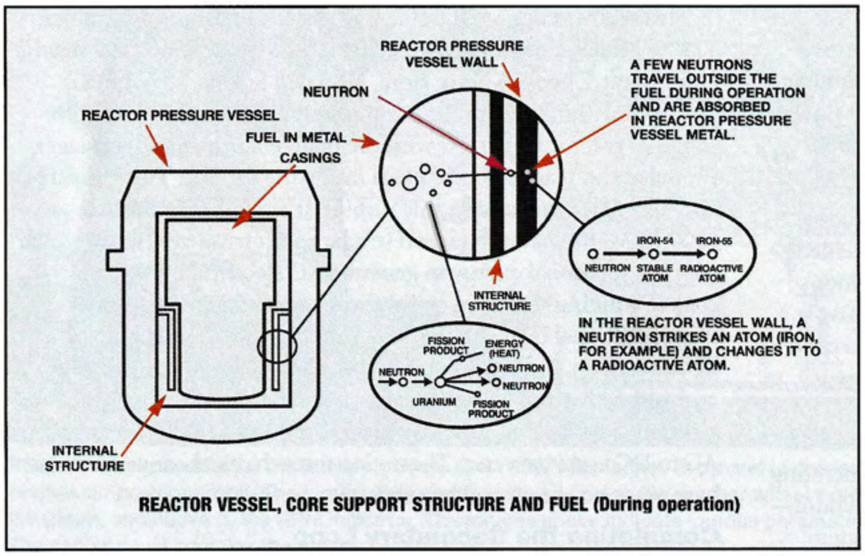
Again, it's been mentioned that water is pumped through the primary loop quite rapidly. Each of the two primary loop circuits has three pumps (six total) to circulate it. These are self-contained, sealed units roughly the size of a couple of refrigerators. They use a significant portion of the electrical power generated to move this primary water through the reactor and steam generators. They are unfortunately also noisy when operating, putting out distinct tonals which can be detected on sonar. Depending on power needs, pumps can be run at different speeds, and usually only two of the three pumps are run, the third being kept quiet as a backup.

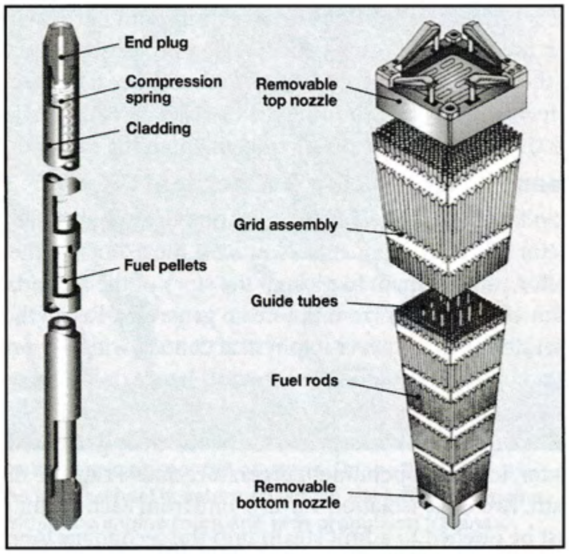
To further improve pump quieting, newer submarines (later SSN and *Ohio* SSBN classes) can employ natural circulation at low speeds, which makes use of the physical principle of hot water rising and cooler water sinking. Careful design and layout of the reactor and elevated steam generator elements make this possible. But once running above low speed, some combination of pumps must move the primary water through the reactor to the steam generators and loop it back to the reactor for increased power.

Water as a moderator has an additional key advantage. Once the reactor is operating, a call for an increase in RPMs (speed) will result in the pumps running faster, meaning more heat energy is transferred to the secondary loop for the propulsion train. This in turn cools the returning primary loop water, increasing its density. This increase in water density means more neutrons are slowed and thermalized, further increasing the rate of U2365 fission and therefore heat generation too. Reducing propulsion demand creates the opposite effect: less heat is removed, water becomes less dense, and fewer neutrons are slowed—reducing the fission reaction. This ability of the reactor to respond to demand changes is known as inherent stability. The operators do not have to make major adjustments in the control rods in response to increased steam demand; physical principles largely take care of it. While pure water loses its radioactivity quickly when the reactor is shut down, contaminants such as minute metal particles shed from the pumps can retain radioactivity for long periods. Consequently, the water is passed through a resin bed, which is periodically disposed of as radioactive waste. Quick loss of radioactivity means the reactor compartment can be entered for maintenance fairly soon after a shutdown. One of the disadvantages of the liquid sodium used in the original S2G reactor variant aboard *Seawolf* (SSN-575) was that the irradiated sodium stayed "hot" for a longer period, extending the time until the reactor compartment could be safely entered.

Pressurizer

One essential piece of equipment is the pressurizer. It acts to keep uniform 1750 psi pressure in the primary circuit and in the





Left: Reactor pressure vessel detail. Right: An individual fuel rod with U235 contained by the zirconium cladding; and a fuel bundle (right), showing the grid assembly with space for the water to circulate among the bundles.

reactor so that water remains liquid. This is critical to reactor function and safety. Steam vapor in the primary system would cause a catastrophic condition leading to damage and the melting of fuel elements. The pressurizer is a tank connected by a pipe to the main coolant system. It has electric heaters which keep the water in the tank at 617°F and 1750 psi, so liquid water and steam vapor can coexist. The steam vapor bubble is at the top of the tank, above the 617°F water. Steam vapor is compressible, whereas liquid water in the reactor system is not. The upper steam vapor bubble acts as a water hammer shock absorber for the system. This is important because, for example, if the main steam valves are closed too quickly, they will cause transient sharp pressure changes. The pressure generated in the pressurizer is transmitted through the water within its piped connection to the water in the reactor's primary loop, thus pressurizing the reactor. As with the other elements of the system described above, the pressurizer is also located inside the reactor compartment.

Emergency Cooling System

The Emergency Cooling System (XC) is one which moves primary water from the core to a heat exchanger, a series of tubes immersed in cold seawater to offload the heat. Cold seawater flows into the tank and exits by convection to remove this heat. Since this happens at sea pressure, the heat exchanger must be a "hard tank." Its cooled primary water flows back into the reactor in a loop.

This emergency system's seawater openings are normally isolated by valves. Using the system runs the risk of a reactor "cold water" accident, which can lead to a fuel meltdown or worse. Thus the system is used only for serious emergencies and must be carefully monitored in operation.

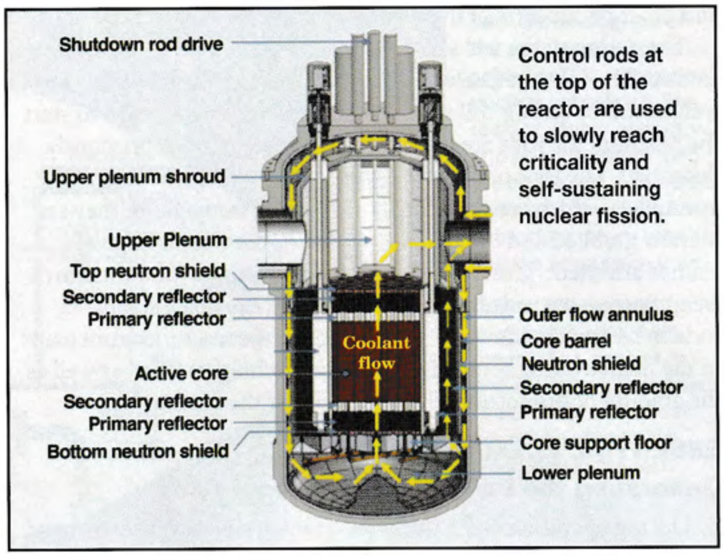
Shields

The reactor, primary loop, steam generators, pressurizer, and other elements such as the reactor's emergency cooling system, are all located within the reactor compartment. When operating, the reactor gives off two kinds of lethal radiation: gamma rays (X-rays) and neutrons. To keep this dangerous radiation away from the crew, the compartment is lined with two types of shields. Six inches of lead prevents gamma rays from entering the tunnel used by the crew to traverse the reactor area. Protecting the same area from neutrons is an additional twelve inches of polyethylene plastic (which contains neutron-absorbing hydrogen). Lead also lines the reactor compartment, but in some areas, either water or diesel fuel is further used as neutron shielding; both have hydrogen in their molecules, offering good neutron protection. Fuel oil tanks are therefore often placed fore and aft of the reactor compartment. As fuel is used while running the diesel, water automatically flows into the bottom of the diesel tank, maintaining safety shielding.

Steam for Propulsion & Electrical Power

So far, we've looked at the operation of a submarine's nuclear reactor and its components. Now we'll move outside the shielded reactor compartment to pick up the story of the secondary loop's steam after it passes from the steam generator. Recall that this generated steam is never in physical contact with any primary loop water circulating through the reactor; hence only heat energy is exchanged to the secondary loop.

During reactor startup, no steam is actually generated. Once the reactor achieves operating temperature and is capable of generating steam, two large isolation valves—one from each steam generator—must be opened to admit steam into the secondary loop system in the spaces powering the propulsion and electrical generation systems. These are called the main steam valves, with MS-1 on the starboard side and MS-2 on the port. They can be rapidly closed in the event of a steam leak. This 455°F steam flows through the large header pipes overhead, all of which are coated with thick insulation (lagging). Because of the thermal expansion of the pipes with increased heat, the steam header pipes make a racetrack-like loop in engineering before entering the main engines and the Ship's Service Turbine Generator (SSTG). Much of the pipe expansion is designed to occur in the racetrack, which doubles back upon itself.



Control rods at the top of the reactor are used to slowly reach criticality and self-sustaining nuclear fission.

Propulsion: Main Engines

Steam is delivered to the two main engines via two lines located port and starboard. These are heavily insulated steam turbine engines—surprisingly small in size for their power. The steam enters and initially goes through an impulse stage. Sets of rotor blades are arranged on a shaft, interspersed with stationary stators mounted in the casing. In this impulse stage, the steam enters and spins the turbine blades; as the steam moves along, the rotor passage expands and the velocity of steam increases (as pressure decreases), transferring further energy to the rotor blades. The steam then gradually gives up its heat and pressure energy to the turbine. At entry, the steam is 455°F and at 440 psi. As it exits the main engine turbine it has reduced to 160°F and 5 psi. The main engines power the propulsive drive train, described a bit later.

Electrical Power: SSTG

Steam is also delivered to the two electrical turbine generators. The SSTG has a manual throttle and a speed governor at the steam's entry point. The SSTGs are large, insulated boxlike structures. Enclosed within them are turning rotor blades interspersed with stationary stator blades. As with the main engines, multiple stages (impulse and reaction) take place inside the turbine. The pressure and heat of the steam spin this turbine at a regulated and steady 3600 RPM. Its shaft is attached to a large electrical generator, which uses the rotational energy to generate AC electrical current via copper windings spinning within a magnetic field. This power is then distributed by two buses, one vital (reactor cooling pumps, lighting, main seawater pumps), the other nonvital (condensate pumps and hydraulic pumps). In earlier nuclear submarines (*Sturgeon* and before), motor-generator sets were employed to convert AC to DC and vice versa. These electromechanical conversion sets have since been replaced by solid-state rectifiers.

Completing the Secondary Loop

The steam exiting the main engines and the SSTGs has now given up the majority of its energy. To recover and recycle the water making up the steam and return it to the steam generator, the main condensers are used. There are two—port and starboard—situated below the turbines. Each condenser is a large horizontal cylindrical vessel containing a series of internal tubes. Cold seawater is continuously pumped by the main seawater pump through this cluster of tubes, and the steam flows around them, cooling and condensing back into liquid water in the process. This condensation lowers the vessels' pressure, creating a vacuum relative to the incoming steam: colder seawater temperatures create lower relative pressures. Seawater enters the system through 18-inch diameter pipes penetrating the hull. Since the pipes are at ambient outside sea pressure, large valves are fitted to them which can be slammed shut in case of a leak. Once steam cools back into water, it's collected at the bottom of the main condenser. A condensate pump then moves the water back to the Main Feed System. Here an elaborate twelve-stage axial pump raises the water pressure to 450 psi and pipes it back through the shield into the reactor compartment, feeding it into the two steam generators to repeat the secondary loop cycle. The water in the loops is periodically tested, and its pH and ions adjusted with chemicals to minimize any corrosive effects on the piping or other components.

The Drive Train

Picking up on the flow of energy into the drive train mentioned above, the first thing to know is that the main engine propulsion shafts turn much too fast to provide useful speeds for the propeller. To reduce this speed to a practical level, the two main engine shafts combine to drive a 15-foot diameter bull gear inside a large reduction gear assembly. Input speed from the main engines is about 10,000 RPM at flank bell, which is reduced to 200 RPM for the actual propeller. Between the propeller shaft and the reduction gear is a hydraulic clutch; the heavy propulsion gears and turbines can be detached from the propeller shaft so when necessary it can be run by the electric emergency propulsion motor instead. There is also a thrust bearing assembly. The screw moving through the water generates a powerful force to push the submarine forward. This thrust is transmitted to the 12-inch diameter propeller shaft, which in turn pushes against the thrust bearing firmly anchored to the submarine's hull. This is how the propulsive force of the propeller is transmitted to the submarine itself. The propeller shaft passes through the hull at the stern, and an elaborate shaft seal keeps water from entering by pressurizing the seal above the exterior water pressure.

This brings us to the conclusion of our look at submarine nuclear propulsion. Obviously, there's a lot of additional complexity which couldn't be addressed here. Naval nuclear power training is a full-year intensive course of study and reactor operation. Submarines also carry massive manuals covering exact procedures for any operation and virtually every possible contingency or reactor casualty. U.S. nuclear submarines boast an enviable record of over sixty-five years of safe and effective operation. I believe that from the above descriptions above you can gain a real appreciation for the general principles and indeed some of the myriad details of submarine reactor plant operation and nuclear propulsion.

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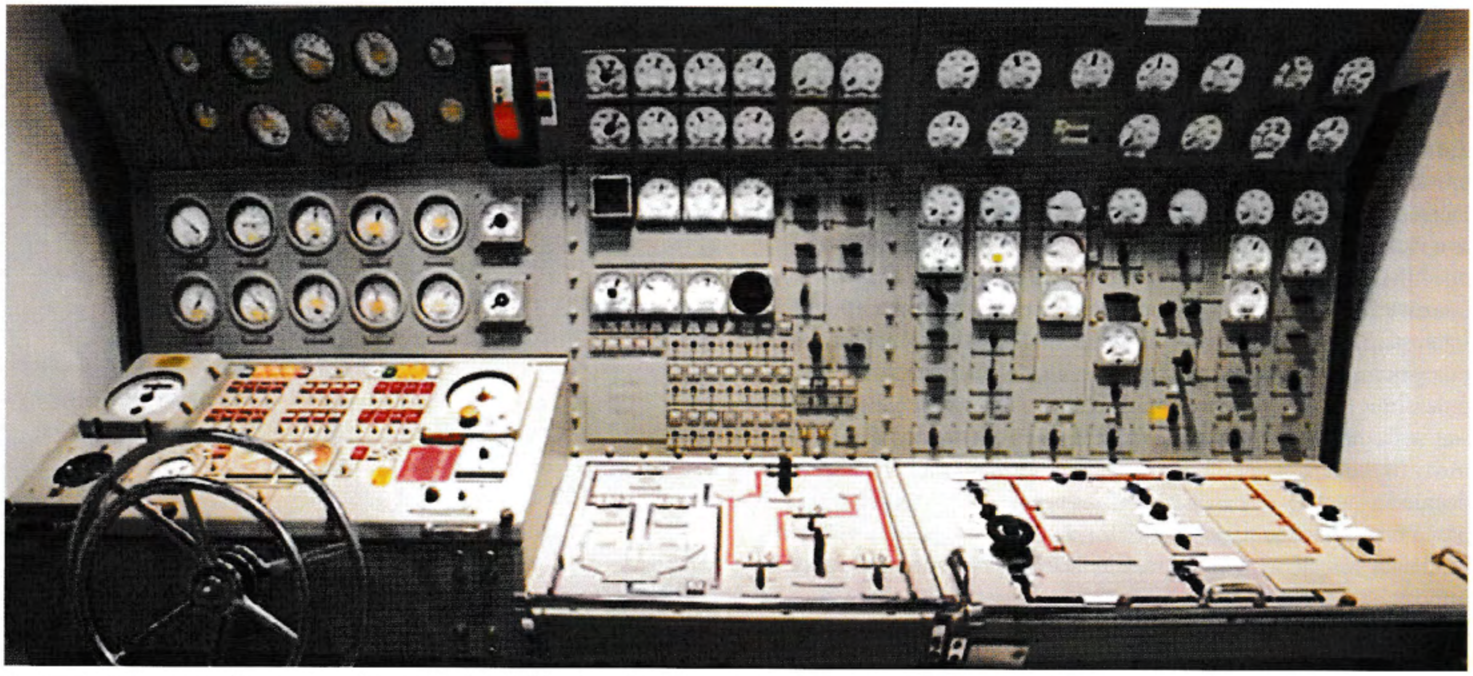

Power control panel in the maneuvering room of an S5W submarine. The panel is divided into three primary control sections. On the left is the propulsion power control. The large wheel controls ahead speed; the smaller wheel inside the larger wheel is astern speed. To the left is the engine telegraph, and above it, the RPM indicator. The gauges above indicate various parameters within the engine room and twin propulsion turbines. The center panel contains the reactor control panel gauges. The right-most panel controls the SSTGs and electrical distribution to the different busses which distribute electrical power. Both AC and DC current are provided. In older submarines, a motor/generator set was employed for AC/DC and DC/AC conversions; newer submarines use solid-state rectifiers.