NUCLEAR MARINE PROPULSION

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1. INTRODUCTION

Several trends are shaping the envisioned future of naval ship technology: the all electrical ship, shrouded jet-pump propulsors, directed energy laser, microwave and electromagnetic weapons, hypersonic cruise missiles, stealth technology, Unmanned Aerial Vehicles (UAVs), swarm Underwater Unmanned Vehicles (UUVs) robot submarines, propulsor water jet propulsion, magneto-hydrodynamic propulsion, littoral vessels and moored barges for power production. The all-electric ship propulsion concept was adopted for the future USA surface combatant power source. This next evolution or Advanced Electrical Power Systems (AEPS) involves the conversion of virtually all shipboard systems to electric power; even the most demanding systems, such as propulsion and catapults aboard aircraft carriers. It would encompass new weapon systems such as modern electromagnetic rail-guns and free electron lasers as well as flywheel and super-capacitors energy storage systems. The USA Navy plans to expand its 284-ship fleet to 355 as soon as the mid-2030s.

With the advent of hypersonic weapons delivery systems, configuring the United States Navy (USN) into smaller, nuclear powered platforms with long range UAV strike capabilities is the wave of the future. Hypersonics would be countered by a distributed fleet of small and fast ships. The threat of swarms of any missile type is a threat to USA carriers and they will probably get smaller with a group of UAVs commanded by a human piloted aircraft. They will be vertical launch vehicles with long range disposable tankers flying with them or miniature nuclear reactors as an energy source for long-term loitering and range endurance.

The ships will be smaller and nuclear powered. Conventional ships need refueling every few days and have to have refueling tankers with them. Nuclear ships have far greater speed and endurance. Space is the next battleground and weapons platforms will be more numerous, smaller and unmanned.

Aircraft carriers are statements of intent and global ambition and a visible projection of military power. They are a versatile and potent force that is capable of humanitarian and disaster relief as well as high-end warfighting. Aircraft carriers with a 5,000 personnel crew are reaching a vulnerability crisis that will lead to smaller ships launching drones from dispersed locations.

The USA Navy operates 10 carriers, the UK has two, China has one and is building another. Russia, France and Italy each have a carrier and have been joined by India. It costs the USA Navy more than $100 million per year to keep one of the Nimitz-class carriers at sea, not including the costs of flying operations, ammunition and the salaries of the crew. A USA carrier has more than 3,000 sailors on board. They are operated as strike groups in high threat areas including air-defense destroyers, anti-submarine warfare frigates and attack submarines along with fuel tankers and solid support ships carrying food and ammunition. Navies around the world use the rule of thirds: or every ship at sea, one is getting ready for a deployment, while another is back in port, undergoing maintenance. Nuclear-powered carriers such as the Nimitz class ones have unlimited operational ranges, whereas conventionally powered ones such as the HMS Queen Elizabeth has a 10,000 miles range.

Most aircraft carriers operate catapults to launch their jets and arresting wires to recover them by what is called "cats and traps". In others, jets take off from a "ski jump" at the front of the ship and then hover to land. The USA Navy operates older F-18 and the newer F-35 aircrafts. The USA Lockheed-Martin F-35 stealth fighter is designed to strike deep into enemy territory while being harder to detect by enemy radar. Three variants of this fighter have been developed: the A variant for land bases, the B variant for Short Take-Offs and Vertical Landings (STOVL) and the C variant for aircraft carriers fitted with "cats and traps". The B variant is more expensive than the A because it needs a lift fan propulsion system to hover. As a result it is also heavier and has a shorter range at about 900 nautical miles (1.036 miles / 1,666km). The production cost for a F-35 is $120 million (£95m). Software, spare parts and support add to the price.

An all-electric ship is the CVN-78 next-generation USA Navy aircraft carrier Gerald R. Ford, planned to replace the retired half-century-old USS Enterprise CVN-65. The CVN-78'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). A design challenge is addressing the vulnerability of electrical systems in general to sophisticated countermeasures and Electro Magnetic Pulses (EMPs).

Littoral vessels are designed to operate closer to the coastlines than existing vessels such as cruisers and destroyers. Their mission would be signal intelligence gathering, stealth insertion of Special Forces, mine clearance, submarine hunting and occasional humanitarian relief missions. Swarms of Unmanned Underwater Vehicles (UUVs) monitored by nuclear-powered Virginia-class submarines would use Continuous Active Sonar (CAS) arrays which release a steady stream of energy, the sonar equivalent of a flashlight and would be used to act as robots to protect carrier groups and in turning attacking or ambushing submarines from being hunters into being prey.

The Russian-deployed supersonic jets-launched hypersonic cruise missile "Kinzhal" is a modified "Iskander" surface to surface medium range missile with a nuclear warhead that does not follow a ballistic trajectory. It is designed to counter aircraft carrier groups. Aircraft carriers are currently protected from missiles by the Phalanx Vulcan guns. A longer range defense system using lasers, electromagnetic guns or a space-based system needs development since with a nuclear tipped missile, like in horse shoes and hand grenades, "even close will count."

A "Force Structure Assessment" report released in December 2016 calls for expanding the Navy from its fleet of 272 to 355 vessels over the next 30 years. Suppliers include General Dynamics Corp. and Huntington Ingalls Industries Inc., the nation's primary makers of combat vessels, as well as Lockheed Martin Corp., with its Aegis combat system, and Raytheon Co., which makes electronic combat systems and the new Air and Missile Defense Radar. The goals would boost by 16 the number of "large surface combatants" such as destroyers, cruisers or both. It would add one aircraft carrier in addition to the 11 mandated by law, 18 more attack submarines and as many as four new amphibious warfare ships. The Congressional Research Service estimates a 350-ship Navy would cost an average of $4 billion extra annually over the current forecast of about $16.3 billion a year for new ship construction through 2021.

The largest experience in operating nuclear power plants since the late 1950s has been in nuclear marine propulsion, particularly aircraft carriers (Fig. 1) and submarines. The nuclear powered vessels comprise about 40 percent of the USA Navy's combatant fleet, including the entire sea based strategic nuclear deterrent. All the USA Navy's operational submarines and over half

of its aircraft carriers are nuclear-powered. Silent submarines cruise at typically 3-5 knots for Missile Carriers boomers and 10-20 for Fast Attack Submarines, SSNs.

The USA Navy had as of 2008, 10 Nimitz-class carriers, one Enterprise-class carrier; to be retired, 18 Ohio-class missile boats; 14 carrying ballistic missiles, and 4 armed with cruise missiles, 44 Los Angeles class attack submarines, and 3 Seawolf class attack submarines; including the signal intelligence and special-forces insertion special warfare designed USS Jimmy Carter. As of 2008 it operated 99 vessels powered by nuclear reactors including 10 nuclear powered aircraft carriers and 71 submarines. It has operated nuclear powered ships for more than 50 years. As of 2001, about 235 naval reactors had been built at a unit cost of about $100 million for a submarine and $200 million for an aircraft carrier reactor.

The main considerations here are that nuclear powered submarines do not consume oxygen like conventional power plants, and that they have large endurance or mission times before fuel resupply, limited only by the available food and air purification supplies on board. Surface vessels equipped with nuclear plants have long refueling intervals and do not need to be accompanied by vulnerable fuel supply tankers.

Figure 1. Nuclear aircraft carrier USS Theodore Roosevelt, Nimitz Class CVN-71, powered with two A4W (A for Aircraft carrier, 4 for fourth generation and W for Westinghouse) nuclear reactors with 100 MW of rated power each, crossing the Suez Canal, Egypt, during the first Gulf War, January 1991. Source: USA Navy.

By 2002, the USA Navy operated 53 fast attack submarines (SSN) and 18 ballistic missile submarines (SSBN) or Boomers. These used by 1999 about 129 nuclear reactors exceeding the number of commercial power plants at 108. The mission for nuclear powered submarines is being redefined in terms of signal intelligence gathering and special operations.

SSNs seek and destroy enemy submarines and surface ships. They comprise 73 percent of the submarine force comprising the Virginia (12 missile tubes, 4 torpedo tubes), Los Angeles (top speed 40 knots) and Seawolf (top speed 25 knots) classes of submarines. The boomers SSBNs, are ballistic missile submarines serving as undetectable launch platforms for intercontinental and nuclear missiles. The Ohio class of submarines can be operated up to 15 years without overhaul and can carry up to 24 ballistic missiles. The SSGNs guided missile submarines can carry 66 special-forces personnel and up to 154 Tomahawk missiles.

During World War II, submarines used diesel engines that could be run on the water surface, charging a large bank of electrical batteries. These could later be used while the submarine is submerged, until discharged. At this point the submarine had to resurface to recharge its batteries and become vulnerable to detection by aircraft and surface vessels.

Even though special snorkel devices were used to suck and exhaust air to the submarine shallowly submerged below the water's surface, a nuclear reactor provides it with a theoretical infinite submersion time. In addition, the high specific energy, or energy per unit weight of nuclear fuel, eliminates the need for constant refueling by fleets of vulnerable tankers following a fleet of surface or subsurface naval vessels. On the other hand, a single refueling of a nuclear reactor is sufficient for long intervals of time.

Initially, the General Electric (GE) Company was assigned to develop a liquid metal concept; and the Westinghouse Company, a pressurized water concept. Each company built an AEC-owned and -financed nuclear development laboratory. Westinghouse purchased the original site of the Allegheny County Airport in a suburb of Pittsburgh, Pennsylvania for what became known as the Bettis Atomic Power Laboratory. GE built the Knolls Atomic Power Laboratory in New York.

The Westinghouse program produced results first. Using pressurized water as the coolant showed how corrosive hot water could be on the metal cladding surrounding the fuel. Westinghouse discovered that pure zirconium resisted such corrosion. Westinghouse built its own facility to produce it. The pure metal initially formed the cladding for the fuel elements to be later replaced by a zirconium alloy, with trade name as Zircaloy that improved its performance.

With a high enrichment level of 93 percent, capable of reaching 97.3 percent in U^{235}, naval reactors are designed for a refueling after 10 or more years over their 20-30 years lifetime, whereas land-based reactors use fuel enriched to 3-5 percent in U^{235}, and need to be refueled every 1-1 1/2 years period. New cores are designed to last 50 years in carriers and 30-40 years in submarines, which is the design goal of the Virginia class of submarines.

Burnable poisons such as gadolinium or boron are incorporated in the cores. These allow a high initial reactivity that compensates for the build-up of fission products poisons over the core lifetime, as well as the need to overcome the reactor dead time caused by the xenon poison changes as a result of operation at different power levels.

Naval reactors use high burn-up fuels such as uranium-zirconium alloys, uranium-aluminum alloys, and metal ceramic fuels, in contrast to land-based reactors which use uranium dioxide UO_2. These factors provide the naval vessels theoretical infinite range and mission time.

For these two considerations, it is recognized that a nuclear reactor is the ideal engine for naval propulsion.

A compact pressure vessel with an internal neutron and gamma ray shield is required by the design while maintaining safety of operation. Their thermal efficiency is lower than the thermal efficiency of land based reactors because of the emphasis on flexible power-level operation rather than steady state operation, and of space constraints.

Rated reactor powers range from 10 MW in prototypes to 20-200 MW in subsurface vessels, and 500 MW in surface ships and larger submarines. Newer designs contemplate the use of jet pump propulsors instead of propellers, and aim at an all electrical system design, including the weapons systems such as lasers and electromagnetic guns.

2. NUCLEAR 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. Figure 3 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 under the Arctic Ocean's ice. 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 2. The "Nautilus", the first nuclear powered submarine, in a movie based on Jules Vernes science fiction book: "One Thousand Leagues Under The Sea".

Figure 3. The "Nautilus", the first nuclear powered submarine at sea, visiting New York, 1953, and now a museum. Source: USA Navy.

Figure 4. Nuclear propulsion is the alternative to vulnerable fuel resupply ships such as the Rappahannock, crossing the Panama Canal.

Figure 5. Nuclear propulsion, as it does not need oxygen to run diesel engines to recharge its storage batteries, eliminates the need for the detectable "snorkel" systems used on German submarines during World War II.

3. POWER REQUIRED TO PROPEL A SUBMERGED BODY

The fluid-mechanics analysis of the motion of a submerged body can be described by the Navier-Stokes Equations. A simple analysis using conservation of energy and conservation of mass is here attempted.

The power required to propel a cylindrical fluid column moving at a constant speed V without friction or drag is the rate of change in its kinetic energy:

$$P = \frac{dE}{dt} \tag{1}$$

Expressing the kinetic energy as:

$$E = \frac{1}{2}mV^2, \tag{2}$$

And substituting from Eqn. 2 into Eqn. 1, we get:

$$P = \frac{dE}{dt} = \frac{d}{dt}(\frac{1}{2}mV^2)$$

Applying the chain rule of differentiation:

$$\frac{d}{dt}(u.v) = u\frac{dv}{dt} + v\frac{du}{dt},$$

then:

$$P = \frac{1}{2}\left(\frac{d}{dt}(mV^2)\right)$$
$$= \frac{1}{2}\left(2mV\frac{dV}{dt} + V^2\frac{dm}{dt}\right)$$

For cruising at a constant speed V,

$$\frac{dV}{dt} = 0$$

And consequently the power can be expressed in terms of its constant speed V and the mass flow rate as:

$$P = \frac{1}{2}\left(\frac{d}{dt}(mV^2)\right)$$
$$= \frac{1}{2}\dot{m}V^2$$

(3)

If the cross sectional area of the cylindrical body is S, and its density is ρ, the mass flow rate is:

$$\dot{m} = \rho SV$$

(4)

By substituting from Eqn. 4 into Eqn. 3, this yields the power content of the columnar body as:

$$P = \frac{1}{2}\rho SV^3$$

(5)

If the diameter of the cylindrical body is D, then:

$$P = \frac{1}{2}\rho\frac{\pi D^2}{4}V^3$$

(6)

Thus, the power content of the cylindrical object is proportional to the *square* of its diameter D, and more significantly to the *cube* of its speed V. This equation shares the same structure as the Betz Equation describing the attainable power production from a wind turbine, with an air column replacing the water column.

From this relationship we can deduce that the theoretical maximum attainable speed would be:

$$V = \left[\frac{8P}{\pi\rho D^2}\right]^{1/3} = \frac{2}{(\pi\rho)^{1/3}}\frac{P^{1/3}}{D^{2/3}}$$

(7)

The submerged body's speed is proportional to the available power and inversely proportional to its diameter.

EXAMPLE

Consider a column of salt water of diameter D = 10 m, moving with a power of 30 MW. Its theoretical attainable speed at that power level, without drag or friction is:

$$V = \frac{2}{(\pi\rho)^{1/3}} \frac{P^{1/3}}{D^{2/3}}$$

$$= \frac{2}{(\pi \times 1,027 \frac{kg}{m^3})^{1/3}} \frac{(30 \times 10^6 \ Watts)^{1/3}}{(10 \ m)^{2/3}}$$

$$= \frac{2}{14.8} \times \frac{310.7}{4.64} = 9.1 \frac{m}{sec}$$

$$= 9.1 \frac{m}{sec} \frac{60 \times 60}{1,000} \frac{km}{m} \frac{sec}{hr} = 32.8 \frac{km}{hr}$$

$$= 32.8 \frac{km}{hr} \frac{1}{1.852} \frac{knot}{km/hr} = 17.7 \ knots \,(nautical \ miles/hr)$$

$$= 32.8 \frac{km}{hr} \frac{1}{1.151} \frac{mph}{km/hr} = 28.5 mph$$

where the knot unit of speed corresponds to one nautical mile per hour or 1.852 km / hr or 1.151 mph.

For comparison, 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.

Notice that the submerged speed is higher than the surfaced speed, because of the absence of wave friction.

The maximum power output of current Air Independent Propulsion (AIP) power plants such as those using fuel cells powered by compressed hydrogen and oxygen, is around 400 HP or 0.3 MW. A conventional diesel-electric plant of the U 212 class of submarines is around 3,000 HP or 2.25 MW. A typical nuclear submarine propulsion plant produces about 20,000 HP or 15 MW. Since the power required to propel a submerged body varies with the cube of its velocity, it is deduced that conventional and nuclear propulsion will predominate in the immediate future.
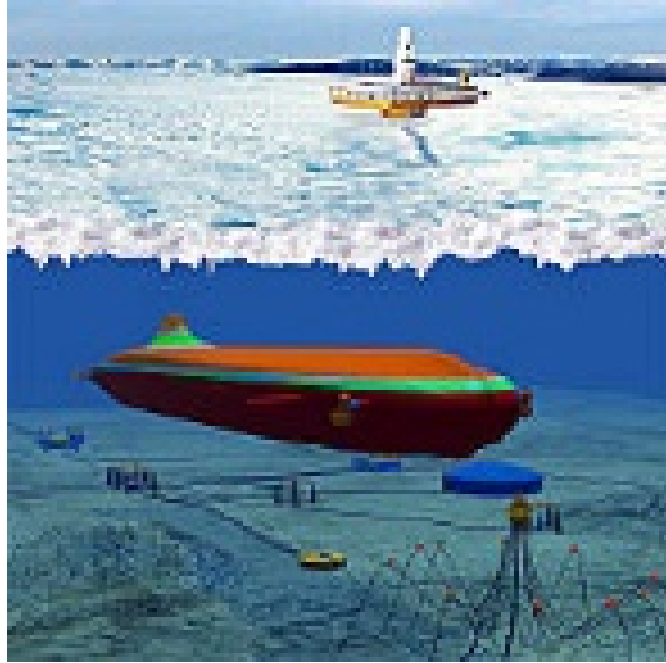
Figure 6. Underwater oil tanker concept for the Arctic region can operate at high submerged speed avoiding surface wave friction and drag.

Figure 7 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.

An 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 Uranium^{235} 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 reactor dead time. The Nautilus broke 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 ZrO_2 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.
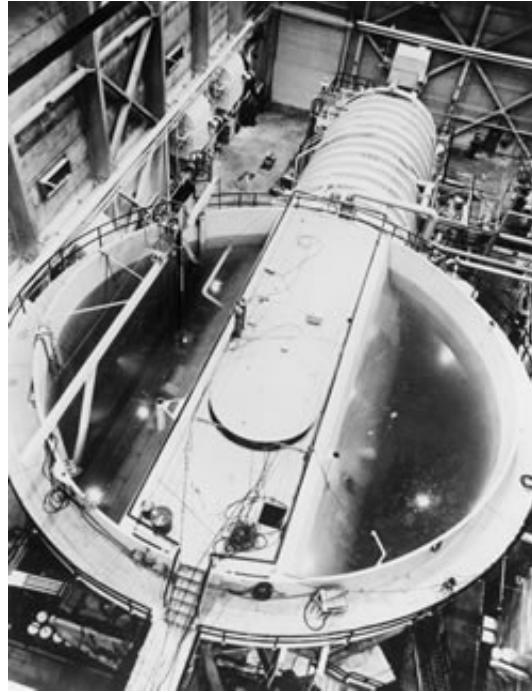

Figure 7. Experimental setup for testing Nautilus-type naval reactors at the Idaho National Engineering Laboratory, INEL, 1989.

4. NAVAL REACTOR EVOLUTION AND 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. Naval reactors went through 9 design generations compared with 3 for land-based systems.

According to the type of vessel they power, they have different first letter designations: A for Aircraft carrier, C for Cruiser, D for Destroyer 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 U^{235}. 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 burnable poison doping provides a long core life, and the radial doping provides for an even power and fuel burnup distribution.

STR OR S1W PRESSURIZED WATER REACTOR DESIGN

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 an alloy of U and Zr and clad in Zr. The maximum temperature in the fuel was 645 ºF and the sheath temperature was 551 ºF 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 U^{235} 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 Seawolf class of submarines was equipped with a single S6W reactor, whereas the Virginia class of submarines is 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 PROTOTYPE PLANTS

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 A1W plant 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 525-545 °F 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 steam 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 by gears 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 UO_2 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.

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, the S1G reactor facility and its Horton Sphere were later reused for the D1G prototype destroyer reactor.

A disadvantage is that the Na 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, Na and CO_2. 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 superheater 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, EBOR

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 UO_2 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, MORE

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 allowed operation at high temperatures but did not corrode metal like water did.

Also, it operated at low pressures, significantly reducing the risk of leakage. 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 ºF 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 eventually turns into a gummy and black breakup product and needs constant replenishment.

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 ºF. 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 natural convection thermal circulation, not by pumps. Use of natural circulation instead of pumps reduced the noise level in a submarine.

Innovations included in the Narwhal were a natural circulation reactor plant, scoop seawater injection; which was not repeated, the ability to cross-connect the main and auxiliary

seawater systems, main air ejectors instead of noisy R-114 units for cooling, and a directly coupled main engine steam turbine. Her small reactor coolant pumps had an on and off speeds. This resulted in the quietest submarine of her era, and for many years to follow. Her silence was equaled only by the Ohio class and finally surpassed by the Seawolf class which is powered by a single S6W nuclear reactor delivering 45,000 hp to a low-noise pump jets. In contrast to a traditional bladed-propellor, the Virginia class also uses pump jet propulsors, originally developed for the Royal Navy Swiftsure class submarines, the propulsor significantly reduces the risks of cavitation and allows quieter operation.

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 fail-safe 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 neutron moderation and hence 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. It produces about 40,000 shaft horsepower, or about 30 MW of power.

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 1. 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, ECF

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.

5. NAVAL REACTORS RESEARCH AND DEVELOPMENT

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 tonnes of spent fuel.

6. COMMERCIAL NUCLEAR SHIPS:

The USA built one single nuclear merchant ship: the Savannah, shown in Fig. 8. Service speeds of 32 knots and even 50 knots are achievable. It was designed as a national showpiece, and not as an economical merchant vessel. In the design of its nuclear reactor, 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.

The PWR reactor was 5.2 m high with a core 1.60 m in diameter and 1.70 cm high, with 32 fuel elements. Each fuel element was 1.3 cm in diameter and housed 164 UO_2 pellets enriched to an average of 4.4 percent. The 16 center elements were enriched to 4.2 percent, and the outer 16 elements to 4.6 percent. The fuel pellets were 1.078 cm in diameter, with pressurized helium gas in the annular space between the pellets and the element walls. Twenty one control rods were used, 170 cm long, 20 cm across and 0.95 cm thick. The level of fuel enrichment required refueling after 3 years after travelling 350,000 miles.

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 was the most successful civilian nuclear ship and operated successfully for ten years (Fig. 9). As a cargo ship and research facility, the vessel was launched in 1964 and refueled in 1972. It sailed 650,000 nautical miles, over 126 voyages. Diesel fuel propulsion was installed in 1979 for economic reasons. In its ten years sailing under nuclear power it saw no major technical difficulties [10].

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. It was carrying a 45 Megawatts Thermal (MWth) Pressurized water Reactor (PWR) for remote power supplies for the USA Army.

Figure 8. The Savannah, the first nuclear USA merchant ship used Low Enriched Uranium (LEU) fuel in the range of 4.2-4.6 percent. It was powered by a single 74 MW Babcock and Wilcox nuclear core powering two De Laval steam turbines.
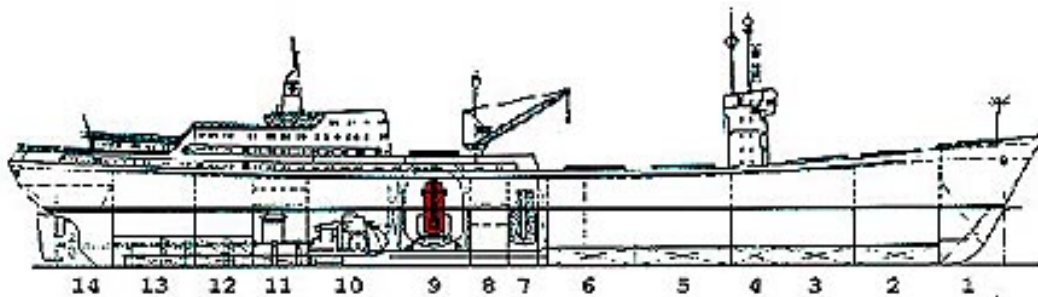
Figure 9. The NS Otto Hahn nuclear bulk carrier.

7. MARINE AND NAVAL 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 arbitrarily enriched to the 3-5 percent range to avoid the circulation of highly enriched fuel, yet negatively impacting the economics in terms of reactor sizes of land-based systems.. 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.
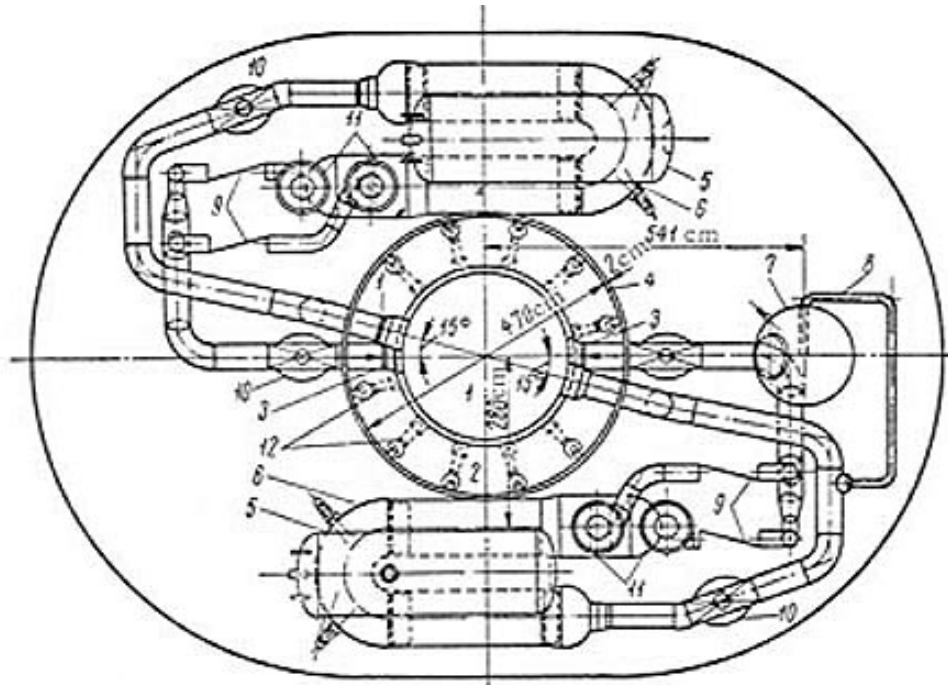
Figure 10. Loop type of naval reactor design for the nuclear ship Savannah. The reactor core is surrounded by the heat exchangers and the steam drums. The horizontal steam generator was replaced by a vertical tube steam generator and an integrated system in future designs. 1: Reactor core, 2: Water shield, 3: Coolant inlet, 4: Pb Shield layer, 5: Steam drum, 6: Heat exchanger, 7: Pressurizer, or volume compensator, 8: Equalizer line, 9: Cutoff channel, 10: Gate valve, 11: Coolant pumps, 12: Channels with apparatus [5].

Figure 11. Savannah Pressurized Water Reactor PWR vessel.
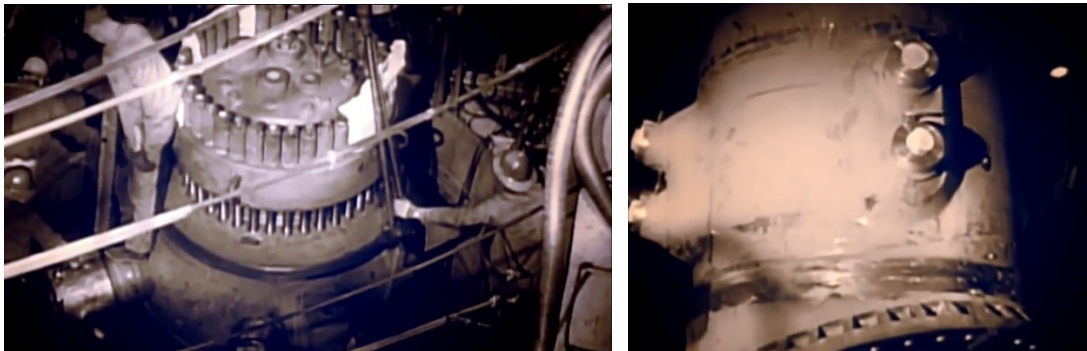
Figure 12. Top and side of Pressurized Water Reactor PWR vessel.

Figure 13. Control Room of the NS Savannah nuclear ship [10].

Figure 14. Submarine steering in control room. Source: USA Navy.
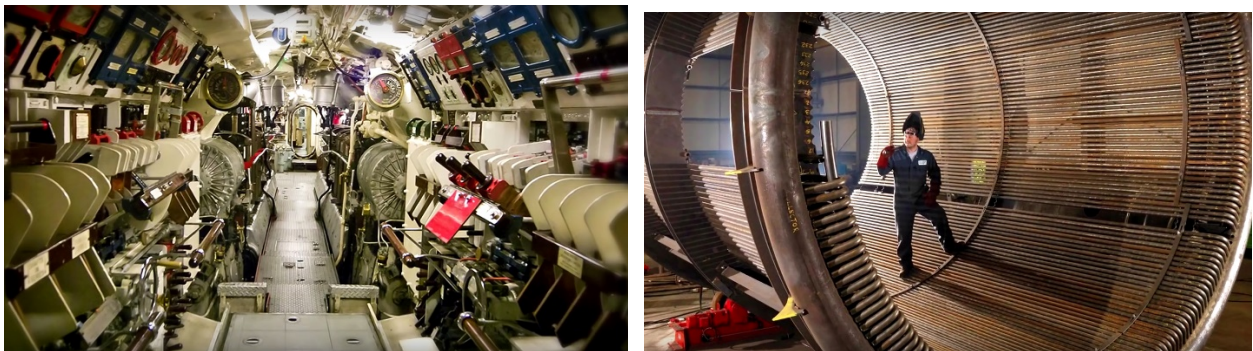
Figure 15. Submarine welded hull interior. Source: USA Navy.
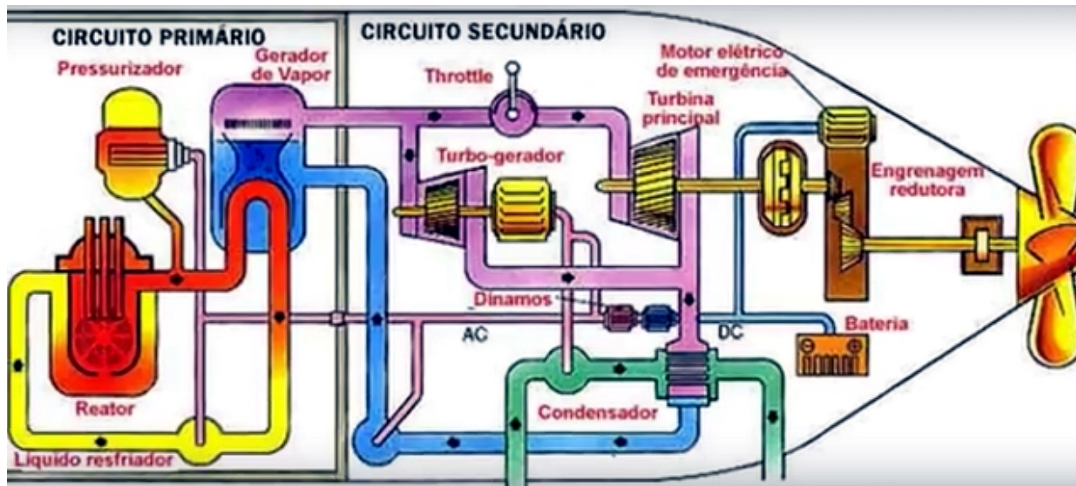
Figure 16. Nuclear submarine primary and secondary propulsion and gear reduction systems. Source: Brazilian Navy.

Figure 17. The MH-1A Sturgis Floating Nuclear Power Plant for remote power applications for the USA Army.

Table 2 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 U^{234}, which ends up being separated with the U^{235} 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 U^{234} 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 U^{234}. Most of the dose prior to operation from the fuel is caused by U^{235} decay gammas and the spontaneous fission of U^{238}. 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 2. 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 Fig. 11 for the Savannah reactor. There exists a multitude of naval reactor designs. More modern designs use the Integral circuit type shown in Fig. 18, where the reactor core and the steam generators are enclosed within the same pressure 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.
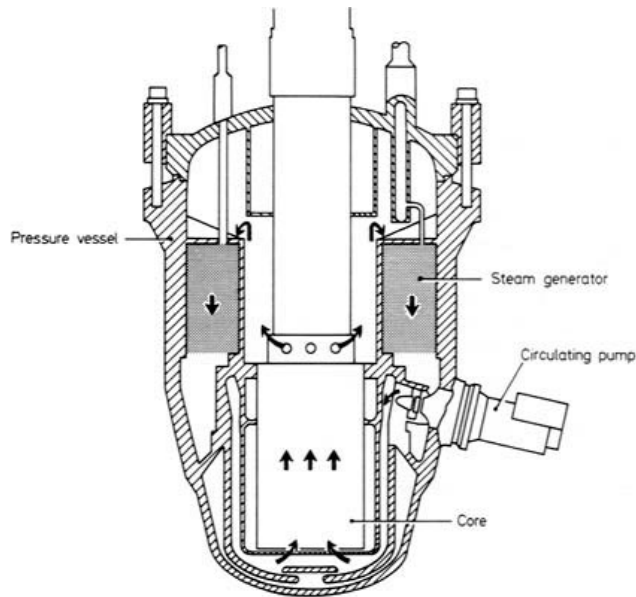
Figure 18. Integral type of naval reactor vessel [4].

The secondary shielding consists of concrete, lead, and polyethylene and is positioned at the top of the containment. A pre-stressed 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 inhomogeneity.

The polyethylene sheets are spaced so as to allow thermal expansion. Thick collison 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 collison 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 18 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.
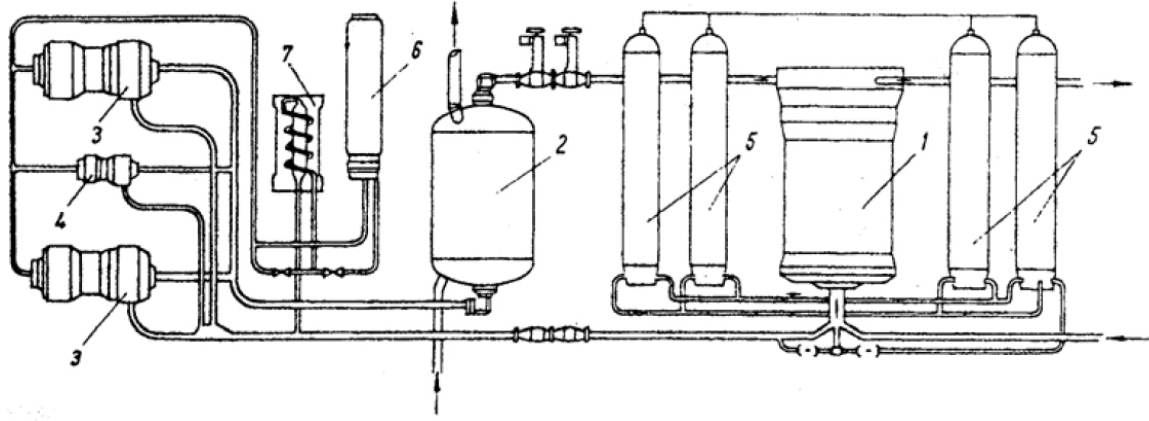

Figure 19. Components of OK-150 plant. 1: Reactor, 2: Steam generator, 3: Main circulation pumps, 4: Emergency cooling pump, 5: Pressurizers, 6: Filter, 7: Filter cooler.
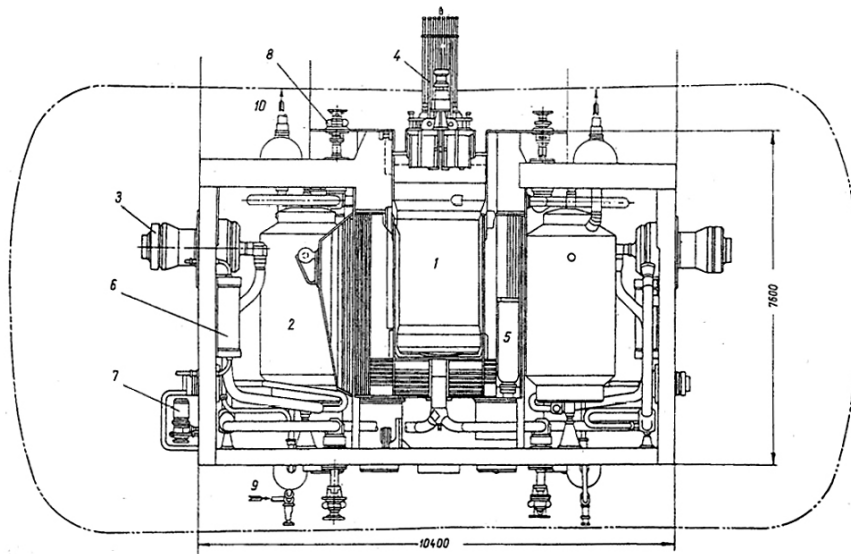

Figure 20. Layout of OK-150 plant configuration. 1: Reactor, 2: Steam generator, 3: Main circulation pumps, 4: Control rod drives mechanism, 5: Filter, 6: Cooler, 7: Emergency cooling pump, 8: Primary circuit pressure relief valve, 9: Feedwater inlet, 10: Steam outlet.
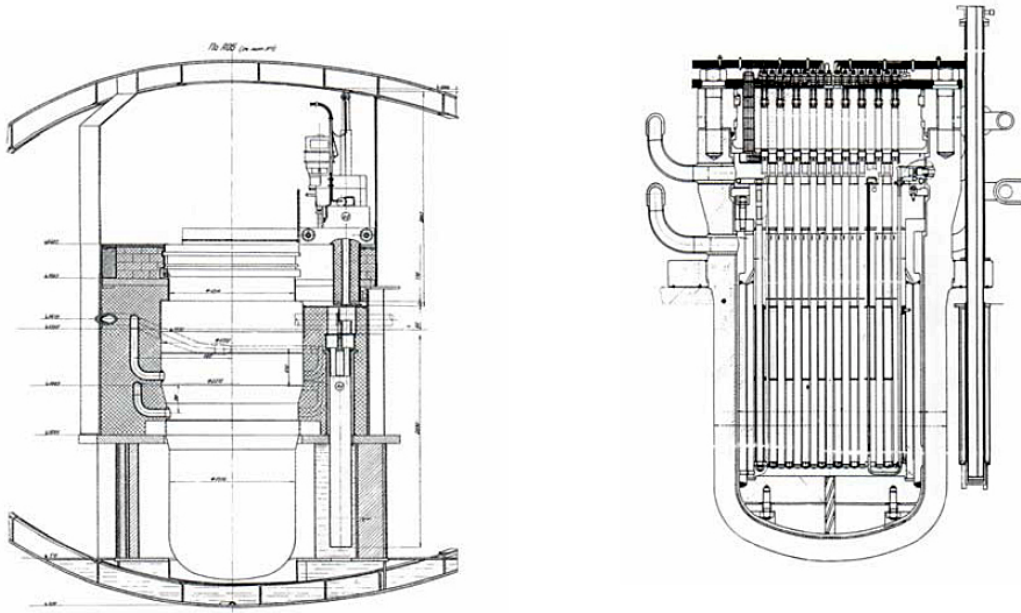
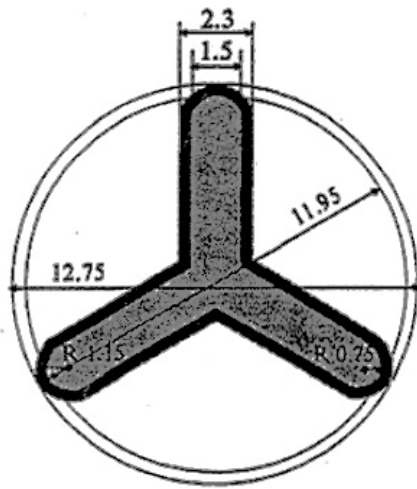Figure 21. First generation VM-A Russian submarine reactor vessel.
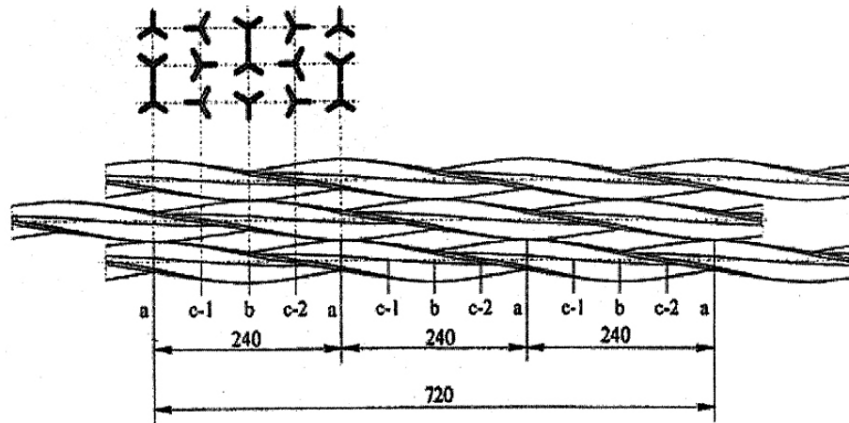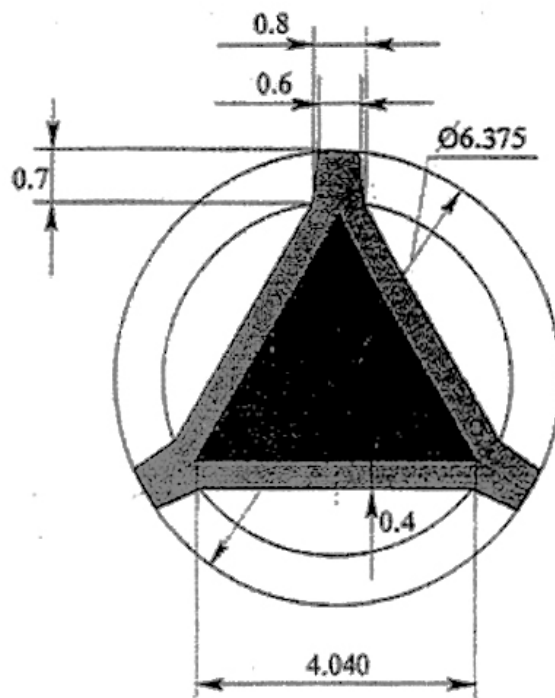
Figure 22. Spiral fuel element configuration.

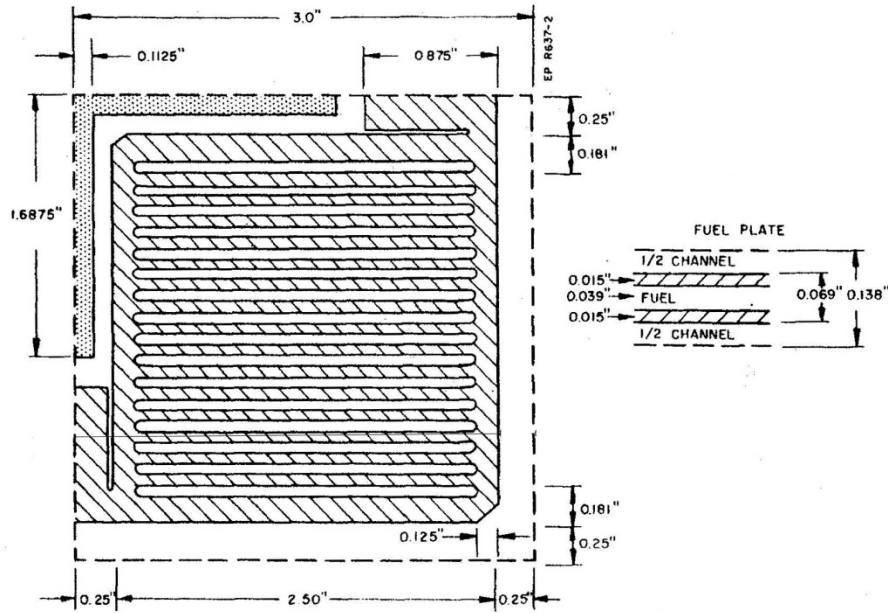Figure 23. Triangular fuel element configuration.

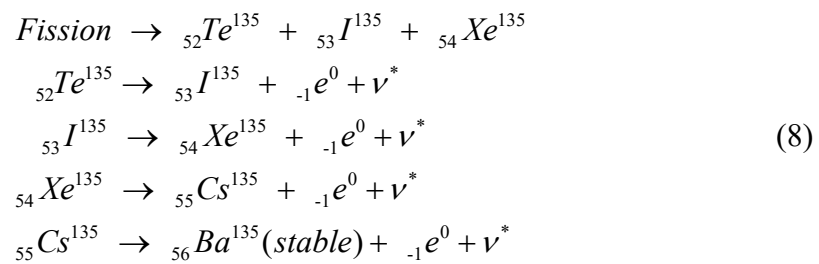Figure 24. Plate fuel element configuration.

8. XENON POISON FORMATION

The fission process generates a multitude of fission products with different yields. Table 3 shows some of these fission products yields resulting from the fission of three fissile isotopes:

Table 3. Fission products yields from thermal 2200 m/sec neutrons, γ_I [nuclei/fission event].

Isotope	$_{92}U^{233}$	$_{92}U^{235}$	$_{94}Pu^{239}$
$_{53}I^{135}$	0.04750	0.06390	0.06040
$_{54}Xe^{135}$	0.01070	0.00237	0.01050
$_{61}Pm^{149}$	0.00795	0.01071	0.01210

The most prominent of these fission products from the perspective of reactor control is $_{54}Xe^{135}$. It is formed as the result of the decay of $_{53}I^{135}$. It is also formed in fission and by the decay of the Tellurium isotope: $_{52}Te^{135}$. This can be visualized as follows:

$$Fission \rightarrow {}_{52}Te^{135} + {}_{53}I^{135} + {}_{54}Xe^{135}$$
$$_{52}Te^{135} \rightarrow {}_{53}I^{135} + {}_{-1}e^0 + v^*$$
$$_{53}I^{135} \rightarrow {}_{54}Xe^{135} + {}_{-1}e^0 + v^* \qquad (8)$$
$$_{54}Xe^{135} \rightarrow {}_{55}Cs^{135} + {}_{-1}e^0 + v^*$$
$$_{55}Cs^{135} \rightarrow {}_{56}Ba^{135}(stable) + {}_{-1}e^0 + v^*$$

The half-lives of the components of this chain are shown in Table 4. The end of the chain is the stable isotope $_{56}Ba^{135}$.

Because $_{52}Te^{135}$ decays rapidly with a half-life of 11 seconds into $_{53}I^{135}$, one can assume that all $_{53}I^{135}$ is produced directly in the fission process.

Denoting I(t) as the atomic density of iodine in [nuclei/cm³], one can write a rate equation for the iodine as:

$$\frac{dI(t)}{dt} = [rate\ of\ formation\ of\ Iodine\ from\ fission]$$

$$- [rate\ of\ radioactive\ transformations\ of\ Iodine] \qquad (9)$$

$$\frac{dI(t)}{dt} = \gamma_I \Sigma_f \psi - \lambda_I I(t)$$

where: γ_I is the fission yield in [nuclei/fission event],

ψ is the thermal neutron flux in [n/(cm².sec)],

Σ_f is the thermal fission cross section in [cm⁻¹],

λ_I is the decay constant in [sec⁻¹], with $\lambda_I = \dfrac{\ln 2}{T_{1/2}}$, $T_{1/2}$ is the half life.

Table 4. Half-lives of isotopes in the xenon chain.

Isotope	Half Life, $T_{1/2}$
$_{52}Te^{135}$	11 sec
$_{53}I^{135}$	6.7 hr
$_{54}Xe^{135}$	9.2 hr
$_{55}Cs^{135}$	2.3×10^6 yr
$_{56}Ba^{135}$	Stable

A rate equation can also be written for the xenon in the form:

$$\frac{dX(t)}{dt} = [rate\ of\ formation\ of\ Xenon\ from\ fission]$$

$$+ [rate\ of\ formation\ of\ Xe\ from\ the\ transformation\ of\ the\ Iodine]$$

$$- [rate\ of\ radioactive\ transformations\ of\ Xenon]$$

$$- [rate\ of\ disappearance\ of\ Xenon\ (X)\ through\ neutron\ absorptions], \qquad (10)$$

$or:$

$$\frac{dX(t)}{dt} = \gamma_X \Sigma_f \psi + \lambda_I I(t) - \lambda_X X(t) - \sigma_{aX} \psi X(t)$$

where σ_{aX} is the thermal microscopic absorption cross section for Xenon equal to 2.65 x 10⁶ [b].

The large value of the absorption cross section of Xe, and its delayed generation from Iodine, affect the operation of reactors both under equilibrium and after shutdown conditions.

9. IODINE AND XENON EQUILIBRIUM CONCENTRATIONS

Under equilibrium conditions, the rate of change of the Iodine as well as the xenon concentrations is zero:

$$\frac{dI(t)}{dt} = \frac{dX(t)}{dt} = 0 \tag{11}$$

This leads to an equilibrium concentration for the Iodine as:

$$I_0 = \frac{\gamma_I \Sigma_f \psi}{\lambda_I} \tag{12}$$

The equilibrium concentration for the Xenon will be:

$$X_0 = \frac{\gamma_X \Sigma_f \psi + \lambda_I I_0}{\lambda_X + \sigma_{aX} \psi} \tag{13}$$

Substituting for the equilibrium concentration of the iodine, we can write:

$$X_0 = \frac{(\gamma_X + \gamma_I) \Sigma_f \psi}{\lambda_X + \sigma_{aX} \psi} \tag{14}$$

10. REACTIVITY EQUIVALENT OF XENON POISONING

Ignoring the effects of neutron leakage, since it has a minor effect on fission product poisoning, we can use the infinite medium multiplication factors for a poisoned reactor in the form of the four factor formula:

$$k = \eta \varepsilon p f \tag{15}$$

and for an unpoisoned core as:

$$k_0 = \eta \varepsilon p f_0 \tag{16}$$

We define the reactivity ρ of the poisoned core as:

$$\rho = \frac{k - k_0}{k} = \frac{\Delta k}{k} = \frac{f - f_0}{f} = 1 - \frac{f_0}{f} \qquad (17)$$

In this equation,

$\eta = \dfrac{\nu \Sigma_f}{\Sigma_{aF}}$, is the regeneration factor,

ε is the fast fission factor,
p is the resonance escape probability,
ν is the average neutron yield per fission event,
Σ_f is the macroscopic fission cross section,
Σ_{aF} is the macroscopic absorption cross section of the fuel,
f is the fuel utilization factor.

The fuel utilization factor for the un-poisoned core is given by:

$$f_0 = \frac{\Sigma_{aF}}{\Sigma_{aF} + \Sigma_{aM}} \qquad (18)$$

And for the poisoned core it is:

$$f = \frac{\Sigma_{aF}}{\Sigma_{aF} + \Sigma_{aM} + \Sigma_{aP}} \qquad (19)$$

where:

Σ_{aM} is the moderator's macroscopic absorption coefficient,
Σ_{aP} is the poison's macroscopic absorption coefficients.

From the definition of the reactivity in Eqn. 17, and Eqns. 18 and 19 we can readily get:

$$\rho = - \frac{\Sigma_{aP}}{\Sigma_{aF} + \Sigma_{aM}} \qquad (20)$$

It is convenient to express the reactivity in an alternate form. For the unpoisoned critical core:

$$1 = k_0 = \eta \varepsilon p f_0 = \eta \varepsilon p \frac{\Sigma_{aF}}{\Sigma_{aF} + \Sigma_{aM}} \qquad (21)$$

From which:

$$\Sigma_{aF} + \Sigma_{aM} \;=\; \eta\varepsilon p\Sigma_{aF} \tag{22}$$

Substituting this value in the expression of the reactivity, and the expression for the regeneration factor, we get:

$$\rho \;=\; -\;\frac{1}{\nu\varepsilon p}\frac{\Sigma_{aP}}{\Sigma_f} \tag{23}$$

For equilibrium Xenon:

$$\Sigma_{aP} \;=\; \sigma_{aX}X_0 \;=\; \frac{(\gamma_X + \gamma_I)\,\Sigma_f\psi\sigma_{aX}}{\lambda_X + \sigma_{aX}\psi} \tag{24}$$

Inserting the last equation for the expression for the reactivity we get:

$$\rho \;=\; -\;\frac{(\gamma_X + \gamma_I)\psi\sigma_{aX}}{(\lambda_x + \sigma_{aX}\psi)\nu\varepsilon p} \tag{25}$$

Dividing numerator and denominator by σ_{aX} we get:

$$\rho \;=\; -\;\frac{(\gamma_X + \gamma_I)\psi}{(\dfrac{\lambda_x}{\sigma_{aX}} + \psi)\nu\varepsilon p} \tag{25'}$$

The parameter:

$$\varphi = \frac{\lambda_X}{\sigma_{aX}} = 0.77x10^{13} \tag{26}$$

at 20 degrees C, and has units of the flux [neutrons/(cm^2.sec)].
    The expression for the reactivity is written in terms of ϕ as:

$$\rho \;=\; -\;\frac{(\gamma_X + \gamma_I)\psi}{(\varphi + \psi)\nu\varepsilon p} \tag{25''}$$

For a reactor operating at high flux,

$$\varphi \approx \psi\,, \tag{27}$$

and we can write:

$$\rho = -\frac{(\gamma_X + \gamma_I)}{\nu \varepsilon p} \tag{28}$$

For a reactor fueled with U^{235}, $\nu = 2.42$, $p = \varepsilon = 1$, the value for ρ for equilibrium xenon is:

$$\rho = -\frac{(0.00237 + 0.06390)}{2.42} = -\frac{0.06627}{2.42} = -0.027384$$

or a negative 2.74 percent.

11. REACTOR DEAD TIME

A unique behavior occurs to the xenon after reactor shutdown. Although its production ceases, it continues to build up as a result of the decay of its iodine parent. Therefore the concentration of the xenon increases after shutdown. Since its cross section for neutrons is so high, it absorbs neutrons and prevents the reactor from being restarted for a period of time denoted as the reactor dead time. In a land based reactor, since the xenon eventually decays, after about 24 hours, the reactor can then be restarted. In naval propulsion applications, a naval vessel cannot be left in the water unable to be restarted, and vulnerable to enemy attack by depth charges or torpedoes. For this reason, naval reactor cores are provided with enough reactivity to overcome the xenon negative reactivity after shutdown.

To analyze the behavior, let us rewrite the rate equations for iodine and xenon with ψ equal to 0 after shutdown:

$$\frac{dI(t)}{dt} = -\lambda_I I(t) \tag{29}$$

$$\frac{dX(t)}{dt} = +\lambda_I I(t) - \lambda_X X(t) \tag{30}$$

Using Bateman's solution, the iodine and xenon concentrations become:

$$I(t) = I_0 \, e^{-\lambda_I t} \tag{31}$$

$$X(t) = X_0 \, e^{-\lambda_X t} + \frac{\lambda_I}{\lambda_I - \lambda_X} I_0 \, (e^{-\lambda_X t} - e^{-\lambda_I t}) \tag{32}$$

Substituting for the equilibrium values of X_0 and I_0 we get:

$$X(t) = \frac{(\gamma_X + \gamma_I)\Sigma_f \psi}{\lambda_X + \sigma_{aX}\psi} e^{-\lambda_X t} + \frac{\gamma_I}{\lambda_I - \lambda_X}\Sigma_f \psi(e^{-\lambda_X t} - e^{-\lambda_I t}) \tag{33}$$

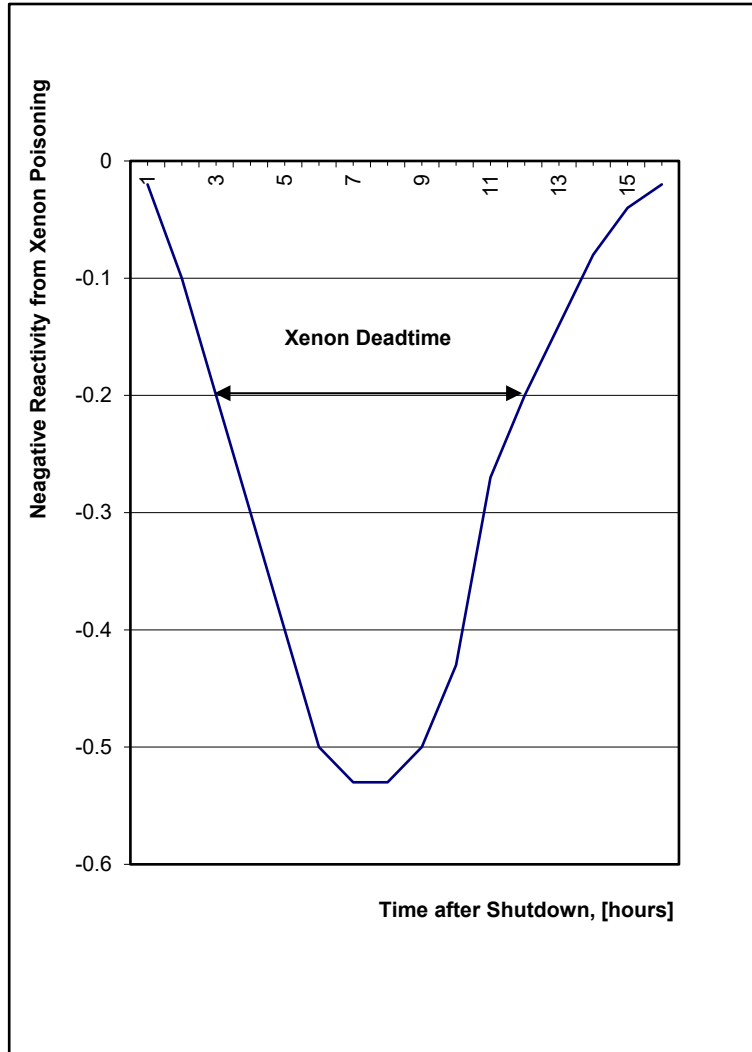The negative reactivity due to xenon poisoning is now a function of time and is given by:

$$\rho(t) = -\frac{1}{\nu \varepsilon p}\frac{\Sigma_{aP(t)}}{\Sigma_f}$$

$$= -\frac{1}{\nu \varepsilon p}\frac{\sigma_{aP}X(t)}{\Sigma_f} \tag{34}$$

$$= -\frac{\sigma_{aP}\psi}{\nu \varepsilon p}\left[\frac{\gamma_X + \gamma_I}{\lambda_X + \sigma_{aX}\psi}e^{-\lambda_X t} + \frac{\gamma_I}{\lambda_I - \lambda_X}(e^{-\lambda_X t} - e^{-\lambda_I t})\right]$$

Figure 25. Negative reactivity due to xenon poisoning. Flux = 5×10^{14} [n/(cm^2.sec)].

Figure 25 shows the negative reactivity resulting from xenon after reactor shutdown. It reaches a minimum value, which occurs at about 10 hours after shutdown. This post shutdown

reactivity is important in reactors that have operated at a high flux level. If at any time after shutdown, the positive reactivity available by removing all the control rods is less than the negative reactivity caused by xenon, the reactor cannot be restarted until the xenon has decayed. In Fig. 25, at an assumed reactivity reserve of 20 percent, during the time interval from 2.5 hours to 35 hours, the reactor cannot be restarted. This period of 35-2.5 = 32.5 hours is designated as the "Reactor Dead Time."

This reactor dead time is of paramount importance in mobile systems that may be prone to accidental scrams. This is more important at the end of core lifetime, when the excess reactivity is limited. For this reason, mobile reactors necessitate the adoption of special design features, providing the needed excess reactivity to override the negative xenon reactivity, such as the use of highly enriched cores.

In land based systems such as the CANDU reactor, booster rods of highly enriched U^{235} are available to override the xenon dead time after shutdown, leading to a higher capacity factor. Power fluctuations induced to follow demand in any power reactor lead to xenon oscillations without any reactor shutdown. The changes of xenon concentrations due to load following are compensated for by adjusting the chemical shim or boron concentration in the coolant, and by control rods adjustments.

12. NUCLEAR NAVIES

INTRODUCTION

The USA Continental Congress authorized on October 13, 1775 the establishment of the first American naval force. The first fleet consisted of seven ships, two 24-gun frigates, two 14-gun brigs and three schooners.

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

In addition to the USA Navy's 10 steaming carriers, three more are now under construction: the U.S.S. Gerald R. Ford should set sail in 2016, the U.S.S. John F. Kennedy is slated to set sail in 2020,and the U.S.S. Enterprise, CVN-80, is slated to sail in 2025.

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 26. Christening of a Trident submarine, with two other vessels 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. Table 5 shows some of the nuclear powered components of the Russian Navy as it existed then.

Table.5. 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	Torpedo Attack submarines.	60
Nuclear Powered Cruiser		
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.

Figure 27. Admiral Kutzetnov Russian non-nuclear aircraft carrier. Uses 8 conventional steam boilers. Because aircraft carriers are banned from passing through the Bosphorus straights under the 1936 Montreux Convention, and otherwise it could not enter the Black Sea, it is referred to as a "battle-cruiser."

Borei-class ballistic-missile submarine, Project 955
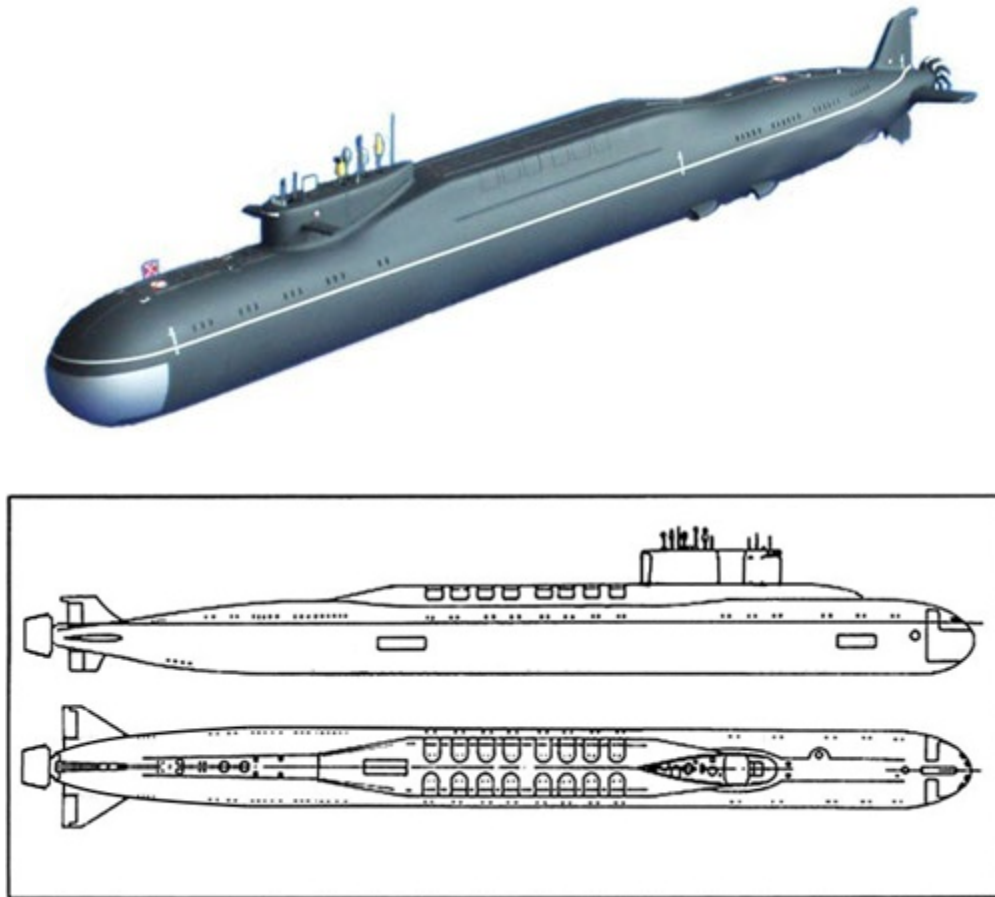
Figure 28. Borei class ballistic missile submarine.

At 14,700 tons of displacement surfaced, the Borei-class submarines are smaller than the large Typhoon-class. Eight are planned to be built, replacing the older Delta-III, Delta IV, and Typhoon class submarines in service. Four would serve with the Northern Fleet and four with the Pacific Fleet.

The first Borei-class submarine, Yuri Dolgoruky, was commissioned into the Russian Navy on January 10, 2013. Three ships have been launched. Construction is being performed by the Sevmash shipyard, which recently completed the transformation of the Indian aircraft carrier Vikramaditya. The class will carry sixteen Bulava submarine launched ballistic missiles, each in turn with 6-10 warheads, for a total of 96 to 196 warheads per submarine. The missile's range is up to 8,300 kilometers.

Yasen class nuclear attack submarine, Project 885

The 4-th generation Russian Project 885 Yasen / Graney-class K-560 Severodvinsk is a hunter submarine. The low-magnetic steel, 90-crew submarine measures 393 feet in length and has a submerged speed of up to 30 knots (32 knots silent and 35 knots maximum) and has a displacement surfaced / submerged of 8,600 / 13,000 tons.

Maximum dive depth is 300 meters. It is armed with long-range (3,100 miles or 5,000 km) cruise missiles, anti-ship cruise missiles, torpedoes and mines, as a replacement for the Akula-class hunter-killer submarines.

Kirov-class nuclear cruisers

The Soviet Union built three Kirov-class nuclear powered battle cruisers in the 1980s. The largest surface combatants built in decades, the Kirov battle cruisers displaced 24,000 tons fully loaded. Of the three ships, Kirov has been scrapped, Pyotr Velikiy is in service and a third, Admiral Nakhimov, is expected to be receive upgrades and return to service.

The Kirov class uses for its primary armament twenty P-700 Granit anti-ship missiles. It was designed so that if just one missile managed to evade the layered defenses of a carrier battle group, it would still do significant damage. Each missile is ten meters long, the size of a small aircraft. Speed is estimated at Mach 2.5, and range at 500 kilometers. The P-700 can carry either a 750 kilogram conventional warhead or a 500 kT of TNT equivalent nuclear warhead.

In the course of their mission, sailing at high speed, battle cruisers would likely outstrip their escorts. Anticipating this the battle cruisers are equipped with strong anti-air defenses. Pyotr Velikiy carries 48 S-300F and 42 S-300FM Fort-FM surface-to-air missiles, the sea-going equivalent of the S-300 "Grumble". For closer-range defense, the ship has 128 SA-N-9 "Gauntlet" surface-to-air missiles, which is the naval version of the SA-15 "Tor" and five Kashtan close-in-weapons systems.

Admiral Kuznetsov Aircraft Carrier

The Admiral Flota Sovetskogo Soyuza Kuznetsov is Russia's only non-nuclear aircraft carrier. Soviet ship designers began work on the design in 1974, and the ship itself was launched in 1985 at the Nikolayev Shipyards in the Ukraine. After the breakup of the Soviet Union the carrier was posted to the Russian Navy's Northern Fleet.

The Admiral Kuznetsov displaces 55,000 tons fully loaded, about half as much as American Nimitz-class carriers. It features three 15-degree ski ramps to assist aircraft takeoff, and has four arrestor wires for landing. Two large elevators can move aircraft back and forth between the hangar and the flight deck. Originally rated to carry up to fifty-two aircraft, the Kuznetsov actually carries much less than that. Her air complement consists of eighteen Su-33 Flanker-D interceptors, four Su-25UTG Frogfoot attack aircraft, fifteen Ka-27 Helix anti-submarine warfare helicopters and two Ka-31 airborne early warning helicopters. The Russian Navy is replacing the Flanker-D fighters with the MiG-29K, a carrier variant of the multi-role fighter originally designed for the Indian Navy.

The aircraft carrier itself has twelve P-700 anti-ship missiles sitting in silos in the bow of the ship, between the aircraft take-off positions. Twenty-four SA-N-9 air defense missiles constitute an outer layer air defense, backed up by eight Kashtan close-in-weapons systems and six AK-630 Gatling guns. Two RPK-5 Liven anti-submarine rocket launchers provide a last-ditch submarine defense.

The Kuznetsov's sister ship, was laid down in 1985 as the "Riga" in Mikolaiv on the Black Sea shipyard in the Ukraine and launched into the water for further construction at the same location in 1988. It was then renamed Varyag after a famous cruiser. Then the Ukrainians sold it

68 percent complete to the Chinese directly in 1998 for a purported use as a floating casino, but eventually was refitted to become China's first aircraft carrier, the Liaoning.

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 already operates a small number of ballistic-missile-carrying submarines and its overall submarine force of some 65 boats is much larger than India's, which stands at some 14 boats.

Figure 29. Jin class Type 094 (top) and 095 (bottom) nuclear powered missile submarine, China's Navy.

Figure 30. Chinese Liaoning non-nuclear aircraft carrier uses 8 conventional steam boilers.

Figure 31. China carrier-targeting missile DF 21D, on parade 2009.

China's naval fleet as of 2008 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 USA's dominance.

China built a submarine factory on the Yellow Sea that will produce nuclear-powered attack submarines. Bohai Shipbuilding Heavy Industrial Corporation (BSHIC) based in Huludao, Liaoning Province, is China's only builder of nuclear submarines. It previously built the Type 091, 093 nuclear attack submarines (SSN) and Type 092 and 094 nuclear ballistic missile submarine (SSBN). It is an enclosed superstructure, where submarines are hidden from snoops, spies, and satellites. It also provides a controlled environment for development and construction. The massive new assembly hall, measures more than 430,000 square feet, and has enough room for two parallel production lines; each production line has one half dedicated to assembling and attaching together submarine modules, and the other half dedicated to finishing the hull with quieting measures like anechoic tiles. That is enough space for four SSN's to be built simultaneously with two sets of modules being assembled at one end, and another pair of assembled hulls being fitted out before launch. Once completed, the SSN is rolled off the line and into the ocean. The assembly hall can also handle construction of the next generation SSBN, the Type 096.

The Type 095 is expected to have a single/hybrid pressure hull, pump-jet propulsion and vertical launch system cells, which are considered as technological advancements compared with older SSNs like the USA's Los Angeles III and Russia's Akula II. The Type 095 SSN, will likely have Vertical Launching System (VLS) cells for launching a wide range of cruise missiles, plus pump-jet propulsion and improved quieting technology.

INDIAN NAVY

India developed a miniature reactor for submarine applications, and is developing the Arihant class of nuclear ballistic submarines. The first submarine, is the INS Arihant (S-73), and

five more are planned. India leased a Charlie class nuclear powered submarine from Russia and planned to acquire two used Akula (Shark)-class submarines. The Arihant has a crew of about 100 sailors on board.

India did lease an older Russian nuclear boat, largely for training purposes, during the late 1980s and early 1990s. Russia supplies about 70 percent of India's military hardware.

A refurbished Russian aircraft carrier with advanced Mig-29K jets will enter service to be followed by an Indian-built aircraft carrier in due course. The refit carrier, the Admiral Gorshkov, and the building of three Krivak-III class frigates have been beset by delays at Russian shipyards.

New USA-built maritime patrol aircraft are on order. Russian and Indian shipyards are completing orders for guided missile frigates and other surface vessels. Six Scorpene-class diesel submarines are being built in India according to a French design.

In 2012, India leased the Russian-built nuclear-powered submarine the INS Chakra for the next 10 years at a cost of about $1bn or £630m. It was originally to be built for the Russian navy. Construction of the Chakra began in 1993 but was halted due to lack of funds. An accidental release of fire-suppressant gas killed a number of workers. The Chakra is an Akula-II class boat; an attack submarine. It is nuclear-powered - enabling it to remain submerged for long periods of time. In the Russian navy it would have carried nuclear-armed weapons but it would not do so in Indian service.

Figure 32. INS Chakra, Indian leased nuclear submarine.

Figure 33. Indian non-nuclear Vikramaditya aircraft carrier.

Figure 34. Charles De Gaulle French nuclear aircraft carrier

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, as shown in Table 6 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 $8 \times 26 = 208$ 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 $2 \times 105 = 210$ MWth. Figure 35 shows the Enterprise (CVN-65); the world's first nuclear-powered aircraft carrier.

Figure 36. The first USS nuclear powered aircraft carrier Enterprise CVN-65, 1998 (upper). Earlier version in the Pacific theater, 1944, before the battle of Midway (lower) and below flight deck (bottom). Source: USA Navy.

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.
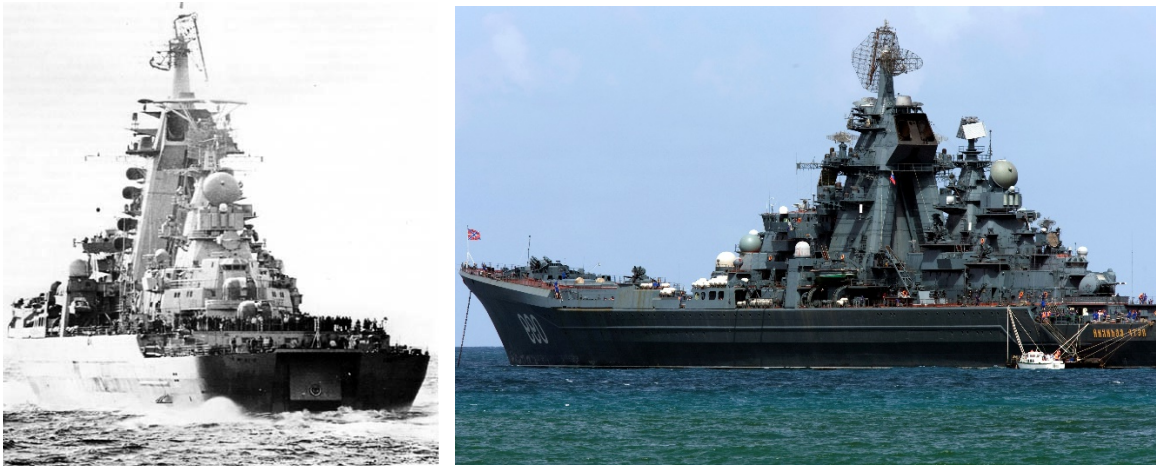
Figure 37. The Russian Nuclear-Powered Guided Missile Cruisers, Kirov (left) and Pyotr Velikiy (right).

Figure 38. The Phalanx radar-guided gun, nicknamed as R2-D2 from the Star-Wars movies, is used for close-in ship defense. The radar controlled Gatling gun turret shooting tungsten armor-piercing, explosive, or possibly depleted uranium munitions on the USS Missouri, Pearl Harbor, Hawaii. Photo: M. Ragheb.

The Russian navy's nuclear powered guided missile cruiser Kirov, shown in Fig. 37 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 (Fig. 38) using tungsten or depleted uranium projectiles, short range surface to air missiles and 100 mm dual purpose gun mounts.

Table 6. Principal Components of the USA Nuclear Aircraft Carrier Fleet.

Designation	Name	Class
CVN-65	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
CVN-68	Nimitz	Nimitz Class, 2 reactors, 4 shafts, 1975. 97,000 tons full load displacement, 1.073 feet flight deck width, 252 ft flight deck width, 32 knots speed, 70 aircraft.
CVN-69	Dwight D. Eisenhower	
CVN-70	Carl Vinson	
CVN-71	Theodore Roosevelt	
CVN-72	Abraham Lincoln	
CVN-73	George Washington	
CVN-74	John C. Stennis	
CVN-75	Harry S. Truman	
CVN-76	Ronald Reagan	
CVN-77	George W. H. Bush	Commissioned 2009, deployed June 2011, cost $6.2 billion.
CVN-78	Gerald R. Ford	Gerald R. Ford class, CVN-21 (for 21st century) carrier design. Carrying capacity: 75 aircraft. Maximum displacement: 100,000 tons. Commissioned 2017, cost $17.5 billion. (including $4.7 billion in R&D for the new carrier class)
CVN-79	John F. Kennedy	Projected service 2022.
CVN-80	Enterprise	Cost $12.6 billion.
CVN-81	?	Cost $15.0 billion.

Figure 39. USS Carl Vinson CVN-70, Nimitz class aircraft carrier, 2005. Source: USA Navy.

Figure 40. USS George Washington CVN-73 Nimitz class aircraft carrier, 2010. Source: USA Navy.

Figure 41. USS John C. Stennis, CVN-74.
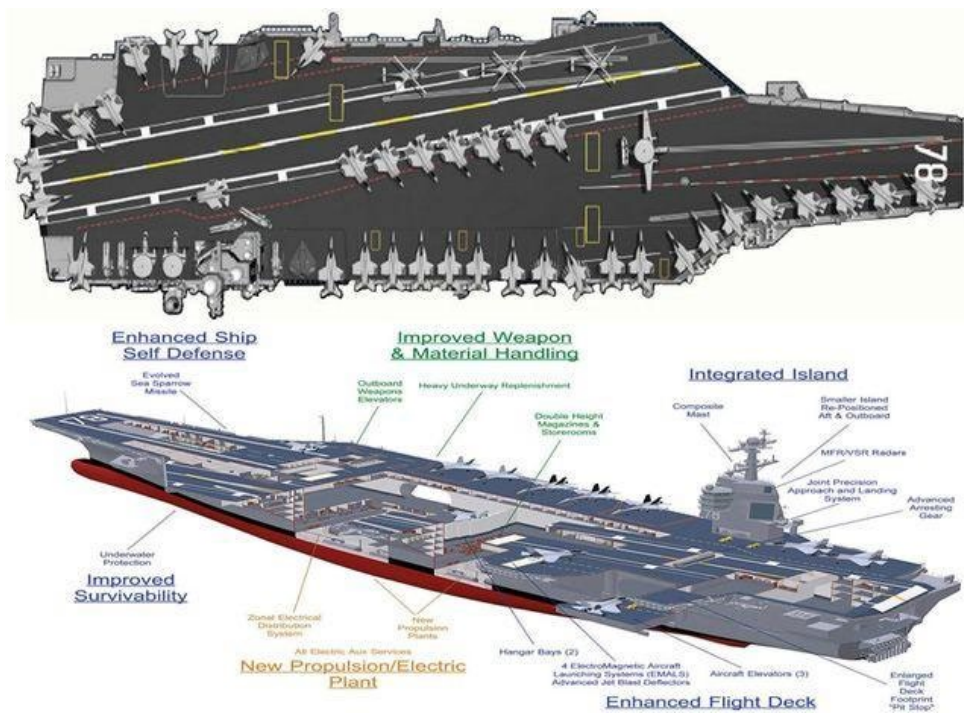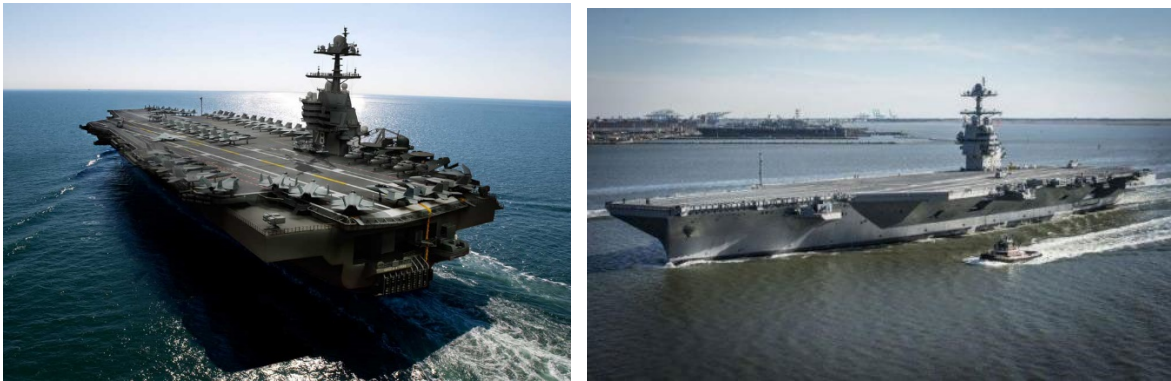
Figure 42. USS Ronald Reagan, CVN-76. Source: USA Navy.

Figure 43. CVN-78 Gerald R. Ford features. The $17.5 billion carrier Gerald R. Ford uses for the first time an Electromagnetic Aircraft Launch System, or EMALS system, which replaces traditional steam-based carrier aircraft launch systems. "Full Ship Shock Trial" under battle conditions using a 40,000 lbs explosive charge. Source: USA Navy

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 anti-ship 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 44. Russian cruise missile submarine Project 949A Orel.

The nuclear powered ECHO I and II, and the CHARLIE I and II can fire eight anti-ship 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 anti-ship 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 the 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 45. The Nuclear Powered Russian Ballistic Missile Submarine Project 667 DRM.

Figure 46. USA Ballistic missile nuclear submarine Ohio.

Figure 47. USS Annapolis SSN 760 breaking through the ice at the Arctic Circle, 2009. Source: USA Navy.

Figure 48. Yuri Dolgoruky Russian ICBM nuclear submarine, 2007.

Figure 49. Yakhont P800 Russian cruise missile, 138 miles range. Source: Ruaviation.

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. Figure 45 shows a DELTA I class SSBN. Figure 46 shows the SSN Ohio ballistic missile submarine.

The Typoon 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 50 shows the known Russian nuclear Ballistic submarines and their missiles systems.
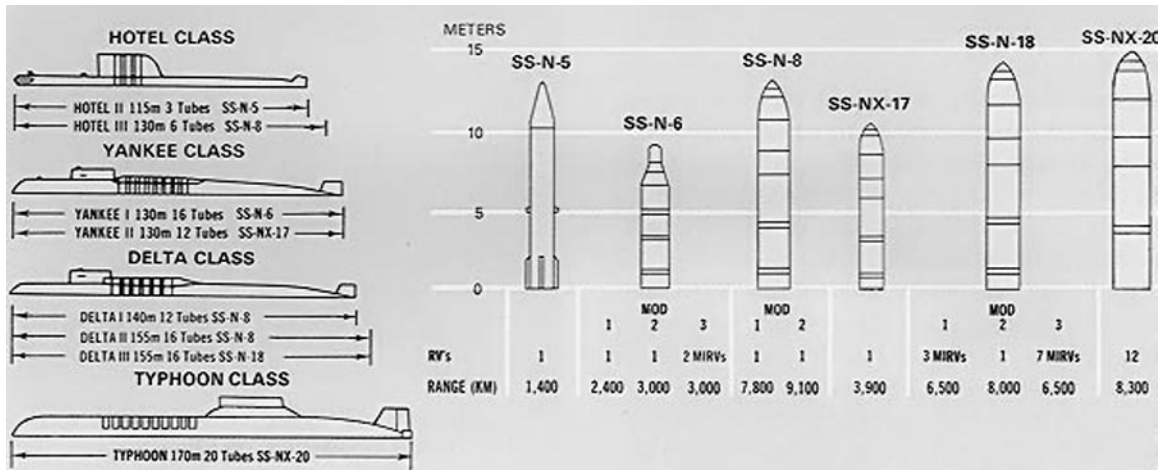
Figure 50. Russian Nuclear Ballistic Missile Submarines and their missiles characteristics.

USS MICHIGAN, CRUISE MISSILE CARRIER

Figure 51. The USS Michigan carries 154 Tomahawk cruise missiles that can travel at 550 mph and a 60 special-forces unit with a SEAL combat insertion unit.

The USS Michigan, is an Ohio-class nuclear-powered submarine armed with Tomahawk cruise missiles. It was first launched in 1980 and commissioned two years later. It was built to carry the Navy's third generation submarine-launched ballistic missile, the Trident C-4. The Michigan carried out its primary mission of deterrence for nearly two decades in over 60 missions. At the end of the Cold War, it was spared from decommission and converted with two other ships to the Ohio-class sea frame. In 2007, it followed the USS Ohio, Florida and Georgia as a guided missile submarine.

The vessel is capable of hitting speeds of over 20 knots while submerged and can drop over 800 feet below sea level. It also contains 22 tubes that carry seven Tomahawks each. The USS Michigan has an unlimited range of travel and can stay at sea for approximately 60 days with full supplies of food.

The Michigan is the third ship to bear the name in the USA Navy's history. The original Michigan was the first iron warship in the USA Navy and likely the first iron or steel warship of its size in the world. It was on duty throughout the Great Lakes during the Civil War but never saw battle. It was renamed the USS Wolverine in 1910 when it was turned over to the Naval Reserve as a training ship.

That same year, the second USS Michigan was commissioned and assigned to the Atlantic Fleet with other first-class battleships. During World War I, the ship escorted convoys, trained recruits and engaged in Fleet maneuvers before being placed on limited commission in 1919.

The third and current Michigan is more than 560 feet long and weighs more than 18,000 tons when submerged. Its home port is Bremerton, Washington.

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 52 shows the SSN 23 Jimmy Carter Seawolf class attack submarine. Figure 53 shows a Victor-class attack submarine, characterized by deep diving capability and high speed.

Figure 52. SSN 23, Jimmy Carter nuclear attack submarine, 2005.

ALFA CLASS, LIRA-CLASS, SUBMARINES

The ALFA class submarine was the fastest submarine in service in any navy. It was a deep-diving to 4,000 feet, titanium-alloy hull submarine with a high buoyancy reserve and 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.
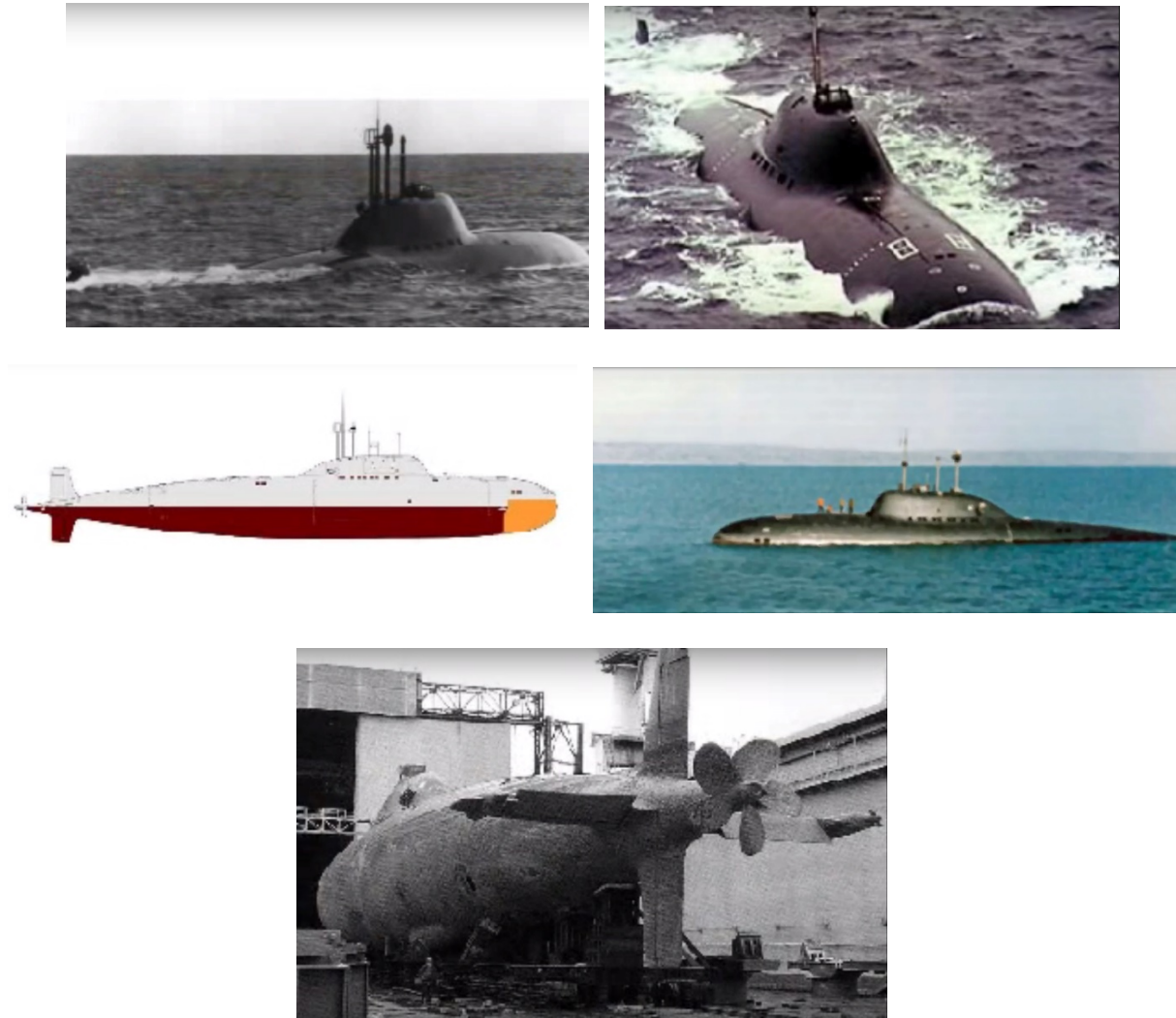

Figure 53. The Nuclear Powered Russian K493 Alfa class attack Submarine at sea and in dock.

The alpha class of Russian submarines used a lead-bismuth alloy cooled fast reactors. They suffered corrosion on the reactor components and activation through the formation of the highly toxic Po^{210} isotope. Refueling and maintenance in dock 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.

The vast majority of Russian submarines past and present are PWRs. The only liquid metal lead and bismuth ones were the Alfas which are all retired, and the 645 class with only one example as the K-27 are decommissioned and sunk with special "furfuryl alcohol/bitumen filling" around the reactor to help stop contamination.

The problem with the liquid metal ones is that the fuel rods fuse with the coolant when they are switched off. The French provided equipment to help decommission the Alfa class submarines.

14. SEAWOLF CLASS SUBMARINES

The Seawolf class of submarines provided stealth, endurance and agility and are the most heavily armed fast attack submarines in the world.

They provided the USA Navy with undersea weapons platforms that could operate in any scenario against any threat, with mission and growth capabilities that far exceed Los Angeles-class submarines. The robust design of the Seawolf class enabled these submarines to perform a wide spectrum of crucial military assignments, from underneath the Arctic icepack to littoral regions anywhere in the world.

This ship class was capable of entering and remaining in the backyards of potential adversaries undetected, preparing and shaping the battle space, and, if so directed, striking rapidly and decisively.

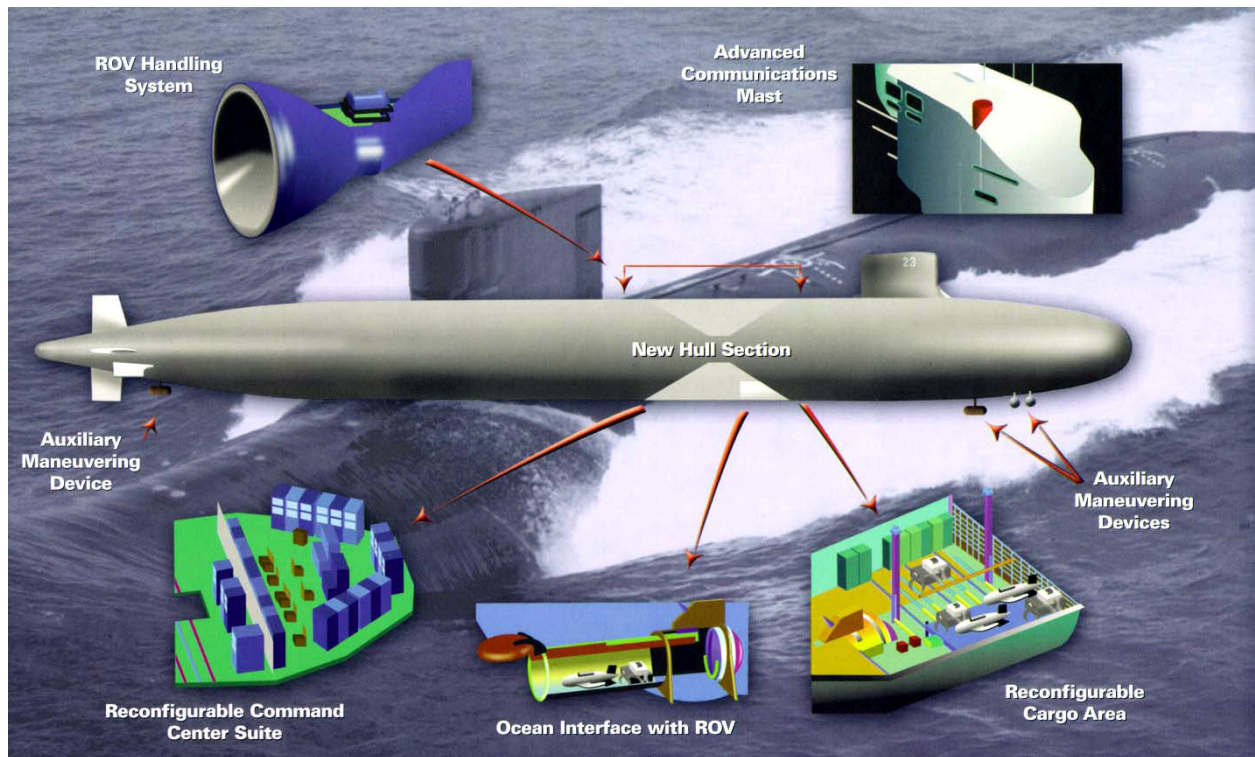Figure 54. Rollout of the SSN 23 Jimmy Carter attack submarine.

Figure 55. Special features of the SSN 23 Jimmy Carter.

Figure 56. Communications gear on the mast of SSN 23, Jimmy Carter.

Their missions include surveillance, intelligence collection, special warfare, cruise missile strike, mine warfare, and anti-submarine and anti-surface ship warfare

Table 7. Seawolf class of submarines technical specifications.

Builder	General Dynamics, Electric Boat Division.
Power plant	One S6W nuclear reactor, one shaft.
Length	SSN 21 and SSN 22: 353 feet (107.6 meters)
	SSN 23: 453 feet (138 meters)
Beam	40 feet (12.2 meters)
Submerged Displacement	SSN 21 and SSN 22: 9,138 tons (9,284 metric tons)
	SSN 23 12,158 tons (12,353 metric tons)
Speed	25+ knots (28+ miles / hour, 46.3+ kilometers / hour)
Crew	140: 14 Officers; 126 Enlisted
Armaments	Tomahawk missiles, MK-48 torpedoes, eight torpedo tubes
Commissioning dates	Seawolf: July 19, 1997
	Connecticut: December11, 1998;
	Jimmy Carter: February 19, 2005.

15. JIMMY CARTER SSN 23

The $3.2 billion Jimmy Carter is the third and last of the USA Seawolf class, the huge, deep-diving subs. With a 50-torpedo payload and eight torpedo tubes, the 453-foot, 12,000-ton vessel is the biggest of them all. It was delayed to install a 100 foot hull extension.
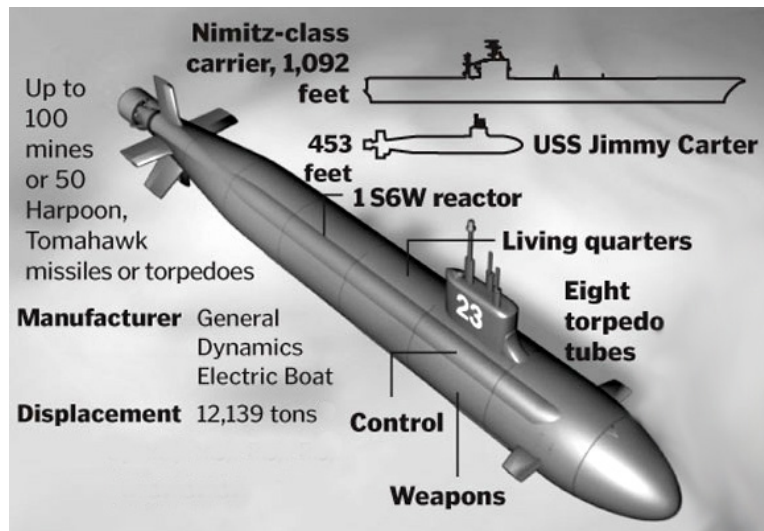
Figure 57. Comparison of the size of SSN 23 Jimmy Carter attack submarine to a Nimitz class carrier.

It possesses the ability to tap fiber optic undersea cables and eavesdrop on the communications passing through them. The Carter was extensively modified for communications or signal intelligence through the airwaves gathering from its basic design, given a $923 million

hull extension that allows it to house technicians and gear to perform cable-tapping, and other secret missions. The Carter's hull, at 453 feet, is 100 feet longer than the other two subs in the Seawolf class.

Some of the Carter's special abilities: In the extended hull section, the boat can provide berths for up to 50 special operations troops, such as Navy SEALs. It has an ocean interface that serves as a sort of hangar bay for smaller Remotely Operated Vehicles (ROVs) and drones. It has the usual torpedo tubes and Tomahawk cruise missiles, and it will serve as a platform for researching new technologies useful on submarines.

To listen to fiber-optic transmissions, intelligence operatives must physically place a tap somewhere along the route. If the stations that receive and transmit the communications along the lines are on foreign soil or otherwise inaccessible, tapping the line is the only way to eavesdrop on it.

During the 1970s, a USA submarine placed a tap on an undersea cable along the Soviet Pacific coast, and subs had to return every few months to pick up the tapes. The mission ultimately was betrayed by a spy, and the recording device is now at the KGB museum in Moscow.

Table 8. USS Jimmy Carter technical specifications.

Displacement:	12,140 tons
Power plant	Single S6W reactor.
Length	453 feet
Beam	40 feet
Payload	50 weapons and special operations forces.
Weapons	Tomahawk land attack missiles, Mark 48 advanced capability torpedoes, advanced mobile mines, and unmanned undersea vehicles.
Special Warfare	Dry Deck Shelter, Advanced SEAL Delivery System, Ocean Interface (OI)
Sonars	Spherical active/passive arrays, wide aperture arrays, TB-16 and TB-29 towed arrays, high frequency sail array, high frequency and low frequency bow arrays
Countermeasures	Internal; reloadable, 32 external non-reloadable

16. OHIO CLASS SUBMARINES

The Ohio class submarine is equipped with the Trident strategic ballistic missile from Lockheed Martin Missiles and Space. The Trident was built in two versions, Trident I (C4), which is being phased out, and the larger and longer range Trident II (D5), which entered service in 1990. The first eight submarines, (SSBN 726 to 733 inclusive) were equipped with Trident I and the following ten (SSBN 734 to 743) carry the Trident II. Conversion of the four Trident I submarines remaining after START II (Henry M. Jackson, Alabama, Alaska and Nevada), to Trident II began in 2000 and is planned to complete in 2008. Lockheed Martin received a contract in January 2002 for the production of 12 Trident II missiles for the four submarines.

The submarine has the capacity for 24 Trident missile tubes in two rows of 12. The dimensions of the Trident II missile are length 1,360 cm x diameter 210 cm and the weight is

59,000 kg. The three-stage solid fuel rocket motor is built by ATK (Alliant Techsystems) Thiokol Propulsion. The US Navy gives the range as "greater than 7,360 km" but this could be up to 12,000 km depending on the payload mix. Missile guidance is provided by an inertial navigation system, supported by stellar navigation. Trident II is capable of carrying up to twelve MIRVs (multiple independent re-entry vehicles), each with a yield of 100 kilotons, although the SALT treaty limits this number to eight per missile. The circle of equal probability (the radius of the circle within which half the strikes will impact) is less than 150 m. The Sperry Univac Mark 98 missile control system controls the 24 missiles.

The Ohio class submarine is fitted with four 533mm torpedo tubes with a Mark 118 digital torpedo fire control system. The torpedoes are the Gould Mark 48 torpedoes. The Mark 48 is a heavy weight torpedo with a warhead of 290kg, which has been operational in the US Navy since 1972. The torpedo can be operated with or without wire guidance and the system has active and/or passive acoustic homing. Range is up to 50 km at a speed of 40 knots. After launch the torpedo carries out target search, acquisition and attack procedures delivering to a depth of 3,000ft.

The Ohio class submarine is equipped with eight launchers for the Mk 2 torpedo decoy. Electronic warfare equipment is the WLR-10 threat warning system and the WLR-8(V) surveillance receiver from GTE of Massachusetts. The WLR-8(V) uses seven YIG tuned and vector tuned super heterodyne receivers to operate from 50MHz up to J-band. An acoustic interception and countermeasures system, AN/WLY-1 from Northrop Grumman, has been developed to provide the submarine with an automatic response against torpedo attack.

The surface search, navigation and fire control radar is BPS 15A I/J band radar. The sonar suite includes: IBM BQQ 6 passive search sonar, Raytheon BQS 13, BQS 15 active and passive high-frequency sonar, BQR 15 passive towed array from Western Electric, and the active BQR 19 navigation sonar from Raytheon. Kollmorgen Type 152 and Type 82 periscopes are fitted.

The main machinery is the pressurized water reactor GE PWR S8G with two turbines providing 60,000 hp and driving a single shaft. The submarine is equipped with a 325 hp Magnatek auxiliary propulsion motor. The propulsion provides a speed in excess of 18 knots surfaced and 25 knots submerged.

17. DEEP SUBMERGENCE NUCLEAR SUBMARINE

The NR-1 is a one of a kind nuclear-powered, deep-submergence submarine, capable of exploring ocean depths to 3,000 feet. Launched on January 25, 1969, and decommissioned on November 21, 2008, it was one of the oldest nuclear-powered submarines in the nuclear USA fleet.

This allows access to most of the world's continental shelves. Its displacement is just under 400 long tons, which is 1/16th the size of a Los Angeles-class submarine. With her small size its crew consisted of a mere three officers and eight enlisted men. It has exceptional endurance with a nuclear propulsion plant allowing uninterrupted bottom operations for up to 30 days. Its operational period is limited only by the food and air purification supplies that it carries on board.

Figure 58. The NR-1 deep submergence submarine and its mother ship the SSV Carolyn Chouest. It could dive to three times the depth of other submarines, and was equipped with wheels to move on the ocean floor and a robotic arm. It has been replaced with remotely controlled submersibles.

The NR-1 was conceived in the 1960s as a deep-ocean, bottom-exploring submarine. Her turbo-electric drive train provides power to twin 50-horsepower propulsion motors outside the pressure hull. This results in a mere maximum speed of 3 knots submerged. She is equipped with four ducted thrusters that enable her to maneuver in every direction, even while hovering within inches of the ocean floor. She has a conventional rudder and diving planes mounted on the sail for depth control.

In its nearly 40-year career, the NR-1 was called for countless missions, from searching for wrecked and sunken naval aircraft to finding debris from the space shuttle Challenger after its loss in 1986, to tapping into underwater communication cables.

Its highly advanced sonar, unlike the system on an attack submarine, which is directed at the entire water column, was pointed downward and could detect an "empty soda can buried in the sand a mile away."

Some unique features of the NR-1 include having wheels for motion on the ocean floor, three viewing ports for visual observation, and 29 exterior lights to support 13 television and still cameras, an object recovery claw, a manipulator robotic arm for various gripping and cutting tools, and a work basket to hold items recovered from the sea. Numerous protuberances around the ship include two retractable bottoming wheels mounted with alcohol filled Goodyear truck tires giving the ship a unique bottom sitting and crawling capability.

The NR-1's nuclear propulsion plant gives her the ability to operate independently of surface ships, since it provides ample electrical power for all onboard sensors and life-support systems and gives the ship essentially unlimited endurance. Due to her small size and relatively slow speed on the surface, the NR-1 is towed while submerged to and from remote mission locations by a dedicated support vessel, the SSV Carolyn Chouest (Fig. 58).

MULTIPURPOSE "DEEP-STATION" RUSSIAN SUBMARINES

A deep water vehicle equipped with robotic arms and positioning thrusters for retrieval and access to underwater objects is project 1910, UNIFORM.
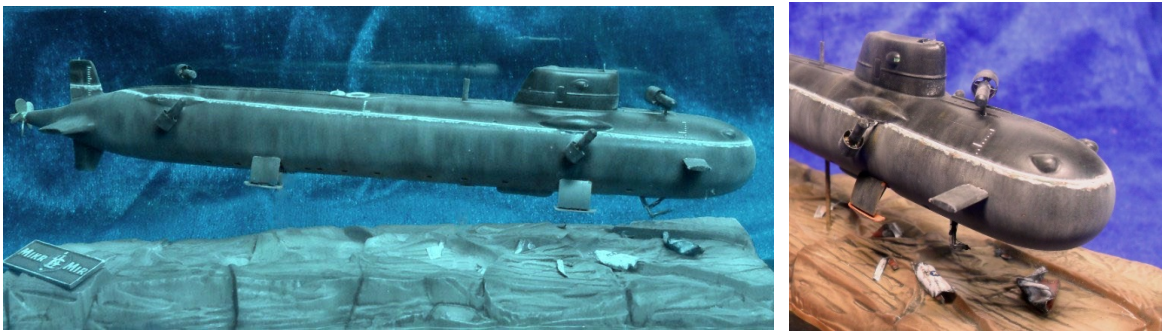
Figure 59. Six thrusters and robotic arms of Russian multipurpose nuclear deep station AGS 1910.
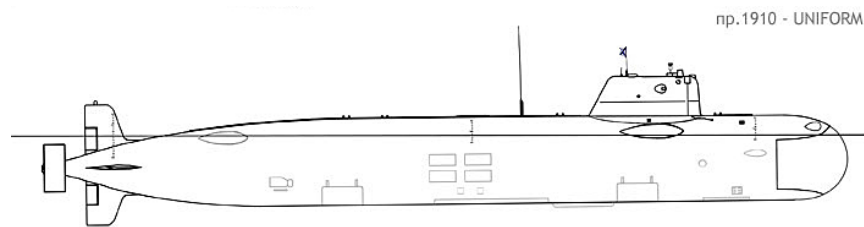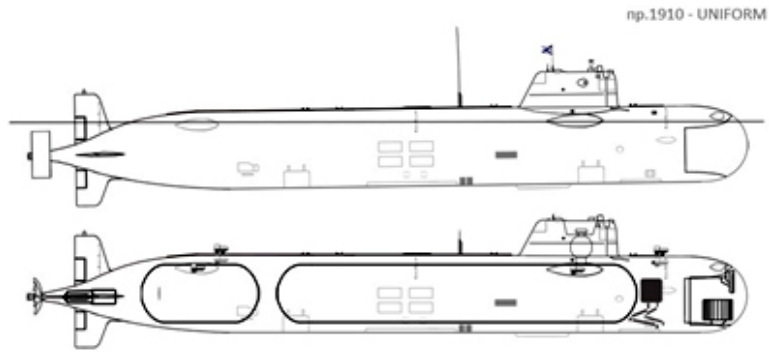
Figure 60. UNIFORM multipurpose deep water project 1910, 2011.

Figure 61. Multipurpose nuclear deep station AS 13 pr. 1910. The right front thruster in retracted position without cover.
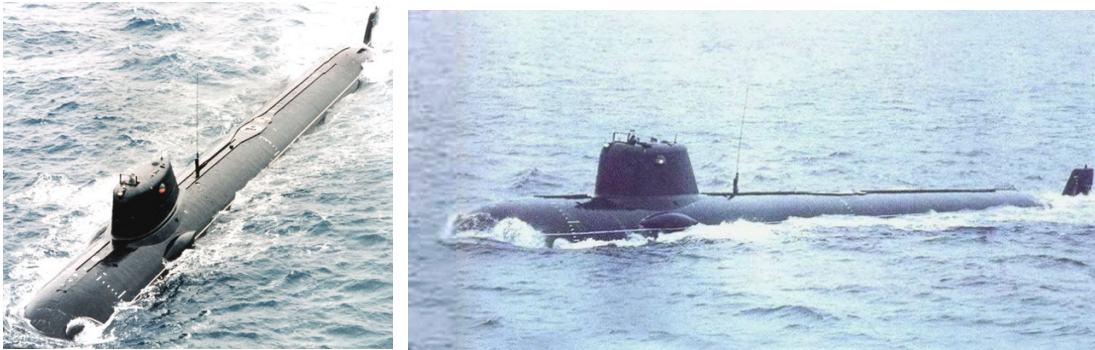

Figure 62. UNIFORM multipurpose nuclear deep station AS 33 pr 1910.

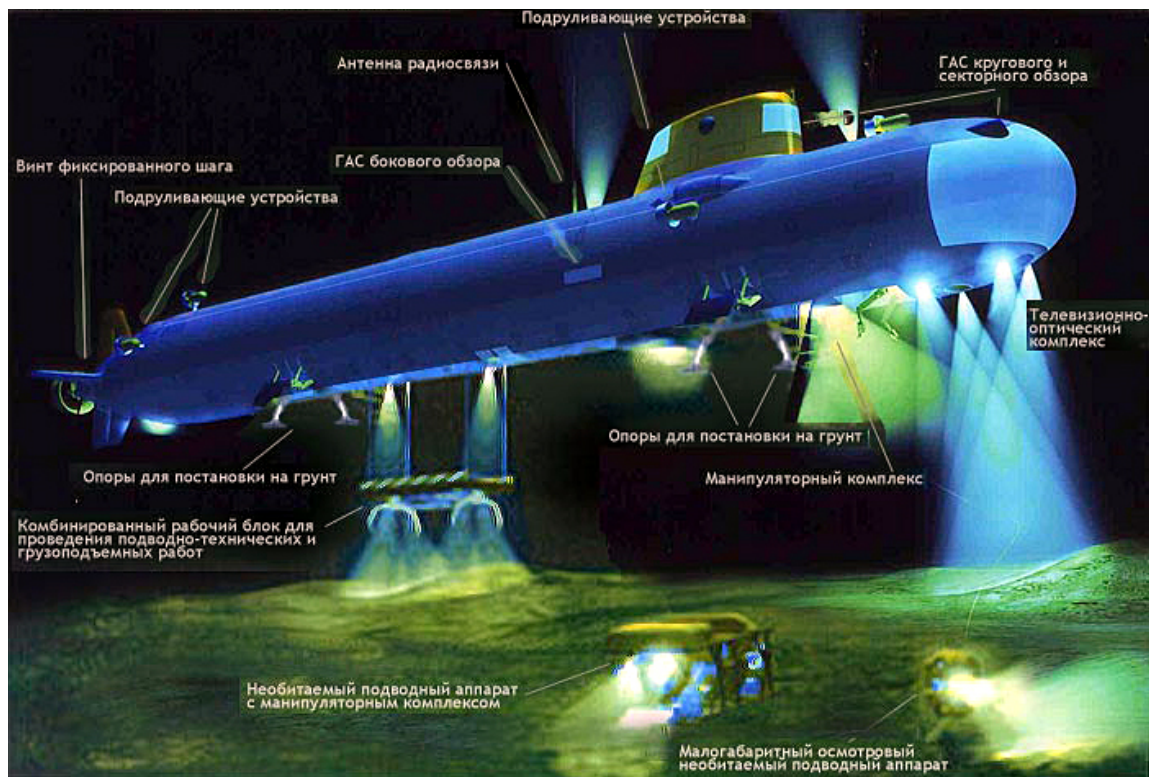Figure 63. Multipurpose nuclear submarine pr. 885 Yasen Graney.

Figure 64. Multipurpose UNIFORM research submarine pr.1910 components.

18. FUTURE SUBMARINE FORCE: VIRGINIA CLASS

The Virginia class of submarines represents the future nuclear navy force in the USA. The USA Navy plans on developing the Virginia Class into a fully modular, all-electric submarine that will accommodate large modules to provide interfaces for future payloads and sensors. It is a 30 ships class replacing the Los Angeles Class SSNs, possessing the stealth of the Seawolf Class of submarines but at a 30 percent lower total cost. It has mission reconfigurable modules capabilities. It is equipped with Unmanned Undersea Vehicles (UUVs) and improved sensors and

communication systems. It is characterized with improved habitability, and is equipped with advanced strike munitions and deployable networked sensors.

The main propulsion units are the ninth generation GE Pressurized Water Reactor S9G, designed to last as long as the submarine, two turbine engines with one shaft and a United Defense pump jet propulsor, providing 29.84 MW. The speed is 25+ knots dived.
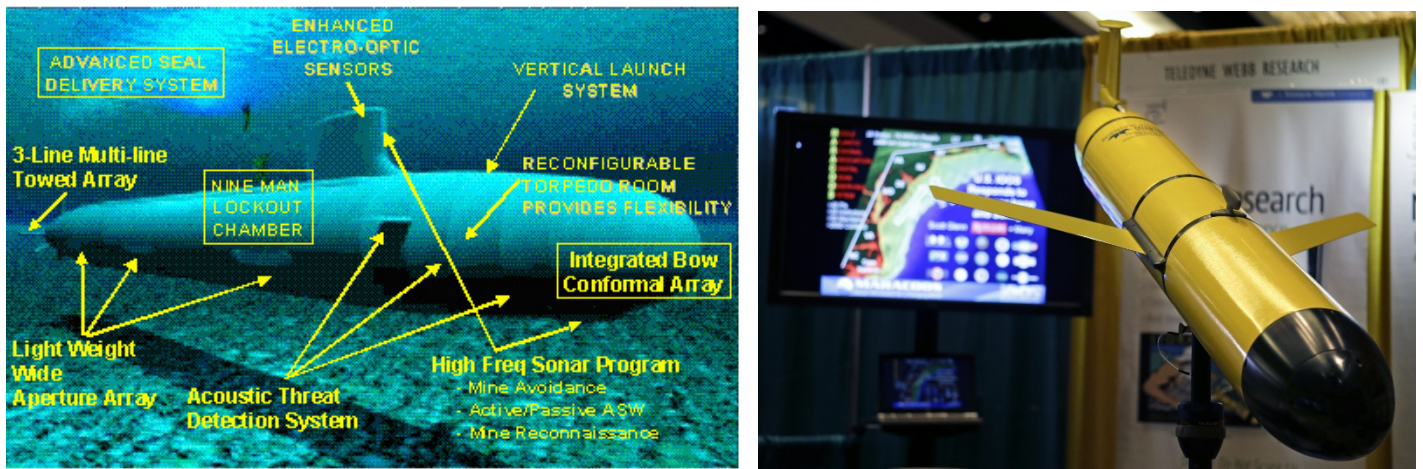

Figure 65. Characteristics of the Virginia class of the nuclear all-electric submarines and Slocum Glider UUV. Source: Teledyne.
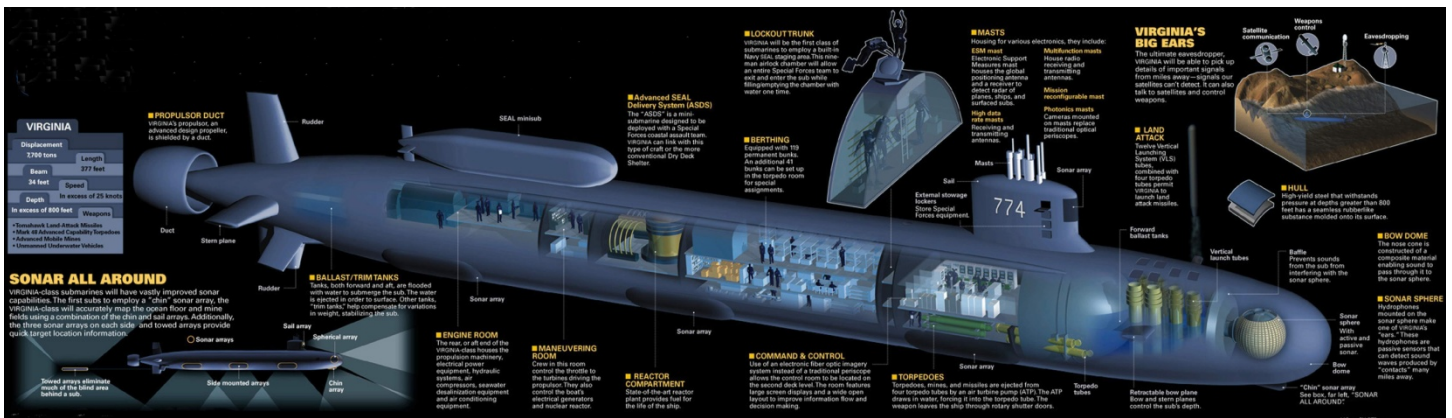
Figure 66. Cutout of Virginia class submarine. The advanced design propulsor system is shielded by a lampshade duct. Submarine Museum, Pearl Harbor, Hawaii. Source: General Dynamics.

Its principal features are:

1. An all electrical ship.
2. Enhanced stealth.
3. Modular isolated decks.
4. Open system architecture.

5. Modular masts.
6. Structurally integrated enclosures.
7. Mission reconfigurable torpedo room.
8. Enhanced special warfare capabilities.
9. Enhanced Littoral performance.

The Technical Specifications of the Virginia Class submarine are listed in Table 9.

Table 9. Technical Specifications of the Virginia Class of Submarines.

Power Plant	Single S9G PWR Single shaft with pump jet propulsion One secondary propulsion submerged motor
Displacement	7,800 tons, submerged
Length	277 ft
Draft	32 ft
Beam	34 ft
Speed	25+ knots, submerged
Horizontal tubes	Four 21 inches torpedo tubes
Vertical tubes	12 Vertical Launch System Tubes
Weapon systems	39, including: Vertical Launch System Tomahawk Cruise Missiles Mk 48 ADCAP Heavy weight torpedoes Advanced Mobile Mines Unmanned Undersea Vehicles
Special warfare	Dry Deck Shelter
Sonars	Spherical active/passive arrays Light Weight Wide Aperture Arrays TB-16, TB-29 and future towed arrays High frequency chin and sail arrays
Counter measures	1 internal launcher 14 external launchers
Crew	113 officers and men

It is designed for mine avoidance, special operations forces delivery and recovery. It uses non acoustic sensors, advanced tactical communications and non-acoustic stealth. In the future it will be equipped with conformal sonar arrays. Conformal sonar arrays seek to provide an optimally sensor coated submarine with improved stealth at a lower total ownership cost. New technology called Conformal Acoustic Velocity Sonar (CAVES) will replace the existing Wide Aperture Array technology and will be implemented starting in early units of the Virginia class.

High Frequency Sonar will play more important role in future submarine missions as operations in the littorals require detailed information about the undersea environment to support missions requiring high quality bathymetry, precision navigation, mine detection or ice avoidance. Advanced High Frequency Sonar systems are under development and testing that will provide submarines unparalleled information about the undersea environment. This technology will be

expanded to allow conformal sonar arrays on other parts of the ship that will create new opportunities for use of bow and sail structure volumes while improving sonar sensor performance.

19. S9G NINTH GENERATION REACTOR DESIGN

The S9G Next Generation Reactor and associated components will have increased energy density. The core that is under development for the New Attack Submarine is expected to last the life of the ship. The design goals include eliminating the need for a refueling, will reduce life cycle costs, cut down the radiation exposure of shipyard workers, and lessen the amount of radioactive waste generated. This is possible because of many developments such as use of advanced computers to perform three-dimensional nuclear, thermal, and structural calculations; further exploitation of the modified fuel process; and better understanding of various reactor technologies which permits more highly optimized designs. Performance improvements are gained through advances in such areas as thermal hydraulics and structural mechanics, and by optimizing reactor-to-systems interfaces.

The new reactor which will have increased energy density, and new plant components, such as a new concept steam generator, with improved corrosion resistance and reduced life-cycle costs. The new steam generators will also allow greater plant design flexibility and decreased construction costs due to smaller size, spatial orientation, and improved heat transfer efficiency which reduces coolant flow requirements. A new concept steam generator would alleviate the corrosion concerns encountered in existing designs of steam generators, while reducing component size and weight and providing greater flexibility in overall arrangement.

20. NUCLEAR ICE BREAKERS

INTRODUCTION

Nuclear power is preferred over diesel engines for ice-breakers propulsion, because it allows these vessels to be out at sea for long periods of time only having to refuel once every 4 years. The limited space that the nuclear fuel takes up on board a surface ship is also a benefit because many ships must carry their own diesel fuel aboard, losing valuable cargo space thus making voyages less cost efficient.

Nuclear-powered icebreakers were constructed by Russia for the purpose of increasing the shipping along the northern coast of Siberia, in ocean waters covered by ice for long periods of time and river shipping lanes. The nuclear powered icebreakers have far more power than their diesel powered counterparts, and for extended time periods. During the winter, the ice along the northern Russian sea way varies in thickness from 1.2 - 2 meters. The ice in the central parts of the Polar Sea, is 2.5 meters thick on average. Nuclear-powered icebreakers can break this ice at speeds up to 10 knots. In ice free waters the maximum speed of the nuclear powered icebreakers is 21 knots.

In 1988 the NS Sevmorpu was commissioned in Russia to serve the northern Siberian ports. It is a 61,900 metric tonnes, 260 m long and is powered by the KLT-40 reactor design, delivering 32.5 propeller MW from the 135 MWth reactor.

APPLICATIONS

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.

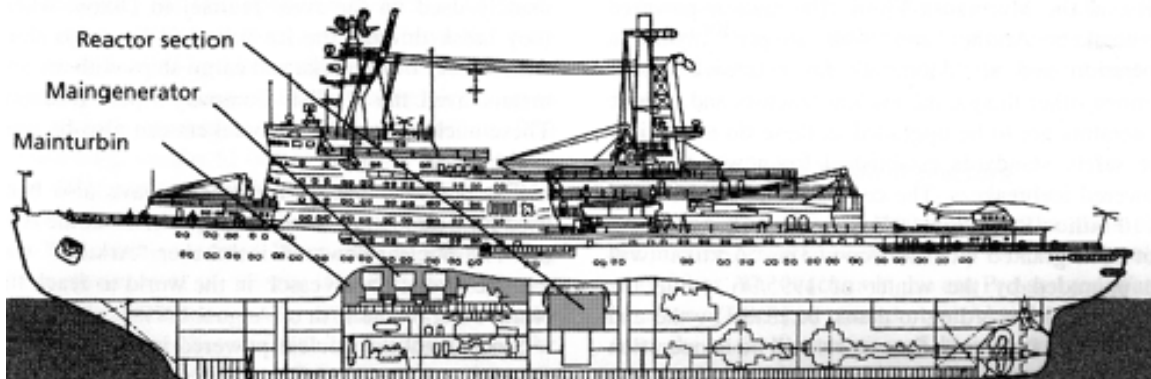Figure 67. Nuclear icebreaker Arktika used Intermediate Enriched Uranium (IEU) of 30-40 percent as fuel.

Figure 68. Schematic of Russian Nuclear icebreaker Arktika showing emplacement of nuclear reactor at its center. The reactor contains fuel enriched to 30-40 percent in U^{235} requires refueling every 3-4 years.
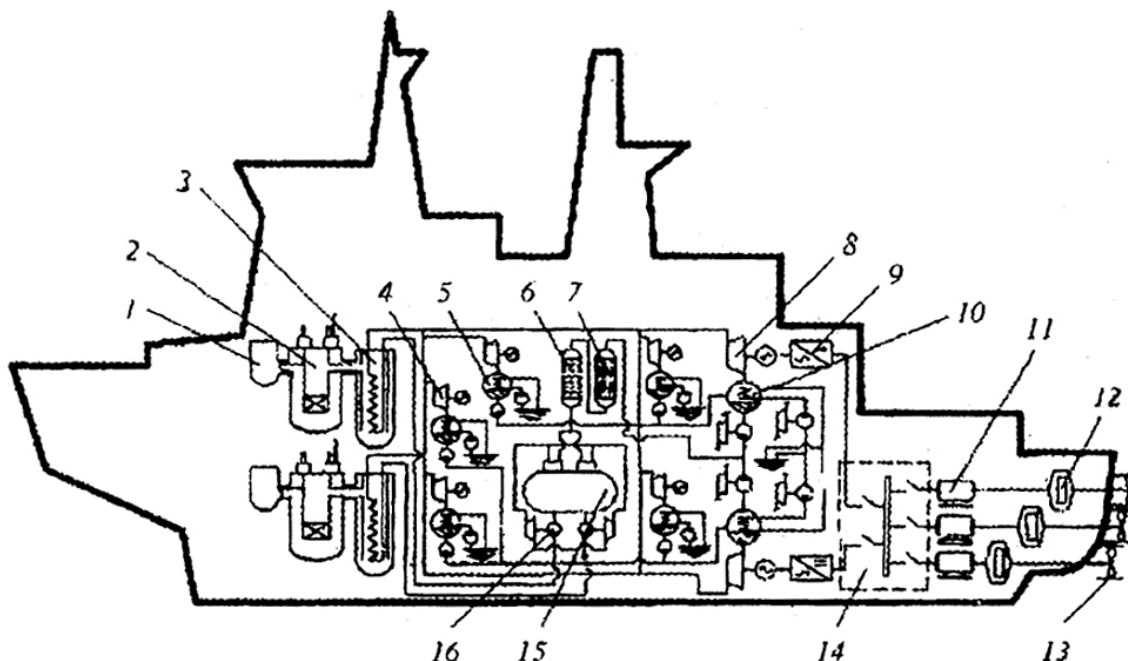
Figure 69. Nuclear reactor components of the icebreaker Arktika. 1: Circulation pumps, 2: Reactor vessel, 3: Steam generator, 4: Auxiliary turbo generator, 5: Condenser, 6: Ion exchange resins filter, 7: Mechanical filter,: 8: Main turbo electrical generator, 9: Converter, 10: Main condenser, 11: Electrical propeller motor, 12: Intermediate bearing, 13: Screw propeller, 14: Circuit breaker for propeller motor, 15: Deaerator, 16: Turbo feed pump.

      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 Table 10.

Table 10. 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

REACTOR TYPES FOR ICEBREAKERS

The Russian nuclear icebreakers are powered by pressurized water reactors of the KLT-40 type. The reactor contains fuel enriched to 30-40 percent in U^{235}. 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 U^{235}. The irradiated fuel in test reactors contains about 32 percent of the original U^{235}, implying a discharge enrichment of 97.3 x 0.32 = 31.13 percent enrichment. Unconfirmed reports suggest that France and China use low enriched uranium in their nuclear vessels. In that case they would still need highly enriched uranium "booster rods" to overcome the xenon reactor dead-time as is used in the CANDU reactors.

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.

21. 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 Poficy 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.

22. SAFETY AND ACCIDENTS OCCURRENCES

INTRODUCTION

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 so as to implement design features that would avoid their tragic occurrence.

USS THRESHER, SSN-593, ACCIDENT, 1963

The USS Thresher, built at Portsmouth Naval Shipyard and based in Connecticut, was out for a routine deep-diving test when it ran into trouble on April 10, 1963. The Navy believes the failure of a brazed weld allowed sea water to spray onto an electrical panel, causing an emergency shutdown of its nuclear reactor. The ballast system also failed, preventing the submarine from surfacing. Filling with water, Thresher descended deeper and disintegrated under the crushing force of the ocean. Its remnants rest on the ocean floor at a depth of 8,500 feet.

The USS Thresher of the Permit class attack submarine was powered with a Westinghouse S5W nuclear reactor, with a displacement of 4,300 metric tonnes, 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 m^2 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, 1968

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 tragically lost with her entire 99-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, 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. 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 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.

Figure 70. Launch of the USS Scorpion.

Two months before the Scorpion sank, a Soviet missile submarine known as the K-129 sank thousands of miles away, in the Pacific Ocean, also under mysterious conditions. There have been assumptions by Russian submarine veterans over the years that the K-129 sank after an alleged collision with a USA attack submarine that had been shadowing it, reportedly the Swordfish submarine. USA military officials asserted that 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.

K-129 GOLF CLASS BALLISTIC MISSILE SUBMARINE, 1968, PROJECT AZORIAN, PROJECT JENNIFER, HUGHES GLOMAR EXPLORER SHIP

The location of the sinking accident in 1968 of the Russian K-129 Golf Class ballistic missile submarine was identified by the system of ocean-bottom hydrophones operated by the USA Navy. Assertions by some submarine veterans are that the K-129 sank after an alleged collision with a USA attack submarine that may have been shadowing it, reportedly the Swordfish submarine. USA military officials insist that 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 USA Navy hydrophones. The submarine sunk about 1,560 miles from the Island of Hawaii. It carried three Russian ballistic missiles. In 1969 President Richard Nixon made a decision to extract vital parts of the located submarine from its sinking depth of 17,500 ft or about 3 miles in the Pacific Ocean using oil fields technology.

A cover story avoiding the public, press, and Russian authorities' scrutiny was built around the deep sea-floor mining of manganese, nickel and other minerals as manganese nodules. The Howard Hughes reclusive millionaire contributed to the effort and led the effort in 1974 in association with the CIA, which named the activity as "Project Jennifer," by the lending of the

name of his company "Global Marine" in construction of a grappling device designated as the S-Clementine capture mechanism.
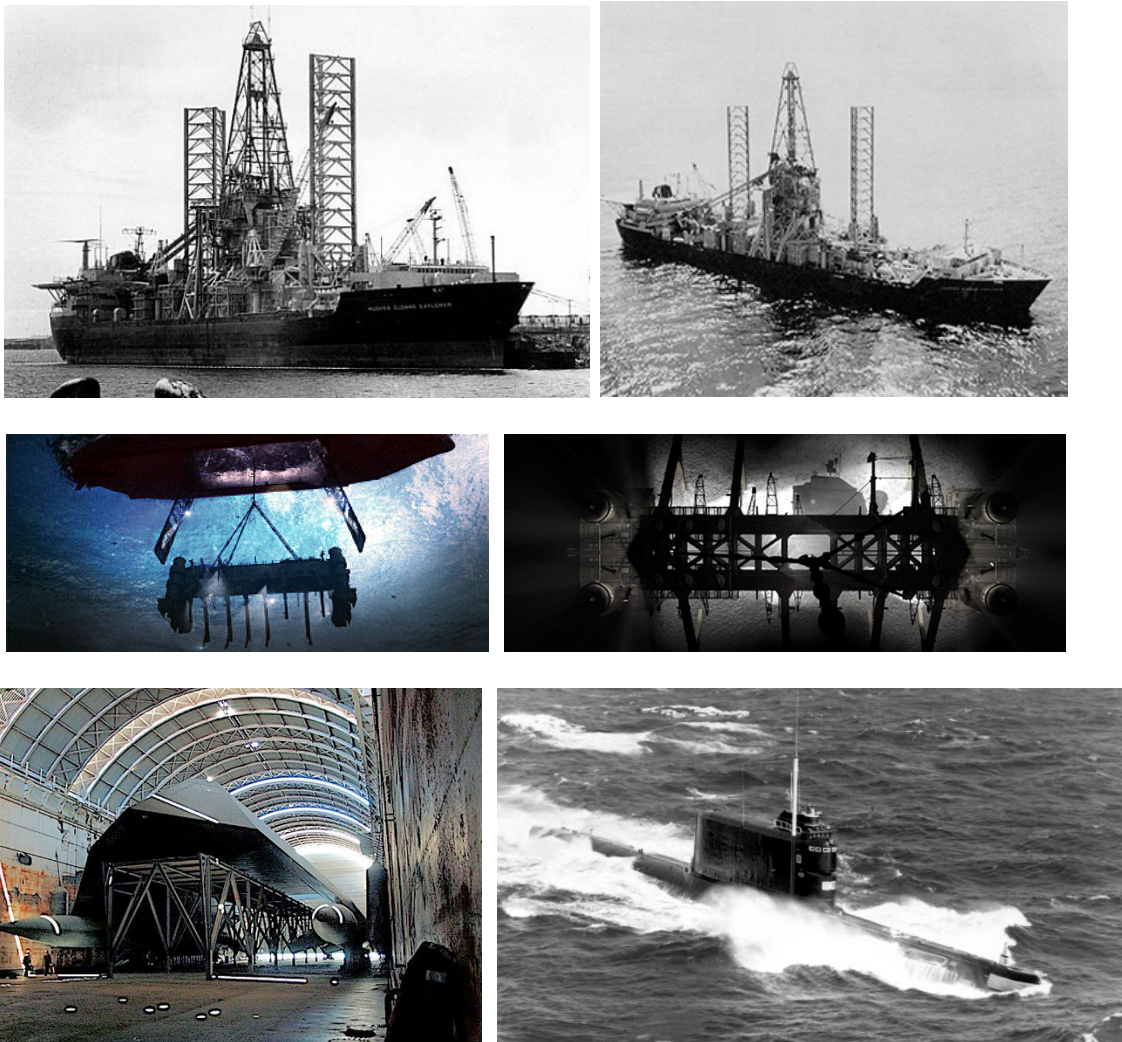

Figure 71. In 1973, the Global Marine Company designed and built the Hughes Glomar Explorer. The unit was contracted to the CIA for a secret mission, reported in the news media to be the recovery of a sunken Soviet submarine. It was retrofitted later as the Glomar Explorer and operated later as the ultra-deepwater drillship GSF Explorer. Grappling device as part of the Azorian Project, mining barge and Golf II class ballistic missile submarine are shown. Source: Global Marine Company, Transocean.

A recovery ship was built by the Global Marine Company's as the Hughes Glomar Explorer which tried to extract its ballistic missiles and possibly the sail containing an advanced navigation system, coding devices, code books and other valuable intelligence targets. The Glomar Explorer was a massive 618-foot-long, 50,000-ton deep-water drilling vessel, which the British Petroleum (BP) oil company contracted to carry out drilling operations in its Gulf of Mexico

Atlantis oil field. Russian officials admitted that the CIA recovered at least two nuclear-armed torpedoes that were crushed by the water pressure.

In addition, the Hughes Mining Barge (HMB-1), a submersible barge about 99-m or 324-ft long, 32-m or 106-ft wide, and 27-m or 90-ft tall was developed as part of the Project Azorian. The HMB-1 was towed to a location near Catalina Island off the coast of California, then was submerged onto stabilizing piers installed on the seafloor. The Glomar Explorer was then maneuvered over the HMB-1, the retractable roof was opened, and the capture device lifted into the massive so-called "moon pool" of the barge which was refloated using compressed air. It was later used as a dry dock for the Sea Shadow stealth ship.

JOHN S. STENNIS, CVN-74 LOCA ACCIDENT, 1999

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 Coolant Accident (LOCA) 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 a tugboat to its pier at high tide. The cleanup cost about $2 million.

SAN FRANSISCO UNDERWATER COLLISION, 2005

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.
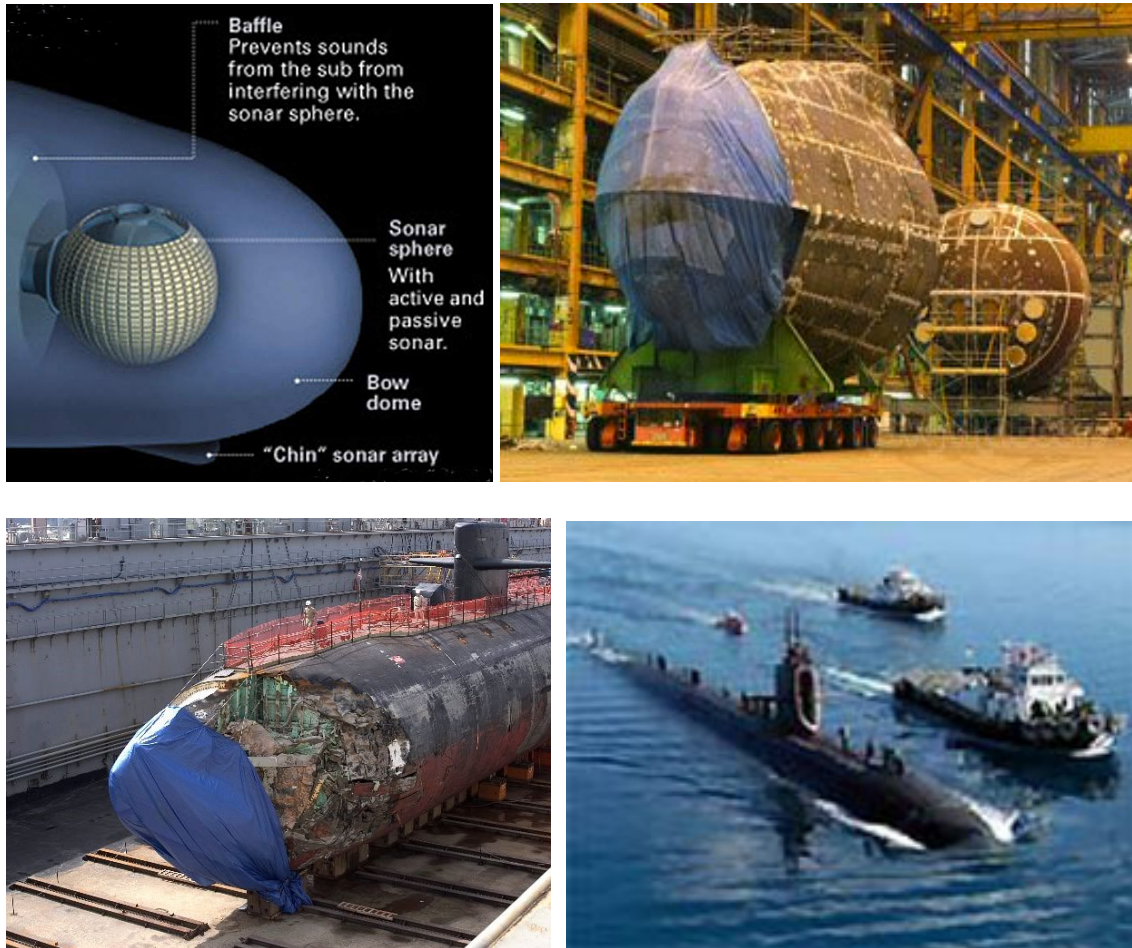

Figure 72. Location of sonar dome on the Astute class of submarines, UK. USS San Francisco SSN 711 accident, January 8, 2005. Damage from the glancing collision to the bow dome and to the double hull structure can be observed. A bulge over the hull can also be noticed.

NERPA, AKULA CLASS FIRE, 2008

An accident occurred on November 8, 2008 on the K-152. 8,140-tonne Nerpa, an Akula II Class Russian nuclear attack submarine on sea trials in the Pacific Ocean in the Sea of Japan. It was planned to be leased to the Indian Navy to be renamed the INS Chakra to be operated from the Visakhapatnam naval base in the Bay of Bengal.

The event claimed 20 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. There were 208 people aboard. 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.
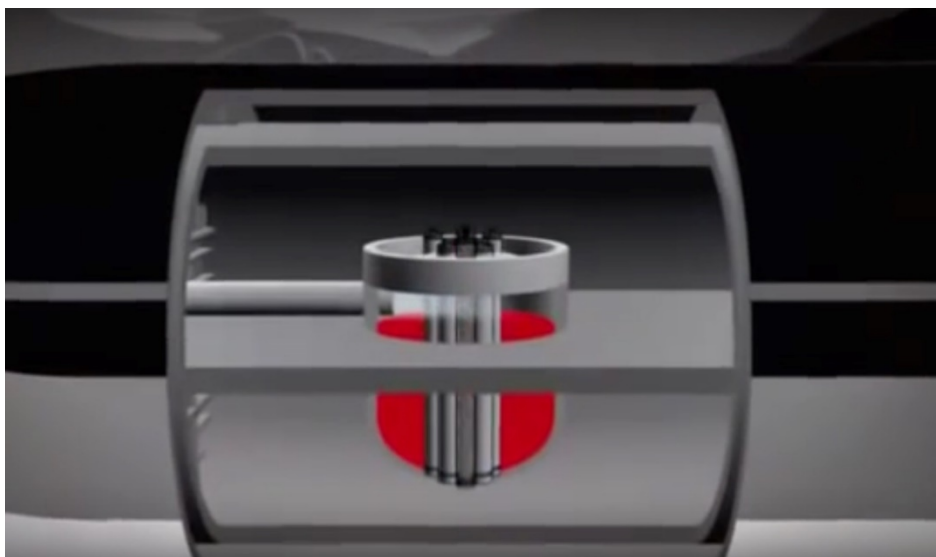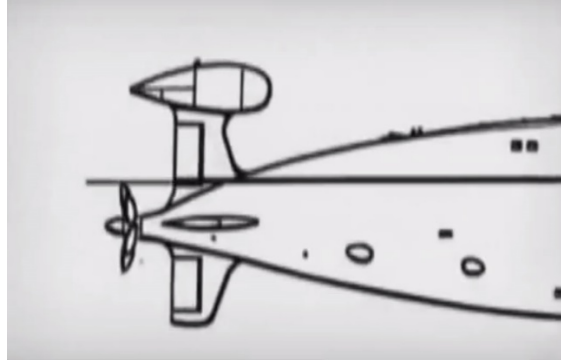
Figure 73. Akula (Shark) Class Russian nuclear submarine with its tail sonar gear, propeller and reactor configuration.

USS HOUSTON COOLANT LEAK, 2008

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, 2009

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.

Figure 74. British nuclear submarine HMS Vanguard to the left and bottom being towed to its base, and French Le Triomphant (The Triumphant) to the right collided in the Atlantic at the Bay of Biskay in 2009.

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.

KURSK ACCIDENT

The Kursk sank with 118 crew members. The hydrogen peroxide fuel of a faulty torpedo ignited and created an explosion onboard that registered on the Richter earthquake scale. In addition, the Russian Oscar class submarines has a shaft seal leakage issue: if the shaft is not turning then water leaks in. Clamps and special air bags have been fitted to some submarines. The shaft seals stop water by using pressurized water from the auxiliary seawater system to leak water outwards. An emergency/maintenance inflatable seal as a toroidal airbag can be used, with the shaft not turning while it is in use.

Figure 75. The retrieved hull of the Russian Oscar-II Class submarine Kursk

Figure 76. Moored Kilo class submarine fire. Vladivostok, January 21, 2018.

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, 2009

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 Strait. 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 or Con Tower 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 subsequent investigation found fault for the collision lay with the commanders aboard the submarine. Several officers and crew aboard the submarine were later disciplined for their roles.

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.

Figure 77. The collision of the Hartford with the New Orleans on March 20, 2009 caused damage to its communication gear and bent its sail.

COLLISION BETWEEN USN MONPELIER (SSN 765) NUCLEAR ATTACK SUBMARINE AND AEGIS CLASS CRUISER SAN JACINTO

Figure 78. Los Angeles Class fast attack submarine USS Monpellier (USS 765) and Aegis Class Cruiser USS San Jacinto (CG 56). Source: USA Navy.

A USA Navy nuclear attack submarine, the Los Angeles Class SS Montpellier (USN 765) and an Aegis Class cruiser, the USS San Jacinto collided during routine training off the USA East

Coast at about 3:30 p.m. on Saturday, October 13, 2012. The Montpelier is a nuclear-powered Los Angeles-class fast attack sub launched in 1991. The San Jacinto is an Aegis-class missile cruiser commissioned in 1988.

Naval vessels collisions at sea are fairly rare as to how often they do take place. Overall damage to both ships was minimal and the nuclear submarine propulsion plant was unaffected by the collision.

The two ships were participating in a "group sail" along with another vessel. The three ships were participating in an anti-submarine exercise in preparation for an upcoming deployment as part of the strike group for the aircraft carrier USS Harry S Truman.

At about 3:30 p.m. the bridge watch aboard the San Jacinto saw the submarine Montpelier rise to periscope depth about 100 to 200 yards ahead of them. The bridge ordered an "all back," but still collided with the sub. The assessment of damage suggests a complete depressurization of the sonar dome aboard the San Jacinto cruiser. Located below the water line of surface warships, sonar domes provide the bulbous shape to the bows of warships. After the collision, the submarine surfaced and communications were established between all the ships on the scene. The carrier USS Harry S Truman provided assistance with the two ships involved in the collision continuing to operate under their own power.

USS MIAMI ARSON FIRE, MAY 2012

The USS Miami, Los Angeles-class nuclear-powered submarine was decommissioned after 24 years of service when a shipyard employee, seeking an excuse to leave work early to go see his girlfriend, set a box of rags on a bunk on fire during a 20-month overhaul. The blaze quickly spread throughout the forward compartments causing $700 million in damage. Casey James Fury pleaded guilty and served a 17-year sentence in federal prison.

The ship had more than a dozen deployments that included clandestine undersea warfare missions and back-to-back deployments in which it fired Tomahawk cruise missiles in Iraq and in Serbia, earning the nickname "Big Gun."

It took 12 hours and the efforts of more than 100 fire-fighters to save the vessel. The fire severely damaged living quarters, the command and control center and a torpedo room, but did not reach the nuclear propulsion components at the submarines rear. Seven people were hurt dousing the flames.

After the fire, the Navy originally intended to return the ship to the fleet next year after extensive repairs. But it decided to scrap the submarine when estimated repair costs grew substantially above a $450 million estimate.

The shipyard workers removed the nuclear fuel and shipped it to a federal repository in Idaho. Enough repairs were made so that the submarine can be towed to Puget Sound Naval Shipyard in Washington State, where it was cut up into scrap. The estimated cost of the inactivation was $54 million.

The USA Navy launched a series of investigations after the fire that led to recommendations, including installation of temporary automatic fire detection systems while submarines and other vessels are being repaired or overhauled.

RONALD REAGAN CONTAMINATION

On March 11, 2011, a massive earthquake and tsunami triggered multiple meltdowns at the Fukushima Daiichi nuclear power plant in Japan. The aircraft carrier USS Ronald Reagan was redirected to the coast of Japan to participate in relief work for the tsunami survivors. Sailors from the ship later reported illnesses. The USA Congress asked the Defense Department for a report on the issue. The Pentagon report concluded that the sailors had not been exposed to enough radiation or contaminated water to cause health effects.

Four years after the event, about 500 sailors have fallen ill, and 247 of them have joined a class-action suit. The ship has since been decontaminated of traces of Cs^{137}.

NARWHAL SSN 671 HURRICANE MOORING ACCIDENT

The Narwhal sustained minor damage on September 22, 1989 as Hurricane Hugo affected the port city of Charleston, South Carolina, USA. She was moored with nine double wires and two three-inch ship's lines. All but one of the lines parted during the first half of the storm, and she went adrift into the Cooper River. The crew and tugboats tried unsuccessfully to move the submarine back to the pier before the second half of the storm. The submarine was submerged in the river and rode out the remainder of the hurricane with only part of the sail exposed.

SWIFTSURE CLASS INCIDENTS

The UK Swiftsure class suffered from a number of design problems and reactor incidents. In the early 1980s the Sceptre submarine collided with a Soviet submarine and her reactor's protection systems would have performed an automatic emergency shutdown and scrammed the reactor, but her captain ordered the safety mechanisms overridden and battleshort enabled. The crew were told to say that they had hit an iceberg. 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 March 6, 2000 the Sceptre suffered a serious accident while inside a dry dock at the Rosyth yards while undergoing trials towards the end of a major refit. The test involved flooding the dry dock, and running the main engines slowly with steam supplied from the shore. However, too much steam was used and the engines went to full speed. The Sceptre broke her moorings and shot forward off the cradle she rested on. The steam line ruptured, the scaffolding buckled, a crane was pushed forward some 15 feet, and the submarine moved forward some 30 feet inside the dock.

The Sovereign submarine underwent an extensive refit in the mid-1990s and was rededicated in January 1997. Cracks were discovered in the tail shaft during the post-refit sea trials and she was sent to Rosyth for 14 weeks of emergency repairs in June 1998.

On May 26, 2008, the Superb submarine 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 re-submerge due to damage to her sonar. After undertaking initial repairs at the Souda Bay NATO base on Crete on June 10, 2008, she passed through the Mediterranean Sea, 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 June 28, 2008. After surveying the damage, the Royal Navy decided to decommission the Superb slightly ahead of schedule on September 26, 2008.

TYPHOON TK17 ACCIDENT, SEPTEMBER 27, 1991

Three out of six Typhoon class boats produced still exist by 2019, with just one remaining in active service. The other two TK-17 and TK-20, were decommissioned awaiting the removal of their nuclear reactors. A single Typhoon class submarine remains in the Russian Navy's service, the first one ever built, the Dmitry Donskoy TK-208 [13].

The nuclear ballistic missile submarine (SSBN) twin nuclear reactor TK-17 was ordered to execute a test launch of one of its 20 SS-N-20 Sturgeon or R-39 Rif submarine-launched ballistic missiles. These three-stage solid-fuel ballistic missiles are massive in size, weighing a staggering 185,000 pounds and able to carry up to ten multiple independently-targeted reentry vehicles (MIRVs) [13].
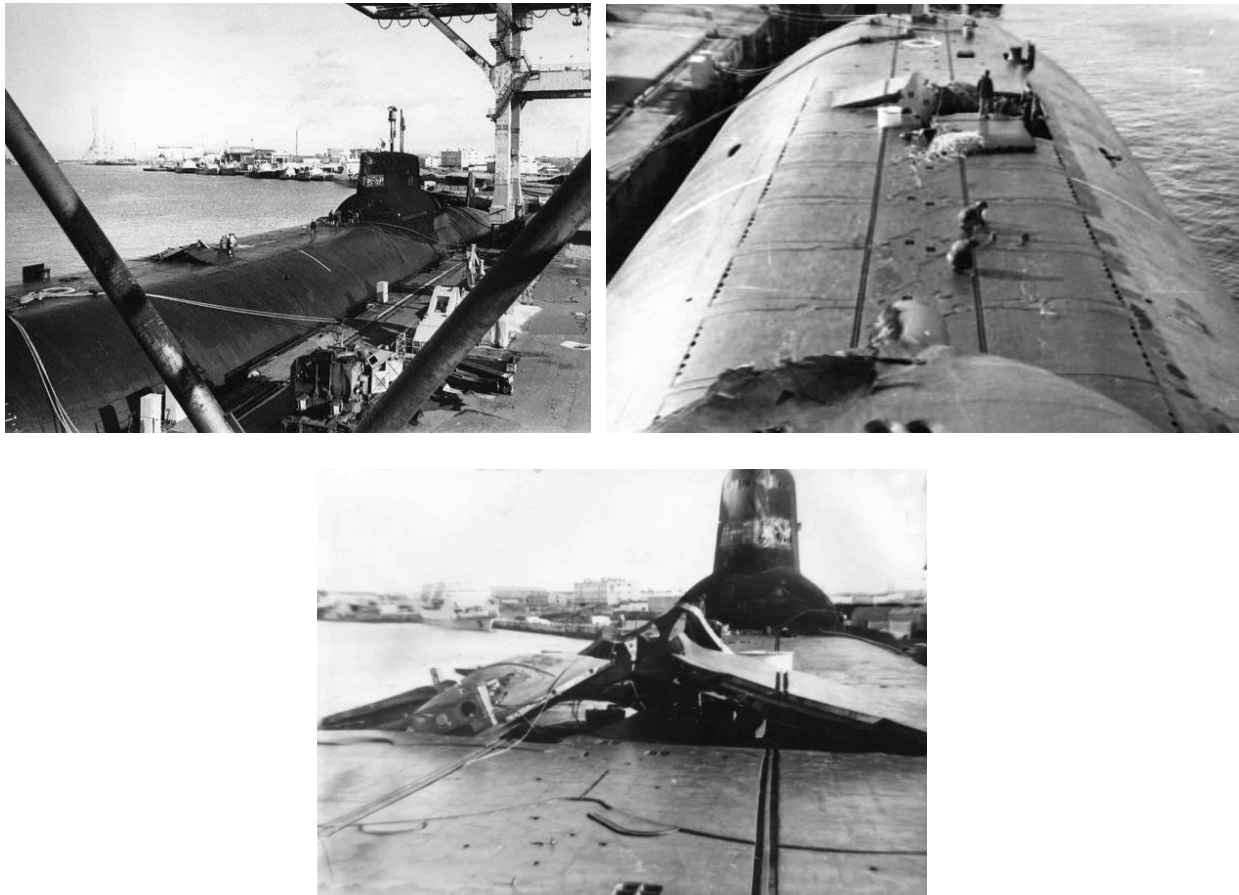
Figure 79. Test missile tube damage on the Typhoon TK-17.

A test missile, which had inert warheads, was loaded into one of TK-17's vertical launch tubes before the submarine headed out to sea. Once launched, it would fly thousands of miles east, impacting on Russia's missile range on the Chukotka Peninsula.

On September 27th, 1991, TK-17 moved into launch depth position and ran through its pre-firing sequence. As the launch clock clicked down towards zero, instead of the 53 foot long,

23 foot wide missile boosting its way towards the ocean's surface it exploded while still cocooned inside its launch tube. The silo door that covered the missile tube was totally blown off.

Captain Igor Grishkov acted quickly and decisively, ordering up an emergency blow of TK-17's ballast tanks, a move that sent the 574 foot long submarine porpoising to the surface. The action was completed successfully and TK-17's crew was able to visually examine the submarine's long forward-set missile farm. There were a series of fires raging near where the test missile had detonated. The missile's solid fuel propellant had scattered across the submarine's upper surface. The rubber anechoic coating that helps the submarine from being detected acoustically was set alight and the fire would rapidly spread. Nineteen other missiles sat tightly packed in two neat lines of ten under and near the blaze.

Captain Igor Grishkov acted quickly and decisively, ordering a dive counter-intuitive maneuver for a submarine that is damaged in ways that crew could not fully understood at the time. His plan was to put the fire out in a way only a submarine can, by submerging the vessel and starving the flames of oxygen. Grishkov knew that the stricken missile's launch compartment would flood, and possibly other sections nearby, and alerted the crew to this possibility, but he had to make a decision that would save the boat from sinking, even if it meant taking on new types of damage and even possibly casualties.

The disciplined crew carried out the snap order far quicker than it could normally have been accomplished. When the boat was ordered back up to the surface again the fires were extinguished. The stricken submarine and its unharmed crew of 160 limped back to Severodvinsk where its burnt skin and badly damaged launch tube were repaired under a shroud of secrecy. The tube would never be used again and was permanently sealed off. TK-17 would go onto serve for 13 more years before being sidelined in 2004.

It's mission?

Submarine-launched ballisitic missile test vessel.

Table 11. Major nuclear and diesel submarine accidents since 1968.

Accident	Location	Date
USA Navy submarine Scorpion sinks with 99 men aboard.	East of Norfolk, Virginia	May-June 1968
French diesel submarine. The Eurydice (S644) sinks with 57 crew members. Did not carry nuclear devices.	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,	Chazma Bay on the Pacific coast by Vladivostock	August 10, 1985

claiming a maintenance crew of 10 people		
Soviet Mike Class submarine develops a fire with a loss of 42 lives	Off northern Norway	April 7, 1989
Toxic fuel leaked from a ballistic missile and poisoned several Russian service men	Russia's far east	June 16, 2000
Russian Oscar-II Class submarine Kursk sinks with 118 crew members. The hydrogen peroxide fuel of a faulty torpedo ignited and created an explosion onboard that registered on the Richter earthquake scale.	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
Collision between Los Angeles Class fast attack submarine USS Montpellier (USS 765) and Aegis Class Cruiser USS San Jacinto (CG 56).	USA East Coast, off northeastern Florida	October 13, 2012, 3:30 pm
USS Miami fire set in a box of rags during overhaul by an employee seeking an excuse to get out of work early	Portsmouth Naval Shipyard	May 2012
The Narwhal SSN 671 sustained minor damage as a result of broken mooring lines	Cooper River, Charleston, South Carolina, USA.	September 22, 1989 during Hurricane Hugo

The breaking of a propeller shaft of the Tullibee nuclear submarine that was due to a combination of corrosion and metal fatigue occurred on June 1978 while she was submerged in the Mediterranean Sea. The engine room flooded. It was taken into dry dock in Rota, Spain, for repairs. The Navy investigated reports that crewmen informed the captain that the shaft was cracking in seven days before it broke. He did nothing about the crew's warnings and omitted any reference to the warnings in his report about the incident, according to allegations by some crewmen. The shaft breaking and unheeded warnings were investigated by the Navy Judge Advocate General (JAG). The engine room crew noticed sand leaking from the shaft's bearing on June 8, 1978, after the Tullibee left Naples, Italy.

The shaft is a hollow tube filled with sand, which gives it stability. The engine room crew assumed the shaft had cracked inside a bearing because sand was leaking through the bearing and piling up in the bilge. The crewmen showed the sand to the captain, who said it was not coming from the shaft. The shaft broke and the engine room flooded. The sub could not surface immediately because destroyers were maneuvering overhead. The captain ordered the ships away but had to wait a few minutes. The engine room flooded and the stern dropped about 15 degrees.

The shaft broke between the inner stern tube bearing bushing and the shaft seal bushing. After the bushings were installed on the shaft, a machinist cut a relief between them that was then filled with rubber for the emergency shaft boot to seal against. The remains of the shaft plugged all but about 3 square inches of the hole the shaft went through. The crew hooked up a submersible pump to a hose connection on the suction of the drain pump and moved water off the ship.

Another interpretation is that the Tullibee's shaft broke due to a rear end misalignment combined with a machinist's error. The original shaft machinist went too deep on a cut between two sleeves into the shaft metal, which is why it broke where it did.

The USS Squalus sank in 1939 after failure of an induction valve. She was not very deep at the time.

HMS Thetis sank in 1939 after someone opened the torpedo tube door in error. She was on the surface at the time.

USS Thresher was lost in 1963 during a deep dive. The most likely theory appears to be the failure of a joint in a salt water piping system due to the sea pressure.

23. ALL ELECTRIC PROPULSION AND STEALTH SHIPS

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 2011-2013 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 80. The Sea Shadow stealth ship in 1990 and in 2004 used radar deflecting technology used in the F-117 Nighthawk stealth fighter. Source: USAF.

Figure 81. To hide it from satellite imaging, the Sea Shadow (later scrapped) stealth ship was moored under the canopy of the "Hughes Mining Barge" as a dry dock. It was reportedly used to retrieve a section of the K-129 sunken Russian Golf Class ballistic submarine with possibly parts of its reactor, code machine, ballistic missiles and nuclear torpedoes weapons systems.

Figure 82. Stealth radar deflecting technology implemented into a French Lafayette class frigate, 2001 (left). The South African stealth Valour class frigates, built by Blohm + Voss from Hamburg, Germany to the MEKO A-200SAN design, uses both screws and water jets, in a "Waterjet and Refined Propeller" or WARP arrangement, with three shaft lines. A single GE

LM2500 gas turbine and a pair of MTU 16V1163 TB93 diesels drive Lips controllable-pitch propellers outboard and a single Lips LJ2 10E water jet on the centerline.

Figure 83. Stealth cruiser.
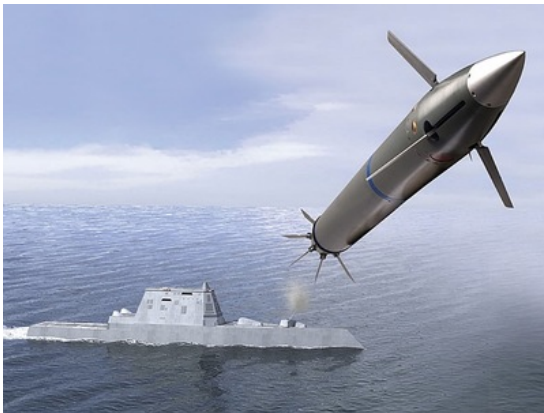
Figure 84. Zumwalt class DDG-1000 stealth destroyer is optimized for firing land-attack missiles; not Ballistic Missile Defense, BMD missiles. The Raytheon Company builds the DDG-1000's SPY-3 radar, and Bath Iron Works, the Maine shipyard, builds the DDG-1000.

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.

24. STEALTH UNMANNED AERIAL VEHICLES, UAVs

A road-map for future research and development envisions drone-carried munitions that deliver much more powerful explosions through the use of "energetic nano-particles" as drone ammunition. Even though drone-based missions have proven significantly cheaper in a monetary

sense compared to more traditional manpower intensive missions, the costs would be further reduced by developing more autonomous robots and off-loading as many human tasks as possible onto machines.

The roadmap considers "nano" drones, which are insect-sized robots designed for land and air, as well as "robotic wingmen" to provide unmanned help to ground-based troops. Ground-based robots too "have proven their worth in Iraq and Afghanistan across a spectrum of mission areas." The roadmap also includes a plan to develop water-based drones for mine-hunting and maritime security.

Figure 85. Lockheed-Martin RQ-170 Sentinel Stealth Unmanned Aerial Vehicle (UAV) drone, known as the Beast of Kandahar. Source: Lockheed-Martin.

Figure 86. X45A UAV.

Figure 87. X-47A UAV.

Figure 88. Navy X47B Grumman UAV on plane elevator of USS George W. Bush aircraft carrier (left) and on USS Harry Truman (right). Source: USA Navy.

Figure 89. Landing and take-off of the X47B at the Edwards Air Force Base and on aircraft carriers. Source: USA Navy.

Figure 90. Northrup- Grumman X47 steam catapult. Source: USA Navy.

Northrop Grumman X-47B drone closely resembles a strike fighter. It can take-off from and land on an aircraft carrier and support mid-air refueling. Unlike the current crop of military UAVs, the X-47B will operate mostly autonomously once airborne.

The X-47B is designed to fly at altitudes of up to 40,000 feet at high subsonic speeds. It is also designed for long range, high endurance missions, performing several tasks including intelligence gathering, surveillance, reconnaissance, targeting, close air support, communications relay, ballistic missile detection, and precision strikes.

The X-47B drones are being built in California and incorporate parts and services from several partners including Lockheed Martin, Pratt & Whitney, GE Aviation, Honeywell, Goodrich, Dell, GKE Aerospace, Eaton Aerospace, Moog Inc., Wind River, Parker Aerospace, Hamilton Sunstrand, and Rockwell Collins.

Figure 91. Navy Northrup=Grumman helicopter drone mq8 c.

Figure 92. Northrup-Grumman helicopter drone.

Figure 93. Skytote counter rotating vertical-landing UAV. Source: AeroVironment.

AeroVironment of Simi Valley, California, has developed a novel UAV configuration designated as the the Skytote. It uses dual counter rotating propellers designed to enable operation in a helicopter mode, while also being able to transition to wing born flight for efficient point-to-point operation. This complex vehicle uses an intricate drive system to allow helicopter operations with cyclic and collective control, as well as blade pitch control, combined with normal aircraft control surfaces in conventional flight operations.

25. LITTORAL COMBAT SHIP (LCS)

Littoral Combat Ships (LCS) 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 USA Navy is acquiring a steel-hulled version of the LCS made in Marinette, Wisconsin, by Bethesda, Maryland-based Lockheed-Martin, as well as an Aluminum trimaran version being built in Mobile, Alabama, by Henderson, Australia-based Austal. 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. A program exists to build a total of 52 ships in the two versions made by Lockheed Martin Corp. and Austal Ltd.

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 with 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 52 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.
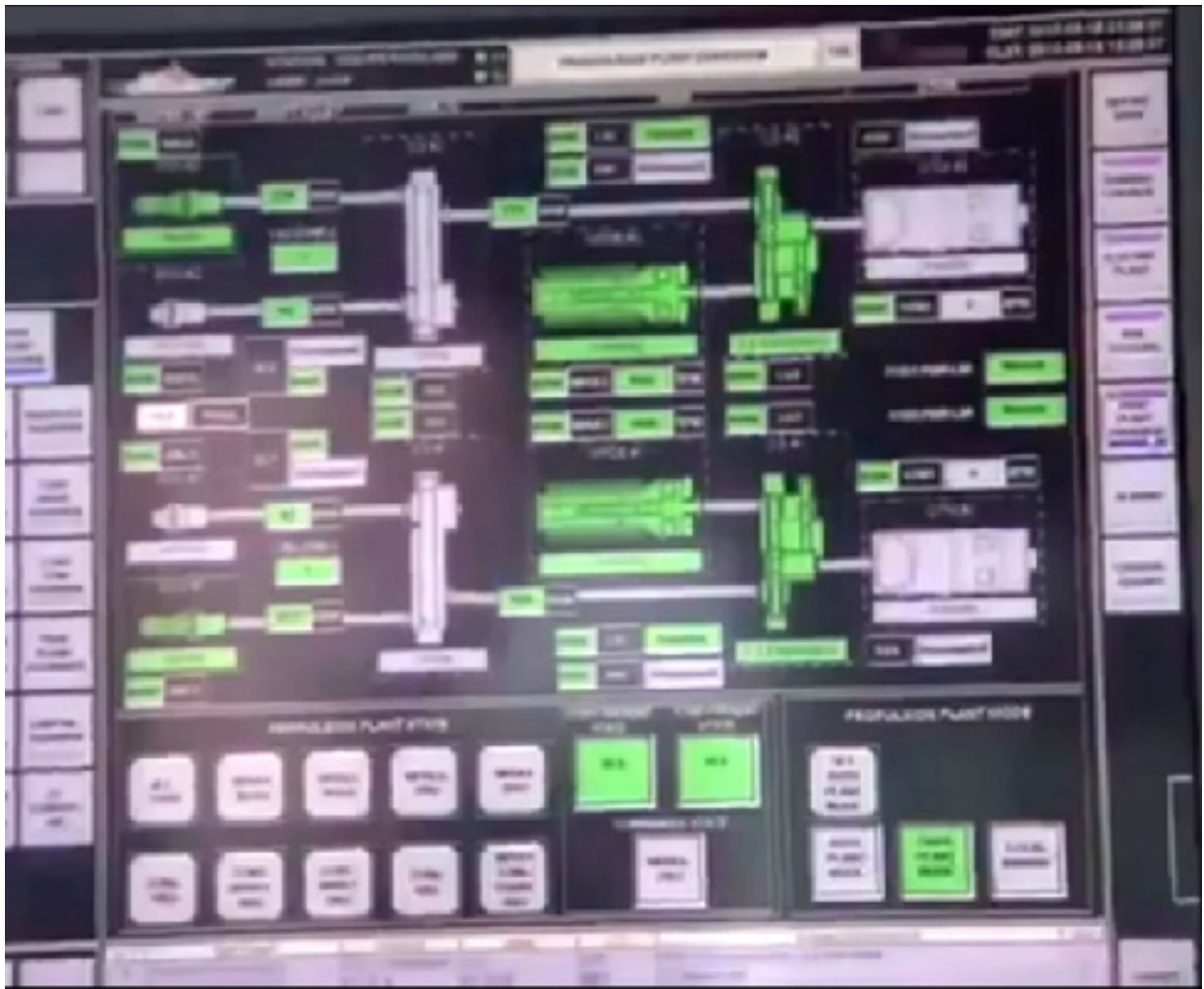
Figure 94. Trimaran Littoral Combat Ship uses water jets propulsion for Independence-class stealth ships. Source: Austal, USA Navy.

Figure 95. LCS 2 Independence-class Littoral Combat Ship high maneuverability. The generated wake from a sharp turn can sink small fast attacking craft.

The prototype vessels have overcome early flaws of cracks, corrosion and breakdowns, including a cable in its water-jet steering system. In their surface warfare role, when all the weapons systems are working as intended, the vessel "is only capable of neutralizing" small fast-attack boats It "remains vulnerable to ships" with anti-ship cruise missiles that can travel more than five miles or 8 kilometers. The vessels will operate with crews of 40 to 50, which is 1/4 - 1/5 smaller than other typical warships. Their sailors must carry out the same administrative, operational and support functions. That means the ships must transmit to their home base a myriad of data constantly to assess their readiness, identify requirements for preventive maintenance and perform other functions from deployments around the world.

26. NOISE CONTROL FEATURES

Multiple features affect the stealth needed for subsurface vessels operation. The first problem is caused by the cavitation noise caused by bubbles formation and collapse on the surface of propellers. The high speed operation of propellers creates low pressures steam bubbles that create a detectable-sound bubble train. The remedy is the special design and machining of slow-moving high-thrust propeller swept blades that minimize the cavitation problem. Conventional propellers are being substituted-for with jet propellers. A shroud is added around them to mask any generated bubble cavitation sound.
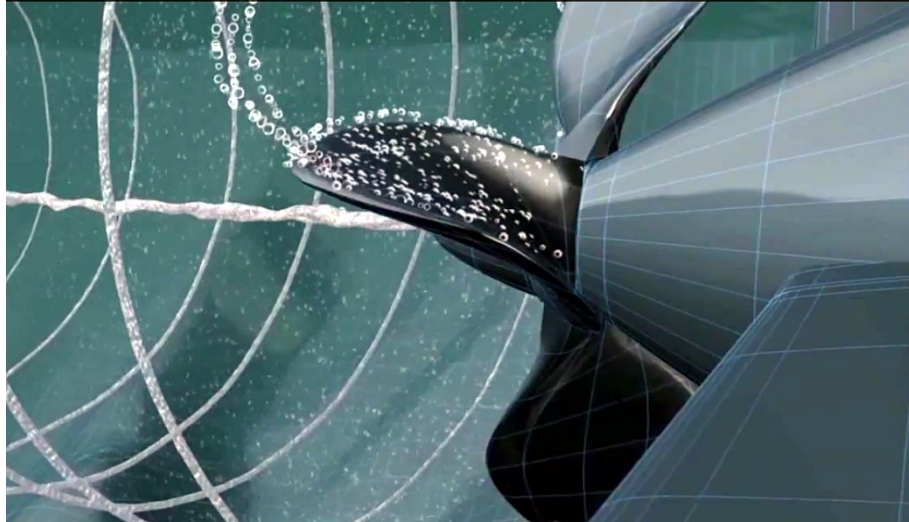
Figure 96. Low pressure cavitation and formation of steam bubbles wake.
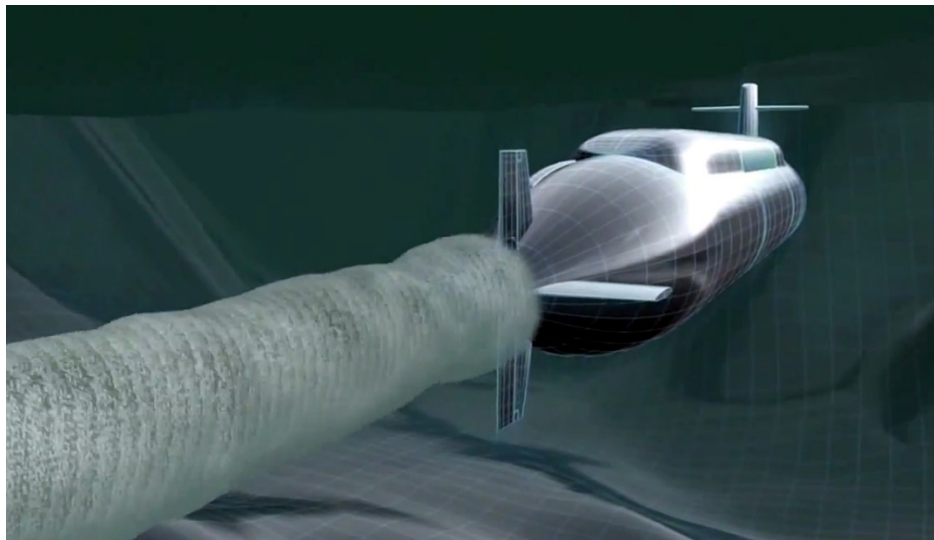
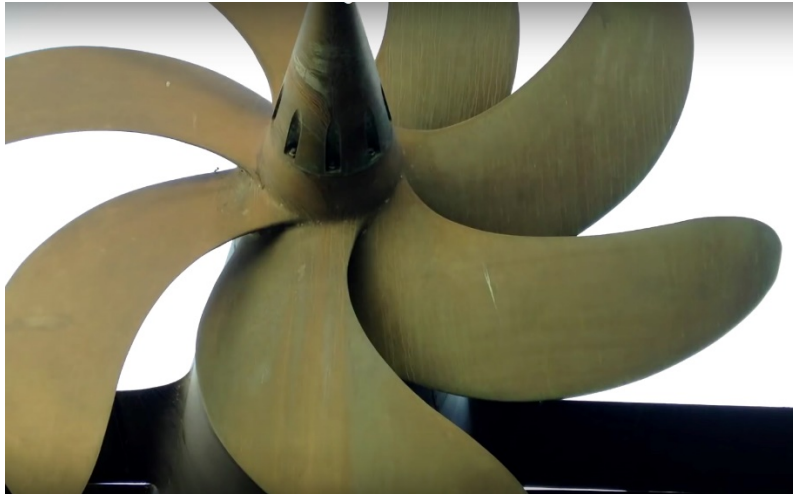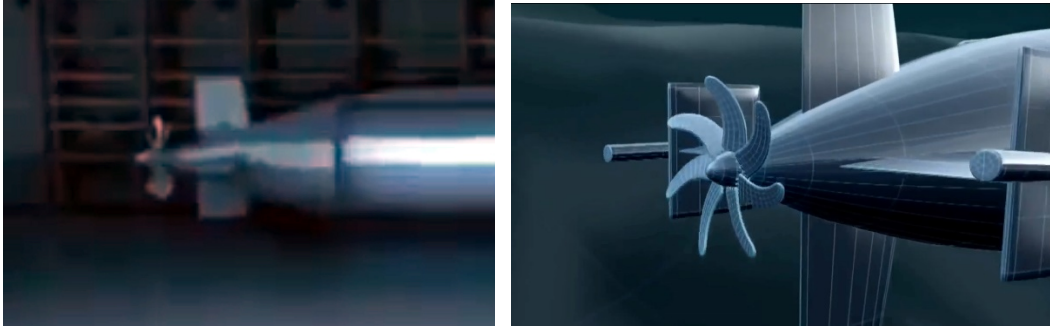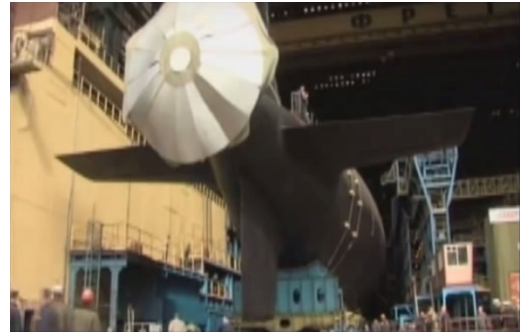Figure 97. Cavitation bubble-train trail from propeller. Cavitation trails persist for many hours.
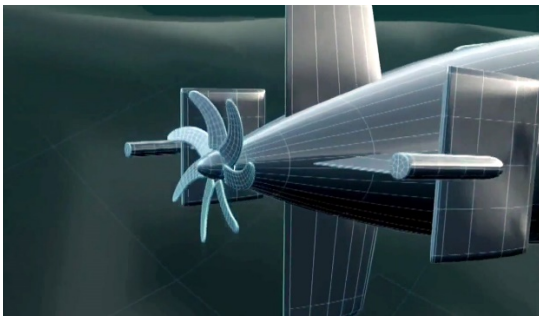
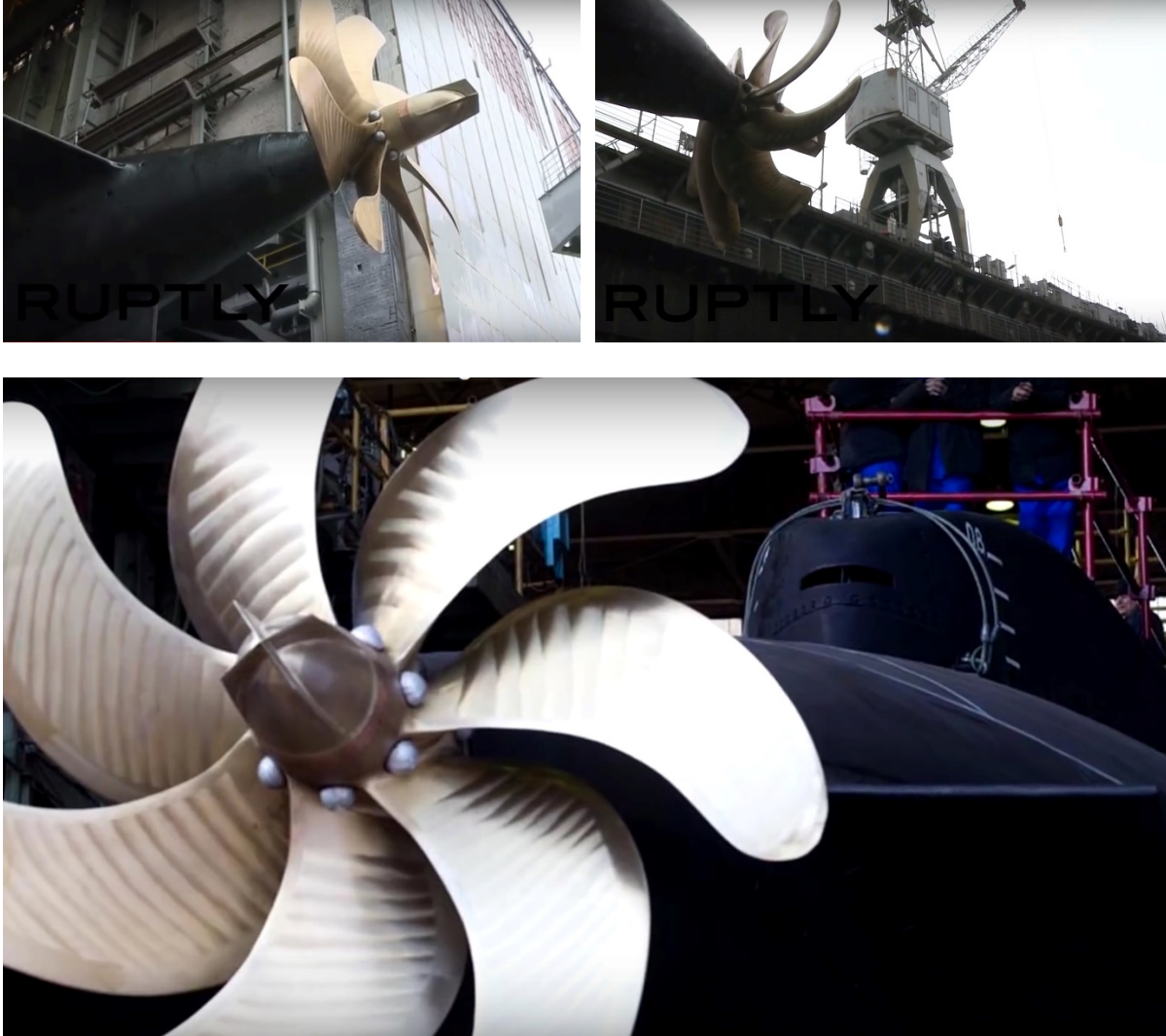Figure 98. High thrust, low speed, low cavitation rotor blades designs.

Figure 99. Swept and serrated propeller blades of the 4-th generation Russian Project 885 Yasen / Graney-class K-560 Severodvinsk hunter submarine in dock, June 23, 2014. The low-magnetic steel, 90-crew submarine measures 393 feet in length and has a submerged speed of up to 30 knots (32 knots silent and 35 knots maximum) and has a displacement surfaced / submerged of 8,600 / 13,000 tons. Maximum dive depth is 300 meters. It is armed with long-range (3,100 miles or 5,000 km) cruise missiles, anti-ship cruise missiles, torpedoes and mines, as a replacement for the Akula-class hunter-killer submarines.
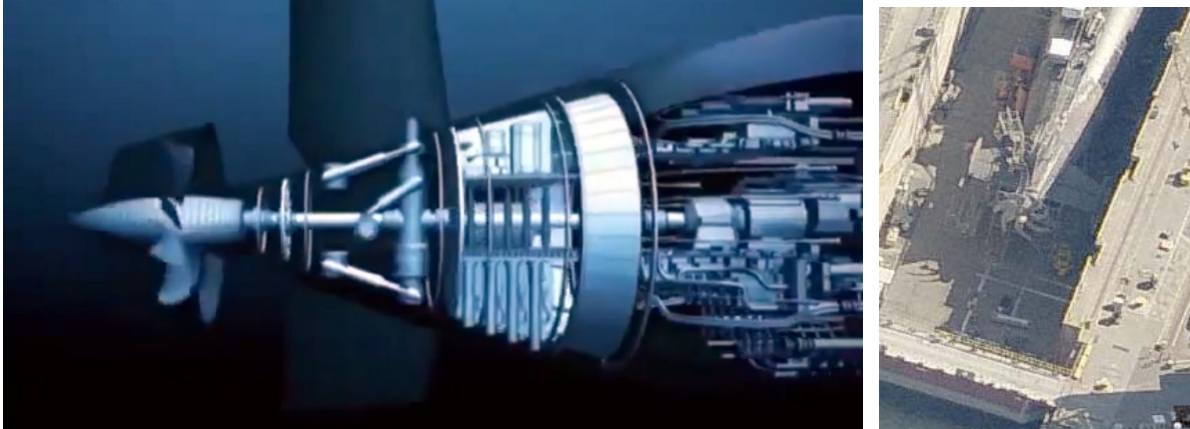
Figure 100. Propulsion system schematic. Swept-blade propellers surrounded by a shroud.

Machinery vibrations are damped out using springs and rubber grommets installed at strategic locations that are sources of machinery vibrations.

Figure 101. Springs vibration suppression system.

Figure 102. Rubber shock absorbers for vibration suppression.

      To cancel sonar echoes, the surface of the vessel is covered with a skin surface rubber mat tiles that is glued to the outer surface of the hull before launching.

Figure 103. Installation of skin surface "anechoic" rubber or urethane tiling to absorb sonar signals on outer surface of hull of a UK nuclear submarine that lost some tiles (top). Peeling urethane tile on Virginia class vessel, USA. Russian Akula class of submarines acoustic coating (bottom).

27. LONG TERM ENDURANCE

Figure 104. Schematic of water electrolysis system for generation of breathing oxygen. The oxygen and hydrogen could be stored for silent operation using fuel cells to drive electrical motors.
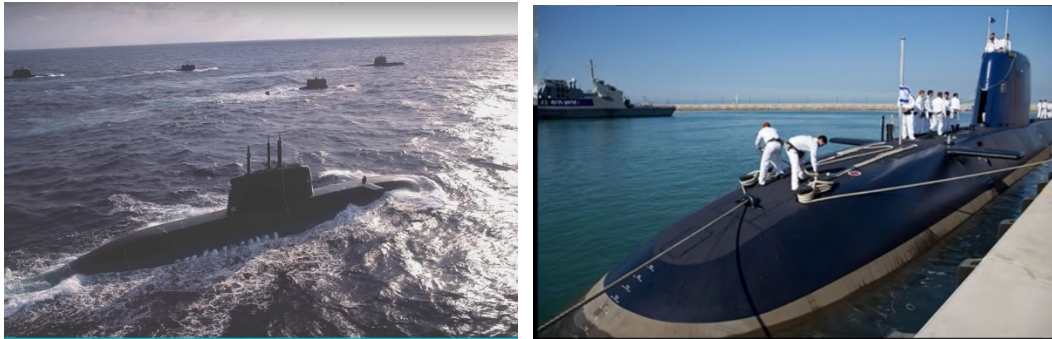
Figure 105. Fleet of fuel cell driven Israeli submarines provided by Germany.

For long term endurance, the oxygen breathing supply to the crew is replenished by a water electrolysis system dissociating water into hydrogen and oxygen. The hydrogen can be stored and recombined with oxygen to run silent-operation fuel cells that would drive electrical motors and provide a power supply for low-power stealthy operation.

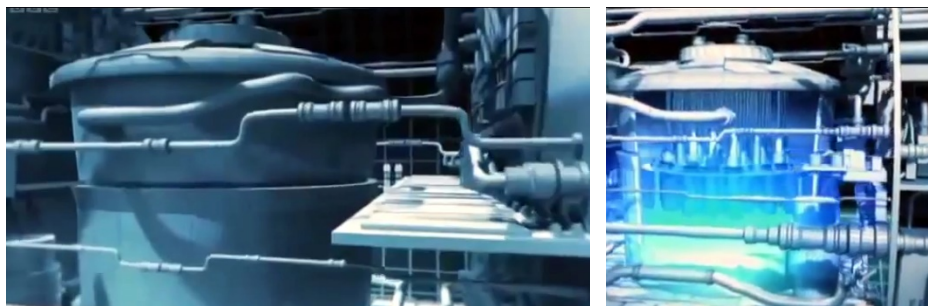# 28. REACTOR CONFIGURATION

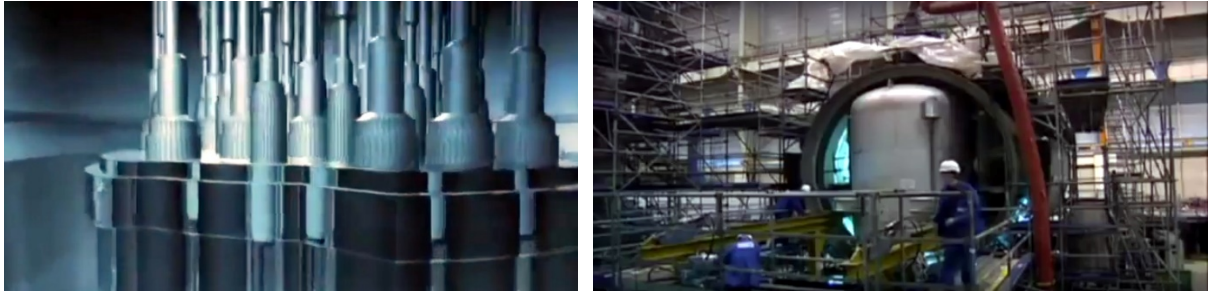Figure 106. Reactor configuration schematic.

Figure 107. Control rods, steam generator and instrumentation configuration and reactor vessel.

A special telescoping configuration system is adopted for the reactor control rods to minimize the reactor pressure vessel height compared with land-based systems.
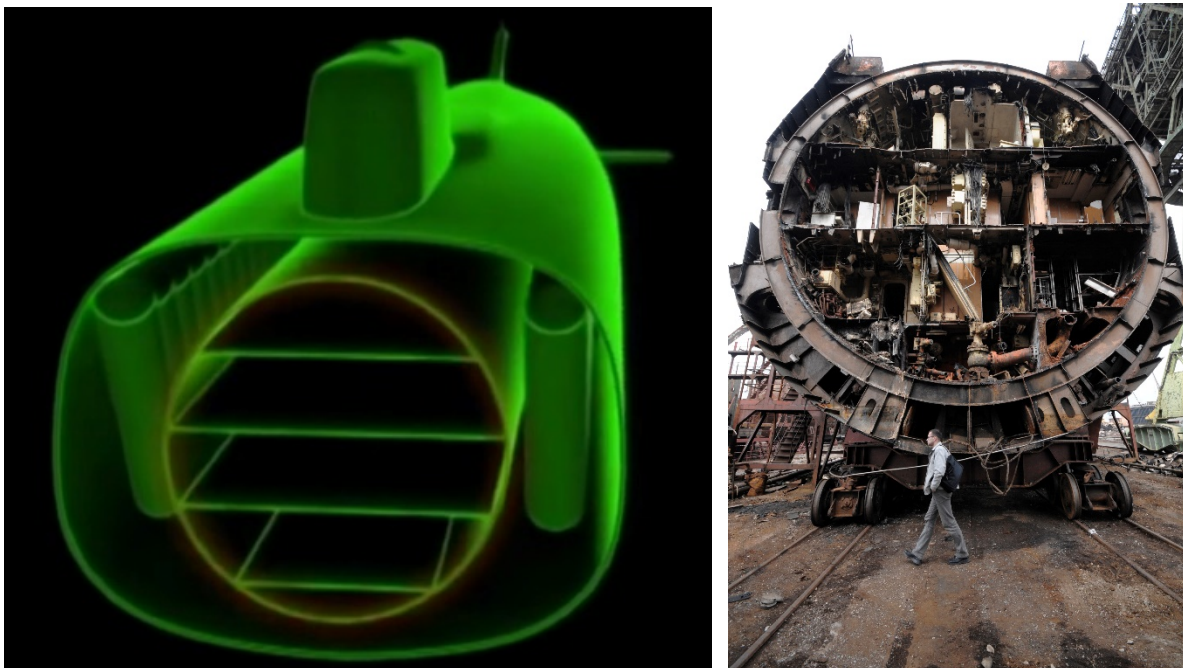
Figure 108. Double-hulled Russian submarine cross-section with missile tubes positioned in annular space.

LASER MINE DETECTION SYSTEM, MAGIC LANTERN LIDAR

LIDAR stands for Light Detection and Ranging.It has the capability to use pulsed laser light to measure variable distances on a surface, such as the Earth. Data is calculated by measuring how long it takes the pulsed laser light to return back to a sensor. The data can then be used to generate 3D information about surface characteristics. NOAA is making use of LIDAR sensors. Extremely accurate maps of the Earth's surface are being generated which can be used to track soil erosion and elevations of sea levels.

A LIDAR system may be conceived to provide a three dimensional map of the immediate surroundings of a submerged vehicle depending on the laser's range in water. Without such an active sensor, submerged vehicles depend on sound as a passive sensor, and are blind to other environmental cues. LIDAR active sensors can be turned on and off as a three dimensional map of the surrounding environment is needed for underwater navigation.

The Airborne Laser Mine Detection System (ALMDS) was developed by the USA Navy to detect and classify floating and near-surface, moored mines on the MH-60S helicopter. Developed by Northrop Grumman, it uses pulsed laser light and streak tube imaging receivers housed in an external equipment pod to image surface-to-depth volume for people, boats, or other objects. It is intended to be capable of day or night operations.

It has also been considered for anti-submarine warfare applications. The laser is fired into the water and cameras capture water reflections to create images. Although the depth that the laser can penetrate and provide quality feedback is limited, it can detect surface mines that Sonar cannot detect.

The Magic Lantern LIDAR system is a blue-green laser unit designed to emit and receive and detect mine-like objects, which would show a greater return of light energy than open water. It was procured following mine incidents during combat operations in the Persian Gulf in the early 1990s.

29. ANTI SUBMARINE WARFARE (ASW) CONTINUOUS TRAIL UNMANNED VESSEL, ACTUV

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, Massachussets, 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, Connecticutt., for development of an exploratory crowd-sourced tactics simulator.

Stealth aircraft are rumored to be detectable by the radio frequency dead spot they cause in the atmosphere. Acoustic dead spots caused by the presence of a stealth submarine could be detected as well. Electromagnetic propulsion may be developed and would require new Electromagnetic Anomaly Detection approaches.

SWARM WARFARE USING UNMANNED UNDERWATER VEHICLES, UUVS

Submarines cannot be made totally noiseless. They displace 8,000-19,000 tons of water and create a massive wake, even at a silent cruise which is typically 3-5 knots for boomers and 10-20 for SSNs. Nuclear reactors, unless using a natural convection mode or magneto-hydrodynamic propulsion, use steam and generate coolant pump noises which can be detected at long ranges. This is sufficient to avoid collision, but not fully reliable from the perspective of detection resulting in a counter-attack.

The future of ASW may evolve into unmanned underwater vehicles (UUVs) the size of a combat delivery vehicle of 10 tons that can maneuver like a torpedo and uses fuel cells. Operation can be in linked pairs with one unit rushing along, using active sonar attracting possible defenses, and the second unit following in a listening silent mode. One UUV goes would travel above a thermocline, and the other below.

The cost would be less than that a $600-800 million diesel-electric hunter-killer SSK submarine, and less than a $3 billion nuclear SSN. The UUVs act as dog hounds preceding the hunter. After a 1-2 week cruise they go back to a tender manned submarine to recharge in hydrogen for their fuel cells. Manned submarines would thus evolve into control centers and weapons magazines for a swarm of UUVs.

Future ASW systems may eventually evolve into the detection of microgravity and magnetic signatures of disturbed particles by the passage of large secondary masses from satellite or loitering drones platforms. This will require a large computer processing power, but will take advantage of the sea bed having already been microgravity-mapped for geo resources such as oil exploration.

30. DIRECTED ENERGY SYSTEMS

OVERVIEW

Directed energy weapons deliver large levels of energy on a target in a short period of time. That is to say that they are characterized by high power delivery. In the case of a laser, you high power of coherent photons are used. When a rail-gun is used, it is high power kinetic energy delivery with a relatively small metal mass moving at a high speed.

Directed energy weapons are also cost-effective against the advent of cheap drones or low-cost cruise missiles. Instead of shooting expensive rounds at the cheap drones, with laser and rail gun technology, those shots cost just a few dollars for the electricity generated.

FREE ELECTRON LASER, FEL TUNABLE LASER

The Free Electron laser is contemplated as a directed energy weapon system that can replace in the 2020s 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 and glass. Chemical lasers use gaseous media and toxic liquid materials. 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 tasks 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 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. The electron accelerator has to eventually be shrunk in size to fit on a naval vessel.

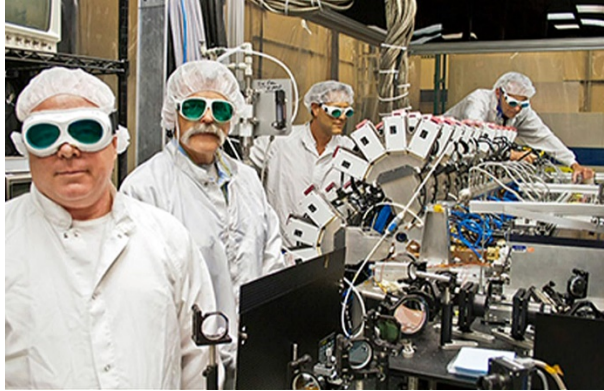Figure 109 Naval laser system. Source: USA navy.

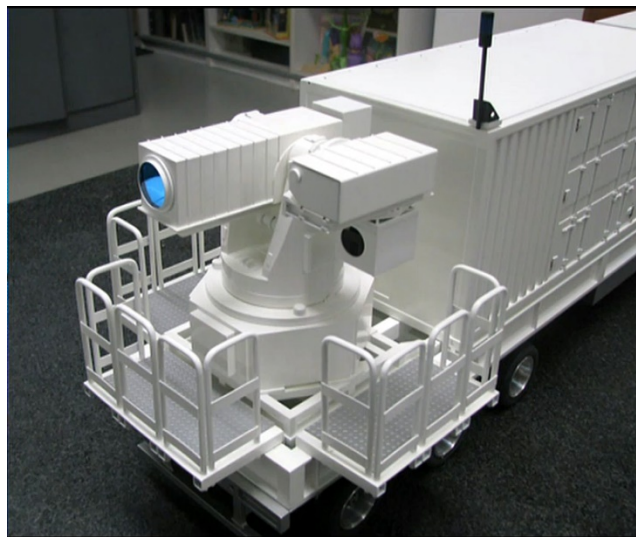Figure 110. Laser laboratory setup, Boeing Company.

Figure 111. Laser platform, Northrup Corporation.

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.
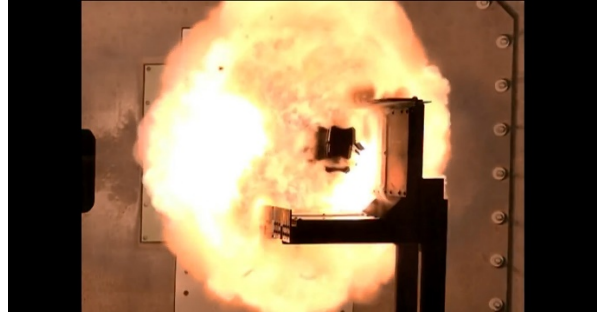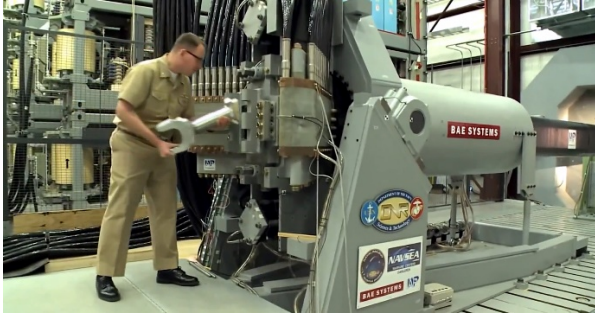
Figure 112. Mach 10 rail-gun setup for the USA Navy. Source: BAE Systems.

Figure 113. Rail-gun experimental setup and firing.

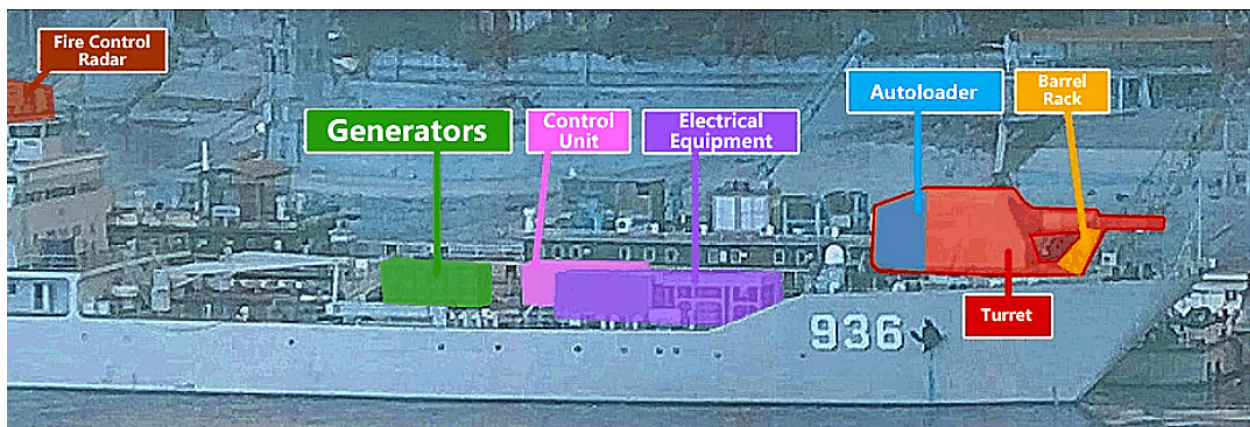Figure 114. General Atomics (GA) Blitzer rail-gun with sabot projectile.

Figure 115. Yuting-II class Type 072III-class landing ship equipped with rail-gun with cooling and reloading equipment.

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 ab out 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/cm^3 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/cm^3 are currently achievable with a goal of 8 joules/cm^3 that is approaching a level where a rail gun can be installed on a tank.

HIGH POWERED MICROWAVE (HPM) 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). 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."

COMBAT PERSONNEL LAUNCHERS, SEAL DELIVERY VEHICLES

Divers introduced from seal delivery vehicles can sabotage port and shore facilities, remove mines or locate them, and can swim under surface ships and submarines and place tracking devices onto them, obtaining accurate details of their area of operations and locations.
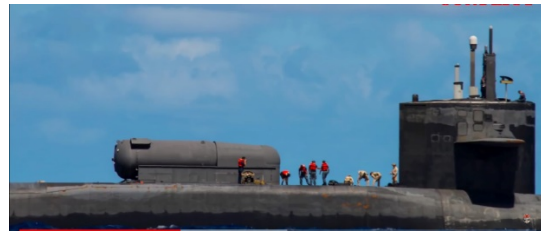
Figure 116. Seawolf class of submarines equipped with multiple combat personnel launchers.

Figure 117. Combat Personnel Launchers.

SEA HUNTER, AUTONOMOUS DRONES, MEDIUM DISPLACEMENT UNMANNED SURFACE VEHICLE, MDUSV, ANTI-SUBMARINE WARFARE (ASW) CONTINUOUS TRAIL UNMANNED VESSEL (ACTUV)

A prototype autonomous ship known as the Medium Displacement Unmanned Surface Vehicle (MDUSV) has been transferred to the USA Navy's Office of Naval Research (ONR) from the Defense Advanced Research Projects Agency (DARPA), after it completed its multi-year Anti-Submarine Warfare (ASW) Continuous Trail Unmanned Vessel (ACTUV) program.

The vessel can travel thousands of miles and even stay at sea for months without the need of a manned crew. The ACTUV represents a new vision of naval surface warfare that trades small numbers of very capable, high-value assets for large numbers of commoditized, simpler platforms that are more capable in the aggregate. The USA military has talked about the strategic importance of replacing 'king' and 'queen' pieces on the maritime chessboard with lots of 'pawns with a strategic purpose of a "surveillance vehicle.

It comes at a relatively cheap $20 million price tag and takes only around $20,000 a day to operate. This figure is less expensive than a crew-run ship and also nixes potential personnel risks when navigating dangerous missions, such as navigating a minefield. Without firepower onboard, the Sea Hunter is currently a surveillance vehicle. Its tests have revolved around how easily and autonomously the vessel can maneuver its 132-foot-long body, accelerate to speeds nearing 27 knots, and using use radar and cameras to spot other vessels.

The USA is embracing artificial intelligence, robotics, and other emerging technologies to maintain relevance on the changing battlefield.

Figure 118. USA Sea hunter double-float catamaran drone.

Figure 119. Sea hunter drone single-float catamaran for Anti-Submarine Warfare (ASW).

Figure 120. Drone submarines, China 70th anniversary October 1st parade, 1949-2019

31. PROPULSOR, PUMP JET PROPULSION, SHROUDED PROPELLER TECHNOLOGY

OVERVIEW

A propulsor is a mechanical device that generates propulsion. The word is commonly used in the marine vernacular, and implies a mechanical assembly that is more complicated than a propeller.

It operates in conjunction with the steering assembly and is surrounded with a shroud which cuts down on blade-tip and surface cavitation and radiated bubble collapse noise. It has a rotor element and a stator. The stator concentrates the thrust in an axial direction and reduces energy wasted in the tangential flow. This is useful in eliminating the torque on the hull and gives the vessel a better stability and maneuverability.

The number of blades in the rotor and stator are typically two different prime numbers to avoid the generation of standing waves. The pitch angles of the blades in the rotor or the stator may be varied to further reduce noise. The physical design and layout is similar to a single stage axial-flow compressor. Examples are the Kort nozzle and pump-jets.

The silent "caterpillar drive" like in the movie 'The Hunt for Red October' using magneto-hydrodynamic propulsion is not yet technically achievable as a practical option.

Water jets constitute a simple and reliable propulsion system, with the pump impeller turning at a constant speed and flow in one direction. The engine loading is constant and in most cases a gearbox is not required. The entire propulsion system receives less stress and requires less maintenance. Noise reduction, resulting in a low sonar signature; this particular system has little in common with other pump-jet propulsors and is also known as "shrouded propeller configuration" applications. Examples in submarine applications are the Royal Navy Trafalgar class and Astute class, the USA Navy Seawolf class and Virginia class, the French Navy Triomphant class and the Russian Navy Borei class. They are also implemented in the Spearfish,

Mk 48 and Mk 50 torpedoes. The USA Navy secured a license to implement the main shaft flexible coupling arrangement in USA submarines.

Water jets have plenty of pickup, can sustain high speed operations, but can stop on easily by reversing the thrust. They are responsive, and ideal for precise maneuvering or station keeping. They can be used in very shallow water and there is no screw that gets fouled.
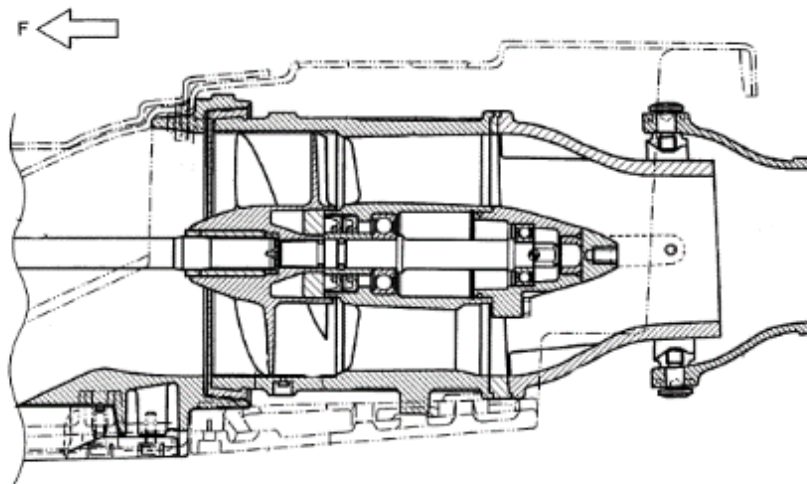
Figure 121. Dual propellers and distributed multi jets propulsor inlets (right) and outlets (left).

High powered water jet propulsion systems are appearing on bigger vessels including warships. Water jets powered craft can operate close to and up to the shore, and even run over obstructions without damaging the propulsion equipment. Flotsam and jetsam are not big problems, even at high speed. At slow speed these may be sucked into the jet unit but are unlikely to cause damage and can easily be removed.

Water jets are fast, packing a lot of power in a small amount of space. Because they have no turning propellers, they emit less noise and so are less susceptible to sonar or acoustic mine detection. Lower noise and less vibration delivers a more quiet and comfortable ride for passengers. Water jets eliminate the screws and rudders that make launching and recovering small boats, unmanned vehicles or swimmers a dangerous and difficult evolution.

A water jet is usually connected to an engine by a direct shaft. Sometimes diesels and gas turbines may be combined, or power may be cross-connected from one engine and applied to another water jet, so some kind of coupling clutch assembly may be required

Australian shipbuilder Incat and its USA subsidiary Bollinger Shipyards, have built several high-speed water jet vessels for the USA military, including the 1,740 ton, 370-ft. Joint Venture (HSV-X1), operated by both the Navy and Army. Joint Venture can achieve speeds up to 48 knots. The catamaran uses four Caterpillar 3618 marine diesel engines with four Lips LJ150D steerable water jets.

Figure 122. Single directional thrust water jet propulsor.

THE ASTUTE CLASS OF SUBMARINES

The BAE Systems Astute class of attack submarines is an example of the trend in jet propulsion. Its published technical specifications are:

Displacement: 7,000 tonnes surfaced, 7,800 tonnes dived.
Dimensions: 97.0 x 11.3 x 10.0 m.
Main Machinery: One modified Rolls-Royce PWR-2 pressurized water reactor; Two sets of GEC-Alston geared turbine drive; one shaft with pump jet propulsion; 27,500 shp, two Paxman auxiliary diesels.
Speed: Officially 29+ knots dived, unofficially probably over 32 knots
Endurance: 70 days submerged
Dive Depth: Over 300 m
Complement: 84 (qualified), accommodation for 12 officers, 97 enlisted
Missiles: SLCM: GDC/Hughes Tomahawk (TLAM-C Block III) land attack; Tercom aided inertial navigation system (TAINS) with GPS backup; range 1,700 km (918 nautical miles) at 0.7 Mach; altitude 15-100 m; 318 kg shaped charge warhead.
Torpedoes: 6-21 in (533 mm) tubes. Marconi Spearfish torpedoes; active/passive homing to 65 km (35 n miles) at up to 60 kt; directed energy warhead.
A total of 38 weapons can be carried for tube-launch, for example: 14 Tomahawk missiles, 24 Spearfish torpedoes.
Mines: Can lay mines.
Sonar: Type 2076 integrated suite (with Type 2074 active/passive bow array); Type 2077 HF under-ice navigational active towed passive array
Electronic Warfare (EW): Racal Outfit UAP(4) intercept suite; launchers for SCAD 101 and SCAD 102 decoys and SCAD 200 sonar jammers
Radar: 1 Kelvin Hughes Type 1007 navigation/search

Rolls-Royce is supplying the PWR2 nuclear propulsion units for all the Astute boats. The plant has a 25-year lifespan. A new long-life core, designated as core H, will power the boat for its full service term, eliminating the need for the expensive and time-consuming refueling process.

Figure 123. HMS Astute 48 class of attack submarine on rollout showing the lampshade noise suppression duct surrounding its shrouded jet propulsor. Source: BAE Systems, UK.

32. SUPER-CAVITATION TECHNOLOGY, UNDERWATER EXPRESS PROGRAM

Super-cavitation technology involves creating a bubble or a cavity of gas around an object within a liquid, reducing drag and allowing the object to travel at high speeds. The approach leads to a 60-70 percent reduction in drag resistance.

Natural cavitation does occur when an object moves so quickly in a liquid that air emerges from the solution. Ventilation super-cavitation is used in the "Underwater Express" program where an underwater craft blows air out of its front to create a bubble around itself.

The technology would allow the development of a class of underwater craft for littoral missions transporting high-value cargo and small units of personnel. The goal is to build a vehicle that can reach 100 knots in speed. By sustaining high velocity, the vessel will be able to outlast torpedo threats. Standard torpedoes operate below the super-cavitation range at approximately 40--60 knots and can be controlled, while nuclear-powered submarines travel at speeds greater than 25 knots. In the demonstrations conducted with a submerged body going fast, it has a tendency to be unstable, the instability increases with the speed and its control becomes challenging.

In the commercial world, instead of transiting the ocean at 50 knots, cargo ships could travel at 200 knots. Marine fleets could be used instead of aircraft for cargo transport requirements.

Super-cavitation has been used to move objects underwater for years, including some torpedoes powered at high speeds for a sustainable period of time. Russia studied a torpedo with super-cavitation capability called the "VA-111 Shkval" in the 1960s, and Iran has reportedly implemented some form of the technology in a torpedo.

33. 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 124. 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.

34. ANTI-SUBMARINE WARFARE, ASW

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 125. Wigwam B3 Betty nuclear depth charge test in open water off San Diego, California. May 15, 1955.

Figure 126. 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 127. The USA Navy's 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.

35. NUCLEAR UNMANNED UNDERWATER VEHICLE (UUV) DRONE SUBMARINES DOOMSDAY NARRATIVE
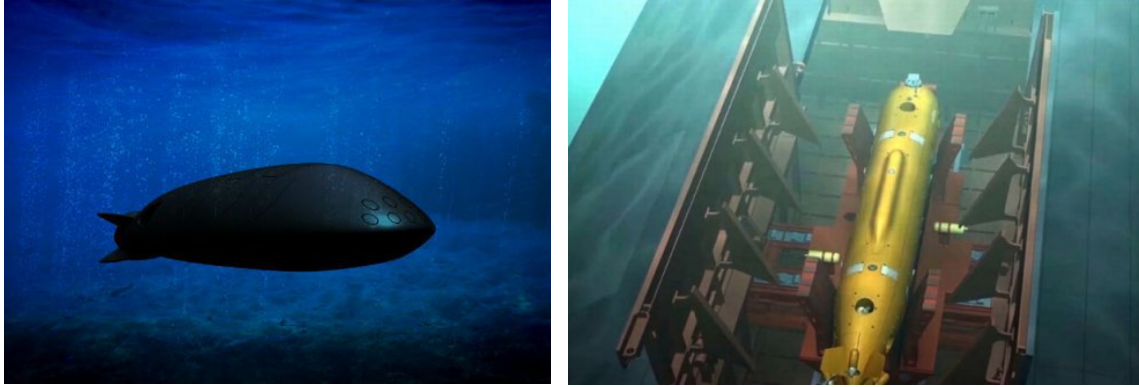
Figure 128. Nuclear drone submarine concept T15. The underwater torpedo/drone UUV would be equipped with up to a 100 Mt of TNT equivalent warhead [11].

During the 1950s, Russian academician and weapon designer Andrei Sakharov suggested to Russian Premier Nikita Khrushchev to deploy tens of doomsday thermonuclear warheads with a yield of 200-500 Mt of TNT equivalent along the USA maritime borders generating destructive tsunamis when triggered. According to Andrei Sakharov, the USSR would have been able to keep an eye on the ball without getting involved in the arms race. Nikita Khrushchev is reported to have rejected the idea as being a barbaric option [11].

During the Cold War, the Soviet Union developed an idea to detonate a nuclear device above the North Sea so it could cause a tsunami that would destroy and flood the UK and the Netherlands. The underwater variation is that it can be mounted on a submarine and go stealth instead of delivering it through an ICBM or strategic bomber.

Early in the nuclear age, Russia attempted the development of a 75-ft long T-15 thermonuclear-tipped torpedo for attacking coastal cities and ports with a range of 15 nautical miles.

With a small nuclear power plant, the Poseidon will approach the target for an intercontinental range at a depth of over 1 km and at a speed of 60-70 knots (110-130 km/h). According to the Tass Russian news Agency: "It will be possible to mount various nuclear charges on the 'torpedo' of the Poseidon multipurpose seaborne system, with the thermonuclear single warhead similar to the Avangard charge to have the maximum capacity of up to 2 megatonnes in TNT equivalent." With the drone's nuclear munition, the underwater craft is primarily designed to destroy reinforced naval bases of a potential enemy.

The first test of a thermonuclear device was conducted by the USA on February 1, 1952 on the island of Elugelab, Enewetak Atoll in the Pacific Ocean Marshall Islands. The test was named Mike, and the explosion surpassed all expectations: its strength was equal to 10 Mt or 10 million tons of TNT equivalent. In the Russian "Tsar Bomba" thermonuclear device, the potential yield of 100 Mt was reduced at the last minute to the achieved record 57 Mt by replacing the depleted uranium tamper by a lead one.

It is not clear whether the suggested 200-500 Mt of TNT equivalent yield is technically attainable. The Fukushima earthquake / tsunami is reported to be of a yield of 480 Mt of TNT equivalent. Associated with a magnitude M9.0 earthquake, an estimated 67 km^3 of ocean water moved towards 860 km of the Japanese coastline with a wave reaching about 24 m in height.

ОКЕАНСКАЯ МНОГОЦЕЛЕВАЯ СИСТЕМА «СТАТУС-6»
Головной исполнитель - ОАО "ЦКБ МТ "Рубин"
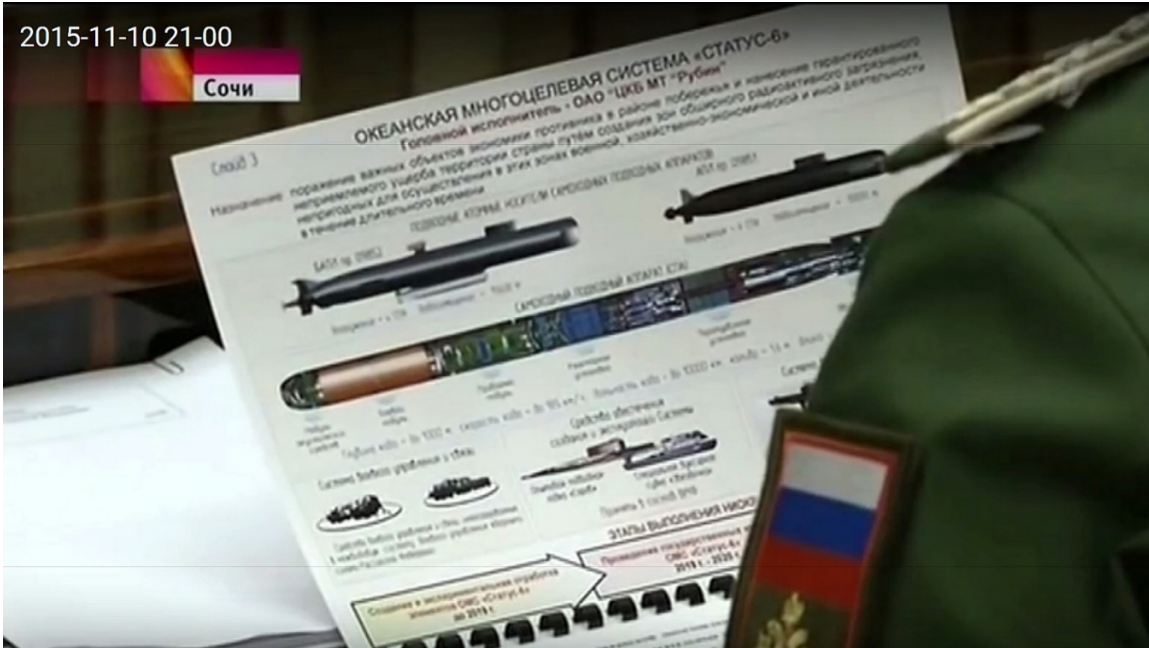
ОКЕАНСКАЯ МНОГОЦЕЛЕВАЯ СИСТЕМА СИСТЕМА "СТАТУС-6"

"Возможные сферы использования таких комплексов различны — работа торпедами по надводным кораблям, смешанная ракетно-торпедная нагрузка, постановка минных заграждений (скрытная в том числе), охота за АПЛ противника"
Алексей Рамм, Дмитрий Корнев, Дмитрий Болтенков

Из "множества целей" публично раскрыто использование боеголовки до 100 Мегатонн с возможной "кобальтовой бомбой"

ПОДВОДНЫЕ НОСИТЕЛИ САМОХОДНЫХ ПОДВОДНЫХ АППАРАТОВ (СПА)

АПЛ Белогород
24 м
СПА
АПЛ Хабаровск

Сравнение длины с 6,2М ОКР Калибр

60 метров
← АС-12 Лошарик

Вооружение - 6 СПА   Водоизмещение - 14700 т

Вооружение - 6 СПА   Водоизмещение - 10000 т

САМОХОДНЫЙ ПОДВОДНЫЙ АППАРАТ (СПА)

6,5 метров

1,6 м

Боеголовка или др.
Аккум Батар.
Реактор
Механика рулей
генератор

Длина - 24 м (по Т-15)

Модуль акустической системы
Боевой модуль
Приборный модуль
Реакторная установка
Паротурбинная установка

Figure 129. Status 6 ocean multipurpose system. Klavesin 2R PM nuclear-powered drone under construction. Russian conceptual design of an oversized thermonuclear-charge-tipped torpedo/drone shown in a military manual as launched and controlled from a mother ship or carried under the belly of a Sarov Class or OSCAR II midget mother ship submarine, project 09852. Project 09851 is a special purpose Khabarovsk sub. Inadvertently or intentionally leaked by a Russian TV crew filming a review meeting on November 10, 2015 chaired by Russian President Vladimir Putin. The "Ocean Multipurpose System 'Status-6'" developer is Russia's TsKB MT Rubin design bureau. Source: Screen grab.

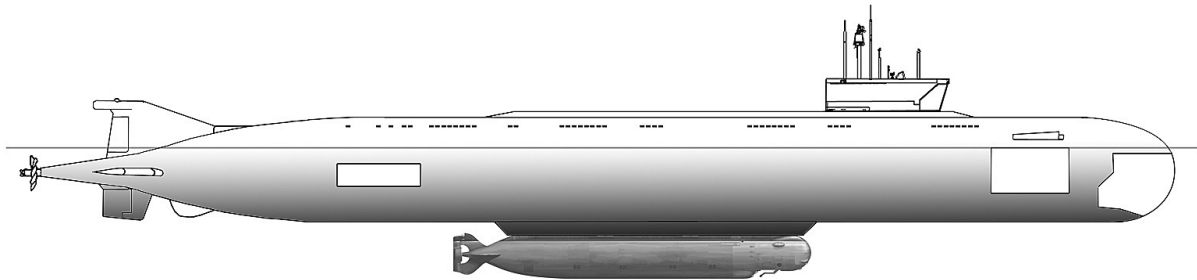ПЛАСН КС-139 "Белгород" пр.09852

Figure 131. PLSAN KC-139 Belgorod, Russian submarine drone mother ship, 2016.

There exist no agreement that would outlaw the creation of unmanned submarines, nor is there an agreement on the limitation of the power of nuclear weapons. Such a submarine would be a robotic submarine capable of traveling under the water at a large depth, escape from enemy vessels and maintain combat readiness for a prolonged period of time.

However, nuclear warheads require constant maintenance, a continuous source of power, and undergo radiation damage with the fission cores having to be rebuilt about every four years. They need replacement of the electronic trigger mechanisms as the radiation field tends to damage them; even though the electronics could be protected by distance and the inverse square law, and the charges could be activated using bus-bars. Components suffer from "radiation rot" to the circuitry. Analogue controls are still in use as solid state components decay within 2 years and the circuitry has to be replaced. Analogue components may survive up to 10 years with enough maintenance before the warhead must be rebuilt. Nuclear devices use molten salt batteries, which in their frozen solid form can hold their charge for a long time. The molten salt is rapidly heated into the liquid state to activate and use the stored energy in the battery.

The hull of an unmanned submarine could be made of high strength titanium or titanium alloy. The material would ensure a diving depth of more than 1,000 meters. The biological shielding protection of the reactor on board an unmanned submarine would be decreased considerably. The construction will thus be lighter, whereas the warheads would be more powerful. The size of the submarine can be made smaller in comparison with manned submarines, and the walls of its hull can be made thicker, thus increasing the immersion depth to 1,000 - 3,000 meters [11].

Doomsday implausible scenarios of unmanned submarines are claimed to be able to approach the coast of an opponent in strategic areas and rest dormant for an extended period of time buried in the sediment at the seafloor awaiting triggering. An order via a satellite, Extremely Low Frequency (ELF) one-way communication at 30 - 300 Hz 10,000 - 1,000 Km wavelength, Very Low Frequency (VLF) at 3-30 kHz deep-sea communication system would cause their simultaneous explosion and trigger giant tsunami waves along the coast. The explosions could be triggered along tectonic fault lines, amplifying their effect.

Russia also leaked a partial conceptual design of a nuclear tipped autonomous submarine drone that is designed to target USA coastal cities. It would be set up so it stays dormant on the sea floor near a major city on the coast, partially buried in the sediment so it is undetectable. It would follow the wake of a cargo ship making its way into a USA port so sonar instrumentation would not detect it. These submarine drones would carry 20 - 50 Mt of TNT equivalent devices and would be detonated underwater or would surface to detonate. This would not be as effective as air bursts from trajectory-changing hypersonic MIRV ICBMs with decoy warheads that are difficult to intercept; but they could use larger yield warheads.

These doomsday scenarios are implausible and highly flawed since the USA Navy and Air Force have deployed an effective surveillance system against similar occurrences. Nuclear devices emit gamma radiation and possess magnetic and thermal signatures which are detectable point sources. If they are buried deep enough to not be detectable then they are probably useless. In addition, the thermal and radiation signatures would bloom on the ocean surface making them detectable via satellite imagery.

The USA Navy has multiple sensor and hydrophone systems in the oceans and on the ocean floors and it publicized a drone submarine that it under development. A nuclear powered long endurance deep diving highly stealthy drone submarine can quietly follow the deployment vehicles and map the deployment locations. Recovery ships such as the Glomar Explorer can retrieve any hidden drone submarines or can deploy intelligent mines on top of them that would destroy them if they are ever launched.

A more plausible feasible alternative, apparently considered by the Russian Navy, is the possibility of deploying high-yield thermonuclear torpedoes, also referred to as "drones" carried under the bellies of existing submarines.

According to Bill Getz [12]:

"Russia conducted a test of a revolutionary nuclear-capable drone submarine that poses a major strategic threat to U.S. ports and harbors. U.S. intelligence agencies detected the test of the unmanned underwater vehicle, code-named Kanyon by the Pentagon, during its launch from a Sarov-class submarine on Nov. 27, said Pentagon officials familiar with reports of the test. No details were available about the location or results of the test."

The drone development program is designated as the "Ocean Multipurpose System 'Status-6.'" The developer is Russia's TsKB MT Rubin design bureau, the defense industry entity that builds Russian submarines. The Kanyon underwater torpedo/drone would be equipped with up to a 100 Mt of TNT equivalent warhead and would target ports and bases used by ballistic missile submarines located at Kings Bay, Georgia, north of the Florida border, and Puget Sound in the

State of Washington. It would envision the use of the area-denying Cobalt[60] doomsday alternative [12].

According to a Russian document disclosed on state television November 10, 2015, the torpedo/drone is a self-propelled underwater craft capable of carrying a nuclear warhead up to 6,200 miles. The vehicle can submerge to a depth of 3,280 feet and travel at speeds of up to 56 knots. The torpedo/drone submarine would be nuclear powered, controlled by surface ships, and supported by a Sarov class submarine. The Sarov is a diesel electric-powered vessel for testing new weapons and technology. It also has been described as an intelligence-gathering submarine [12].

In addition to the nuclear-tipped torpedo/drone, Russian nuclear modernization includes an emphasis on nuclear systems to compensate for weaker conventional alternatives. These include a new class of ballistic missile submarines called the Borey Class, new Bulava submarine-launched ballistic missile, two new land-based intercontinental ballistic missiles as replacements to the SS-18, and a new long-range Tu-160 Blackjack strategic bomber and an air launched long range KH-101 cruise missile. Russia also is building a new railroad-based mobile missile system. The USA Navy is developing new conventionally-armed non-nuclear underwater drones.

COLUMBIA CLASS NUCLEAR BALLISTIC MISSILE SUBMARINE (SSBN)

A Propulsor rather than a plain propeller has been used in the Sea Wolf class of submarines and will equip the Columbia class. The projected Columbia-class of 12 vessels program has an estimated value of approximately $128 billion including research and development costs, with $115 billion for procurement. The General Accounting Office (GAO) said that makes it the third-costliest program for any weapon systems in the USA Pentagon's history. At about $10 billion each, they present a challenge to the Russian Typhoon class which cost $2 million in the 1990's
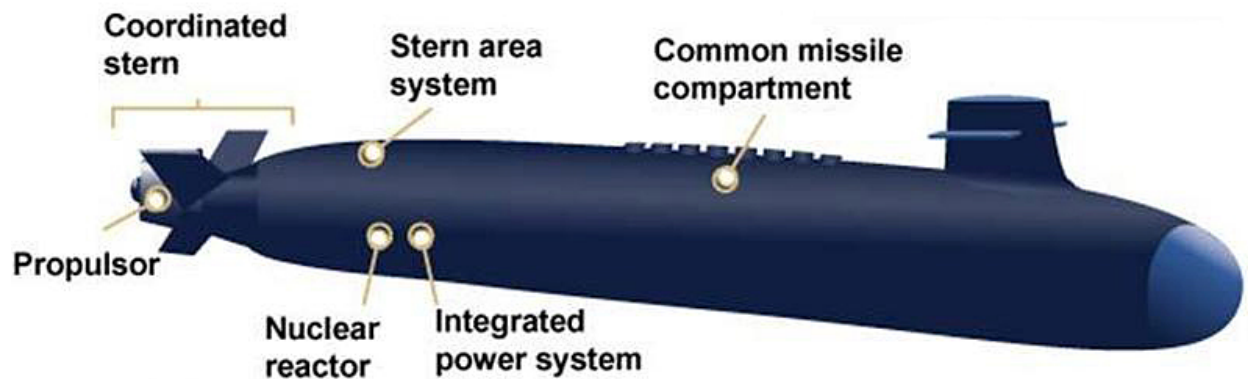
Figure 132. Columbia class submarine. The fleet of submarines is to be built by the General Dynamics Corp.'s Electric Boat division.

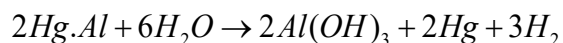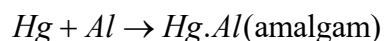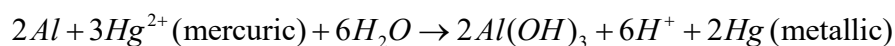Figure 133. Typhoon class of submarines.

36. DRONE SWARMS, GALLIUM-MERCURY-ALUMINUM AMALGAM

Swarm of drones could use an artificial vision capability to identify then penetrate the paint and oxide layer on Al metal devices and smear on it a payload of the Hg-Ga alloy that would chemically dissolve through the amalgamation process the metallic structure within hours and cause its structural failure. If Ga is used, it would penetrate the oxide layer. Ga can be initially used to penetrate the oxide layer followed by Hg to amalgamate or to form an alloy with it. Hg and Ga form a symbiotic relationship to oxidize the Al. The Ga permeates the Al and the Hg disrupts the formation of the protective Al oxide (also called "feathers" because of its appearance) or sapphire coating that normally inhibits corrosion. Without this oxide coating, the Al is rapidly oxidized and basically rusts several thousand times faster than Fe.

The Ga weakens the Al but cannot finish it; Hg does. In the presence of water, it is a good way to produce H$_2$. As the H is produced, the Al is left as an oxide powder and the Ga is still reusable. The oxidized Al powder from the gallium-water-aluminum reaction is one of the key ingredients to the production of thermite, used for welding. This technique was used by resistance saboteurs against German aircraft in World War II.

Ga causes the Al oxide protective layer to break down. This leaves the Al to oxidize easily. In water, the bond between Al and O is stronger than with H. The solution will dissolve the Al much faster and leave a solution of alumina with the Ga removable from the solution with a cheese cloth. This leaves the Al oxide solution in the state where one can apply electricity to convert it back into Al. The process produces H$_2$. Al pellets in a tank of Ga and water, can be mixed to provide a stored fuel for a fuel cell and is a safe form of storage for H$_2$.

In detail, the presence of water in a solution, the electron-rich Hg-Al amalgam will oxidize Al and reduce H$^+$ from water, creating Al hydroxide Al(OH)$_3$ and H$_2$. The electrons from the Al reduce mercuric Hg^{2+} ion to metallic Hg. The metallic Hg can then form an amalgam with the exposed Al metal. The amalgamated Al then is oxidized by water, converting the Al to Al hydroxide and releasing free metallic Hg. The generated Hg then cycles through the last two steps until the Al metal supply is used-up:

$$2Al + 3Hg^{2+}(\text{mercuric}) + 6H_2O \rightarrow 2Al(OH)_3 + 6H^+ + 2Hg\,(\text{metallic})$$
$$Hg + Al \rightarrow Hg.Al(\text{amalgam})$$
$$2Hg.Al + 6H_2O \rightarrow 2Al(OH)_3 + 2Hg + 3H_2$$

The Al-Hg amalgam alone may be prepared by either grinding Al pellets or wire in Hg, or by allowing Al wire to react with a solution of Hg(II) chloride in water. Almost all metals can form amalgams with mercury with the notable exceptions being Fe, Pt, W and Ta. An Au-Hg amalgam is used in the extraction of Au from its ores, as well as Ag. Arquerite is a naturally occurring amalgam of Ag and Hg.

The Ga and Hg amalgamate with the Al. Al is very reactive, the surface almost instantly reacts with O$_2$ which stops the prevents from reacting, but Ga and Hg inhibit its ability to keep a solid layer of Al oxide, and with Ga or Hg added as new forms, it flakes off. It is like how Fe oxide flakes off of Fe so that the underneath layer can oxidize, only much faster. The Ga-Al alloy is very soft and brittle. A eutectic mix of Ga and Al is liquid at room temperature. Ga is handled with gloves because it has a tendency to stain the skin into a dark brown color.

The process works with non-ferrous metals, the interaction with other structural metals such as Cu, Fe and Ti is not clear, except that Ga interacts weakly with steel. Hg amalgamates with Pb, Sn, Ag and Li. The Ag-Hg amalgam was used as a cavity filler by dentists. The Hg-Sn amalgam is used in mirroring surfaces. Magicians place Ba on an Al I beam, which bends under its own weight after an appropriate spiel for the occasion. This is probably how magician Uri Geller bent Al spoons. Incidentally, large amounts of Hg and Ga are not allowed on airplanes or submarines, even in the form of old barometers or thermometers, as a possible hazard. Hg is not allowed to be used in any products in the EU.

37. ELECTRIC PROPULSION, ELECTRONIC JAMMING WARFARE, KHIBINY

An electric ship uses steam turbine- or diesel engine-driven DC generators that power electric motors coupled directly to the propeller screws, eliminating the noisy gear boxes. A manual rheostat varies the amount of current going to the motors to control speed. This is much like diesel-electric train locomotives.

Other advanced technologies such as electromagnetic guns, high-energy free-electron lasers, high-power sensors, and organic and surveillance drones, would be implementable. Such a design would enhance the combat capability and mission flexibility of the ship. It would have lower manning and operating costs. Greater survivability would ensue because power generation could be distributed throughout the ship matching the typical combat operating profile of high-speed transit followed by low-speed loiter. An electric propulsion system frees the ship designer to locate the equipment wherever they wish to optimize the weight and balance of the ship and connect them with electric cabling; which enhances the ship's survivability.

However, all-electric nuclear or conventional vessels pause a design challenge in countering possible sophisticated jamming countermeasures and Electro Magnetic Pulse (EMP) generation.

On April 10, 2014, the destroyer USS Donald Cook DDG-75 entered the waters of the Black Sea and on April 12, 2014 a Russian Sukhoy-24 tactical bomber flew over the vessel, which is a fourth generation guided missile destroyer whose key weapons are Tomahawk cruise missiles with a range of up to 2,500 kilometers, and capable of carrying nuclear explosives. This ship carries 56 Tomahawk missiles in standard mode, and 96 missiles in attack mode.

Surveillance drone
- 10,000–15,000 feet
- Beam power to aircraft
- Minimal handling—no refueling

High-powered sensor
- Combination sensor and weapon
- High-powered microwave
- 100's kilowatt-powered laser

Electromagnetic gun
- 17 megajoules on target
- 250 nautical miles in 6 min.
- 6–12 rpm
- 15–30 MW

High-energy laser
- Enhanced self-defense
- Precision engagement
- No collateral damage
- Megawatt-class laser

Integrated power system
- Affordable power for weapons and propulsion
- Power-dense, fuel-efficient propulsion
- Reduced signatures
- Power conversion flexibility

All-electric auxiliaries
- No hydraulics
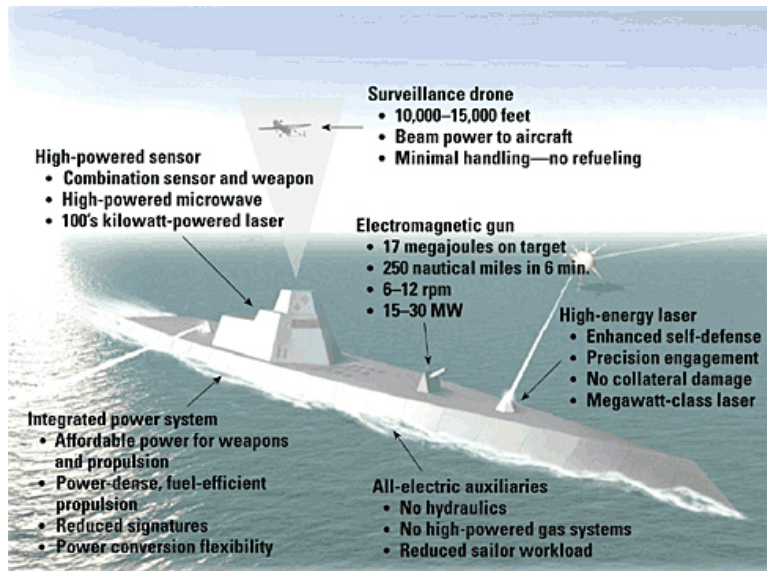- No high-powered gas systems
- Reduced sailor workload

Figure 134. Zumwalt class destroyer all-electric naval vessel. Source: USA Navy.

The USA destroyer is equipped with the Aegis Combat System. It is an integrated naval weapons systems which can link together the missile defense systems of all vessels embedded within the same network, so as to ensure the detection, tracking and destruction of hundreds of targets at the same time. In addition, the USS Donald Cook is equipped with 4 large radars, whose power is comparable to that of several stations. For protection, it carries more than fifty anti-aircraft missiles of various types.

The Russian Su-24 that buzzed the USS Donald Cook carried neither bombs nor missiles. According to the Russian newspaper Rossiyskaya Gazeta, it may have been equipped with a Russian electronic warfare device called Khibiny; named after the mountain range in the Kola Peninsula around the Arctic Circle. As the Russian jet approached the USA vessel, the electronic jamming device apparently disabled some electronic systems such as radars, control circuits, and information transmission systems on board the destroyer.

Figure 135. Russian Sukhoy-24 buzzing USS Donald Cook destroyer. The jamming was possibly produced by the two pods; other than the fuel tanks, visible under the wings of the aircraft. On larger aircraft, more massive versions seem to be positioned at the tips of the wings. Source: USA Navy.

Figure 136. Pods of Khibiny electronic warfare system mounted on Russian aircraft.

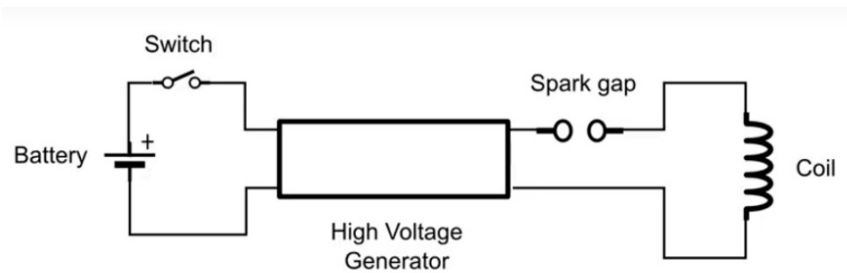Figure 137. Boeing EA-18G Growler electronic jamming warfare aircraft carries pods at tips of wings.

Figure 138. Basic circuit of Electro Magnetic Pulse (EMP) generation. Russian sources claim the use of obscure signal targeting devices based on what they call "torsion field technology", which the USA generally calls "scalar technology". They target systems that are hard shielded. They stopped publishing research papers on so-called torsion fields around 2005.

Figure 139. Comparison of Electronic Jamming Warfare, EW components on USA Growler and Russian Sukhoy aircraft. The Growler also carries the ADM-160 MALD subsonic Miniature Air-

Launched Decoy. USA bombers can launch swarms or waves of them, and so can most Western tactical aircraft.

The Russian unarmed Su-24 then simulated a missile attack against the USS Donald Cook. As if carrying out a training exercise, the Russian aircraft repeated the same maneuver 12 times before flying away. The destroyer set sail towards a port in Romania. Vladimir Balybine, director of the research center on electronic warfare and the evaluation of "visibility reduction" techniques attached to the Russian Air Force Academy made the comment: "The more a radio-electronic system is complex, the easier it is to disable it through the use of electronic warfare."

Figure 140. Hydrophones sound detection system mounted on a submarine hull.
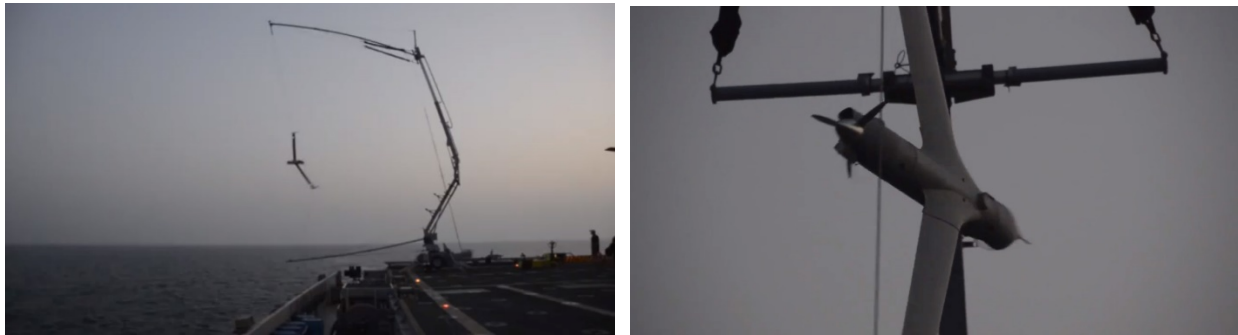

Figure 141. Scan Eagle surveillance drone launch and retrieval on USS Ponce 1.

SUPER-CAVITATION UNDERWATER VEHICLES

An evolution beyond electric torpedoes and wire guided and programmed torpedoes is the development of super-cavitation torpedoes. By the injection of a compressed gas at the nose of an underwater vehicle, the water drag can be reduced. The drag reduction allegedly allows such super-cavitation under-water vehicles to reach 230 mph speeds.

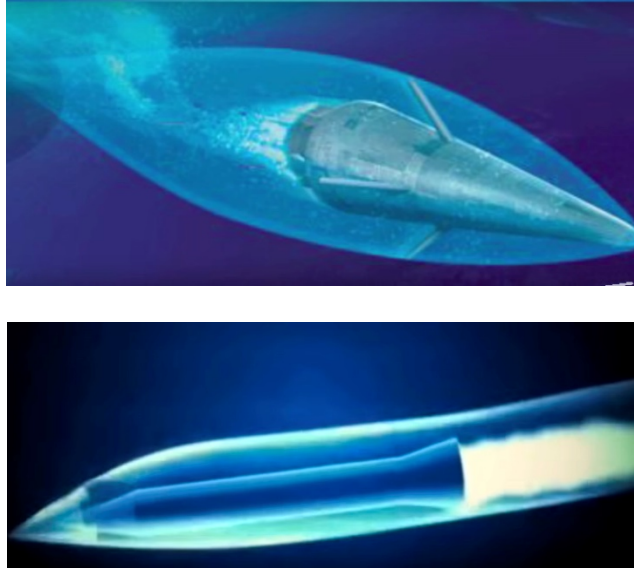Figure 142. Mark 24 Tigerfish electric torpedo replacing compressed air torpedoes.
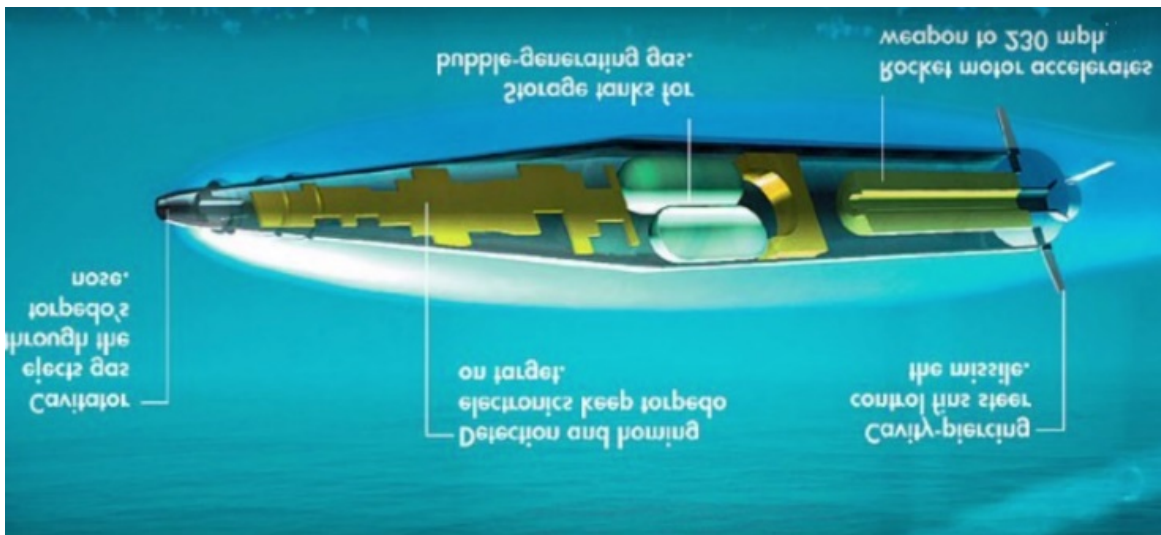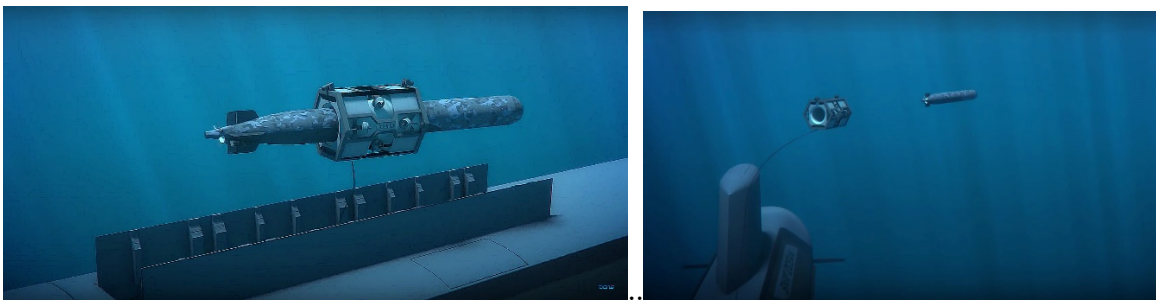
Figure 143. Super-cavitation under-water vehicles are alleged to be capable of reaching 230 mph speeds.

Figure 144. VA 111 Shkval Russian super-cavitation torpedo's nozzle is controlled by a four-wire system at the nose.

HYPERSONIC CRUISE MISSILES

The submarine-launched hypersonic missile 3M22 Zircon is a scramjet-powered maneuvering anti-ship hypersonic cruise missile to be launched from the latest nuclear-powered cruise missile submarine called the K-561 Kazan. Zircon is a winged hypersonic cruise missile that can travel at Mach 8 to Mach 9 (6,090 to 6,851 mph). The missile's range is estimated at 620 miles, can already be launched from aircraft, ships, and ground-based launch systems.

For much of the Cold War, the missiles carried by Russian submarines were focused against ships at sea. In the conflict in Syria, Russia used submarine-launched cruise missiles in a similar way to the US Navy's Tomahawk missile; as a long-range surgical strike weapon. The Tomahawk Land Attack Missile is primarily launched from submarines and ships by the USA Navy and the UK Royal Navy. It flies at Mach 0.75 (575 mph) with a range 1,550 miles. By 2030 Russia may have 8 submarines armed with Zircon missiles, and 17 by 2040.

«3M22 ZIRCON»

ENGINE:	SCRAMJET
OPERATIONAL RANGE:	300 KM (186.4 MI)
SPEED:	MACH 7 (8,575 KM/H; 5,328 MPH; 2.3820 KM/S)
LAUNCH PLATFORM:	SHIP, SUBMARINE, AIRCRAFT AND LAND-BASED MOBILE LAUNCHERS.

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Figure 145. Testing of 3M22 Zircon Mach 7 cruise missile. Anti-ship operational range is 180-620 miles. The USA is deploying a radar that can detect and target hypersonics.

HYPERSONICS INTERCEPTION

The Sprint Missile accelerates from stationary to Mach 10 in 5 seconds. That Surface to Air (SAM) system became operational in 1972. It is a two-stage, solid-fuel anti-ballistic missile (ABM), armed with a W66 enhanced-radiation thermonuclear warhead used by the USA Army. It was designed to intercept incoming Reentry Vehicles (RV) after they had descended below an altitude of about 60 kilometers (37 miles), where the thickening air stripped away any decoys or radar reflectors and exposed the RV to observation by radar. As the RV would be travelling at about 5 miles (8.0 km) per second, Sprint had to have phenomenal performance to achieve an interception in the few seconds before the RV reached its target.

Sprint accelerates at 100 g, reaching a speed of Mach 10 in 5 seconds. Such a high velocity at relatively low altitudes created skin temperatures up to 6,200 °F (3,430 °C), requiring an ablative shield to dissipate the heat. The high temperature caused a plasma to form around the missile, requiring extremely powerful radio signals to reach it for guidance. The missile glowed bright white as it flew.

Figure 146. Sprint two-stage Surface to Air Missile SAM interceptor.

EXERCISE

1.   For a reactor fueled with U^{235}, $\nu = 2.42$, p= 0.8, $\varepsilon = 1.05$, calculate the value for the reactivity ρ for equilibrium xenon.

ACKNOWLEDGEMENT

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APPENDIX

SHIPPINGPORT PRESSURIZED WATER REACTOR AND LIGHT WATER BREEDER REACTOR

The 60 MWe 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 meant to demonstrate both civilian and nuclear propulsion power applications. 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 naval propulsion cores, and the blanket assemblies had natural uranium in the first two cores. The last core used Thorium and U233 and demonstrated the possibility of breeding in a thermal neutron spectrum with a breeding ratio of 1.014 with 1.4 percent more produced fissile fuel than consumed.. The plant was retired after 25 years of operation.

The introduction of the PWR concept for nuclear propulsion is credited to Admiral Hyman G. Rickover, who is considered as the father of the USA's nuclear navy.
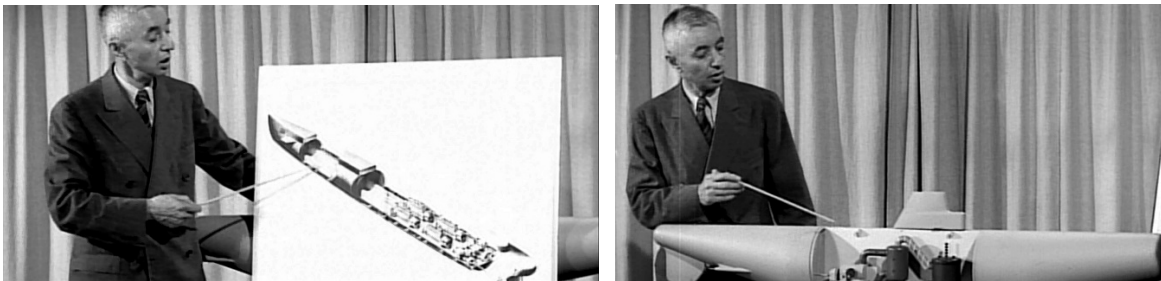
Figure 1. Admiral Hyman G. Rickover describing the concept of submarine nuclear propulsion.

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 U^{235} loading for the first seed core 75 kgs and the subsequent seeds had 90 kgs loadings.

Figure 2. Shippingport power plant, Pennsylvania fuel loading.

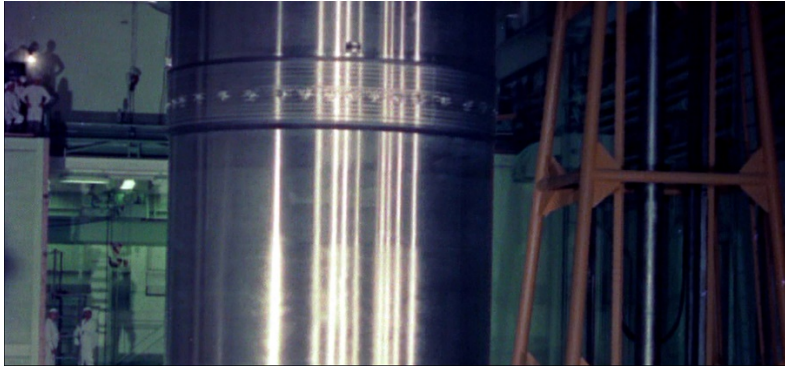Figure 3. Top fuel channels grid of Shippingport power plant.

Figure 4. Vessel of Shippinport, Pennsylvania first commercial nuclear power plant.
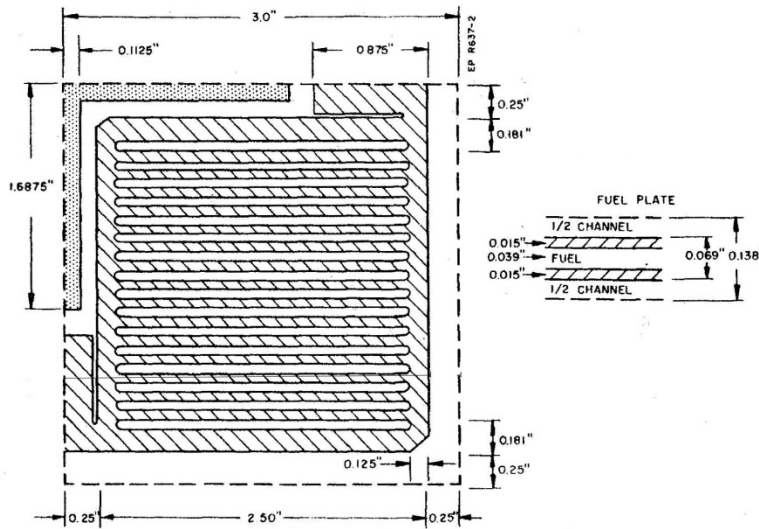

Figure 5. Shippingport Reactor PWR-1 seed subassembly showing control rod and plate fuel elements of highly enriched zirconium clad fuel and coolant channels. Dimensions in inches.
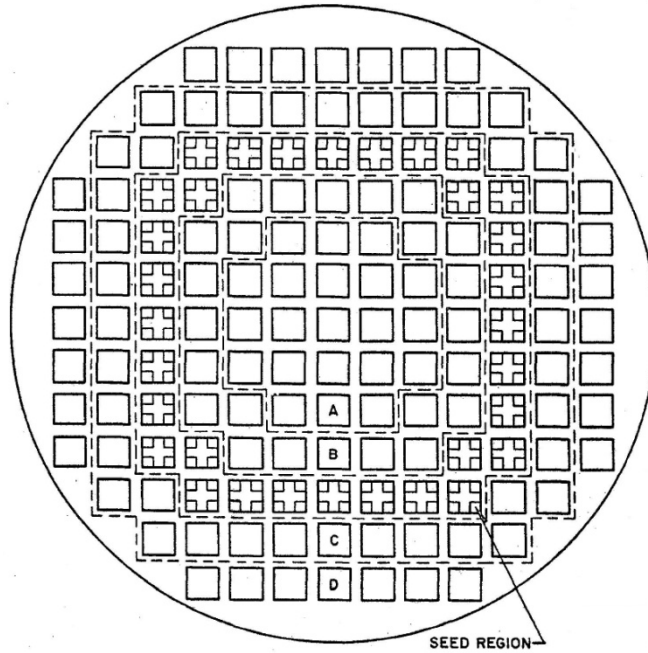
Figure 6. Cross section of Shippingport PWR-1 core showing the seed region and the blanket regions A, B, C and D.
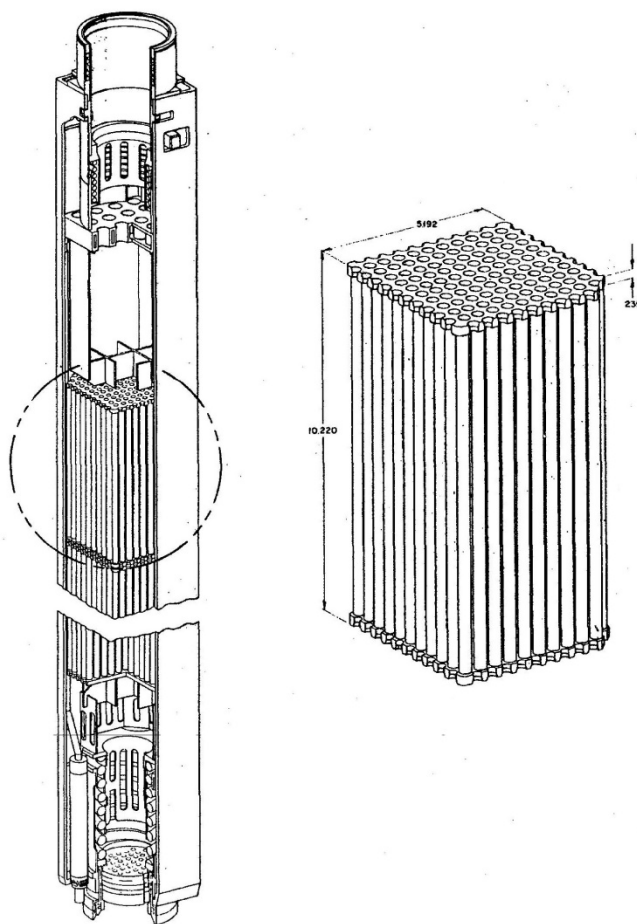
Figure 7. Shippingport reactor blanket cylindrical fuel rods assembly.

The PWR-1 blanket fuel was made of natural uranium in the form of natural UO_2 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 U^{233} is bred from Th^{232} in a thermal neutron spectrum.