

Marine Nuclear Power: 1939 – 2018

Part 2A:
United States - Submarines

Peter Lobner
July 2018

Foreword

In 2015, I compiled the first edition of this resource document to support a presentation I made in August 2015 to The Lyncean Group of San Diego (www.lynceans.org) commemorating the 60th anniversary of the world's first "underway on nuclear power" by *USS Nautilus* on 17 January 1955. That presentation to the Lyncean Group, "60 years of Marine Nuclear Power: 1955 – 2015," was my attempt to tell a complex story, starting from the early origins of the US Navy's interest in marine nuclear propulsion in 1939, resetting the clock on 17 January 1955 with *USS Nautilus*' historic first voyage, and then tracing the development and exploitation of marine nuclear power over the next 60 years in a remarkable variety of military and civilian vessels created by eight nations.

In July 2018, I finished a complete update of the resource document and changed the title to, "Marine Nuclear Power: 1939 – 2018." What you have here is *Part 2A: United States - Submarines*. The other parts are:

- *Part 1: Introduction*
- *Part 2B: United States - Surface Ships*
- *Part 3A: Russia - Submarines*
- *Part 3B: Russia - Surface Ships & Non-propulsion Marine Nuclear Applications*
- *Part 4: Europe & Canada*
- *Part 5: China, India, Japan and Other Nations*
- *Part 6: Arctic Operations*

Foreword

This resource document was compiled from unclassified, open sources in the public domain. I acknowledge the great amount of work done by others who have published material in print or posted information on the internet pertaining to international marine nuclear propulsion programs, naval and civilian nuclear powered vessels, naval weapons systems, and other marine nuclear applications. My resource document contains a great deal of graphics from many sources. Throughout the document, I have identified all of the sources for these graphics.

If you have any comments or wish to identify errors in this document, please send me an e-mail to: PL31416@cox.net.

I hope you find this informative, useful, and different from any other single document on this subject.

Best regards,

Peter Lobner
July 2018

Marine Nuclear Power: 1939 – 2018

Part 2A: United States - Submarines

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Marine Nuclear Power: 1939 – 2018

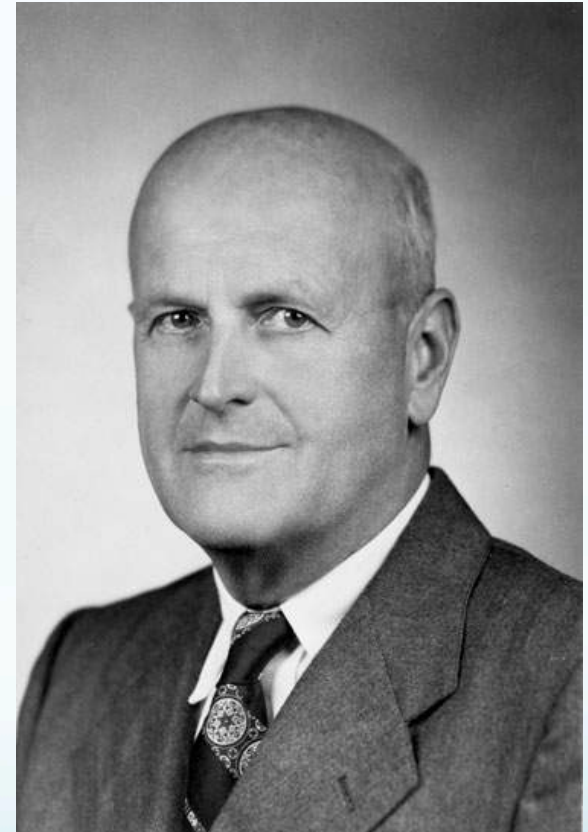
Refer to Part 2B, United States Surface Ships, for the following content related to US marine nuclear power:

- US Navy nuclear-powered surface ships
- Naval nuclear vessel decommissioning and nuclear waste management
- US civilian marine nuclear vessels and reactors
- US marine nuclear power trends

Timeline for development of marine nuclear power in the US

Timeline for development of marine nuclear power in the US

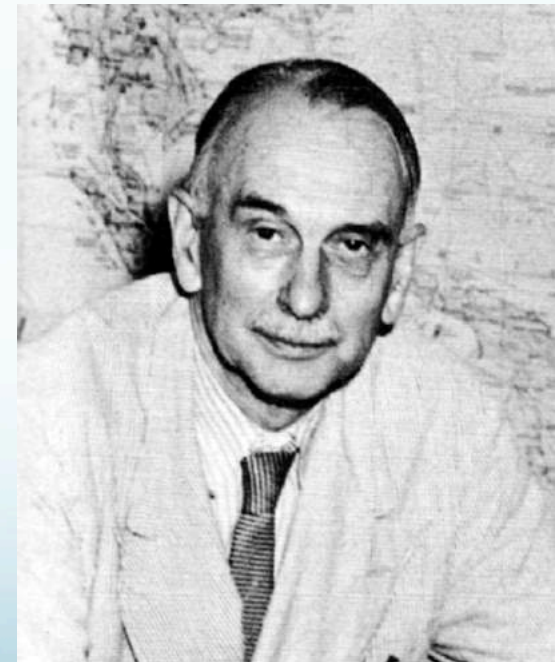
- **17 March 1939:** Enrico Fermi briefed the Navy Department on the current state of nuclear fission research and prospects for its application in weapons and power generation.
 - Naval Research Laboratory (NRL) physicist and head of the Mechanics and Electricity Division, Ross Gunn, attended this meeting.
 - Later in March 1939, Gunn, with support from the Director of NRL and the head of the Navy's Bureau of Steam Engineering (a predecessor of BuShips), received funding and initiated an investigation into uranium and nuclear propulsion. This was seven months before the Manhattan Project was established.
- **June 1939:** In a memo to the director of NRL, Ross Gunn reported:
 - "Under certain special circumstances of bombardment by neutrons, the heavy element uranium dissociates into two other elements with the evolution of tremendous amounts of energy which may be converted directly into heat and used in a flash boiler steam plant. Such a source of energy does not depend on the oxidation of organic material and therefore does not require that oxygen be carried down in the submarine if uranium is used as a power source. This is a tremendous military advantage and would enormously increase the range and military effectiveness of a submarine."



Dr. Ross Gunn. Source: NRL

Timeline for development of marine nuclear power in the US

- **2 December 1942:** A team led by Enrico Fermi established the first controlled, self-sustained nuclear chain reaction in Chicago Pile 1 (CP-1).
- **During WW II:** Ross Gunn was a member of the Navy's Uranium Committee, and, with Philip Abelson, focused on developing the thermal diffusion process for uranium enrichment.
- **mid-1944:** Art Snell's physics experiments at the X-10 reactor in Oak Ridge confirmed that Alvin Weinberg's concept for a water-moderated, enriched uranium reactor could be made to chain react.
- **August 1944:** General Leslie Groves (Director of the Manhattan Project) appointed a committee headed by Dr. Richard C. Tolman, vice chairman of the National Defense Research Committee, to make recommendations on a post-war policy for the development of atomic energy. Rear Admiral E.W. Mills, assistant chief of BuShips was a committee member.
 - In November 1944, the Tolman Committee met at NRL with Ross Gunn, Philip Abelson and NRL director Rear Admiral A.H. von Keuren, who advocated for development of nuclear submarines.
 - In December 1944, the Toleman Committee's final report urged the government "to initiate and push, as an urgent project, research and development studies to provide power from nuclear sources for the propulsion of naval vessels."



Dr. Richard C. Tolman circa 1945.
Source: <https://en.wikipedia.org/>

Timeline for development of marine nuclear power in the US

- **18 September 1944:** Alvin Weinberg first described the basis for a Pressurized Water Reactor (PWR), with ordinary water as both coolant and moderator operating at high pressure, and producing steam for power production.
- **Late 1945:** After WW II, Gunn resumed his work on the use of nuclear power in submarines.
 - At a nuclear symposium organized by Gunn and held at NRL on 19 Nov 1945, papers were presented describing the use of nuclear propulsion in naval vessels, particularly submarines, and even raised the prospects of ballistic missiles launched from submarines.
 - Further Navy access to nuclear research was hindered by General Leslie Grove, who was unwilling to release information to anyone outside the Manhattan District without Presidential authorization.
- **14 March 1946:** Secretary of the Navy James Forrestal sent a letter to Secretary of War Robert Patterson stating the Navy's desire to undertake the engineering of atomic power for ship propulsion and assume responsibility for the program.
 - Secretary Patterson replied that the Manhattan District had taken the first steps toward developing an atomic pile (the Oak Ridge Daniels Pile) and that the best and most rapid method for initiating a Navy program was to assign Navy personnel to the Manhattan District.



Dr. Alvin Weinberg.

Source: Oak Ridge National Laboratory

Timeline for development of marine nuclear power in the US

- **Early 1946:** Abelson led a small team at Clinton Laboratories (Oak Ridge, TN) that investigated the feasibility of replacing the diesel and battery power system with a nuclear power plant within the physical constraints of a modern conventional submarine; specifically a advanced German Type XXVI. Abelson presented the results in the report, *"The Atomic Energy Submarine,"* dated 28 March 1946.
- Abelson concluded that it was feasible to construct an atomic power plant of a size and output suitable for ship propulsion.
- This marked the first reported Navy interest in liquid metal coolants for reactors:

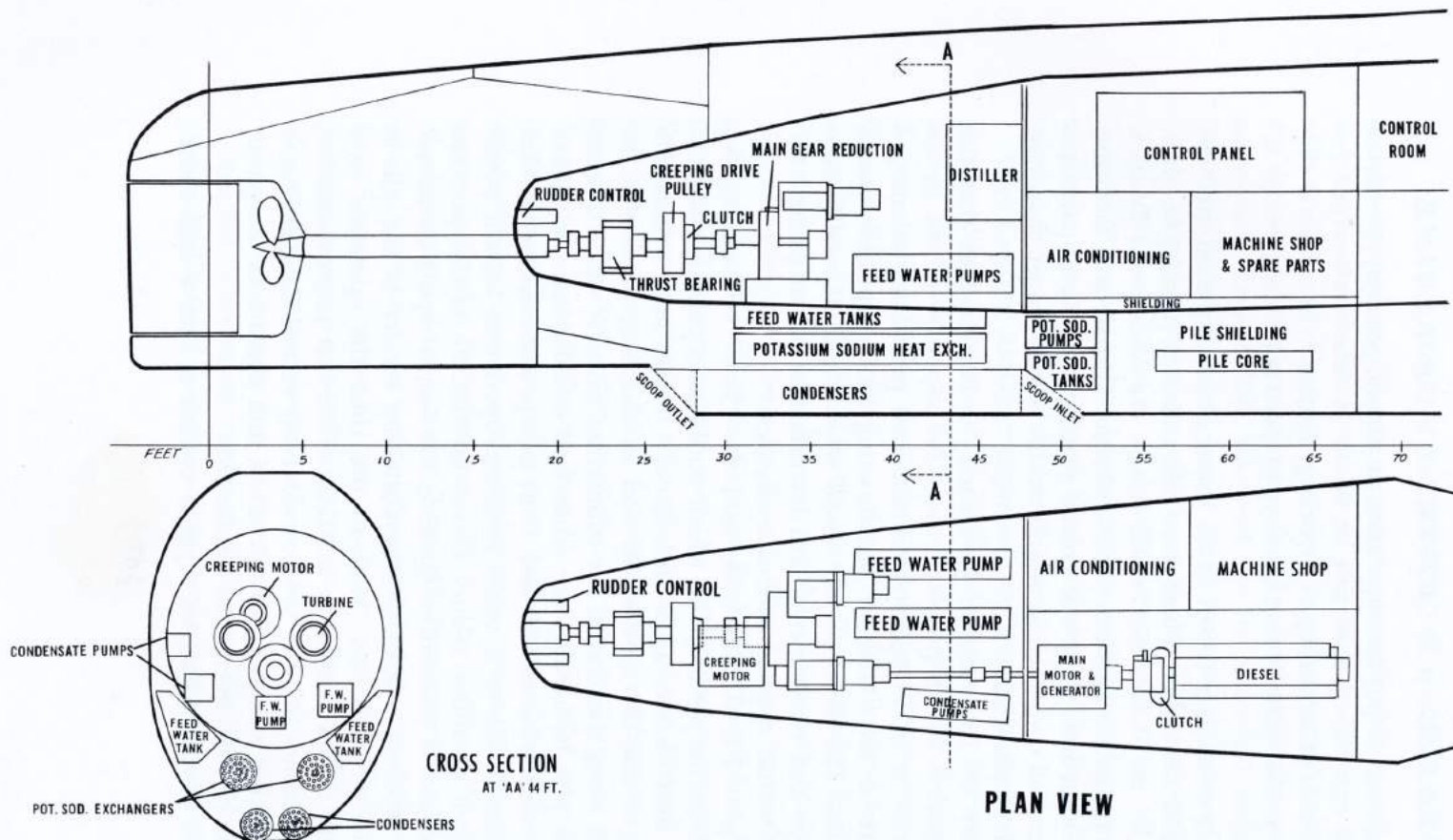
"Thermal energy generated in the atomic 'pile' would be transferred to liquid sodium-potassium (KNa) alloy recirculated through the pile," states Abelson. "This heat would drive a steam turbine...and the pile, together with its shielding and the KNa heat exchanger, would be located outside the pressure hull along the keel of the submarine. It would be necessary for the pile to be a cube that could conform to the streamline shape of the hull. This arrangement would allow for convenient maintenance and replacement in drydock."

- **April 1946:** NRL forwarded this report to the Bureau of Ships.



Dr. Philip Abelson. Source: NRL

The Gunn-Abelson 1946 submarine nuclear propulsion plant design concept



The long-classified plans of the Gunn-Abelson A-sub design show an advanced German Type XXVI U-boat hull with a nuclear power plant. Note duplicate components of power plant designed to keep sub running even with part of the plant out of action. This is an artist's copy of the original plan. (Drawing by Philbeck)

Source: Drawing by Philbeck in N. Polmar, "Atomic Submarines," D. Van Nostrand Company, Inc., 1963, p. 68

Timeline for development of marine nuclear power in the US

- **10 April 1946:** Alvin Weinberg and F. H. Murray (Oak Ridge, Clinton Laboratory) publish, “*High-pressure water as a heat-transfer medium in nuclear power plants*,” in which the design characteristics of a water cooled and moderated pressurized-water reactor (PWR) were presented.
 - This was a thorium-breeder PWR with a “seed-and-blanket” core, which used enriched uranium in the central “seed” section and thorium in the “blanket”.
 - Naval Reactors and Westinghouse developed a uranium “seed-and-blanket” PWR design in 1952 for the large surface ship reactor known as Carrier Vessel Reactor (CVR).
- **5 May 1946:** General Electric formed Knolls Atomic Power Laboratory (KAPL).
- **June 1946:** Five naval officers, including Capt. Hyman Rickover, and three civilians were detailed by BuShips to the Manhattan Project and sent to Oak Ridge, TN to learn about nuclear technology at Eugene Wigner’s Clinton Training School and from scientists working at Clinton Laboratory on various aspects of nuclear reactor development.



Dr. Eugene Wigner

Source: [https://](https://www.manhattanprojectvoices.org/)

www.manhattanprojectvoices.org/

Timeline for development of marine nuclear power in the US

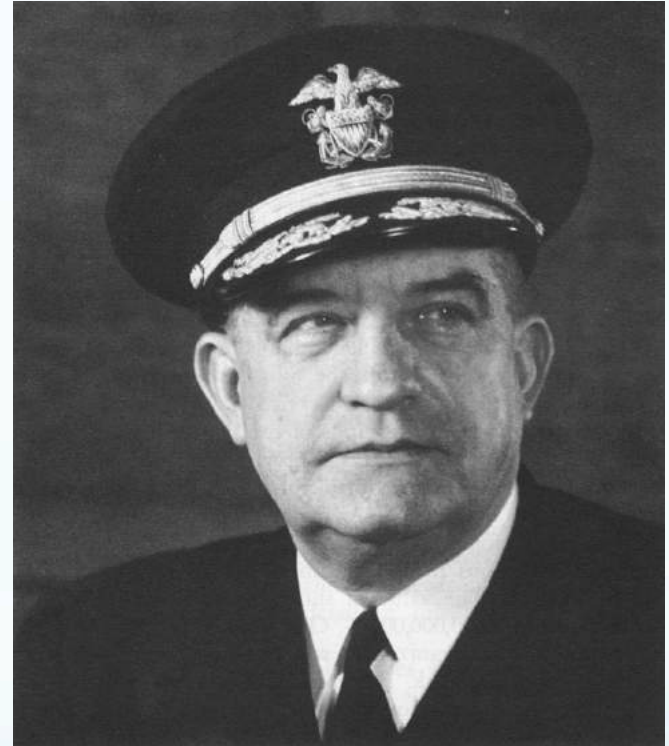
- **mid-1946:** A submarine desk was established in the office of the Assistant Chief of Naval Operations (CNO) for Atomic Defense. The first officer assigned was Lt. Commander Edward L. Beach, who became a naval aid to President Eisenhower, and later CO of the nuclear submarine *USS Triton*.
- **1 August 1946:** Atomic Energy Act of 1946 was signed into law, enabling closer cooperation between the Navy and the new Atomic Energy Commission (AEC).
- **1 January 1947:** The AEC took over responsibility from the Army for the entire Manhattan Project, with the Commission having exclusive authority over nuclear research and development.
- **January 1947:** Chief of Naval Operations, Admiral Chester Nimitz, approved a program for the design and development of nuclear power plants for submarines. This was the Navy's first authoritative statement of an operational requirement for nuclear power in submarines.
- **July 1947:** BuShips funded GE *Project Genie*, a non-nuclear study of heat transfer systems with liquid metal (sodium) coolant.
- **September 1947.** Work on the Daniels Pile was abandoned.

Timeline for development of marine nuclear power in the US

- **September 1947:** Rickover returned from ORNL to BuShips Washington D.C., which at the time was struggling to define its role with respect to the AEC in developing a nuclear submarine.
 - Admiral Mills, then Chief of BuShips, appointed Rickover as Special Assistant to the Chief, with the task of obtaining high-level Navy and DoD authorization for the construction and installation of an atomic propulsion plant in a submarine.
- **December 1947:** After a briefing at ORNL, Rickover decided zirconium was suitable for use in naval reactor cores. With naturally-occurring hafnium removed, ORNL had confirmed that refined zirconium absorbed few neutrons and it also had favorable metallurgical properties for use in a reactor core. The industrial processes for delivering suitable zirconium products were yet to be developed.
- **31 December 1947:** AEC decided to centralize all reactor development at Argonne National Laboratory, setting up a long-running battle with the Navy to determine roles and leadership of the emerging naval reactor program.
- **20 January 1948:** Admiral Mills forwarded to the AEC a detailed proposal for designing and constructing a nuclear power plant for a submarine. The proposal was endorsed in March by the DoD Research and Development Board, which was headed by Dr. Vannevar Bush. The Board recommended that the AEC give formal recognition to the project and assign priority to the work.

Timeline for development of marine nuclear power in the US

- **27 April 1948:** The AEC gave formal project status and high priority to the development of a water-cooled reactor for submarine propulsion.
- **28 June 1948:** BuShips funded Westinghouse *Project Wizard*, a non-nuclear study of heat transfer systems with pressurized water coolant. The goal was to design a power conversion system for a naval vessel.
- **4 August 1948:** Admiral Mills (BuShips) announced creation of a nuclear power branch (Code 390), with Rickover in charge. This was the start of the Naval Nuclear Propulsion Program (NNPP).
- **5 October 1948:** Westinghouse formed its atomic power division.
- **10 December 1948:** Westinghouse signed a contract with the AEC for the design and development of the Mark I reactor, including a land-based prototype that would meet Navy specifications for installation on a submarine and subsequent models for installation on a submarine. This became the Submarine Thermal Reactor (STR).



Vice Admiral Earle W. Mills
Chief of Bureau of Ships, Nov. 1946 - Feb. 1949
Source: <https://www.ibiblio.org/>

Timeline for development of marine nuclear power in the US

- **1949:** AEC contracted Westinghouse to form Bettis Atomic Power Laboratory as a government-owned, contractor-operated lab
- **February 1949:** Rickover was assigned dual roles that greatly strengthened his control over developing the first naval reactor.
 - Director, Naval Reactors Branch of BuShips
 - Head of AEC's Division of Reactor Development (later Deputy Administrator for Naval Reactors)
- **August 1949:** Chief of Naval Operations (CNO) established a 1 January 1955 "ready-for-sea" date for development of a submarine nuclear propulsion plant.
- **July 1950:** Westinghouse was authorized to establish a zirconium metal plant at Bettis Laboratory. This plant manufactured most of the zirconium needed for the STR Mark I reactor.
- **August 1950:** Construction started on the Submarine Thermal Reactor (STR) Mark I prototype at the Naval Reactor Testing Station (NRTS), Idaho.



Rear Admiral Hyman Rickover, circa 1955.
Source: US navy photo

Timeline for development of marine nuclear power in the US

- **August 1950:** President Harry Truman authorized construction of the first nuclear submarine.
- **July 1951:** Congress authorized funding for the construction of the first nuclear-powered submarine.
- **August 1951:** BuShips signed contracts with Westinghouse & Electric Boat for construction of *USS Nautilus*.
- **1952:** The NR Large Ship Reactor (LSR) program's Carrier Vessel Reactor (CVR) was authorized.
- **Early 1952:** By this time, Rickover had transferred most of Argonne's naval reactor responsibilities to Westinghouse.
- **14 June 1952:** The keel was laid for *USS Nautilus* by President Harry Truman at General Dynamics Electric Boat Division, Groton CT.
- **July 1952:** Contracts signed for the 2nd US nuclear submarine, *USS Seawolf*.



President Truman signs the *Nautilus*' keel at the keel laying ceremony.
Source: <http://navsource.org/archives/08/571/0857111.jpg>

Timeline for development of marine nuclear power in the US

- **August 1952:** Ground was broken for the liquid metal cooled Submarine Intermediate Reactor (SIR) Mark A prototype at KAPL, West Milton, NY
- **1953:** AEC approved the Submarine Fleet Reactor (SFR) program for the S3W & S4W reactors
- **30 March 1953:** Initial criticality at the STR Mark I PWR prototype (aka S1W).
- **April 1953:** Funding for the CVR was eliminated from the FY 1954 defense budget and redirected to a new civilian project to develop the first US commercial nuclear power plant. The entire Westinghouse development team was transferred while maintaining Naval Reactors in a leadership role on this new civilian nuclear power project.
- **25 June 1953:** The STR Mark I PWR prototype achieved full power and soon thereafter completed a 96-hour high-power run.
- **7 September 1953:** The keel was laid for *USS Seawolf* (SSN-575).
- **8 December 1953:** President Dwight Eisenhower delivered his *"Atoms for Peace"* speech to the UN General Assembly in New York City and proposal to establish an international agency to promote peaceful applications of atomic energy.



Source: <https://en.wikipedia.org/>

Timeline for development of marine nuclear power in the US

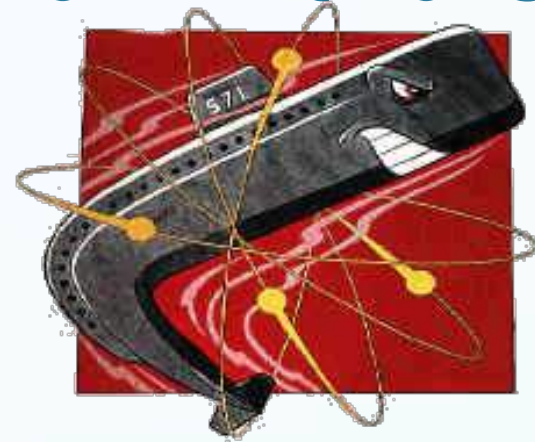
- **21 January 1954:** 1st nuclear-powered submarine (and 1st nuclear-powered vessel), *USS Nautilus* (SSN-571), was launched at Electric Boat, Groton, CT.
- **9 September 1954:** The NR-directed project for the 1st US civilian PWR nuclear power station broke ground at Shippingport, PA. The reactor design was based on the NR's cancelled CVR large ship reactor.
- **30 August 1954:** President Eisenhower signed the Atomic Energy Act of 1954, a major revision of the 1946 Act. The new law made possible greater participation by private industry and more cooperation with other countries in developing the peaceful uses of nuclear energy.
- **20 December 1954:** *USS Nautilus'* STR Mark II (S2W) reactor initial criticality.
- **3 January 1955:** *USS Nautilus'* reactor achieved full power alongside the pier, prior to the first underway tests.



Rickover aboard Nautilus. Source: US Navy

Timeline for development of marine nuclear power in the US

- **17 January 1955:** *USS Nautilus* Commanding Officer, Capt. Eugene P. Wilkinson, reported “*Underway on nuclear power.*” The message was sent by flashing light signal to Commander Submarine Forces Atlantic. This milestone met the CNO’s “ready for sea” target date established in 1949.



| U. S. NAVAL DISPATCH | | | |
|--|----------------------|---------------------------|------------|
| IND-GEN-1007 | | | |
| FROM: | USS NAUTILUS SSN 571 | CLASSIFICATION | PRECEDENCE |
| | | UNCL | ROUTINE |
| ACTION: | CONSULANT | | |
| INFO: | | | |
| NJOF DE NWCL -T-YZZF -R-171601Z -FM NWCL -TO YZZF CR 1/ BT | | | |
| UNDERWAY 1133R ON NUCLEAR POWER BT.... | | | |
| TOP / 1133R F.A. / 1133R FBR | | WU/ELT | |
| [Signature: Eugene P. Wilkinson] CAPT. E. P. WILKINSON | | [Signature: F.A.] F.A. | |
| TOP 1133 R | | DATE 17 JAN 55 | |
| 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 | | 171601Z | |
| 1 X | | 15 X | |
| 24 | | 24 | |
| IND-NAVAL (1007) | | | |

Above: Capt. Eugene P. Wilkinson & *Nautilus*. Source: US Navy
 Upper right: Source: <http://www.subguru.com/nautilus571.htm>

Source: US Navy

Timeline for development of marine nuclear power in the US

- **April 1955:** President Dwight Eisenhower endorsed building a nuclear-powered merchant ship as a showcase for his "Atoms for Peace" initiative.
- **20 March 1955:** Initial criticality of the liquid metal cooled Submarine Intermediate Reactor (SIR) Mark A prototype (aka S1G) at KAPL's Kesselring Site, NY.
- **21 July 1955:** 2nd US nuclear-powered submarine, *USS Seawolf* (SSN-575), was launched at Electric Boat, Groton, CT.
- **21 July 1955:** The keel was laid for *USS Skate* (SSN-578), which was the lead boat for the first series-produced class of US nuclear submarines.
- **Early 1956:** Construction started on the A1W aircraft carrier PWR prototype at the NRTS, Idaho.
- **29 May 1956:** The keel was laid for the *USS Skipjack* (SSN-585), which combined NR's latest reactor, the S5W Advanced Submarine Fleet Reactor (ASFR), with a streamlined (teardrop-shaped) hull pioneered by the *USS Albacore* (AGSS-569). The combination yielded unprecedented submarine performance.
 - S5W became the most-used reactor propulsion system design in the US nuclear fleet.
 - Variations of the *Albacore* / *Skipjack* streamlined hullform set the standard for US submarine design to the present day.
- **25 June 1956:** Initial criticality of *USS Seawolf's* S2G liquid metal cooled reactor.



Source: <https://www.priorservice.com/ussnasspa.html>

Timeline for development of marine nuclear power in the US

- **Summer 1956:** Naboska Study developed recommendations affecting the design of nuclear subs and submarine-launched ASW tactical nuclear weapons. Also confirmed credibility of technology advances needed for the Polaris SLBM.
- **20 August 1956:** Initial failures occurred in the *Seawolf's* superheaters. This and a series of subsequent operational issues with the liquid metal cooled S2G plant ultimately led Rickover in 1958 to order its removal from *Seawolf* and replacement with the same PWR as *Nautilus*. Thereafter, all US naval nuclear-powered vessels have been powered by PWRs.
- **By the mid-1950s:** Admiral Rickover had established Naval Reactors in firm control of the Naval Nuclear Propulsion Program (NNPP) and had established the technical and industrial infrastructure that was enabling the program to deliver safe, reliable nuclear submarines to the US fleet. Meanwhile, civilian marine nuclear power in the US was beginning to make progress, but lacked strong central leadership and a clear demand for nuclear-powered vessels from maritime ship operators.
- **1956:** President Eisenhower directed the AEC and the Maritime Administration (MARAD) of the Department of Commerce to jointly develop plans for constructing the first US nuclear-powered civilian ship. That plan evolved into:
 - A dry-cargo merchant ship, which would demonstrate the feasibility of using nuclear propulsion for commercial vessels.
 - A nuclear propulsion plant designed specifically for the merchant ship by a private contractor, rather than a copy of the *Nautilus* reactor. Babcock & Wilcox was selected to develop the civilian marine nuclear propulsion plant.

Timeline for development of marine nuclear power in the US

- **1956:** The Maritime Administration initiated the marine gas-cooled reactor program, which planned to develop by the early 1960s a closed-cycle nuclear gas turbine propulsion plant capable of delivering 22,000 shp for a 38,000 ton DWT merchant vessel, enabling a speed of 20 – 21 knots.
- **Dec 1957 – Feb 1958:** Within two months, keels were laid for the first two US nuclear-powered surface warships, the cruiser *USS Long Beach* (CGN-9, keel laid 2 Dec 1957) and the aircraft carrier *USS Enterprise* (CVN-65, keel laid 4 Feb 1958).
- **11 May 1958:** A few months later, the keel was laid for the 1st US civilian nuclear-powered merchant ship, *NS Savannah*, on Maritime Day at New York Shipbuilding Corp., Camden, NJ.
- **1 Nov 1958:** The keel was laid for the SSN *USS Scorpion*, which became the first Polaris Fleet Ballistic Missile (FBM) submarine, *USS George Washington* (SSBN-598).
- **1959:** Combustion Engineering's S1C prototype in Windsor, CT operational.
- **2 – 22 January 1959:** *USS Seawolf's* S2G liquid-metal core was removed. Thereafter, all US naval reactors would be pressurized water reactors.
- **21 July 1959:** *NS Savannah* was launched.
- **21 Dec 1961:** Initial criticality of *NS Savannah's* Babcock & Wilcox PWR reactor.
- **Mar 1962:** *NS Savannah* delivered to the Maritime Administration.
- **20 Aug 61:** *NS Savannah* maiden voyage.

Timeline for development of marine nuclear power in the US

- **By the early 1960s:** The first US civilian nuclear-powered vessel was being tested and outfitted for operation and several design studies of merchant ship nuclear propulsion systems were underway in the US and other nations. The prospects for civilian marine nuclear power seemed promising.



Source: <http://www.oceanlinerlapelpins.com/>

- **By the early 1960s:** Just a decade after starting work to build the first naval reactor prototype and submarine, Naval Reactors was operating prototype reactors at three sites (NRTS Idaho, West Milton, NY and Windsor, CT) and developing or supporting many different PWR naval reactor designs for a rapidly expanding nuclear-powered fleet. A diverse industrial infrastructure was in place to support this growth. Improved fuel system designs enabled longer reactor core life, fewer refuelings and greater ship operational capabilities.
 - Submarine reactors: S1W/S2W, S3W/S4W, S5W, S3G/S4G and S1C/S2C
 - Surface ship reactors: C1W, A1W/A2W, also D1G was under development
- **1982:** After 64 years of naval service, including 33 years as Director of the Naval Nuclear Propulsion Program, Rickover retired from the Navy as a full admiral on 19 January 1982. He died on July 8, 1986.

Recommended readings on the early US marine nuclear power programs

- NRL History – Philip Abelson, the Atomic Age,
<https://www.nrl.navy.mil/media/news-releases/2011/nrl-history--phil-abelson--the-atomic-age>
- Ahern, Joseph-James, “*The United States Navy’s Early Atomic Energy Research, 1939–1946*,” International Journal of Naval History, Vol. 1, No. 1, April 2002
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http://www.ijnhonline.org/wp-content/uploads/2012/01/article_ahern_pdf_apr03.pdf
- Cantonwine, Paul (ed.), “*The Never-Ending Challenge of Engineering: Admiral H.G. Rickover in His Own Words*,” American Nuclear Society, 2013
- Hewlett, R.G. & Duncan, F., “*Nuclear Navy 1946 – 1962*,”
<https://energy.gov/sites/prod/files/2013/08/f2/HewlettandDuncanNuclearNavyComplete.pdf>
- Weinberg, Alvin M., “*The First Nuclear Era – The Life and Times of a Technological Fixer*,” AIP Press, 1994 (includes a short history on the origins of the PWR)
- Winters, Ann Marie Daniel, “*Underway on Nuclear Power – The Man Behind the Words, Eugene P. Wilkinson Vice Admiral USN*,” American Nuclear Society, 2016

US current nuclear vessel fleet

As of mid-2018

US current nuclear vessel fleet

As of mid-2018

- Since 1991, the US Navy has operated an all-nuclear fleet of submarines and, since 2007, it has operated an all-nuclear fleet of aircraft carriers. The current US naval nuclear fleet is comprised of 79 operational vessels and two non-operational training submarines.
- The nuclear submarine fleet consists of 68 vessels in the following classes:
 - 50 attack subs (SSNs):
 - 32 x Los Angeles-class SSNs (Flight I, Flight II & 688i), dropping to 30 by the end of 2018.
 - 3 x Seawolf-class SSNs
 - 15 x Virginia-class SSNs (Block I, II & III), increasing to 17 by the end of 2018.
 - 14 x Ohio-class strategic ballistic missile subs (SSBNs)
 - 4 x Ohio-conversion cruise missile subs (SSGNs)
- The nuclear aircraft carriers fleet consists of 11 vessels in the following classes:
 - 10 x Nimitz-class CVNs
 - 1 x Ford-class CVN
- In addition, the US Navy operates two converted, former SSBNs that are serving as non-deployable Moored Training Ships (MTS).
- The US Coast Guard does not operate any nuclear-powered icebreakers.
- The US does not operate any commercial nuclear-powered vessels.

US current nuclear vessel fleet

As of mid-2018

| Ship Type | Ship Class | # in Class | Average Ship Age (yrs) | Ship Service Life (yrs) * | Reactor Type | Reactor Life |
|-----------|----------------------------------|------------|------------------------|-----------------------------|-------------------|--|
| CVN | Nimitz | 10 | 27 | 50 | 2 x A4W | Mid-life refueling required at about 25 years. Five CVNs refueled, one in process in 2018, last to be completed by about 2034. |
| CVN | Ford | 1 | 1 | 50 | 2 x A1B | Mid-life refueling required at about 25 years. 1 st CVN refueling due in about 2042. |
| SSBN | Ohio | 14 | 27 | 42 (extended from 30) | S8G | Mid-life refueling required at about 21 years. Ten SSBNs refueled, last to be completed in about 2022. |
| SSGN | Ohio (cruise missile conversion) | 4 | 35 | 42 (extended from 30) | S8G | Mid-life refueling required at about 21 years. All have been refueled. |
| SSN | 688 Flight I | 2 *** | 35.5 | 33 ** (extended from 30) | S6G/D1G, then D2W | Mid-life refueling required at about 15 years. The three remaining boats have been refueled with a D2W core. |
| SSN | 688 Flight II | 8 | 31 | 33 ** (extended from 30) | S6G/D2W | Life-of-the-boat |
| SSN | 688i (improved) | 22 | 25 | 33 ** (extended from 30) | S6G/D2W | Life-of-the-boat |

* Service life is the established calendar period (years) that a submarine is permitted to operate, with defined start and end dates for each boat. Service life starts the day the ship is delivered to the Navy, and ends on the anniversary date after the prescribed number of calendar years.

**The Navy is considering extending Los Angeles-class SSN service life further to 36 – 37 years to help mitigate the impending fleet shortfall in SSNs. Three Flight I boats currently are operating beyond the class 33 year service life.

*** Both remaining 688 Flight I boats are scheduled to be decommissioned in 2018.

US current nuclear vessel fleet

As of mid-2018

| Ship Type | Ship Class | # in Class | Average Ship Age (yrs) | Ship Service Life (yrs) * | Reactor Type | Reactor Life |
|-----------|--|------------|------------------------|---------------------------|--------------|--|
| SSN | Seawolf (SSN-21, -22) | 2 | 20 | 30 | S6W | Life-of-the-boat |
| SSN | Seawolf (SSN-23, <i>Jimmy Carter</i>) | 1 | 13.5 | 30 | S6W | Life-of-the-boat |
| SSN | Virginia Block I | 4 | 11 | 33 | S9G | Life-of-the-boat |
| SSN | Virginia Block II | 6 | 7 | 33 | S9G | Life-of-the-boat |
| SSN | Virginia Block III | 5 | 2 | 33 | S9G | Life-of-the-boat |
| MTS | Lafayette- and James Madison-class SSBNs | 2 | 54 | Not applicable | S5W | The existing MTS boats are <i>USS Daniel Webster</i> and <i>USS Sam Rayburn</i> . They are approaching the end of core life and will be replaced by two Los Angeles Flight I SSNs that are being converted into MTS configuration. |

* Service life is the established calendar period (years) that a submarine is permitted to operate, with defined start and end dates for each boat. Service life starts the day the ship is delivered to the Navy, and ends on the anniversary date after the prescribed number of calendar years.

Comparison of current US nuclear submarines



Source: USS Colorado (SSN-788) Commissioning Committee, <https://usscoloradocommittee.org>

US naval nuclear infrastructure

Executive Order 12344

Naval Nuclear Propulsion, 1 Feb 82

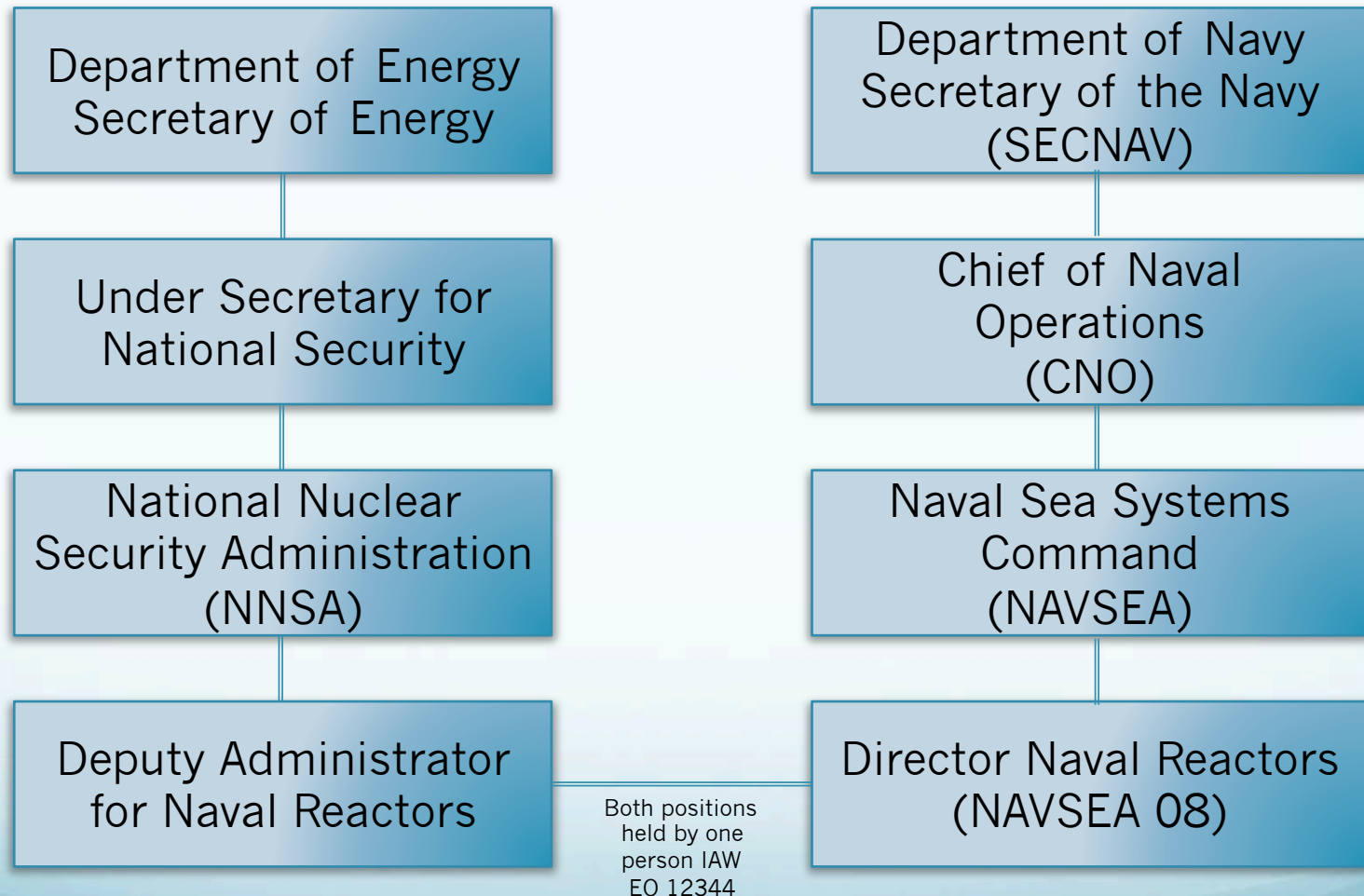
- For the purpose of preserving the basic structure, policies, and practices developed for this Program in the past and assuring that the Program will continue to function with excellence, it is hereby ordered as follows:
 - Naval Nuclear Propulsion Program is an integrated program carried out by two organizational unit: Department of Energy & Department of the Navy
 - Both organizational units shall be headed by the same individual so that the activities of each may continue in practice under common management.
- Secretary of Energy shall assign to the Director the responsibility of performing the functions of the Division of Naval Reactors transferred to DOE by Section 309(a) of the Department of Energy Organization Act (42 USC. 7158), including assigned civilian power reactor programs, and any naval nuclear propulsion functions of DOE.
- Secretary of the Navy shall assign to the Director responsibility to supervise all technical aspects of the Navy's nuclear propulsion work.

Executive Order 12344

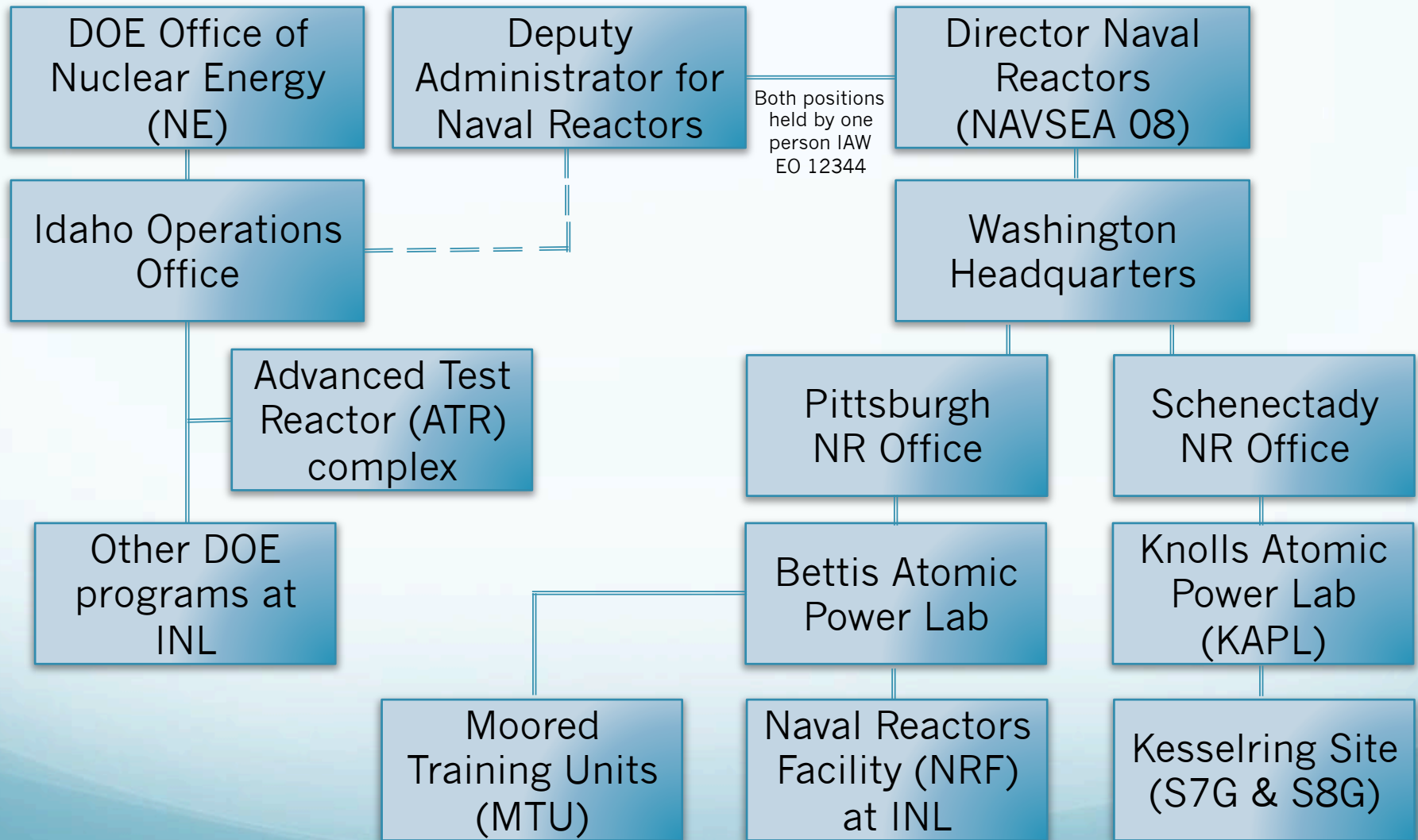
Naval Nuclear Propulsion, 1 Feb 82

- The Director's roles & responsibilities include:
 - Direct supervision of Bettis and Knolls Atomic Power Laboratories, the Expanded Core Facility, and naval reactor prototype plants;
 - Research, development, design, procurement, acquisition, specification, construction, inspection, installation, certification, testing, overhaul, refueling, operating practices and procedures, maintenance, supply support, and ultimate disposition, of naval nuclear propulsion plants, including components thereof, and any special maintenance and service facilities related thereto;
 - Safety of reactors and associated naval nuclear propulsion plants, and control of radiation and radioactivity associated with naval nuclear propulsion activities;
 - Training, including training conducted at the naval prototype reactors of DOE and Nuclear Power Schools of the Navy;
 - Administration of the Naval Nuclear Propulsion Program.

Naval Nuclear Propulsion Program (NNPP) Management



Naval Nuclear Propulsion Program (NNPP) Management



Naval Nuclear Propulsion Program (NNPP) Management

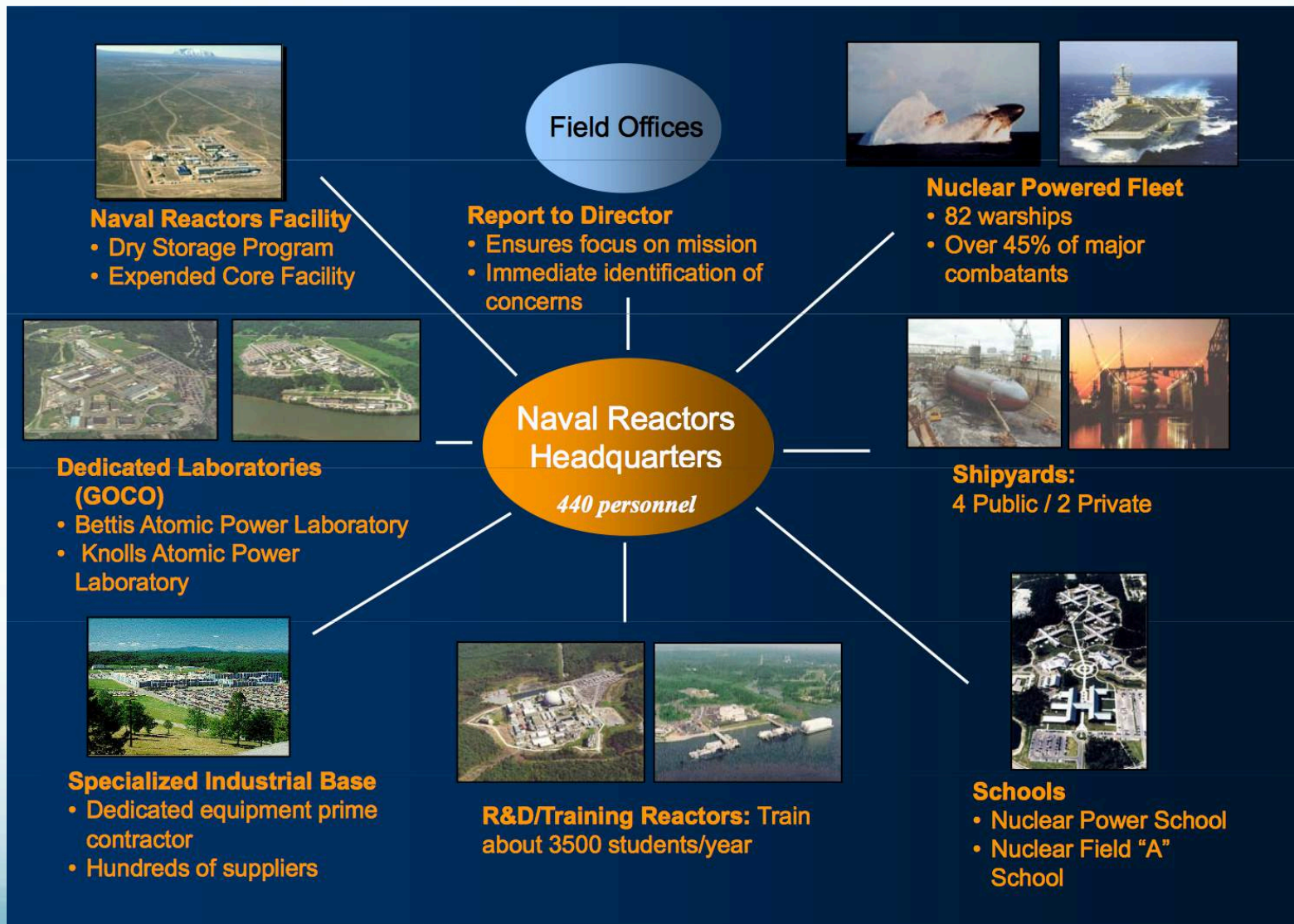
- Mission statement:

“The Naval Nuclear Propulsion Program provides militarily effective nuclear propulsion plants and ensures their safe, reliable and long-lived operation. This mission requires the combination of fully trained US Navy men and women with ships that excel in endurance, stealth, speed, and independence from supply chains.”
- Washington Headquarters
 - This is Naval Reactors Headquarters, which administers the NNPP.
- Pittsburgh Naval Reactors Office
 - This office oversees the Bettis Atomic Power Laboratory, including the Expanded Core Facility at the Naval Reactors Facility (NRF) located within the Idaho National Laboratory (INL).
- Schenectady Naval Reactor Office
 - This office oversees the Knolls Atomic Power Laboratory.
- Idaho Operations Office
 - This office oversees the operation of the Advanced Test Reactor (ATR) at INL. Naval Reactors is the primary customer for ATR irradiation services.



Source: Naval Reactors

Major components of NNPP



Directors of Naval Reactors

| Director of Naval Reactors | Start term | End term |
|----------------------------|--------------|---------------------------|
| Adm. Hyman G. Rickover | Feb 1949 | Feb 1, 1982 |
| Adm. Kinnaird R. McKee | Feb 1, 1982 | Oct 22, 1988 |
| Adm. Bruce DeMars | Oct 22, 1988 | Sep 27, 1996 |
| Adm. Frank “Skip” Bowman | Sep 27, 1996 | Nov 5, 2004 |
| Adm. Kirkland H. Donald | Nov 5, 2004 | Nov 2, 2012 |
| Adm. John M. Richardson | Nov 2, 2012 | 5 Aug 2015, became CNO |
| Adm. James F. Caldwell Jr. | 5 Aug 2015 | present |

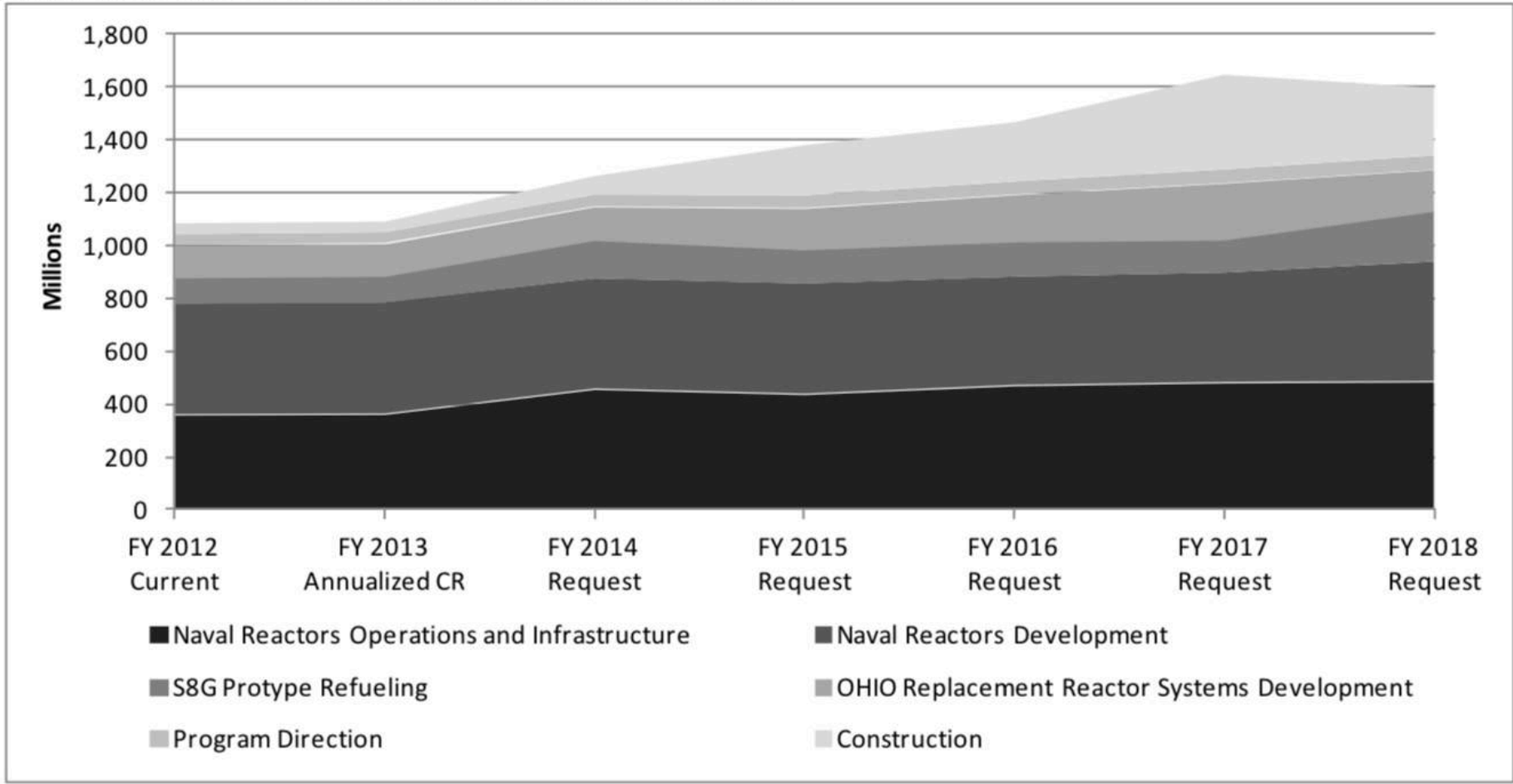
Naval Reactors 2018 budget request

| (Dollars in Thousands) | | | | |
|--|--------------------|---------------------------|--------------------|-----------------------|
| | FY 2016 Enacted | FY 2017 Annualized CR* | FY 2018 Request | FY 2018 vs FY 2016 |
| Naval Reactors | | | | |
| Naval Reactors Operations and Infrastructure | | | | |
| Research Reactor Facility Operations & Maintenance | 138,670 | 147,619 | 122,176 | -16,494 |
| MARF Defueling and Layup | 0 | 0 | 4,200 | +4,200 |
| Laboratory Facility Regulation, Compliance, & Protection | 93,046 | 91,803 | 117,642 | +24,596 |
| Nuclear Spent Fuel Management | 133,767 | 128,671 | 132,604 | -1,163 |
| Radiological/Environmental Remediation & Demolition | 59,168 | 50,652 | 67,862 | +8,694 |
| Capital Equipment | 2,845 | 2,569 | 4,500 | +1,655 |
| General Plant Projects | 17,700 | 23,036 | 17,900 | +200 |
| Total, Naval Reactors Operations and Infrastructure | 445,196 | 444,350 | 466,884 | +21,688 |
| Naval Reactors Development | | | | |
| Ship Construction & Maintenance Support | 44,753 | 40,145 | 39,424 | -5,329 |
| Nuclear Reactor Technology | 128,657 | 132,615 | 143,453 | +14,796 |
| Reactor Systems & Component Technology | 180,271 | 192,407 | 195,690 | +15,419 |
| Advanced Test Reactor Operations | 77,200 | 69,966 | 82,000 | +4,800 |
| Capital Equipment | 16,015 | 10,913 | 12,700 | -3,315 |
| Total, Naval Reactors Development | 446,896 | 446,046 | 473,267 | +26,371 |
| S8G Prototype Refueling | | | | |
| Capital Equipment (MIE) | 122,770 | 131,195 | 189,210 | +66,440 |
| General Plant Project (GPP) | 3,630 | 1,552 | 790 | -2,840 |
| Total, S8G Prototype Refueling | 133,000 | 132,747 | 190,000 | +57,000 |
| Columbia -Class Reactor Systems Development (formerly Ohio Replacement Reactor Systems Development) | | | | |
| Program Direction | 186,800 | 186,445 | 156,700 | -30,100 |
| Construction | 42,504 | 42,423 | 48,200 | +5,696 |
| Total, Naval Reactors | 121,100 | 120,870 | 144,700 | +23,600 |
| Total, Naval Reactors | 1,375,496 | 1,372,881 | 1,479,751 | +104,255 |

* The FY 2017 Annualized CR amounts reflect the P.L. 114-254 continuing resolution level annualized to a full year. These amounts are shown only at the congressional control level and above, below that level, a dash (-) is shown.

Naval Reactors budget trends

Figure 1: Relative Out-Year Funding Priorities in Naval Reactors



Source: Department of Energy 2014 Congressional Budget Justification, p. NR-6.

Naval Nuclear Laboratory

- The “Naval Nuclear Laboratory” is comprised of the following US Department of Energy facilities that, collectively, are responsible for developing advanced naval nuclear propulsion technology, providing technical support to the fleet to ensure the safety and reliability of fleet reactors, and training the operating crews.
 - Bettis Atomic Power Laboratory, West Mifflin, PA
 - Knolls Atomic Power Laboratory (KAPL), Schenectady, NY
 - Kenneth A. Kesselring Site, West Milton, NY
 - Naval Reactors Facility (NRF), ID
- These Naval Nuclear Laboratory facilities are operated government-owned, contractor-operated (GoCo) contract by Bechtel Marine Propulsion Corporation, which is a wholly-owned subsidiary of Bechtel National Corporation.

Bettis Atomic Power Laboratory

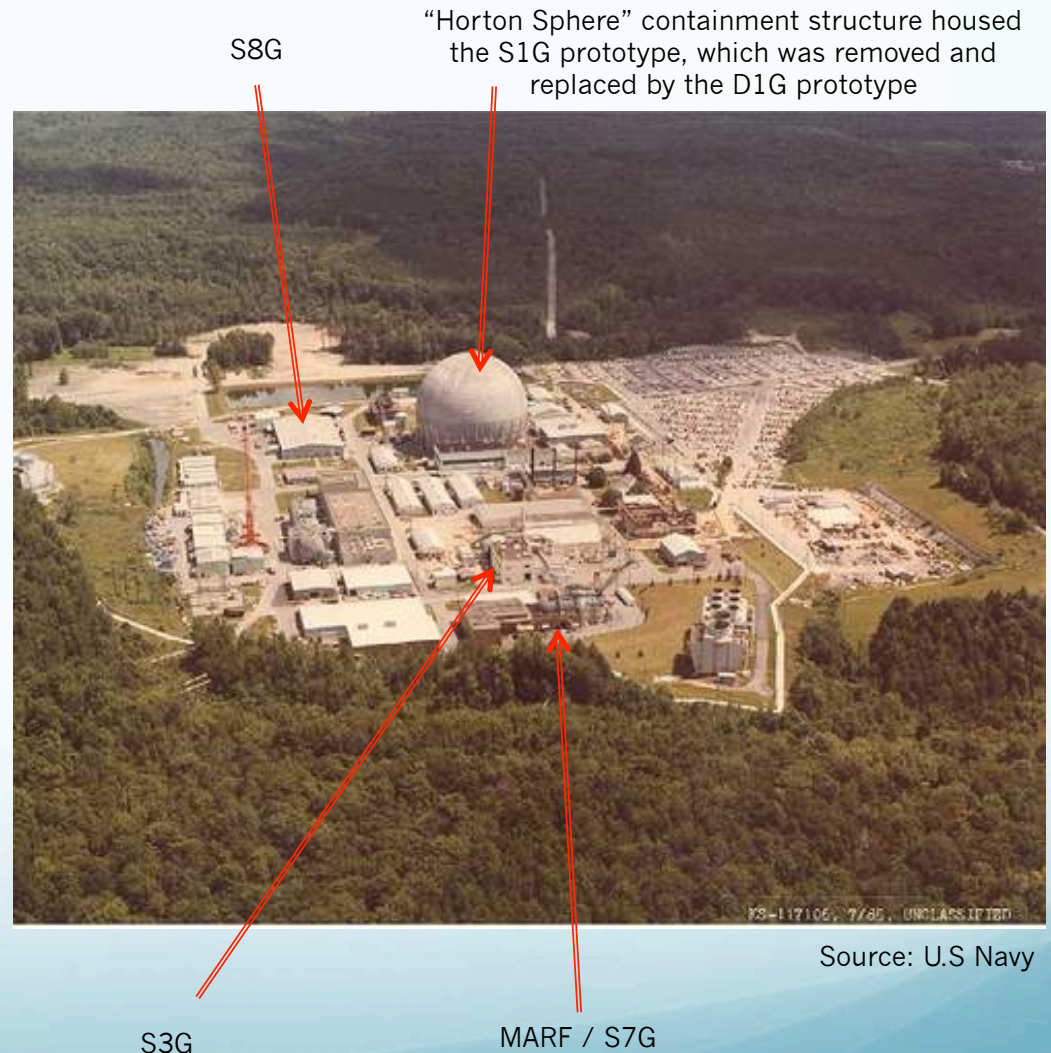
- Bettis is one of two government-owned, contractor-operated laboratories solely dedicated to naval nuclear propulsion work for Naval Reactors.
- Bettis is located in West Mifflin, near Pittsburgh, PA, and has been operated by Bechtel Marine Propulsion Corp. since 2009, when Naval Reactors consolidated the management of KAPL and Bettis.
 - 1949 – 1998: Westinghouse was the founder and original operating contractor
 - 1998 – 2008: Bechtel Bettis, Inc. was the second operating contractor
- Bettis' mission is to help ensure the continued safe and reliable operation of the Navy's nuclear reactor propulsion plants and to develop new reactor plants to meet evolving defense requirements.
 - Bettis developed the original Oak Ridge National Laboratory design of the pressurized water reactor for operational naval use, and in collaboration with Argonne National Lab, developed the Submarine Thermal Reactor (STR) that was installed on *USS Nautilus* (SSN-571) and made the world's first "underway on nuclear power."
- Bettis has a specialized testing facility for full-scale steam generator testing and a control drive mechanism test facility.
- The laboratory is home to the US Navy's Bettis Reactor Engineering School. This school provides a post-graduate certificate program in Nuclear Engineering (through the Naval Postgraduate School) with a focus on nuclear reactor design, construction, and operations.

Knolls Atomic Power Laboratory

- Knolls Atomic Power Laboratory (KAPL) is one of two government-owned, contractor-operated laboratories solely dedicated to naval nuclear propulsion work for Naval Reactors.
- KAPL is located in Niskayuna, near Schenectady, NY, and has been operated by Bechtel Marine Propulsion Corp. since 2009, when Naval Reactors consolidated the management of KAPL and Bettis.
 - 5 May 1946: Founded when General Electric received a research contract from the Manhattan Engineering District.
 - 1950: GE started research on small reactors for submarines.
 - 1946 – 1995: GE remained the operating contractor.
 - 1995 – 2009: Lockheed Martin was the second operating contractor.
- KAPL's mission is to help ensure the continued safe and reliable operation of the Navy's nuclear reactor propulsion plants and to develop new reactor plants to meet evolving defense requirements.
- KAPL has fuel manufacturing development capabilities and unique thermal-hydraulic test capabilities. In addition, the Radioactive Materials Laboratory (RML) supports core and plant material development.
- KAPL operates two Naval reactor prototypes at the Kenneth A. Kesselring Site in West Milton, NY.
 - The prototype reactors are used for operational testing of new materials and technologies under typical operating conditions prior to fleet introduction and for training Navy nuclear operators. The prototypes are MARF/S7G and S8G.
 - Nuclear Power Training Unit (NPTU) Ballston Spa is located at the Kesselring site.

Kenneth A. Kesselring Site

- Located in West Milton, near Saratoga, NY.
- Two land-based naval reactor prototypes are operating at the Kesselring Site: S8G & MARF/S7G.
- S8G is in an extended refueling / overhaul outage from 2018 - 2021. Thereafter, it will be running the Technology Demonstration Core (TDC), which will support development of the S1B reactor for the Columbia-class SSBN.
- MARF/S7G is running the Developmental Materials Core (DMC). Funding for defueling and layup is included in the NR FY2018 budget.
- Prototypes previously operated at the site were S1G, D1G and S3G. These have been permanently shut down and their sites are being dismantled and cleaned up.



Naval Nuclear Power Training Unit (NPTU) Ballston Spa, NY.

- Two land-based naval reactor prototypes at the Kesselring Site have been used for training US Navy officers, enlisted personnel and contractors to safely operate naval nuclear propulsion plants.
 - S8G
 - MARF/S7G
- By 2012, KAPL had trained over 50,000 students since the beginning of the laboratory.
- To maintain training capabilities while the S8G prototype is in an extended overhaul and refueling outage (2018 - 2021), new dedicated training facilities were built: an Engine Room Team Trainer and other task trainers.
- The planned MARF/S7G defueling and layup also will have an impact on available training resources.

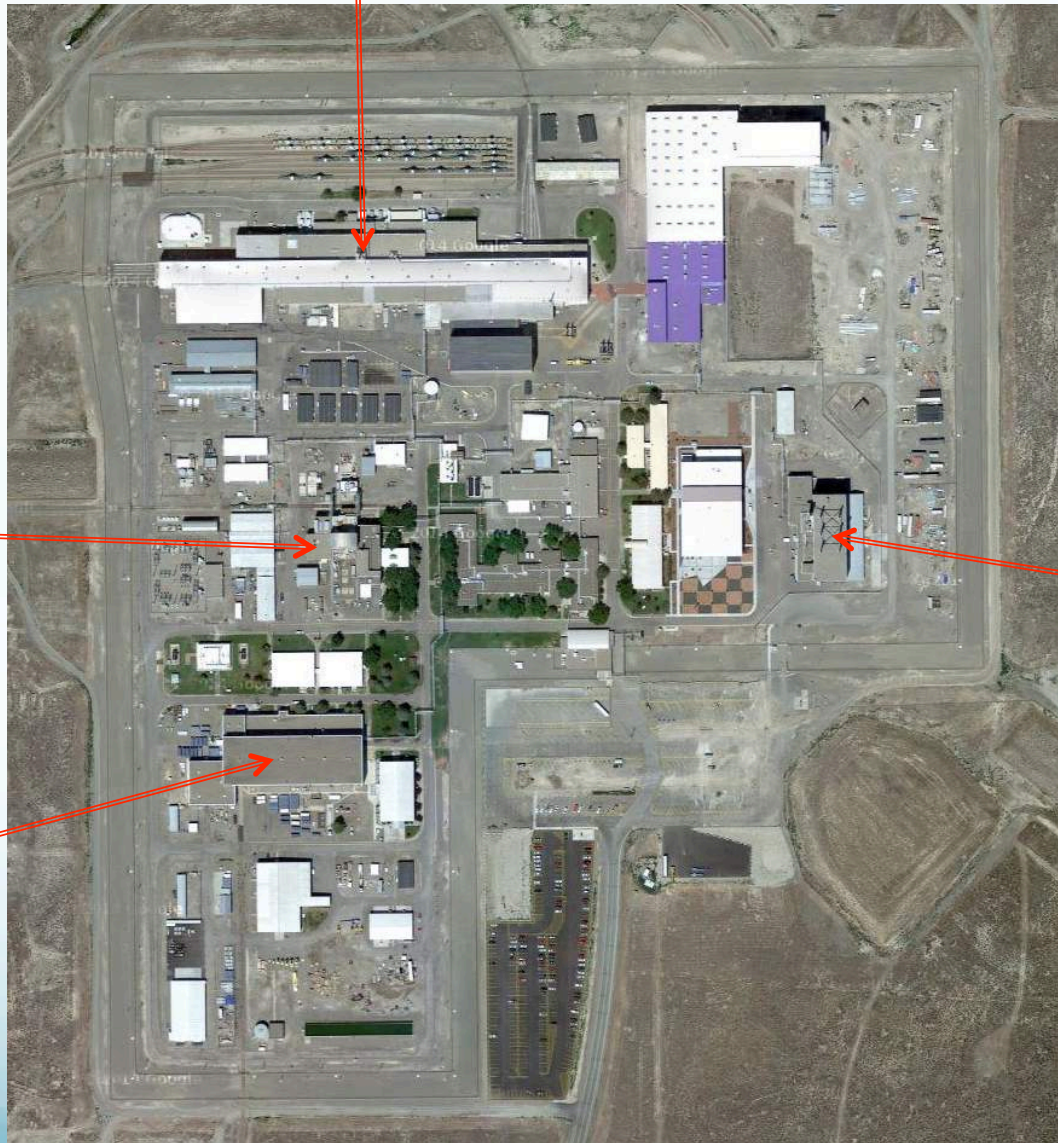


Source: <https://www.netc.navy.mil>

Naval Reactors Facility (NRF)

- NRF is located on the Idaho National Lab (INL) and has been operated by Bechtel Marine Propulsion Corporation since 2009.
- NRF was the site of the Nuclear Power Training Unit (NPTU) Idaho and the S1W, A1W and S5G reactor prototypes.
 - About 38,500 personnel were trained at NPTU Idaho to operate surface ship and submarine nuclear propulsion plants.
 - All NRF prototypes have been permanently shut down.
 - S1W operated 36 years from May 1953 – Oct 1989
 - A1W operated 35 years from Sep 1959 – Jan 1994
 - S5G operated for 30 years from 1965 - March 1995
- The only remaining active facility at NRF is the Expended Core Facility (ECF) / Dry Storage Facility, which provides for processing, examination and storage of spent fuel from US naval reactors.
 - A “Spent Fuel Handling Recapitalization” project is underway to modernize the 50-year old ECF and give it the capability to handle the longer fuel elements from aircraft carrier reactors.
 - The 1995 “Idaho Settlement Agreement” requires that all naval spent nuclear fuel be in dry storage by 2023 and removed from Idaho by 2035.
 - Startup of dry storage operations began in late FY 2006 at NRF. This involves the packaging of spent nuclear fuel from wet to dry storage for ultimate shipment to a geological repository.

Expended Core Facility (ECF)



A1W

S5G

Naval Reactors Facility (NRF)

S1W



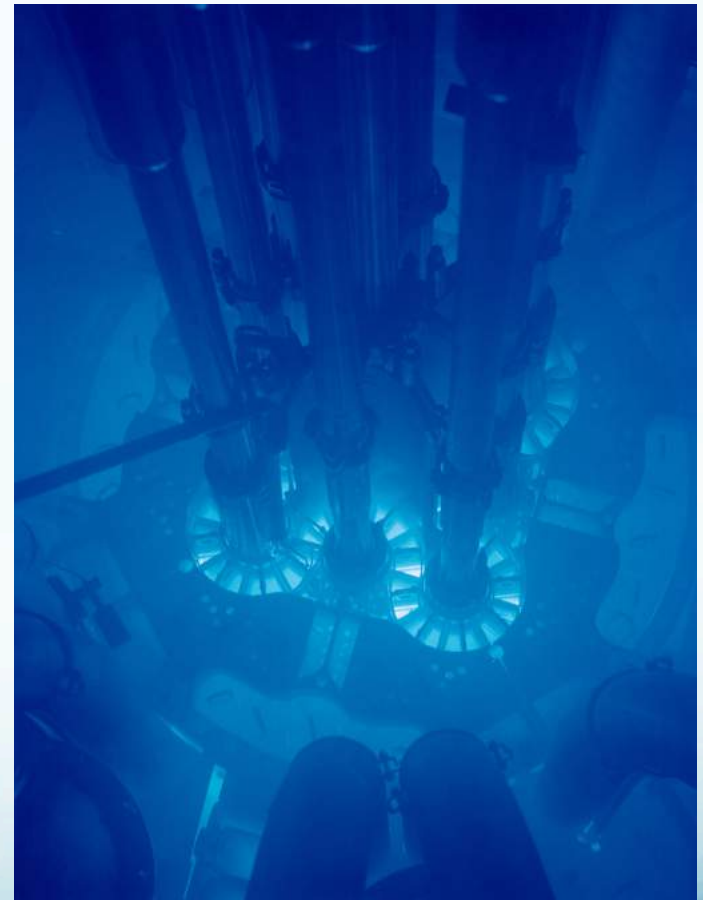
Source: adapted from <http://wikimapia.org>

Source: USNavyPatch.com

DOE Idaho Operations Office

- This DOE Nuclear Energy (NE) Field Office oversees operation of DOE programs at the Idaho National Laboratory (INL) and coordinates NR programs at the DOE-owned Advanced Test Reactor (ATR) Complex.
- ATR is a 250 MWt PWR materials test reactor built in 1967.
 - NR is the primary customer for ATR.
 - The ATR, which offers high thermal neutron flux and large test volumes, is the primary national facility with the capability for performing material irradiation testing.
 - This facility is the NR's main source of data on the performance of reactor fuel, poison, and structural materials under irradiated conditions.
 - ATR was designated as a National Scientific User Facility in April 2007. Coordination with other users is handled by the Idaho Operations Office.
- ATR Critical Facility (ATRCF) is a “zero-power” reactor used for making physics measurements of various core configurations.

ATR



Source: Argonne National Lab

Nuclear Power Training Unit (NPTU) Charleston, SC

- Two decommissioned nuclear submarines are moored dockside and used as training platforms with fully-operational nuclear propulsion plants.
- Modifications made for the training role include:
 - Special mooring arrangements, with a mechanism to absorb power generated by the main propulsion shaft.
 - Removal of missile compartment from SSBNs.
 - Addition of a new hull section containing training spaces, offices, and a new reactor emergency safety system.

| Moored Training Ship (MTS) | Reactor | Years delivered | Years in service |
|--|---------|----------------------------|---|
| <i>Daniel Webster</i> (former SSBN 626) - moored training ship MTS-626 | S5W | Aug 1990 | 1990 – present (expected thru Nov 2022) |
| <i>Sam Rayburn</i> (former SSBN-635) – moored training ship MTS-635 | S5W | Jul 1989 | 1989 – present (expected thru May 2019) |
| <i>La Jolla</i> (former SSN-701) | S6G | Conversion started in 2015 | Will replace <i>Sam Rayburn</i> |
| <i>San Francisco</i> (former SSN-711) | S6G | Conversion started in 2017 | Will replace <i>Daniel Webster</i> |



Sources: Above: wikimapia.org; Below: <http://www.navsource.org/archives>

Conversion of *USS La Jolla*

Norfolk Navy Yard, September 2015



Source: U.S. Navy photo by Shayne Hensley via <https://en.wikipedia.org/>

BWXT Nuclear Operations Group, Inc.

- BWXT Nuclear Operations Group, Inc., a subsidiary of BWX Technologies, Inc., provides a broad range of nuclear components and services, including the manufacture of nuclear reactor components for the US Naval Nuclear Propulsion Program as well as other nuclear and non-nuclear research & development and component production.
- Four locations support the NNPP:
 - Lynchburg, Virginia – principally manufactures naval nuclear reactors for submarines and aircraft carriers
 - Barberton, Ohio and Mount Vernon, Indiana – manufacture heavy components for nuclear reactor plants used in submarines and aircraft carriers
 - Euclid, Ohio – manufactures electro-mechanical components for naval reactors used in submarines and aircraft carriers
- In 1990, BWXT became the sole supplier for naval reactor components for the US Navy.
- BWXT Nuclear Operations Group manufactured the reactor plants for the Navy's Ohio-class SSBNs and SSGNs, the Virginia-, Seawolf- and Los Angeles-class SSNs, and the Nimitz- and Ford-class aircraft carriers.
- In 2016, BWXT was awarded a \$3.1 billion contract for naval nuclear reactor components and fuel.

Nuclear Fuel Services (NFS)

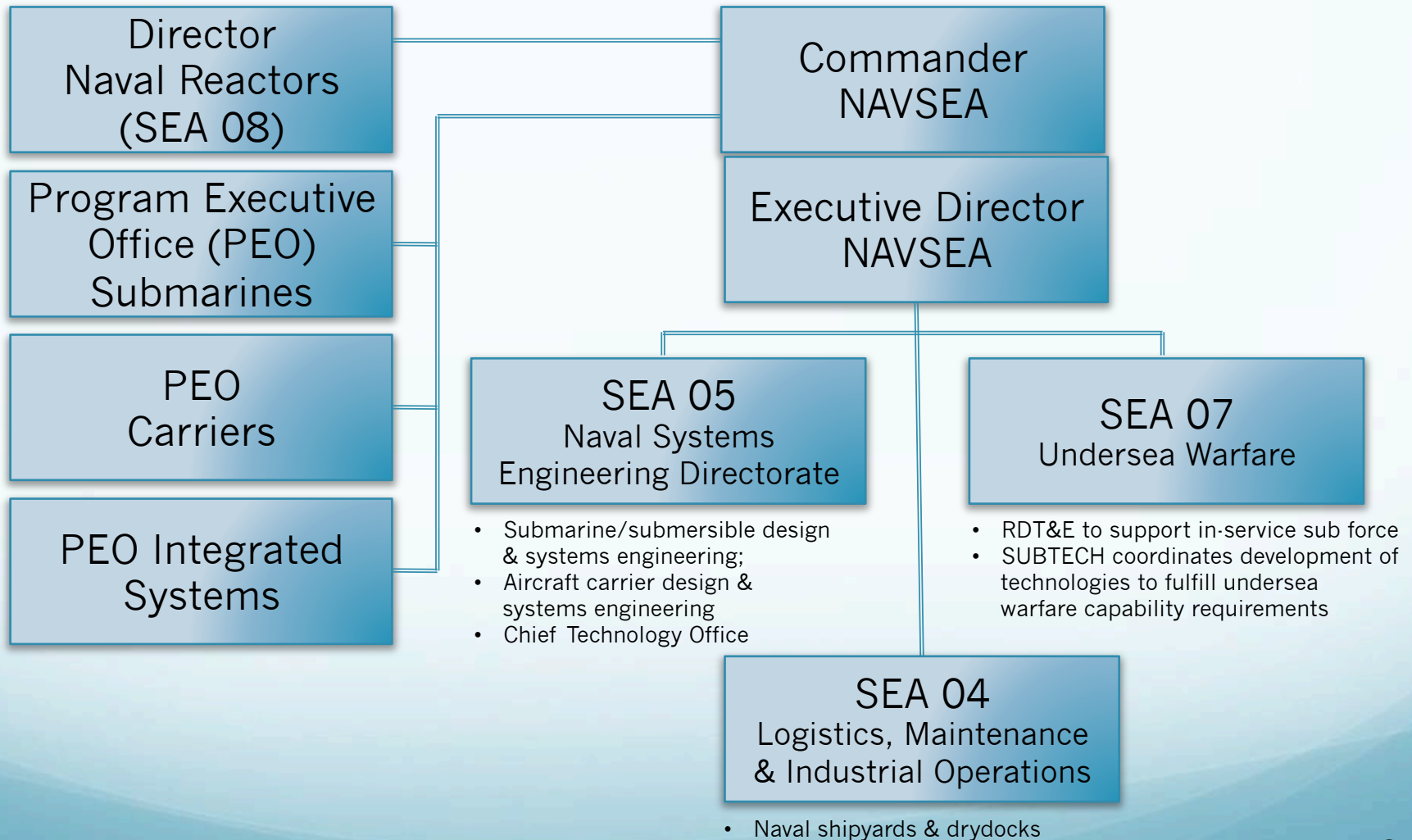
- NFS, which is a subsidiary of BWXT Nuclear Operations Group, Inc., operates a uranium fuel materials production facility in Erwin, TN. This is one of two commercial facilities in the US that is licensed to possess, handle and store HEU.
- NFS also converts government-supplied HEU into material suitable for further processing into LEU commercial reactor fuel.
- NFS timeline:
 - 1957: NFS established in Erwin, TN
 - 1964: NFS became the sole manufacturer of nuclear fuel for the US Navy
 - 1965: Naval Fuel Production Plant constructed
 - 1996: Advanced Naval Fuel Manufacturing Facility constructed
 - 2009: B&W purchased NFS from NFS Holdings, LLC
 - 2012: NFS receives and Nuclear Regulatory Commission (NRC) operating license for an additional 25 years, through 2037.



Source: <http://enformable.com>

- 2014: NFS was awarded two contracts for fuel and materials services totaling up to \$302 million from the DOE, Naval Reactors Laboratory Field Office:
 - Manufacture and deliver fuel and support activities for NNPP.
 - Develop materials for future Naval Reactors programs.
- 2016: NFS was awarded \$535.1 million in contracts primarily to manufacture fuel for Virginia-class SSNs and Ford-class CVNs.

Naval Nuclear Ship Program Management



Nuclear-capable private shipyards

- Newport News Shipbuilding (a division of Huntington Ingalls Industries)
 - The sole designer and builder of aircraft carriers for the US Navy.
 - Services the carriers through their lifetime, including a 4-year mid-life refueling + complex overhaul (RCOH)
 - Teamed with Electric Boat for construction of Virginia-class SSNs
 - Will be a subcontractor to Electric Boat for construction of the Columbia-class SSBNs.
- Electric Boat (EB) Corporation (a division of General Dynamics), Quonset Point & Groton, CT
 - Prime contractor for Virginia-class SSNs.
 - The EB Quonset Point automated steel processing facility manufactures submarine hull cylinders and then outfits each with tanks, propulsion and auxiliary machinery, piping, wiring, lighting, and special hull coatings.
 - These hull cylinders are transported by barge to EB Groton or Newport News Shipbuilding for completion of the submarine.
 - Selected as prime contractor for the Columbia-class SSBNs.
- Together, Newport News and GD/EB have built every Navy nuclear-powered submarine (SSN & SSBN) and surface ship (CVN & CGN) procured since FY1969.

Electric Boat shipyard

Groton, CT



Source: <https://breakingdefense.com/2016/03/>

Electric Boat shipyard

Groton, CT



Source: <http://wikimapia.org/730886/General-Dynamics-Electric-Boat-Division-shipyard>

Newport News shipyard

Newport News, VA



Source: <http://virginiaengineersconference.org/presentation/windshield-tour-of-the-newport-news-shipbuilding>

Newport News shipyard

Newport News, VA



Source: <https://news.usni.org>

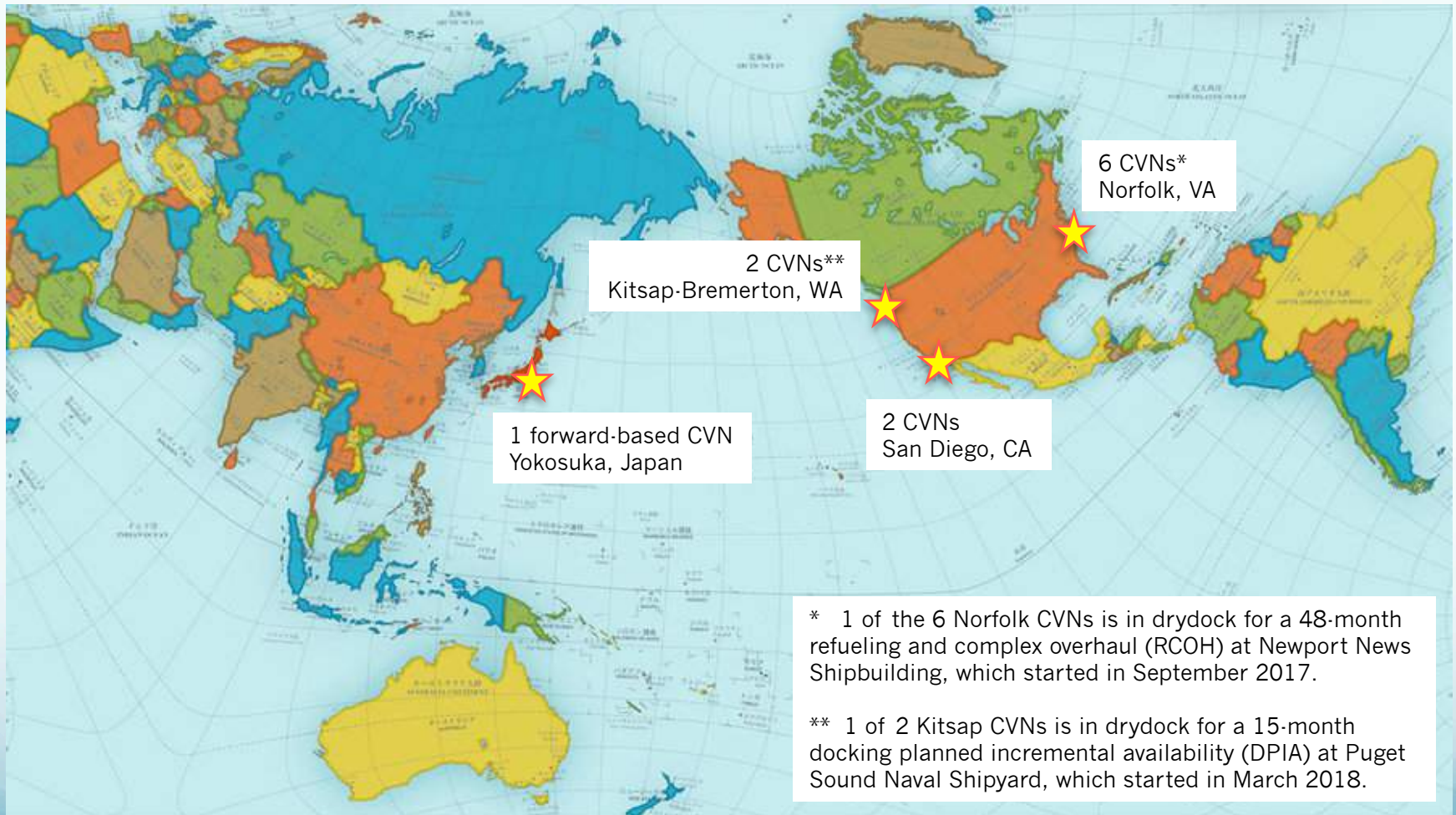
Nuclear-capable naval shipyards

- Puget Sound Naval Shipyard and Intermediate Maintenance Facility
 - Responsible for aircraft carrier and nuclear submarine intermediate (depot-level) maintenance
 - Sole shipyard for final disposition of nuclear vessels under the Nuclear Ship & Submarine Recycling Program (NSSRP)
- Pearl Harbor Naval Shipyard and Intermediate Maintenance Facility
 - Submarine repairs (*USS San Francisco, Hartford, Greenville, Newport News*)
- Portsmouth Naval Shipyard, Kittery, Maine
 - Submarine Maintenance Engineering, Planning and Procurement (SMEPP) Office
- Norfolk Naval Shipyard, Portsmouth, VA
 - Responsible for aircraft carrier and nuclear submarine intermediate (depot-level) maintenance
 - Responsible for converting *USS La Jolla* (former SSN 701) and *USS San Francisco* (former SSN-711) from an operational SSN into a Moored Training Ship (MTS).

Former new-construction shipyards

- From the 1950s through the mid-1970s, the US had as many as seven nuclear-qualified, new-construction shipyards. That diverse infrastructure lasted through the commissioning of the last of several classes of Polaris SSBNs in the late-1960s and the Sturgeon-class SSNs in the mid-1970s. The following shipyards no longer are doing nuclear new construction work.
 - Portsmouth Naval Shipyard, Kittery, Maine
 - Skate, Permit & Sturgeon-class SSNs and three classes of Polaris SSBNs
 - Mare Island Naval Shipyard (MINSY), Vallejo, CA (closed in 1996)
 - Halibut SSGN, Skate, Skipjack, Permit & Sturgeon-class SSNs and four classes of Polaris SSBNs
 - Bethlehem Steel (now General Dynamics), Quincy, MA
 - Cruisers Long Beach & Bainbridge, Sturgeon-class SSNs
 - New York Shipbuilding, Camden, NJ
 - Cruiser Truxtun, NS Savannah, Permit & Sturgeon-class SSNs
 - Ingalls Shipbuilding, Pascagoula, MI
 - Skipjack, Permit & Sturgeon-class SSNs
- Thereafter, the Navy focused all submarine new construction on just two shipyards, Electric Boat and Newport News Shipbuilding, starting with the Los Angeles-class SSNs in 1972 and the Ohio-class SSBNs in 1976. All CVN new construction has been done at Newport News Shipbuilding.
- Portsmouth Naval Shipyard continues as a nuclear qualified shipyard for maintenance and repair.

US aircraft carrier home ports



AuthaGraph World Map. Source: Adapted from <http://bigthink.com/design-for-good/award-winning-map-shows-a-more-accurate-world>

US submarine home ports

Bangor, WA
COMSUBGRU 9
SUBDEVRON-5
SUBRON-17
SUBRON-19

San Diego, CA
SUBRON-11



Pearl Harbor, HI
COMSUBPAC
SUBRON-1
SUBRON-7



Guam
SUBRON-15



Kings Bay, GA
COMSUBGRU-10
SUBRON-16
SUBRON-20

Groton, CT
COMSUBGRU-2
SUBDEVRON-12
SUBRON-4
Norfolk, VA
COMSUBFOR
SUBRON-6

Source: adapted from US Navy

Submarine Base San Diego

Ballast Point, circa early 1970s



Source: <http://www.navsource.org/>

US submarine forward bases and support activities

- In the 1960s, Polaris SSBN Advanced Refit Sites were established and maintained in Holy Loch, Scotland, Rota, Spain, and in Guam.
- Holy Loch (Site One)
 - Submarine Squadron 14, headquartered aboard the serving submarine tender, arrived in Holy Loch on 3 March 1961, aboard the *USS Proteus*. The number of submarines being supported by the Squadron varied over the years.
 - Five different submarine tenders were stationed at various times at Holy Loch.
 - The Floating Dry Dock *USS Los Alamos* (AFDB 7) was towed to Scotland in 1961 and assembled in six months. Over a 30 year span, *Los Alamos* completed over 2,800 submarine docking operations.
 - With the end of the Cold War it was announced on 6 February 1991 that the Holy Loch Base would close. In March 1992, the last US Navy ship departed, ending 31 years of American presence in the Dunoon area.

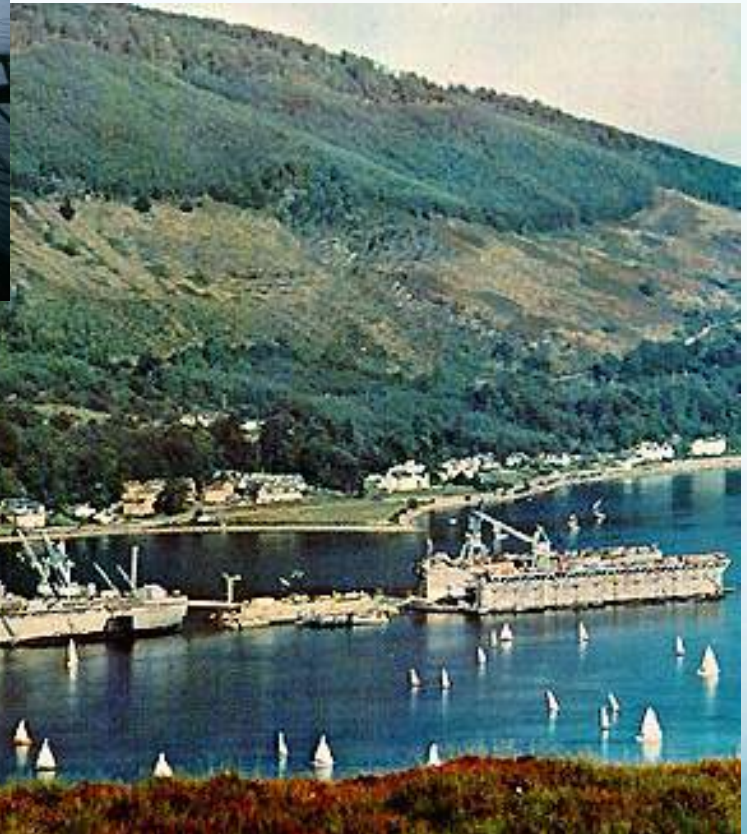


Source: <http://aboutsbs.com/holy-loch.htm>

Holy Loch

Near Dunoon, Argyll,
Scotland

Left: Floating drydock *USS Los Alamos* at Holy Loch.
Source: <https://www.pinterest.com/>



Above: Tender (*USS Holland*, AS-32). Right: *USS Holland* and floating drydock *Los Alamos* with one barge between them.
Source, both photos: <http://www.tendertale.com/ttd/ttd17/ttd17.html>

Holy Loch

Near Dunoon, Argyll, Scotland



Submarine tender Simon Lake (AS-33) with Squadron 14 SSBNs at Holy Loch.

Source, three photos: <http://snakesafe.jalbum.net/My%20Military%20history/>

US submarine forward bases and support activities

- Naval Station Rota, Spain
 - SSBN Submarine Squadron 16 (SUBRON 16) deployed to Rota on 28 January 1964 and embarked on the serving submarine tender, *USS Proteus* (AS-32).
 - *USS Lafayette* completed its first Fleet Ballistic Missile (FBM) deterrent patrol with the Polaris SLBM and commenced the first refit and replenishment at Rota.
 - During the early 1970s, the SSBNs assigned to SUBRON 16 were completing conversion to the Poseidon missile. That transition was completed when *USS Francis Scott Key* returned to Rota on 14 January 1974.
 - Treaty negotiations between Spain and the US in 1975 resulted in a planned withdrawal of SUBRON 16 from Spain by July 1979.
 - Kings Bay, Georgia was established as the replacement SSBN refit site.



Source: <http://www.flyingtigerssurplus.com/submarine-squadron-patches.html>

Rota, Spain



Above: Tender (*USS Holland*, AS-32) with a submarine tied up alongside. Source: <https://www.pinterest.com/>

Above: Rota, Spain naval base. Source, both photos: <http://www.tendertale.com/ttd/ttd17/ttd17.html>

Rota, Spain



Missile handling on an FBM submarine tied up alongside a tender at Rota, Spain.
Source: <https://www.pinterest.com/>

US submarine forward bases and support activities

- Naval Base Guam
 - In October 1964, the permanent assignment of Commander Submarine Squadron 15 was changed from Pearl Harbor to Guam. The SSBNs were based and serviced in the inner harbor, which became known as Polaris Point.
 - Subsequently, seven FBM submarines joined *USS Proteus* in Guam. This provided a short transit time to SSBN operating areas in the western Pacific.
 - With the advent of Ohio-class SSBNs armed with the longer-range Trident II SLBMs in 1981, forward basing of SSBNs no longer was needed. Squadron 15 was disestablished in 1981.
 - From 25 December 1964 when *USS Daniel Boone* departed Guam on the first Polaris deterrent patrol in the Pacific until October 1981 when *USS Robert E. Lee* returned to Pearl Harbor from the last Polaris deterrent patrol, 23 different SSBNs completed 398 Polaris deterrent patrols in the Pacific.
 - Submarine Squadron 15 was reactivated in 2001 as an attack submarine squadron operating Los Angeles-class SSNs out of Guam. The Squadron also supports all SSNs and SSGNs operating in the Pacific.



Source, above: <https://www.ebay.com/itm/Submarine-Squadron-15-Patch/>
Source, below: <http://www.milart.com/>

Naval Base Guam



Apra Harbor, Guam.
Left, source: https://en.wikipedia.org/wiki/Naval_Base_Guam

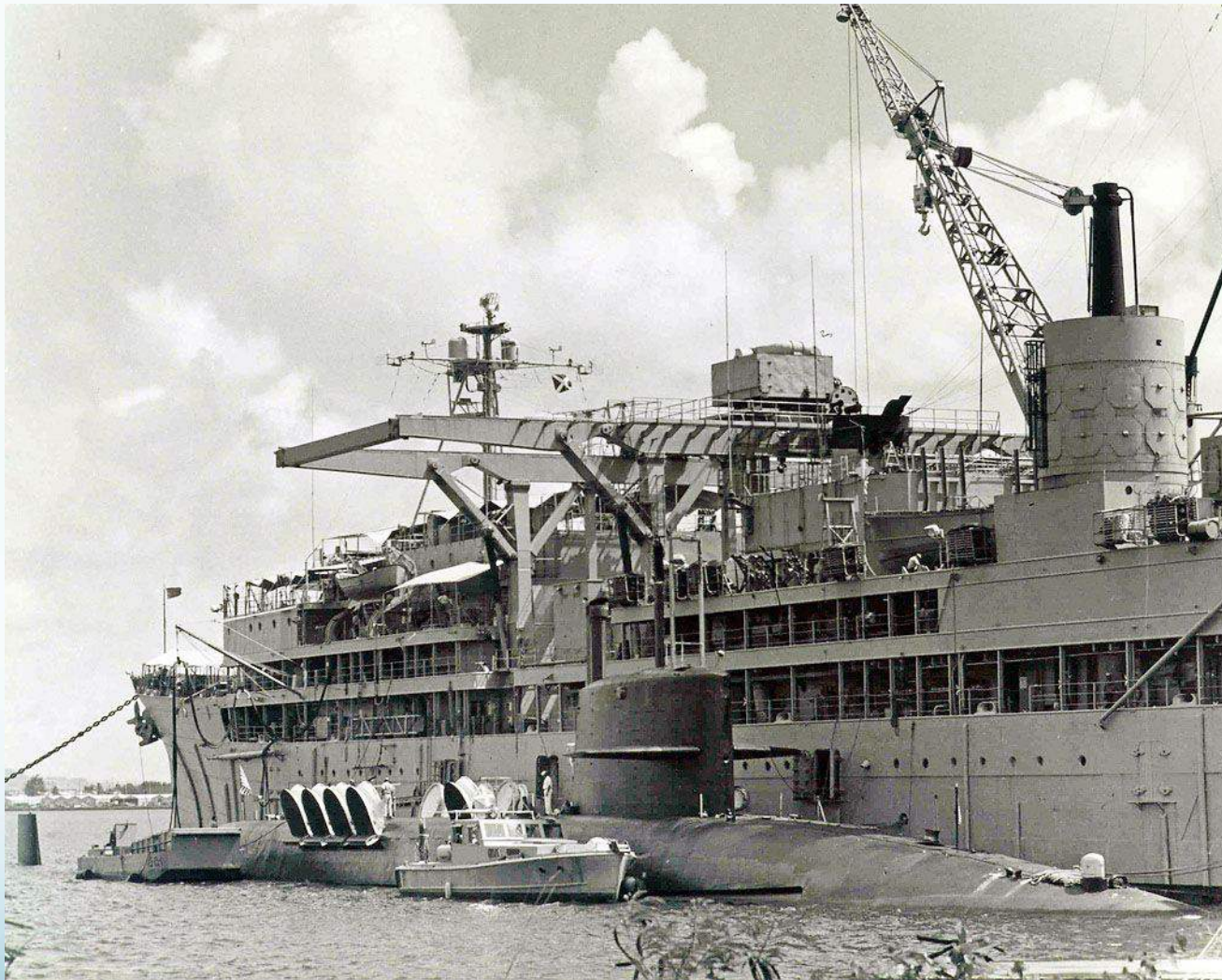


Right, source: <http://www.tendertale.com/ttd/ttd14/ttd14.html>



Above, An SSBN and a Sturgeon-class SSN tied up alongside *USS Proteus* (AS-19) in the inner harbor at Polaris Point. Another SSBN is tied up to the dock at Polaris Point, Naval Base Guam. Source: <https://www.pinterest.com/>

Naval Base Guam



USS Mariano G. Vallejo (SSBN-658) alongside USS Proteus (AS-19) in Guam.

Source: <https://www.flickr.com/photos/25195478@N05/4396573205/>

Naval Base Guam



Two Los Angeles-class SSNs moored to the submarine tender *Emory S. Land* (AS-39). At left, the Ohio-class SSGN *USS Michigan* with one dry deck shelter is moored alongside the pier. Source: US Navy photo

US submarine forward bases and support activities

- Naval Support Activity (NSA) La Maddalena, Sardinia, Italy
 - This strategically located base was set up in 1972 for the US Army under a secret accord between US and Italian officials, without the blessing of the Italian Parliament.
 - In 1993, the base was renamed to NAS La Maddalena and was taken over by the US Navy. It served as a logistical and technical hub for US nuclear submarines operating in the Mediterranean Sea.
 - A submarine tender was moored at nearby Santo Stefano island, which also is the site of a NATO base. The first tender was the *USS Robert Fulton* (AS-11); the last was *USS Emory S. Land* (AS-39), which departed in September 2007.
 - The NSA was twice used as a repair base for submarines after undersea collisions.
 - In 2005, the US announced that it would be closing NSA La Maddalena. In January 2008, the NSA was disestablished.



Source: <http://www.milart.com/>

Naval Support Activity (NSA) La Maddalena, Sardinia, Italy



SSNs tied up alongside a tender at La Maddalena. Source, above: La Nuova Sardegna (newspaper)

Source, above:
<http://militarybases.co/directory/nsa-la-maddalena-navy-base-in-la-maddalena-italy/>

Current submarine tenders

- The US Navy currently operates two aging submarine tenders (39 years old in 2018) to support its nuclear submarine fleet in forward locations.
- *USS Emory S. Land* (AS-39):
 - Commissioned in July 1979.
 - Homeported at La Maddalena, Italy to support Submarine Group 8 from 1999 – 2007.
 - After a refit, homeported at Naval Support Facility Diego Garcia from 2010 – 2016.
 - In April 2016 arrived at its new home port at Naval Base Guam.
- *USS Frank Cable* (AS-40):
 - Commissioned in October 1979
 - Spared from decommissioning in 1999, reactivated and refit to serve as the lead repair facility conducting forward area maintenance of submarines and surface vessels deployed in the US 5th and 7th Fleet areas of responsibility (5th Fleet: Persian Gulf, Red Sea, Arabian Sea, and parts of the Indian Ocean; 7th Fleet: Indo-Asian Pacific region)
 - Homeported at Naval Base Guam to support Submarine Squadron 15.
 - Departed Guam in March 2017 for a scheduled drydock maintenance availability in Portland, OR. Replaced by *USS Emory S. Land*.

Current submarine tenders



Above, USS Emory S. Land (AS-39)
Source,
both photos:
navysite.de.



Los Angeles-class SSN and tender USS Emory S. Land (AS-39)

Current submarine tenders



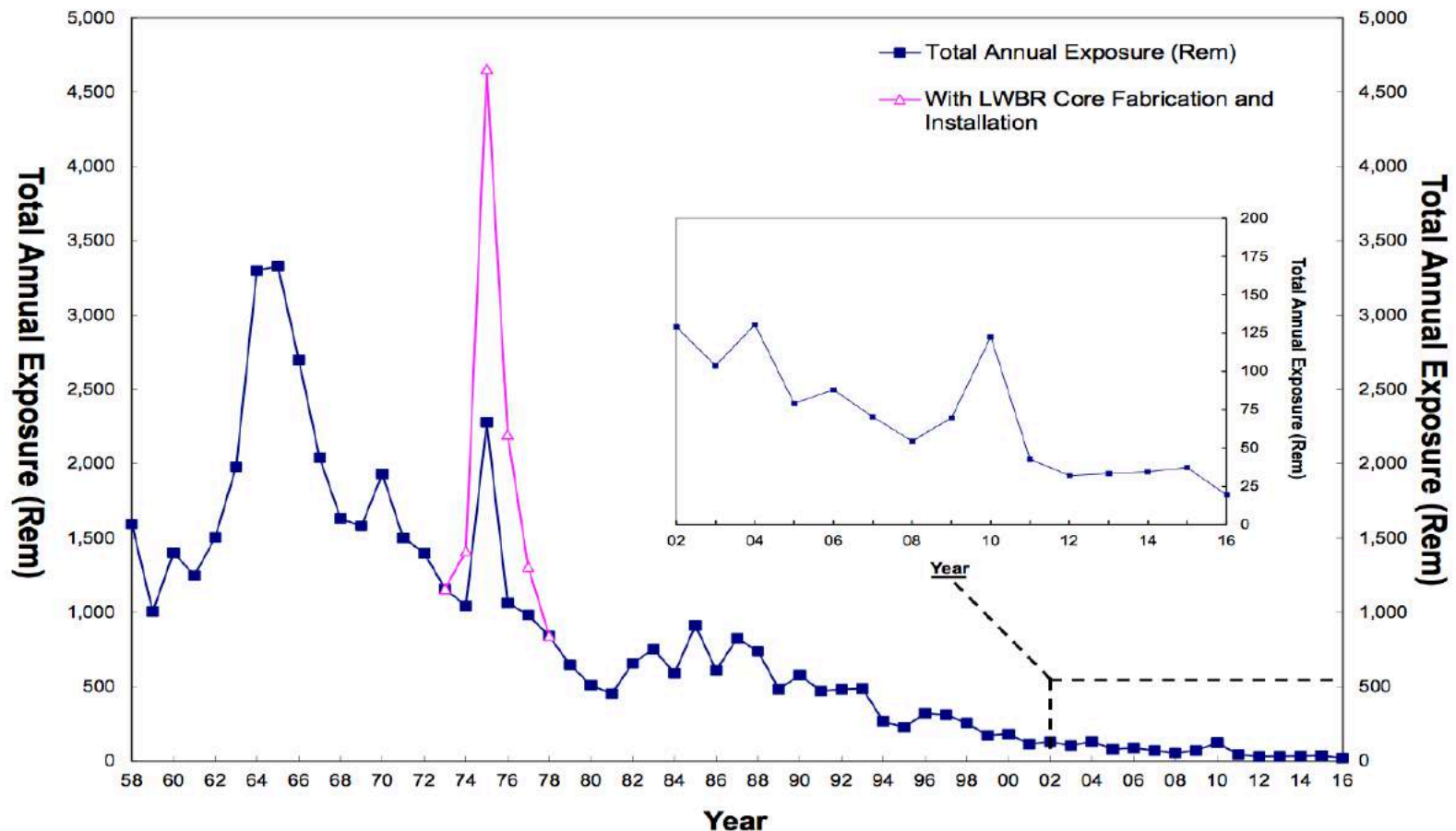
Ohio-class SSGN *USS Florida* (SSGN-728) with dry deck shelter tied up alongside tender *USS Emory S. Land* (AS-39) in 2016 at Naval Support Facility Diego Garcia. Source: US Navy

NNPP radiation safety performance

- May 2017, Office of Naval Reactors Report NT-17-3, “*Occupational Radiation Exposure from Naval Reactors Department of Energy Facilities*,” reported:
 - The current Federal annual occupational radiation exposure limit is 5 Rem per person.
 - Total radiation exposure of all monitored staff in 2016 was 19 rem; average annual exposure was 0.003 Rem per person (3 mRem/year; 0.03 mSv/year).
 - According to the standard methods for estimating risk, the lifetime risk to the group of personnel occupationally exposed to radiation associated with the Naval Reactors Program is less than the risk these same personnel have from exposure to natural background radiation. This risk is small compared to the risks accepted in normal industrial activities and to the risks regularly accepted in daily life outside of work.
 - DOE requires appointing an Accident Investigation Board (AIB) for a radiation exposure occurrence that causes an individual's external radiation exposure to equal or exceed 10 Rem.
 - Since the beginning of operations at NR's DOE facilities, there has never been a single radiation incident that met the criteria requiring appointment of an AIB.

NNPP radiation safety performance

**TOTAL RADIATION EXPOSURE RECEIVED BY PERSONNEL
AT NAVAL REACTORS' DEPARTMENT OF ENERGY FACILITIES
1958 - 2016**



Source: Naval Reactors Report NT-17-3

Use of highly
enriched uranium
(HEU) in US naval
reactors

US naval reactors use highly-enriched uranium (HEU) fuel

- HEU fuel enables high power density and long-lived reactor cores:
 - More compact naval reactor plants
 - Long life and “life of the ship” cores minimize the need for costly refueling
 - Greater energy available from the core provides operational flexibility for the ship or submarine (i.e., sustain a higher operational tempo or extend the life of the sub).
- US has a large inventory of HEU reserved for Naval Reactors use.
 - On 31 March 2016, the White House issued a fact sheet reporting the US HEU inventory as of 30 September 2013.
 - The total US HEU inventory was 585.6 metric tons.
 - Of this amount, 499.4 metric tons of HEU were for national security or non-national security programs including nuclear weapons, naval propulsion, nuclear energy, and science.
 - The HEU for current naval reactors comes from two sources:
 - The part of the national HEU stockpile reserved for Naval Reactors, with an HEU enriched to 97%.
 - HEU returned from decommissioned nuclear weapons with an enrichment of 93%.
 - In July 2016, NNSA and DOE reported: “Given current policy choices, and assuming weapons stockpile reductions occur as planned, the HEU inventory allocated for naval reactors will be sufficient for forecasted Navy needs until 2064.”

US naval reactors use highly-enriched uranium (HEU) fuel

- The initial U-235 core loadings of the various naval reactor designs is not known.
 - Since the Navy uses a “once-through” fuel cycle, all of the U-235 and fission products in the core remain in the spent fuel and will be disposed of in a repository. There is not reprocessing to recover and recycle unburned U-235.
- The annual U-235 utilization rate of the nuclear-powered fleet is not known. However, a rough estimate may be possible.
 - In 1995, with 158 operating naval reactors, NR reported that the annual burn-up of U-235 by the entire fleet was about 1.1 tons (998 kg). As a crude approximation, the “average” naval reactor burned about 7 kg of U-235 during that one year of operation.
 - Applying that average burn rate to the 2018 fleet with 80 vessels and 91 naval reactors yields an annual U-235 consumption of 637 kg (about 0.64 metric tons per year).
- Naval Reactors has established a more than 60 year track record of safe naval reactor operation with HEU-fueled reactors.
- The latest generation of the Navy’s submarines and surface ships already have been designed with long-life HEU reactor cores that will be in service for the next five decades or more.
 - Virginia-class SSNs and Columbia-class SSBNs have been designed with “life of the ship” cores and will be in service for 33 (Virginia) to 42 (Columbia) years.
 - Ford-class aircraft carriers have been designed for only one mid-life refueling in a 50 year service life.

Evolution of life-of-the-boat submarine reactors

- All US nuclear-powered surface ships require at least one refueling. Life-of-the-boat reactors are only found in modern US submarines.
- Until the first Los Angeles Flight II-class SSN, *USS Providence* (SSN-719), joined the fleet in 1985, all previous US nuclear submarine classes were designed for at least one refueling during their service life.
 - All Skate-class SSNs had an S3W / S4W reactor that required two refuelings.
 - All Skipjack- and early Permit-class SSNs and all Polaris SSBNs had an S5W reactor that required two refuelings.
 - Later Permit-class and all Sturgeon-class SSNs had an S5W reactor with a longer-life core (S3G Core 3 or S5W Core 4) that required one mid-life refueling.
 - All Los Angeles Flight I-class SSNs originally had an S6G / D1G-2 reactor that required one mid-life refueling.
 - All Ohio-class SSBNs / SSGNs have an S8G reactor that requires one mid-life refueling
- US submarines with life-of-the-boat reactors are:
 - Los Angeles (SSN-688) Flight II- and 688i-class boats have an S6G / D2W reactor intended for a 33 year SSN service life.
 - Seawolf (SSN-21)-class SSNs have an S6W reactor intended for a 30 year SSN service life.
 - Virginia-class SSNs have an S9G reactor intended for a 33 year SSN service life.
 - The future Columbia class SSBNs will have an S1B reactor intended for a 42+ year SSBN service life.

Evolution of life-of-the-boat submarine reactors

- In their FY 2005 Congressional Budget Request, Naval Reactors made the following observation regarding life-of-the-boat reactors:

“Long-term Program goals have been to increase core energy, to achieve life-of-the-ship cores, and to eliminate the need to refuel nuclear powered ships. Although efforts associated with this objective have resulted in planned core lives that were sufficient for the 30-plus year submarine (based on past usage rates) and an extended core life planned for CVN-21, fleet size is down and national security demands require a higher operating tempo and greater speed during deployments. Since September 11, 2001, submarine operating requirements have increased by 30 percent. Continuing this pace will reduce the expected core life to less than 30 years.”
- The key point is that the “life-of-the-boat” HEU-fueled reactors in existing Los Angeles-, Seawolf- and Virginia-class SSNs may not last for the full service life of the boat because the current operational tempo of the SSN fleet is greater than NR expected when the reactors were designed. With the SSN fleet getting smaller for the next decade, operation tempo will remain high.

Evolution of life-of-the-boat submarine reactors

- This issue was the primary motivation for NR to develop the Transformational Technology Core (TTC), which was intended to be a forward-fit core for Virginia-class SSNs.
 - TTC was intended to do one or more of the following: extend ship life by as much as 30 percent; increase operating hours per operating year; or allow operation at a higher average power during ship operations. The intended result was significantly greater operational ability and flexibility. Work on TTC was terminated in FY2008.
 - Instead, NR is developing the Next-Generation Reactor (NGR) as a lower cost, and lower performance forward-fit core for Virginia-class SSNs.
- This leaves the Navy with a potential long-term SSN resource utilization problem.
 - If SSN life-of-the-boat cores reach their end-of-life sooner than originally planned, the Navy will need to decide if the affected SSNs will be retired early or if it is cost-effective to extend their service life and refuel the boats.
 - One way to extend the life of the existing reactor cores is to budget the number of Equivalent Full Power Hours (EFPH) burned each year. This would mean limiting operational assignments for the SSN fleet (and saying NO to some requested tasking).

Summary of the refueling cycles of US nuclear submarines

| Ship type | Ship class | Representative ships ⁽¹⁾ | Ship years in service ⁽²⁾ | Reactor type | Core # | Avg. core life (years) | Notes |
|------------|-------------------|-------------------------------------|--------------------------------------|--------------|--|-----------------------------------|--|
| SSN | Nautilus | Nautilus | 1954 - 1980 | S2W | Core 1 Core 2 Core 3 Core 4 Core 5 | 2.2 2.1 3.4 6.4 5.2 | 1 st naval reactor Ship service life 25 yr |
| SSN | Skate | Skate, Sargo & Seadragon | 1957 - 1989 | S3W | Core 1 Core 2 Core 3 | 3.5 3.5 15.3 | |
| SSN | Triton | Triton | 1959 - 1969 | 2 x S4G | Core 1 Core 2 | 2.8 5.3 | Only 2-reactor US sub. 2 nd refueling cancelled. |
| SSN | Skipjack | Skipjack, Sculpin, Shark & Snook | 1959 - 1990 | S5W | Core 1 Core 2 Core 3 | 6.4 6.4 14.5 ⁽³⁾ | |
| SSGN / SSN | Halibut | Halibut | 1960 - 1976 | S3W | Core 1 Core 2 | 8.6 5.8 | |
| SSN | Tullibee | Tullibee | 1960 - 1988 | S2C | Core 1 Core 2 Core 3 Core 4 | 3.9 5.1 5.0 5.7 | Only naval reactor from Combustion Engineering (C-E). |
| SSBN | George Washington | A. Lincoln | 1961 - 1981 | S5W | Core 1 Core 2 Core 3 | 4.5 5 9.7 | |

Notes:

(1) Refueling overhaul dates could be determined for the identified “representative” ships.

(2) Years in service apply to the named representative ships, not to the class of ship.

(3) Long-life cores in S5W reactor plants likely were either S3G Core 3 or S5W Core 4.

Summary of the refueling cycles of US nuclear submarines

| Ship type | Ship class | Representative ships ⁽¹⁾ | Ship years in service ⁽²⁾ | Reactor type | Core # | Avg. core life (years) | Notes |
|------------|--|-------------------------------------|--------------------------------------|--------------|----------------------------|-----------------------------------|-------|
| SSBN | Ethan Allen | T. Jefferson | 1963 - 1985 | S5W | Core 1 Core 2 Core 3 | 4 5 9.2 | |
| SSBN / SSN | Ethan Allen (modified for SSN/SOF role) | J. Marshall | 1962 - 1992 | S5W | Core 1 Core 2 Core 3 | 6.7 6.6 16.2 ⁽³⁾ | |
| SSBN | Lafayette | A. Hamilton | 1963 - 1993 | S5W | Core 1 Core 2 Core 3 | 4 4.5 17.8 ⁽³⁾ | |
| SSN | Permit (early) | Barb | 1963 - 1989 | S5W | Core 1 Core 2 Core 3 | 4.5 4.5 14 ⁽³⁾ | |
| SSN | Permit (later) | Haddo, Guardfish & Flasher | 1964 - 1992 | S5W | Core 1 Core 2 | 8.7 15.4 ⁽³⁾ | |
| SSBN | James Madison | Tecumseh | 1964 - 1993 | S5W | Core 1 Core 2 Core 3 | 5.5 13 10 | |
| SSBN / SSN | Ben Franklin (modified for SSN/SOF role) | J. K. Polk | 1966 - 1999 | S5W | Core 1 Core 2 Core 3 | 5.3 9 16 ⁽³⁾ | |

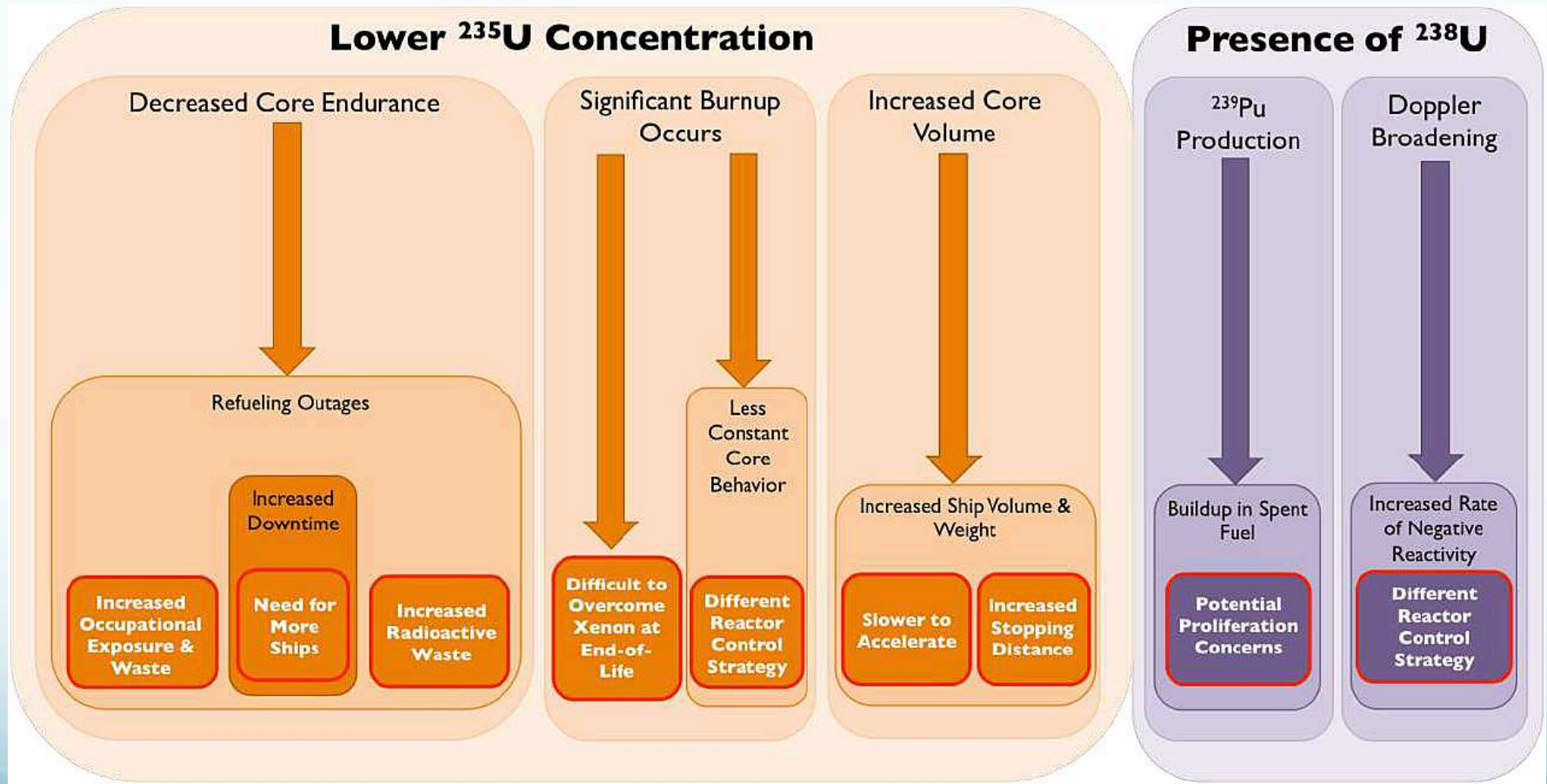
Summary of the refueling cycles of US nuclear submarines

| Ship type | Ship class | Representative ships ⁽¹⁾ | Ship years in service ⁽²⁾ | Reactor type | Core # | Avg. core life (years) | Notes |
|-----------|-------------------------------------|---|--------------------------------------|----------------------|------------------|--|--|
| SSN | Sturgeon (early) | Whale, Tautog, Ray & Hawkbill | 1968 - 2000 | S5W | Core 1 Core 2 | 8.5 18 ⁽³⁾ | |
| NR-1 | NR-1 | NR-1 | 1969 - 2008 | GE special | Core 1 Core 2 | 24 20 | |
| SSN | Sturgeon (later) | Drum, Parche & W. Bates | 1972 - 2005 | S5W | Core 1 Core 2 | 14 ⁽³⁾ 13 ⁽³⁾ | |
| SSN | Los Angeles Flight I (not refueled) | Baton Rough, Omaha, Groton, Cincinnati & Birmingham | 1977 - 1999 | S6G/D1G-2 | Core 1 | 18 | These boats were retired early after Core 1 was expended. |
| SSN | Los Angeles Flight I (refueled) | Dallas, Buffalo, Memphis & Houston | 1977 - 2017 | S6G/D1G-2 S6G/D2W | Core 1 Core 2 | 18 15 | D1G-2 original core; refueled with a D2W core. |
| SSGN | Ohio (conversion) | Ohio | 1981 - present | S8G | Core 1 Core 2 | 22 18.5 | Est. Core 2 life after 42 yr. ship service life with 18 mo. mid-life refueling overhaul. |
| SSBN | Ohio | Kentucky | 1991 - present | S8G | Core 1 Core 2 | 20.5 20 | Est. Core 2 life after 42 yr. ship service life with 18 mo. mid-life refueling overhaul. |

Summary of the refueling cycles of US nuclear submarines

| Ship type | Ship class | Representative ships ⁽¹⁾ | Ship years in service ⁽²⁾ | Reactor type | Core # | Avg. core life (years) | Notes |
|-----------|------------------------------|-------------------------------------|--------------------------------------|--------------|-----------------------|------------------------|---------------------------|
| SSN | Los Angeles Flight II & 688i | Providence, Pittsburgh & Pasadena | 1985 - present | S6G/D2W | Life of the boat core | 33 | 33 yr. ship service life. |
| SSN | Seawolf | Seawolf & Connecticut | 1997 - present | S6W | Life of the boat core | 30 | 30 yr. ship service life. |
| SSN | Virginia | Virginia | 2004 - present | S9G | Life of the boat core | 33 | 33 yr. ship service life. |
| SSBN | Columbia | Columbia | 2031 est. IOC | S1B | Life of the boat core | 42.5 | 42.5 yr. ship svc life. |

Issues related to converting naval reactors from HEU to LEU fuel



Source: *Investigation into the Unintended Consequences of Converting the US Nuclear Naval Fleet from HEU to LEU*, Virginia Tech Nuclear Science and Engineering Lab (NSEL) at Arlington, 2014

Naval Reactors studied changing from HEU to LEU fuel

- At the request of Congress, the Office of Naval Reactors issued reports in 1995 and 2014 on the potential to convert US naval nuclear vessels to use LEU fuel in place of HEU fuel. Basic findings were:
 - Conversion is “technically feasible, but uneconomic and impractical.”
 - LEU as a fuel “offers no technical advantage to the Navy, provides no significant non-proliferation advantage, and is detrimental from environmental and cost perspectives.”
- In their 2014 report, NR noted that, “the potential exists to develop an advanced fuel system that could increase uranium loading,” so that LEU fuel could meet the Navy’s needs. NR also noted that, “it is not practical ... to work on an advanced fuel system without additional sources of funding.” Finally, NR noted that, “...success is not ensured.”
 - Research and development was estimated to require up to 15 years and \$2 billion.
- Congress has taken no action to draft legislation and provide funding for a program to develop LEU fuel for future US naval reactors.

US submarine reactors & prototype facilities

US naval reactor designation scheme

- Each naval reactor type is identified with a three character designator: X#X (i.e., S3G, A1W)
- 1st character is a letter that identifies the naval platform intended to use the reactor:
 - S = Submarine
 - A = Aircraft carrier
 - C = Cruiser
 - D = Destroyer-Leader class ship (all DLGNs were re-classified as cruisers, CGNs)
- 2nd character is a number that identifies the reactor design in the sequence of designs from a particular manufacturer
 - Some reactors prototypes and their corresponding fleet reactors often were given different number designations. For example, S1W was the prototype and S2W was the similar reactor used on a submarine.
- 3rd character is a letter that identifies the reactor manufacturer
 - W = Westinghouse
 - G = General Electric
 - C = Combustion Engineering
 - B = Bechtel Marine Propulsion Corp.

US naval submarine reactors

| Reactor | Estimated Reactor Power (MWt) | Estimated Propulsion Power (shp) | Initial ops | Application |
|----------------|-------------------------------|----------------------------------|-------------|--|
| S1W, S2W, S2Wa | 70 | 13,400 | 1953 | <ul style="list-style-type: none"> S1W prototype, NFR Idaho S2W on <i>USS Nautilus</i> (SSN-571) and S2Wa <i>USS Seawolf</i> (SSN-575) replacement powerplant |
| S3W | 38 | 7,300 | 1957 | <ul style="list-style-type: none"> <i>USS Halibut</i> (SSGN-587) 2 of 4 Skate-class: <i>USS Skate</i> (SSN-578) and <i>USS Sargo</i> (SSN-583) |
| S4W | 38 | 7,300 | 1957 | <ul style="list-style-type: none"> S3W core in an S4W plant with an alternate arrangement of some equipment 2 of 4 Skate-class: <i>USS Swordfish</i> (SSN-579) & <i>USS Seadragon</i> (SSN-584) |
| S5W | 78 | 15,000 | 1958 | <ul style="list-style-type: none"> Used on 98 US nuclear subs in 8 classes and on the first UK nuclear sub, <i>HMS Dreadnought</i>, making S5W the most used Navy reactor plant design to date. Most S5W plants were refueled with S3G core 3. |
| S6W | 220 | 45,000 | 1994 | <ul style="list-style-type: none"> Core tested in the S8G prototype Used on all SSN-21 Seawolf-class subs. Life-of-the-boat core. Seawolf SSN service life is 30 years |
| S1C, S2C | 13 | 2,500 | 1959 | <ul style="list-style-type: none"> S1C prototype, Windsor, CT S2C on <i>USS Tullibee</i> (SSN-598) |
| S1G, S2G | 78 | 15,000 | 1955 | <ul style="list-style-type: none"> S1G prototype, West Milton, NY (later became the D1G prototype) <i>USS Seawolf</i> (SSN-575) original sodium-cooled reactor plant, which was removed and replaced by an S2Wa PWR |

US naval submarine reactors

| Reactor | Estimated Reactor Power (MWt) | Estimated Propulsion Power (shp) | Initial ops | Application |
|---------------------|-------------------------------|----------------------------------|-------------|---|
| S3G, S4G | 78 | 15,000 | 1958 | <ul style="list-style-type: none"> S3G prototype, West Milton, NY <i>USS Triton</i> (SSN-586), which had 2 x S4G reactors. An S3G core 3 installed in an S5W reactor plant was original equipment in many later Sturgeon-class SSNs, which required one mid-life refueling. This core also was used to refuel many S5W plants. |
| S5G | 90 | 17,300 | 1965 | <ul style="list-style-type: none"> S5G natural circulation prototype, NRF Idaho <i>USS Narwhal</i> (SSN-671) |
| S6G with D1G-2 core | 150 | 30,000 | 1976 | Los Angeles-class Flight I boats. One mid-life refueling was required for the original 30 year service life of the boat (extended to 33 years). Some Flight I boats were not refueled and were decommissioned early. |
| S6G with D2W core | 165 | 33,500 | 1985 | Original equipment in all Los Angeles-class Flight II and 688i boats. Designed as a life-of-the-boat core for an original 30 year service life (extended to 33 years). Also installed on Los Angeles-class Flight I boats that had a mid-life refueling. |
| S7G / MARF | Not known | Not known | 1997 | MARF prototype, West Milton, NY. Originally a “rodless core”, later replaced by the Developmental Materials Core (DMC). |
| S8G | 185 | 35,500 | 1980 | <ul style="list-style-type: none"> S8G prototype, West Milton, NY All Ohio-class SSBNs and SSGNs. One mid-life refueling was required. Original design life of the boats was 30 years; then increased to 42 years. S8G reactor core life is at least 20 years. |

US naval submarine reactors

| Reactor | Estimated Reactor Power (MWt) | Estimated Propulsion Power (shp) | Initial ops | Application |
|---------|-------------------------------|----------------------------------|-------------|---|
| S9G | 210 | 40,000 | 2004 | All Virginia-class SSNs. Naval Reactors describes S9G as “the first core specifically designed to operate without refueling for the service life of the ship.” (NR FY 2004 Congressional Budget). Virginia SSN has a 33 year service life. |
| TTC | > S9G | > S9G | Design only | Transitional Technology Core, intended to replace the current core in S9G reactor plants on future Virginia-class SSNs. Expected to have 35% more energy than the original S9G core. Development was terminated in FY2007 after completing the fuel design. |
| NGR | Similar to S9G | Similar to S9G | Not known | Next Generation Reactor, aka NGR-93 (93% enriched HEU), |
| S1B | Not known | Not known | 2031 (plan) | All Columbia-class SSBNs. Designed as a life-of-the-boat core for the SSBN, which has a 42+ year service life. |

Westinghouse S1W, S2W, S2Wa

Submarine Thermal Reactor (STR)

- Bettis developed the original Oak Ridge National Laboratory design of the pressurized water reactor for operational naval use, and in collaboration with Argonne National Lab, developed the Submarine Thermal Reactor (STR).
 - Fuel elements were clad in an alloy of Zirconium.
 - Reactor physics measurements were made in Argonne National Lab's Zero Power Reactor 1 (ZPR-1), which was built in 1950.
- The Navy ordered three S1W/S2W two-loop PWRs from Westinghouse.
- S1W prototype timeline:
 - The first reactor became the land-based prototype, initially named STR Mark I and then S1W, built at the Naval Reactor Facility (NRF) at National Reactor Testing Station (NRTS), Idaho (later Idaho National Laboratory, INL).
 - April 1948: A formal project for the submarine reactor was established at Argonne National Laboratory.
 - June 1948: Original Navy - Westinghouse contract.
 - December 1948: Original Atomic Energy Commission – Westinghouse contract.
 - August 1950: Start of S1W construction at the NRTS, Idaho.
 - 30 March 1953: S1W initial criticality

Westinghouse S1W, S2W, S2Wa

Submarine Thermal Reactor (STR)

| Core # | Est. operating period | Est. core life | Notes |
|--------|----------------------------|----------------|---|
| 1 | 30 Mar 53 – Sep 55 | 2.5 yr | 25 June 1953: Start of a 96-hour high-power run to simulate a submerged transit across the Atlantic. |
| 2 | Mar 56 – Nov 57 | 1.7 yr | Included a 66-day (about 1,584 hours) continuous full-power run, equivalent to steaming twice around the globe. |
| 3 | Early 1958 – late 1960 | 2.5 yr | |
| 4 | Early 1961 – late 1965 | 4 yr | Major overhaul. S5W core 4 installed. |
| 5 | Late summer 67 – 17 Oct 89 | 24 yr | Prototype permanently shut down. |

- S1W prototype timeline (continued):
 - Mid-1960s: The S1W Core 4 was removed after about 4 years of operation and the prototype was modified to enable testing the S5W core 4.
 - The reactor vessel was extended to fit the larger S5W reactor core. Steam dumps were added to dump the excess steam generated when the plant was operated at higher power levels.
 - Late summer 1967: Initial criticality of the S5W Core 4.
 - 17 Oct 1989: The S1W / S5W Core 4 prototype facility was shut down permanently.
 - About 12,500 students were trained at the S1W prototype in 36 years.

Westinghouse S1W, S2W, S2Wa

Submarine Thermal Reactor (STR)

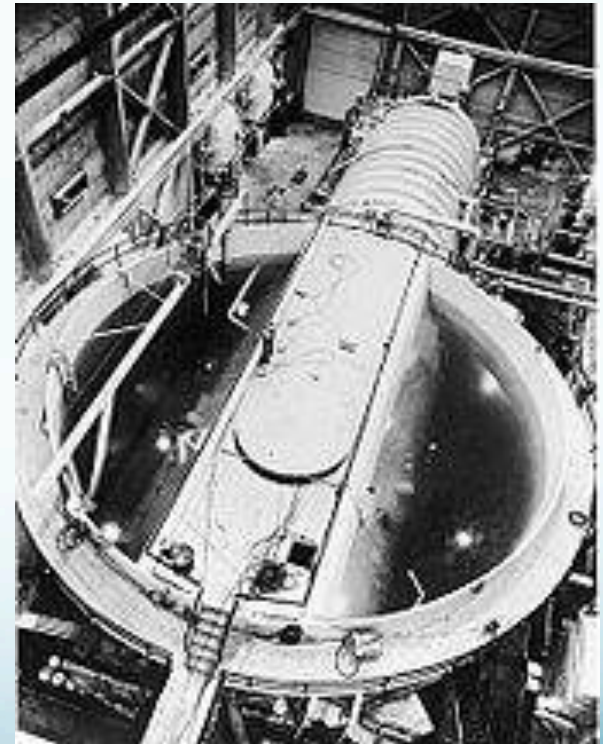
- Operational application: S2W, *USS Nautilus* (SSN-571)
 - The second reactor plant was named STR Mark II and then S2W. It was installed in *USS Nautilus* and became the reactor that made the world's 1st "Underway on nuclear power" on 17 Jan 1955.
 - Propulsion system consisted of 1 x S2W Westinghouse PWR rated @ 70 MWt (est.); 2 x main steam turbines delivering a total of 13,400 shp (10 MW) to 2 x screws.
- Operational application: S2Wa, *USS Seawolf* (SSN-575) replacement reactor
 - This "spare" S2W reactor plant was installed on *USS Seawolf* (SSN-575) in 1958 after removal of its original S2G liquid metal-cooled reactor plant and conversion of the secondary propulsion plant to operate with saturated steam.

Westinghouse S1W prototype

To meet the delivery schedule for the first nuclear submarine, Naval Reactors followed a concurrent engineering approach, with the design and construction of the full-scale S1W (Mark I) prototype running slightly ahead of the design and construction of the S2W (Mark II) and *USS Nautilus*. To the extent practical, lessons learned during S1W construction helped improve the design and construction of the S2W (Mark II) plant installed in the *USS Nautilus*.



An aerial view of the S1W prototype site, located at the Naval Reactor Facility on the Idaho National Laboratory. Source, INEEL.
Source, 2 photos: Naval Reactors / INEEL



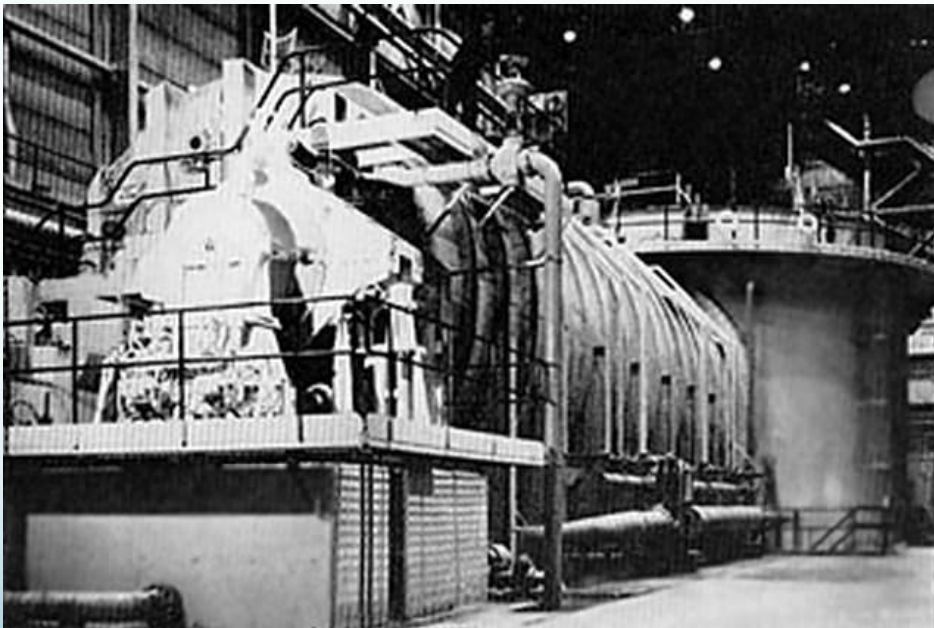
Overhead view of the shield water tank surrounding the reactor compartment.

Westinghouse S1W prototype

The S1W (Mark I) prototype PWR and propulsion plant were built inside a steel cylinder less than 30 feet (9.1 meters) in diameter, simulating a submarine hull.

A single propeller was simulated using a water brake. During reactor operation, large, outdoor water spray ponds dissipated heat from the main condenser and water brake.

Historians Richard Hewlett and Francis Duncan, in their book, *Nuclear Navy 1946 - 1962*, noted that the S1W "was the world's first fully-engineered nuclear reactor capable of producing practical amounts of energy on a sustained and reliable basis."



The cylindrical hull in the foreground contained the engine room and a maneuvering room (the control room for the reactor and propulsion systems). The shield water tank surrounding the reactor compartment is in the background; the water brake in the foreground.



Port side stern view, with the water brake for the shaft barely visible on the lower right. The shield tank is in the upper left background.

Source, both photos: Naval Reactors / INEEL

Westinghouse S3W, S4W

Submarine Fleet Reactor (SFR)

- This reactor was a scaled-down version of *USS Nautilus'* S2W reactor with about half the power output.
 - Unfortunately, scaling down the reactor did not proportionally reduce the weight of reactor shielding, and it was eventually realized that further downsizing was impractical.
- There was no S3W / S4W prototype.
- Operational applications:
 - The propulsion plant consisted 1 x S3W reactor rated @ 38 MWt (est.); 2 x main steam turbines delivering a total of 7,300 hp (5.4 MW) to 2 x screws.
 - The S3W propulsion plant was installed on *USS Halibut* (SSGN-587) and two of the Skate-class SSNs: *USS Skate* (SSN-578) and *USS Sargo* (SSN-583).
 - The S3W reactor plant had horizontal steam generators as in S1W & S2W.
 - The S4W propulsion plant was installed on the other two Skate-class boats; *USS Swordfish* (SSN-579) and *USS Seadragon* (SSN-584).
 - The S4W reactor plant used the S3W reactor core with an alternate arrangement of primary system equipment.
 - Initial core lifetime was about 2,000 equivalent full power hours (EFPH), increasing to 2,500 EFPH in later cores.

Westinghouse S5W

Advanced Submarine Fleet Reactor (ASFR)

- The S5W was a two-loop PWR rated at 78 MWt, with two vertical U-tube steam generators.
- Reactor core life improved significantly:
 - The early S5W reactor on the *HMS Dreadnought* was reported to have a core life of about 5,500 equivalent full power hours (EFPH)
 - Later S5W cores had increased life; about 10,000 EFPH.
 - Many S5W reactors were refueled with the S3G core 3, with the same 78 MWt power rating and a core life of about 18,000 EFPH. Many later S5W plants received S3G core 3 as the original core.
- There was no separate S5W prototype.
- Operational applications:
 - The submarine propulsion plant consisted of 1 x S5W reactor rated @ 78 MWt; 2 x main steam turbines delivering a combined 15,000 shaft horsepower (11.19 MW) to a single propeller.
 - The S5W was used on 98 US nuclear submarines of 8 classes and on the first British nuclear submarine, *HMS Dreadnought*, making it the most used Navy reactor design to date.
 - First use of the S5W propulsion plant was on *USS Skipjack* (SSN-585) launched in May 1958.
 - The submarine reactor compartment for the S5W reactor plant had an outside diameter of 31.5 feet (9.6 m), a length of 25 feet (7.6 m) and a weight of about 1,130 tons.
 - As of early 2018, two S5W reactor plants remain in service on moored training ships; ex-*USS Daniel Webster* (MTS-626) and ex-*USS Sam Rayburn* (MTS-635).

Westinghouse S6W

Advanced Fleet Reactor (AFR)

- S6W is large reactor plant designed to fit in the 42.3 ft (12.9 m) diameter hull of a Seawolf (SSN-21)-class sub.
- There was no separate S6W prototype. The original S8G core in the S8G land-based prototype was replaced with an S6W core.
 - Initial criticality with the S6G core in the S8G prototype occurred in March 1994.
 - S8G operation with the S6G core continues until the start of a refueling outage scheduled to start in September 2018.
- Operational applications: used only on three Seawolf-class SSNs
 - The propulsion plant consists of 1 x S6W reactor rated @ 220 MWt (est.); 2 x steam turbines delivering a combined 45,000 shp (34 MW) to a single pump-jet propulsor.
 - The core was loaded on *USS Seawolf* (SSN-21) in March 1995.
 - The S6W core is intended to be a life-of-the-boat core without refueling.
 - Seawolf-class SSNs currently have a 30 year service life.

Combustion-Engineering S1C, S2C

Submarine Reactor, Small (SRS)

- This small Combustion-Engineering (C-E) 2-loop PWR plant had the same general layout as a Westinghouse S5W plant.
- The unique secondary system delivered propulsion power via turbine generators that drove an electric motor that was directly coupled to the main shaft and propeller.
 - No propulsion turbines or reduction gear
 - Designed to be quieter than other contemporary nuclear propulsion systems
- S1C prototype was located in Windsor, CT
 - The S1C prototype operated from 1959 until 1993. During that time, over 14,000 operators were trained there.
 - The site has been permanently closed and environmental remediation was completed in 2006.
- Operational application: S2C was used only on the *USS Tullibee* (SSN-598)
 - The propulsion system consisted of 1 x S2C PWR rated @ 13 MWt (est.); 2 x steam turbine generators delivering a combined 1.86 MW (2,500 shaft horsepower) to the electric drive for a single propeller.
 - Expected size and weight savings were not realized, primarily because radiation shielding requirements did not scale proportionately with reactor power.

The S1C prototype site, Windsor, CT



Source: <https://en.wikipedia.org>

General Electric S1G, S2G

Submarine Intermediate Reactor (SIR)

- This was the first liquid metal (sodium) cooled reactor developed for use on a submarine.
 - In the late 1940s, GE was conducting Atomic Energy Commission (AEC)-sponsored work to develop a land-based intermediate spectrum power-breeder reactor. This project was had run into budget problems.
 - In July 1947, BuShips funded GE to conduct *Project Genie*, a non-nuclear study of heat transfer systems with liquid metal (sodium) coolant.
 - In about 1950, the AEC project was transferred to NR for development into a land-based naval reactor prototype and a submarine reactor.
- The design promised a more compact reactor with greater thermal efficiency and higher power density than *Nautilus'* S2W PWR, while delivering superheated steam to drive the turbines. There were unique hazards:
 - Sodium has a much longer half-life than water (14.7 hours vs. 8 seconds). This increases the radiation hazard for post-shutdown work in the reactor compartment.
 - Sodium reacts violently with water.
- Basic design features:
 - Reactor:
 - Highly-enriched UO_2 fuel (90% enrichment) was clad in stainless steel, with beryllium as a moderator and reflector.
 - Three reactor cores were built: S1G (prototype), S2G (*Seawolf*) and one spare.
 - Core operating life was expected to be 900 equivalent full power hours (EFPH).

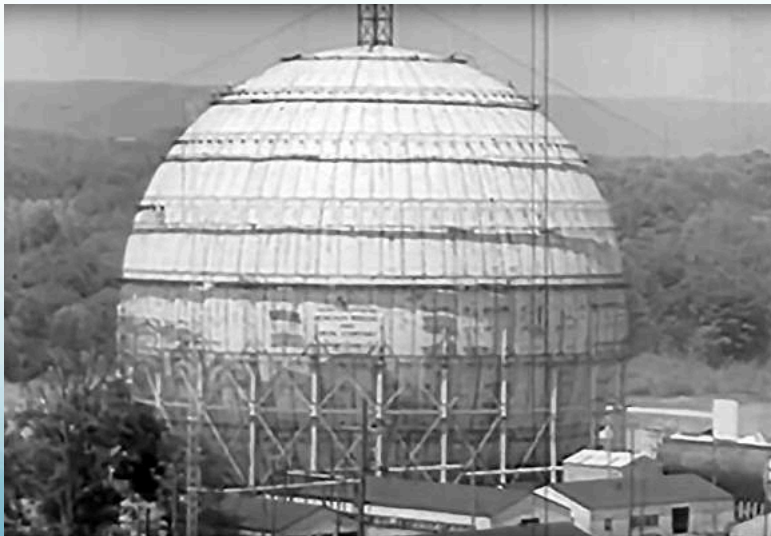
General Electric S1G, S2G

Submarine Intermediate Reactor (SIR)

- Basic design features (cont'd):
 - Primary coolant system:
 - Sodium coolant was circulated by electromagnetic (EM) pumps, with flow regulated by changing voltage. The pumps had no moving parts.
 - Steam generators:
 - All steam generator tubes, including superheater tubes, were double-walled.
 - Primary sodium coolant flowed inside the tubes.
 - Secondary water / steam flowed outside the tubes.
 - The space between the tube double walls was filled potassium-sodium alloy to transfer heat from the primary to the secondary system and provide a barrier against direct sodium-water contact.
- S1G prototype (SIR Mark A)
 - The S1G prototype and its “Horton Sphere” steel containment building were constructed at the Kesselring Site in West Milton, NY.
 - Key dates leading up to S1G initial operation were:
 - January 1952: Construction at the West Milton, NY site was approved by the AEC.
 - August 1952: Start of construction
 - 20 March 1954: The simulated submarine hull was moved into the Horton Sphere.
 - 20 Mar 1955: Initial criticality
 - 18 May 1955: The plant generated useful power

General Electric S1G prototype

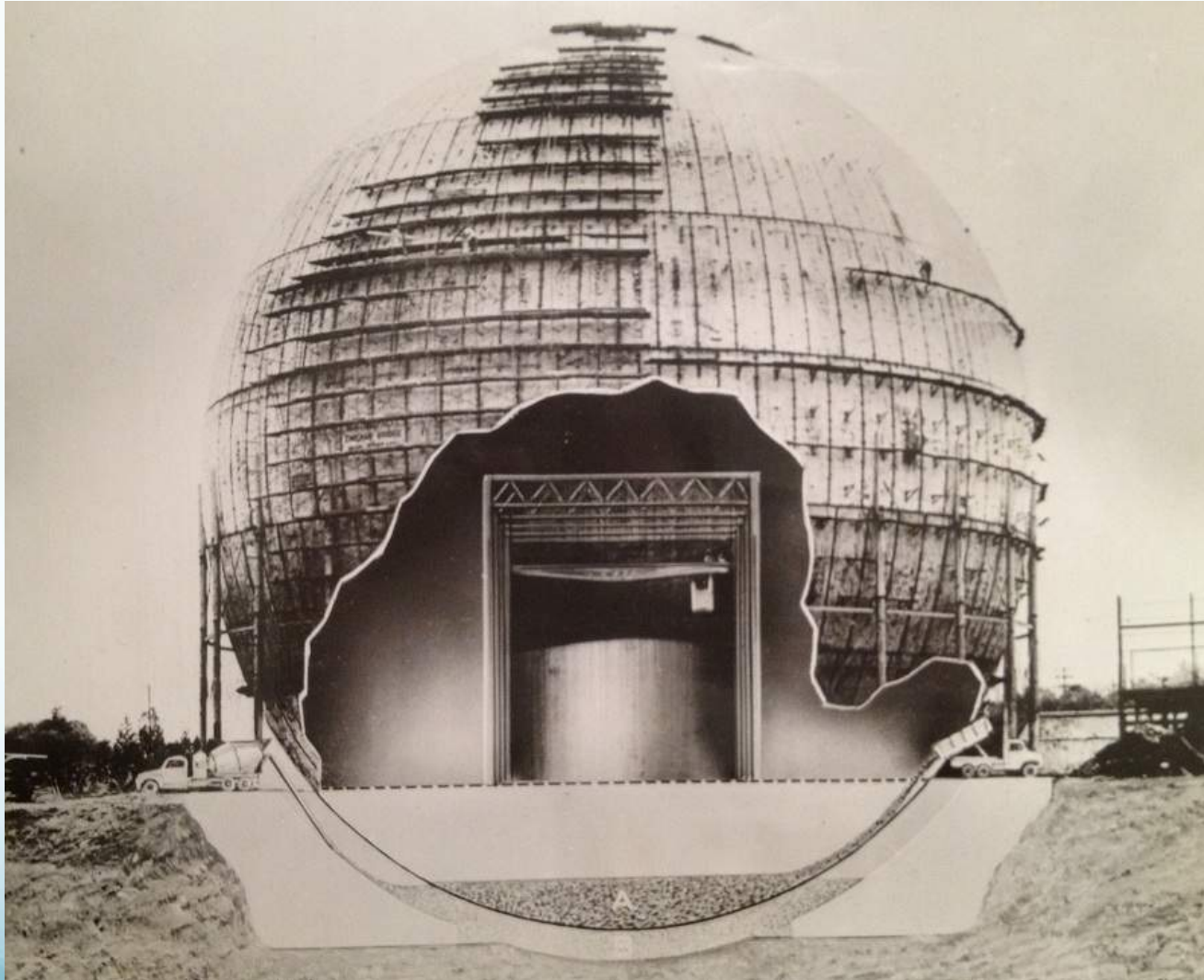
Building the 225 foot (68.6 m) diameter Horton sphere



Source: Screenshots from YouTube video, "*The Atom Goes to Sea*," General Electric Company, 1954

General Electric S1G prototype

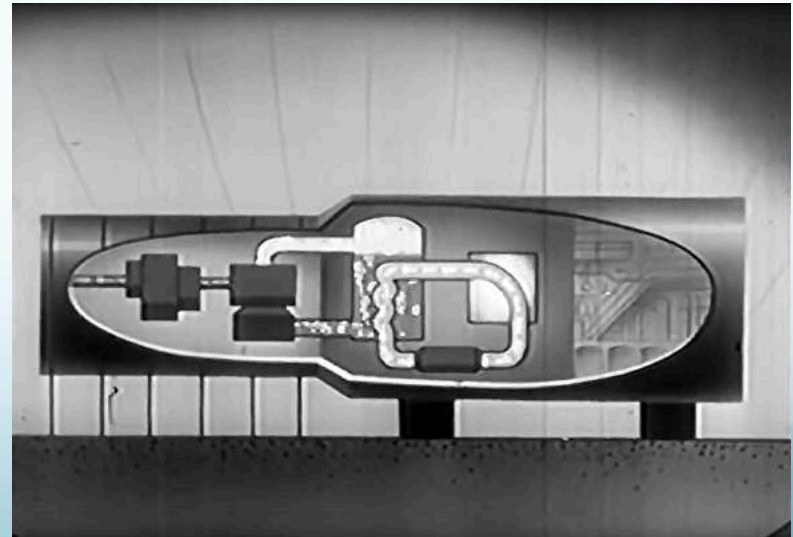
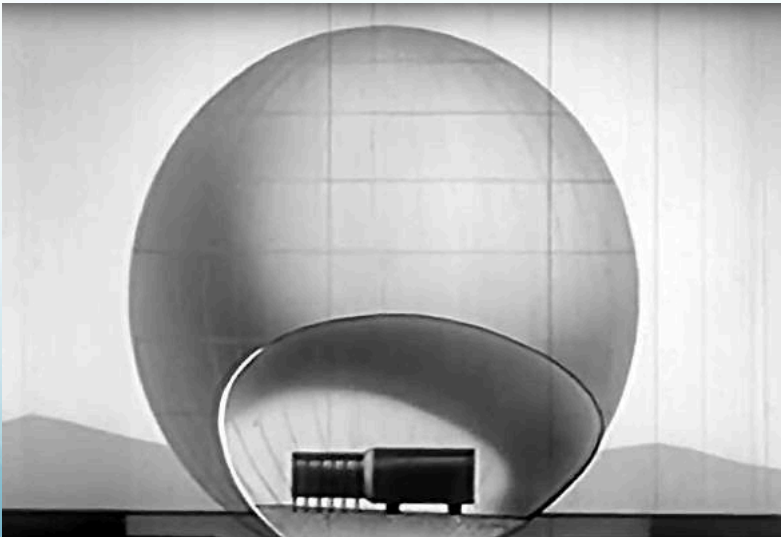
Details of the Horton Sphere containment building



Source, diagram + photo: atomicpowerreview.blogspot.com

General Electric S1G prototype

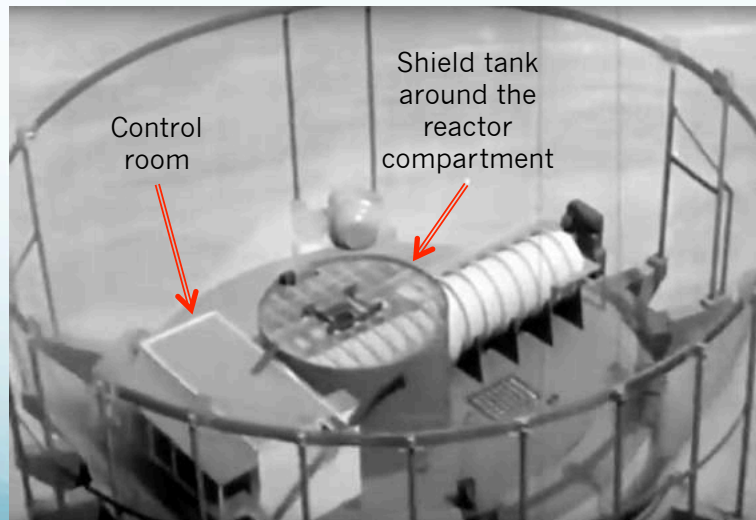
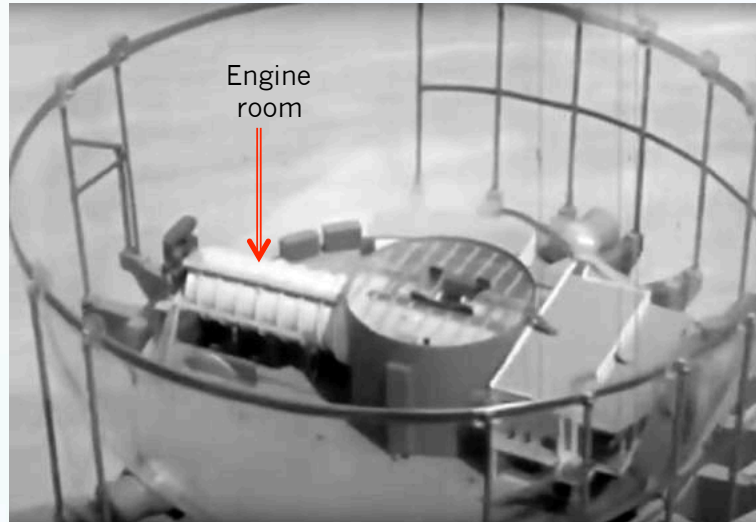
Installing the S1G prototype in the Horton sphere, 20 Mar 1954



Source: Screenshots from YouTube video, "The Atom Goes to Sea," General Electric Company, 1954

General Electric S1G prototype

Arrangement inside the Horton sphere



S1G model. Source: Annotated screenshots from YouTube video, "The Atom Goes to Sea," General Electric Company, 1954



Hull (left) and shield tank for the S1G prototype
Source: atomicpowerreview.blogspot.com

General Electric S1G, S2G

Submarine Intermediate Reactor (SIR)

- Operation of the S1G prototype (SIR Mark A):
 - July 1955: Within two months of initial operation, leaks had developed in the steam generator superheaters. These were repaired by January 1956, when operation resumed.
 - The Naval Research Laboratory (NRL) had reported on the adverse effects of sodium on 347 stainless steel. Apparently, this information was missed by GE and NR, which selected 347SS for the S1G superheater tubes.
 - The S1G superheaters suffered from tube sheet weld cracks, which allowed high-pressure steam to leak into the low-pressure primary system and react with the sodium to form sodium hydroxide and H₂. Radioactive tritium (³H) also formed as a free gas in the primary system.
 - The S1G prototype's secondary system could be aligned to drive an external 10 MWe turbine-generator that delivered power to the Niagara Mohawk electrical grid.
 - March 1957: Rickover informed the JCAE that the S1C would be permanently shutdown.
 - Subsequently, the S1C was removed from the Horton Sphere, which was reused as the containment building for a large PWR intended for use on frigates. This would become the D1G prototype.

General Electric S1G, S2G

Submarine Intermediate Reactor (SIR)

- S2G (SIR Mark B) operation on *USS Seawolf* (SSN-575):
 - The S2G nuclear plant was installed in *Seawolf* in December 1955, only six months after superheater leaks first occurred at the S1G prototype.
 - Since *Seawolf* shared many common hull design features with *Nautilus*, the reactor compartment was much larger than required for the more compact S2G reactor plant.
 - Key dates for S2G (SIR Mark B) operation on *Seawolf*:
 - April 1956: Fuel installed
 - 20 August 1956: Full-power dockside tests were conducted and superheater leaks developed during the test. During the next three months, leak sources were located and isolated by plugging the affected tubes. Rickover reported to the Joint Committee on Atomic Energy (JCAE) that this resulted in a loss of about 10% of heat exchanger capacity, limiting reactor power and *Seawolf's* top speed to about 90%.
 - November 1956: Rickover informed the AEC that he would take steps toward replacing the S2G in *Seawolf* with a water-cooled plant similar to that in the *Nautilus*.
 - Rickover had concluded that a sodium-cooled submarine propulsion plant was, "expensive to build, complex to operate, susceptible to prolonged shutdown as a result of even minor malfunctions, and difficult and time-consuming to repair."

General Electric S1G, S2G

Submarine Intermediate Reactor (SIR)

- S2G (SIR Mark B) operation on *USS Seawolf* (SSN-575) (cont'd):
 - February 1957: Initial sea trails were conducted.
 - Sometime in 1957: Rickover ordered the third (unused spare) core to be dismantled. *Seawolf's* S2G reactor was not going to be refueled.
 - 1957 – 1958: *Seawolf* steamed about 71,000 miles in two years on the S2G core.
 - No reactor compartment entry was made during this period. The only instance of a sodium primary coolant leak occurred while still in the shipyard.
 - It has been reported* that *Seawolf* operated with the steam generator superheaters bypassed, with reactor power limited to 60 - 80%, and the steam turbines operating on lower-pressure saturated steam.
 - December 1958: At end-of-core-life, *Seawolf* was turned over to Electric Boat.
 - 2 – 22 January 1959: *Seawolf's* S2G core was defueled dockside at Electric Boat.
 - The removed S2G fuel elements were cleaned of sodium and shipped by train to NR's Expended Core Facility in Idaho.
 - The reactor vessel was sealed inside a 30 foot (9.1 m) high steel containment vessel, towed out to sea on a barge, then sunk about 120 miles (193 km) east of Maryland in 9,100 feet (2,774 m) of water. In 1980, the Navy was unable to relocate the container.
- Rickover remarked to the JCAE, "There may be advantages for sodium for shore-based atomic power plants, but I cannot see it for a ship. It is too dangerous for a ship."

* Two sources: E. P. Loewen, "The *USS Seawolf* Sodium-Cooled Reactor Submarine," address to Washington DC ANS Local Section, 17 May 2012 (80%), and Will Davis, ANS Nuclear Café post, "A small but nagging point," 1 December 2016 (60%).

General Electric S3G, S4G

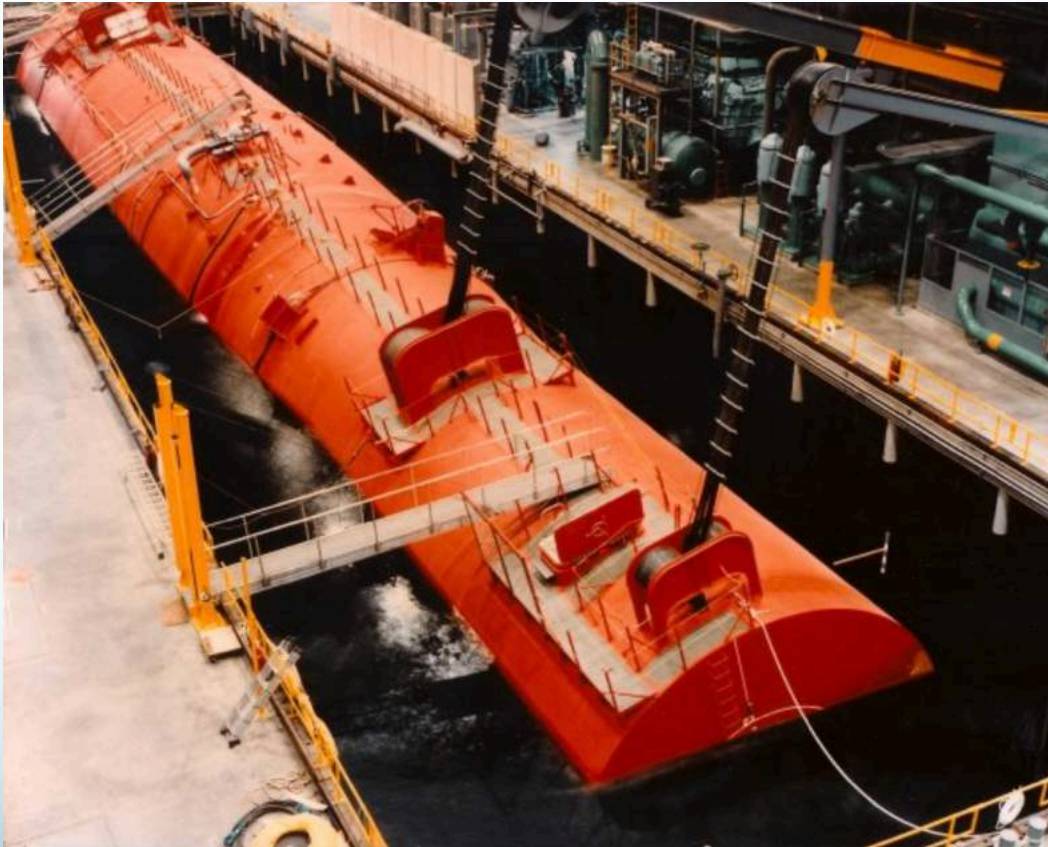
Submarine Advanced Reactor (SAR)

- The S3G plant was a two-loop PWR with horizontal steam generator.
- Development started in April 1953.
- S3G (SAR-1) prototype at the Kesselring Site, West Milton, NY
 - The prototype started went critical on 18 August 1958 and reached 100% power on 1 October 1958.
 - S3G core 3 was a very successful design, being used as an S5W replacement core.
 - The core incorporated a unique “skew-divergent” design in which the fuel element arrangement looked like a bunch of pencils that were held at the middle and twisted to flare out the top and bottom of the bunch. This arrangement gave more space in the reactor head area for maintenance.
 - Another unique feature of the S3G core 3 was the use of "Y" shaped control rods versus the standard cruciform control rods used in the S5W reactor.
 - S3G core 3 had an operating life of about 18,000 equivalent full power hours.
 - The final core was the S3G-ATC (Advanced Technology Core).
 - This prototype was permanently shut down in 1992 and subsequently decommissioned.
- Operational application: S4G was used only on the *USS Triton* (SSN-586)
 - Triton is the only US submarine to have two reactors.
 - The propulsion plant consisted of 2 x S4G (SAR-2) General Electric PWRs rated @ 78 MWt, arranged fore-and-aft in the hull; 2 x steam turbines rated @ a combined 30,000 shp (est.), driving 2 x shafts.
 - Triton was only refueled once and then decommissioned early. The replacement core for a planned second refueling in 1967 had already been manufactured.

General Electric S5G

- The S5G reactor plant was designed for natural circulation core cooling and was capable of operating at a significant fraction of full power without reactor coolant pumps. It was the precursor of the S8G reactor used on Ohio-class SSBNs and SSGN-conversions.
- The S5G prototype at the Naval Reactors Facility (NRF), Idaho.
 - The prototype floated in a large pool of water and rotated about the long axis of the hull to simulate the motion of a submarine at sea making a hard turn.
 - Two-loop PWR optimized for natural circulation: larger-diameter primary system piping and steam generators located higher than in S5W plants
 - The S5G had primary coolant pumps, but they were only needed when operating at high power. These smaller single-speed pumps were either ON or OFF.
 - The S5G prototype started operation in 1965. It was permanently shut down in May 1995. About 11,500 students were trained at S5G in 30 years.
- Operational application: only used on *USS Narwhal* (SSN-671)
 - The propulsion system consisted of 1 x S5G reactor rated at 90 MWt; secondary system supplying steam to one large-diameter, directly-coupled main turbine (no reduction gear) with an output of 17,300 shp (est.), driving a single shaft.
 - Reactor core life was 10,000 equivalent full power hours (EFPH)
 - The single main turbine measured 12 feet in diameter, and about 30 feet long.
 - This powerplant required a larger submarine hull diameter than the previous Sturgeon-class with an S5W reactor plant (33 ft. vs. 31.6 ft.)

General Electric S5G



The S5G prototype at INEL. Source: Naval Reactors



Source: INEL

General Electric S6G

- The S6G submarine reactor plant originally was designed to use the 150 MWt D1G-2 core, similar to the D1G / D2G reactor core used on guided missile cruisers (CGNs). Later, the more powerful D2W core, also originally intended for use on CGNs, became the standard, life-of-the-boat core for the S6G propulsion plant.
- Operational applications: all Los Angeles-class SSNs
 - There was no separate S6G prototype. The D1G-2 core had been tested previously in the D1G prototype at the Kenneth A. Kesselring Site in West Milton, NY.
 - Starting in the mid-1970s, the S6G propulsion plant with a D1G-2 core was installed on 31 x Los Angeles-class 688 Flight I subs.
 - 1 x S6G reactor plant with a D1G-2 reactor core rated @ 150 MWt; 2 x main steam turbines delivering a combined 30,000 shp (22 MW) to a single propeller.
 - The D1G-2 cores in 20 x 688 Flight I boats were replaced with D2W cores during their mid-life refueling
 - The mid-life refuelings for the remaining 11 x Flight I boats were cancelled and the boats were decommissioned early.
 - Starting in the mid-1980s, all Los Angeles-class 688 Flight II and Improved 688i submarines, starting with *USS Providence* (SSN-719), received S6G propulsion plants with a more powerful D2W core and an uprated secondary propulsion system.
 - 1 x S6G reactor plant with a D2W reactor core rated @ 165 MWt; 2 x main steam turbines delivering a combined 33,500 shp (est.) to a single propeller.
 - The S6G / D2W reactors in Flight II and 688i boats were intended to have “life-of-the-boat” cores without refueling.
 - These boats originally had a 30 year service life, extended in 2000 to 33 years.
 - The SSN-688 submarine reactor compartment for the S6G reactor plant has an outside diameter of 33 feet (10.1 meters), a length of 42 feet (12.8 meters) and a weight of about 1,680 tons.

General Electric S7G

Modifications and Additions Reactor Facility (MARF)

- The MARF / S7G is an experimental reactor core in a modified S5W reactor plant. It is located adjacent to the S3G prototype at the Kenneth A. Kesselring site in West Milton, NY. MARF was not used operationally on any submarine; though it has served as an important test platform with two different cores.
- Rod-less core: MARF began operation in 1976 with a rod-less core that did not use conventional control rods.
 - Instead of using moveable hafnium control rods, as used in other Navy reactors, reactivity in the MARF core was controlled by stationary gadolinium-clad tubes partially filled with water. The basis for reactivity control is outlined below.
 - Gadolinium has a high cross-section for thermal neutrons and a lower cross-section for fast neutrons.
 - Neutrons passing through the section of the gadolinium tube with water were likely to be thermalized (moderated) inside the tube and captured by the gadolinium on their way out of the tube.
 - Neutrons passing through the section of the gadolinium tube without water were much less likely to be thermalized inside the tube and more likely to simply pass through the tube, re-enter the active core and be moderated before encountering with the U-235 fuel.
 - The reactivity control system controlled reactor power by regulating the water levels inside the gadolinium tubes.

General Electric S7G

Modifications and Additions Reactor Facility (MARF)

- The rod-less Core 1 reactivity control system pumped water from inside the gadolinium tubes to a reservoir above the core, or allowed water to flow back from the reservoir into the tubes.
 - During reactor startup, water level in the tubes was gradually lowered, decreasing the neutron absorption by the gadolinium tubes and permitting the reactor to enter the power range
 - The gadolinium tubes provide a desirable negative reactivity feedback. For example, an increase in reactor power causes all the water in the reactor to expand, including the water in the gadolinium tubes. As water level in the tubes rises, more neutrons are thermalized and absorbed in the gadolinium, thereby limiting the core neutron population and limiting the power increase.
 - The rod-less core pumping system was configured so that the pump needed to run continuously to keep the level pumped down. On loss of power, all the water in the reservoir would flow back into the tubes, shutting down the reactor.
- Developmental Materials Core (DMC): In the late 1980s, the original rod-less core was removed and replaced by DMC.
 - Operation at a “utilization factor” of greater than 90% (typical for MARF, excludes periodic maintenance outages) results in an annual core depletion of about 5,000 EFPD.
 - MARF defueling and layup is funded in the FY2018 Congressional Budget, by which time DMC will have operated for almost 30 years.

General Electric S8G

- The original S8G reactor plant was designed for natural circulation core cooling and is capable of operating at a significant fraction of full power without reactor coolant pumps operating. The original S8G core was a development of the S5G.
- S8G prototype is located at the Kenneth A. Kesselring Site, West Milton, NY.
 - Originally built as a prototype for the Ohio-class SSBN propulsion plant (S8G), this reactor also has been used to develop advanced fuel system technologies for the Seawolf-class (S6W) and Virginia-class (S9G) SSNs.
 - Core 1: In about 1980, the prototype started operation with an S8G core.
 - Core 2: In 1994, the original S8G core was replaced with an S6W core then being developed as a life-of-the-boat core for the Seawolf-class SSNs.
 - Core 3: From September 2018 to 2021, the S8G prototype is scheduled for a 3-year refueling and major overhaul outage. It will be refueled with the Technology Demonstration Core (TDC).
 - As noted in the FY18 Presidential Budget Request, the S8G prototype will be refueled with a core, “to facilitate Columbia-class reactor (S1B) development efforts and provide reactor-based training for fleet operators.”
 - The TDC will include technologies and features planned for the S1B reactor. NR reported that the ability to conduct comprehensive tests in a prototype reactor will help reduce technical, cost and schedule risk to the ship construction program.

General Electric S8G

- Operational applications: all Ohio-class SSBNs and SSGN-conversions
 - The propulsion plant is comprised of 1 x S8G PWR rated at 185 MWt (est.), 2 x main steam turbines with a combined rating of 35,500 hp (26.5 MW) (est.) driving a single shaft and propeller.
 - Some sources cite a reactor power rating of 220 MWt, but this seems higher than necessary for delivering 35,500 shp (est.) propulsion power.
 - S8G reactor compartment for the Ohio-class submarines is 42 feet (13 m) in diameter, 55 feet (17 m) long and weights 2,750 tons.
 - The original service life for the Ohio-class submarine was 30 years; then increased to 42 years following approval of a service life extension.
 - Ohio-class subs require a mid-life refueling.
 - The S8G reactor core used in the fleet has been demonstrating a life is at least 20 years.

General Electric S9G

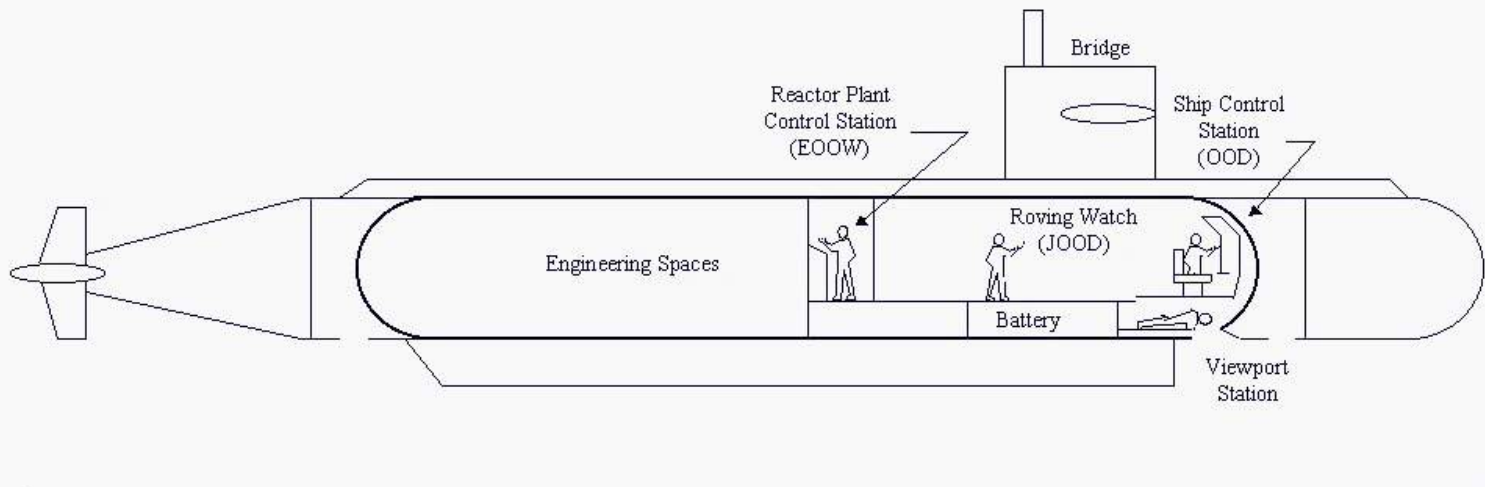
- The S9G reactor plant was designed for the Virginia-class SSN, which has a 33 ft (10.1 m) diameter hull, the same as *USS Narwhal* (SSN-671) and all Los Angeles-class SSNs.
 - It is believed that S9G is designed for natural circulation core cooling and is capable of operating at a significant fraction of full power without reactor coolant pumps.
- There was no S9G prototype, although features of the S9G core were tested in the S8G prototype.
- Operational applications: all Virginia-class SSNs, which currently have a 33 year service life.
 - The propulsion system consists of 1 x S9G reactor rated @ 210 MWt (est.); with the secondary steam plant delivering a combined 40,000 shaft horsepower (29.8 MW) to a single shaft and pump-jet propulsor.
 - In FY 2004, Naval Reactors described the S9G as “the first core specifically designed to operate without refueling for the service life of the ship.” However, in FY 2005, NR offered the following view: “Since September 11, 2001, submarine operating requirements have increased by 30 percent. Continuing this pace will reduce the expected core life to less than 30 years.”
- NR has been developing an advanced core that is intended for “forward fitting” into Virginia-class submarines. This advanced core originally was called the Transformational Technology Core (TTC).

General Electric NR-1

- This one-of-a-kind nuclear propulsion plant was comprised of a very small PWR packaged with a compact turbo-electric propulsion system that was designed to fit inside the small diameter hull (12.5 ft, 3.8 meter O.D.) of the deep-diving NR-1 special operations submarine.
- The reactor reportedly delivered a total output of 130 hp (97 kW).
 - 60 hp (44.8 kW) to electrical propulsion motors for a top speed of about four knots, and
 - 70 hp (52.2 kW) to all other electrical loads
 - At 30% thermal efficiency, that puts reactor thermal power at about 323 kWt (1/3 of a megawatt).
- The plant configuration is not known. However, GE apparently was given instructions to keep cost down and built the plant from standard components that were used on naval nuclear plants of the day*. This suggests a standard Rankine-cycle secondary system rather than other alternative power conversion systems.
 - The compact engineering space suggests that the primary system may have been a single-loop PWR with an single steam generator and main coolant pump and an electrically-heated pressurizer. The secondary system reportedly consisted of a single turbine-generator.
 - The reactor, electrical system and propulsion system were run from a single control panel by one crew member. Controls were not automated.
 - The electrical system included a 400 Hz converter for certain electronic systems.

* Source: L. Vyborny & D. Davis, "*Dark Waters*," The American Library, 2003, also <http://www.nr-1-book.com/index.html>

General Electric NR-1



NR-1 near the seabed with all watch stations manned

* Source: <http://www.nr-1-book.com/index.html>

- There was no reactor prototype.
- NR-1 initial operations were in 1969 (it never was commissioned). The submarine was overhauled and refueled in 1993 after 24 years of service. The reactor was defueled in 2008 after another 20 years of service.
- Thereafter, NR-1 was consigned to the Navy's Nuclear Ship & Submarine Recycling Program (NSSRP).

Transformational Technology Core (TTC)

- In FY 2004, NR began TTC core and equipment reference design work.
- The original design goal for the TTC was to deliver 30% more lifetime energy, while still fitting in the S9G reactor vessel used in the Virginia-class SSN.
 - This core was intended to provide greater operational flexibility by allowing fleet commanders to choose among: (a) extending ship life, (b) increasing annual operating hours, and/or (c) allowing ship operation at a higher average power.
 - NR noted in FY 2004 that the current outlook for future submarine operational tempo, particularly with the smaller US SSN fleet that will exist for decades, may necessitate refuelings (of Virginia-class SSNs) that would not be needed with TTC. The end result is significantly greater operational capability and flexibility.
 - This would be accomplished primarily through use of advanced core material that allow safe operation at higher power density.
- This advanced core was intended for “forward fitting” into Virginia-class SSNs that also had upgraded plant systems to exploit the anticipated performance improvements of the TTC.
- In the FY 2004 NR Congressional Budget proposal, NR reported that: “The timing of TTC development also corresponds with the need to transition from 97 to 93 percent enriched uranium fuel. This transition is necessitated by the shutdown of the high enrichment plant and the decision to use uranium recovered from retired nuclear weapons as starter material for naval nuclear reactors.”

Transformational Technology Core (TTC)

- Funding for TTC work continued into FY 2007. NR reported the overall project was 34% complete in FY 2006, and expected to place a fabrication contract in FY 2008 and deliver the first TTC core in 2015.
- In FY 2008, there was no funding for TTC in NR's Congressional budget request. NR explained that a lower-cost core was needed to help meet the Navy's goal of reducing unit cost of Virginia-class submarines to \$2 billion.
- In the FY 2009 Congressional Budget Request, NR reported that the TTC project was 100% complete in FY 2007, with the endpoint being just the completion of TTC fuel system design.

Next Generation Reactor (NGR)

(aka NGR-93)

- NR stopped work on the TTC, and instead redirected work to a lower-cost, forward-fit core design that would help meet the Navy's goal of reducing unit cost of Virginia-class submarines to \$2 billion.
- Thereafter, the forward-fit Virginia-class reactor core project became known as NGR (Next Generation Reactor) or NGR-93 (93% enriched) and various project activities were described in NR's FY 2008 – 2012 Congressional Budget Requests.
- It seems that somewhere in the Virginia SSN construction cycle the NGR will be introduced to the fleet. NGR will be a 93% enriched core that won't have all of the higher performance promised by the TTC, but it probably will equal or better the performance of the original S9G core designed in the 1990s.

Bechtel S1B

- S1B will be a life-of-the boat reactor for the new Columbia-class (previously known as the Ohio replacement) SSBN, which will have a 42 year service life.
 - The S1B will have the longest design life of any reactor ever developed by NR, exceeding Virginia-class SSN's S9G core life by more than 10 years.
 - This core life would be impossible with the current cladding in fleet reactors. Alternate clad and manufacturing processes have been developed to enable longer core life and will be validated in the S8G land-based prototype.
 - This will enable the Columbia-class SSBNs to accomplish the strategic deterrent mission with two fewer SSBNs than the Ohio-class SSBNs (ref. NR 2013 Congressional Budget Justification)
- There is no separate S1B prototype. S1B will leverage Virginia-class S9G reactor technology and implement new materials and features that will be tested on the S8G prototype after it returns to operation in 2021 with the Technology Demonstration Core (TDC).
 - In the NNSA FY2012 Congressional budget request, NR noted that, by constructing the replacement core for the S8G prototype with technologies and capabilities planned for the Columbia-class S1B reactor, technical, cost, and schedule risk to the ship construction program will be significantly mitigated.
- Current funding in the FY2018 Congressional Budget request is to support reactor plant system and long-lead time component development to support FY2019 procurement.

US Navy nuclear-powered submarines



Submarine operating cycles

- OPNAV Instruction 3120.33C, dated 22 January 2013, defines the major maintenance frequencies and the service life of each submarine class. The goal is to ensure that all submarines are maintained to maximize their safe and effective operation throughout their respective service lives.
- Maintenance strategies:
 - Two different maintenance strategies are implemented in the submarine fleet:
 - Engineered operating cycles, which apply to most classes of SSNs.
 - Phased planned maintenance (PM) cycles, which apply to SSBNs/SSGNs and the three Seawolf-class SSNs.
 - Ship submerged operations are not allowed with an expired maintenance OPINTERVAL or OPCYCLE.
 - The maintenance and overhaul capacity of the current US nuclear shipyard infrastructure, which has declined significantly from its peak in the 1960s – 1970s, is unable to keep up with the demand for servicing nuclear submarines. As a result, many subs are not operational because required maintenance has been delayed and the boats can't be certified to dive.
 - In October 2017, the maintenance backlog was reported to have idled 15 SSNs for a total unplanned delay of 177 months (14.75 submarine-years).
 - Part of the problem arises from US government-created budget issues (budget sequestration limits and delayed fiscal year budget approvals). Another contributor is the Navy's spending prioritization on operations, new construction and higher-priority maintenance for SSBNs and CVNs. Yet another contributor is the Navy's current unwillingness to expand its shipyard infrastructure base and engage privately-owned shipyards in the nuclear vessel maintenance and overhaul tasks assigned now to government-owned naval shipyards.

Submarine operating cycles

- Service Life & Service Life Extension (SLE):
 - Service life is the established calendar period (years) that a submarine is permitted to operate, with defined start and end dates for each boat. Service life starts the day the ship is delivered to the Navy, and ends on the anniversary date after the prescribed number of calendar years.
 - A Service Life Extension must be requested by the type commander (TYCOM), technically evaluated by NAVSEASYS COM, and authorized by OPNAV.
 - Many currently-operating submarines have been granted SLEs:
 - Ohio-class SSBNs & SSGNs received a 12 year SLE, extending their original 30 year service life to 42 years.
 - Los Angeles-class SSNs originally had a 30 year service life, which was extended to 33 years. The Navy is considering extending the service life of Los Angeles-class Flight II and 688i boats to 36 – 37 years to help mitigate the impending fleet shortfall in SSNs.
 - Ship submerged operations are not allowed with an expired service life.
 - This means that many subs in the aging US submarine fleet are approaching their service life limits and will have to be retired if an SLE is not granted.

Nuclear-powered fast attack submarines (SSN)

U.S fast attack subs (SSN)

| Class | # in Class | Length | Beam | Displacement (tons) | Reactor | Shaft hp | Max speed (kts) | Years delivered | Years in service |
|---|--------------------|--------------------|-----------------|-------------------------------------|-----------------------|---------------------|-----------------|-------------------|------------------|
| Nautilus (SSN-571) | 1 | 98.4 m (323.8 ft) | 8.4 m (27.7 ft) | 3,533 (surf) 4,092 (sub) | S2W (STR Mk II) | 13,400 | 23 | Sep 1954 | 1955 – 80 |
| Seawolf (SSN-575) | 1 | 103 m (350 ft) | 8.5 m (28 ft) | 3,250 (surf), 4,150 (sub) | S2G, replaced by S2Wa | 15,000, then 13,400 | 19 | Mar 1957 | 1957 - 87 |
| Skate (SSN-578) (Skate & Sargo) | 2 | 81.6 m (267.7 ft) | 7.6 m (25 ft) | 2,590 (surf), 2,894 (sub) | S3W | 7,300 | 22 | Dec 1957 – Apr 58 | 1957 - 88 |
| Skate (SSN-578) (Swordfish & Seadragon) | 2 | Same | Same | Same | S3W core in S4W plant | Same | Same | Sep 1958 – Dec 59 | 1958 - 89 |
| Triton (SSRN/SSN-586) | 1 | 136.4 m (447.6 ft) | 11 m (37 ft) | 6,058 (surf), 7,898 (sub) | 2 x S4G | 34,000 | 27+ | Nov 59 | 1959 - 69 |
| Skipjack (SSN-585) | 6 (1 lost at sea) | 77 m (251.7 ft) | 9.6 m (31.5 ft) | 3,124 (surf), 3,600 (sub) | S5W | 15,000 | 33 | Apr 1959 – Oct 61 | 1959 - 90 |
| Tullibee (SSN-597) | 1 | 83 m (273 ft) | 7.2 m (23.6 ft) | 2,353 (surf), 2,649 (sub) | S2C | 2,500 (est.) | 14.8 | Nov 1960 | 1960 - 88 |
| Permit (SSN-594) | 14 (1 lost at sea) | 84.9 m (278.4 ft) | 9.6 m (31.6 ft) | 3,810 (surf), 4,369 (sub) | S5W | 15,000 | 28 | Aug 1961 – Jan 68 | 1961 - 96 |
| Sturgeon (SSN-637, short-hull) | 28 | 89 m (292 ft) | 9.6 m (31.6 ft) | 3,640 (surf), 4,640 (sub) | S5W | 15,000 | 27 | Mar 1967 – Sep 72 | 1967 - 2005 |
| Sturgeon (SSN-637, long-hull) | 9 | 92 m (302 ft) | 9.6 m (31.6 ft) | 4,530 (surf) 5,040 (sub) | S5W | 15,000 | 26 | Dec 1971 – Aug 75 | 1967 - 2005 |
| Narwhal (SSN-671) | 1 | 95.7m (314 ft) | 10.1 m (33 ft) | 4,300 (surf) (est.), 5,350 (sub) | S5G | 17,000 (est.) | 25 (est.) | July 1969 | 1969 - 99 |

U.S fast attack subs (SSN)

| Class | # in Class | Length | Beam | Displacement (tons) | Reactor | Shaft hp | Max speed (kts) | Years delivered | Years in service |
|---|---------------------|---------------------|---------------------|-----------------------------|--|----------|-----------------|----------------------|------------------|
| CONFORM (CONcept FORMulation) | 0 design study only | Similar to Sturgeon | Similar to Sturgeon | 4,800 (sub) | Modified S5G | 20,000 | 30+ | 1967 – 69 study only | |
| APHNAS (Advanced Performance High-speed Nuclear Attack Submarine) | 0 design study only | 143.8 m (472 ft) | 12.2 m (40 ft) | 12,075 (surf), 13,649 (sub) | D1W | 60,000 | 33 - 35 | 1971 – 72 study only | |
| Glenard P Lipscomb (SSN-685) | 1 | 111.3 m (365 ft) | 9.6 m (31.6 ft) | 5,906 (surf), 6,584 (sub) | S5W | 15,000 | 23 | Dec 1974 | 1974 - 89 |
| George Washington-class SSBN conversion to SSN ("slow attack") | 3 Mod SSBN | 16.3 m (381.6 ft) | 10.1 m (33 ft) | 6,000 (surf), 6,880 (sub) | S5W | 15,000 | 20+ | 1979 | 1979 - 85 |
| Ethan Allen-class SSBN conversion to SSN ("slow attack") | 3 Mod SSBN | 125.1 m (410.3 ft) | 10.1 m (33 ft) | 7,070 (surf), 8,010 (sub) | S5W | 15,000 | 20+ | 1981 | 1981 - 85 |
| Los Angeles (SSN-688) Flight I | 31 | 110 m (362 ft) | 10.1 m (33 ft) | 6,082 (surf), 6,927 (sub) | S6G with D1G-2 core, refueled with D2W | 30,000 | > 30 | Nov 1976 – Jul 85 | 1976 - present |
| Los Angeles (SSN-688) Flight II | 8 | 110 m (362 ft) | 10.1 m (33 ft) | 6,082 (surf), 6,927 (sub) | S6G with D2W core | 35,000 | > 30 | Jul 1985 – Jun 89 | 1985 - present |
| Improved Los Angeles (SSN-688i) | 23 | 110 m (362 ft) | 10.1 m (33 ft) | 6,082 (surf), 6,927 (sub) | S6G with D2W core | 35,000 | > 30 | Aug 1988 – Sep 96 | 1988 - present |

U.S fast attack subs (SSN)

| Class | # in Class | Length | Beam | Displacement (tons) | Reactor | Shaft hp | Max speed (kts) | Years delivered | Years in service |
|------------------------------|--------------------|------------------|------------------|---------------------------|---------|----------|-----------------|--------------------------------|------------------|
| Seawolf (SSN-21) | 3 | 107.6 m (353 ft) | 12.9 m (42.3 ft) | 7,568 (surf), 9,137 (sub) | S6W | 52,000 | > 30 | Jul 1997, Dec 1998, Feb 2005 | 1997 - present |
| Virginia (SSN-774) Block I | 4 | 114.8 m (377 ft) | 10.1 m (33 ft) | xxxx (surf), 7,800 (sub) | S9G | 40,000 | 25+ | Oct 2004 - May 08 | 2004 - present |
| Virginia (SSN-774) Block II | 6 | 114.8 m (377 ft) | 10.1 m (33 ft) | xxxx (surf), 7,800 (sub) | S9G | 40,000 | 25+ | Oct 2008 - Sep 13 | 2008 - present |
| Virginia (SSN-774) Block III | 4 + 4 plan | 114.8 m (377 ft) | 10.1 m (33 ft) | xxxx (surf), >7,800 (sub) | S9G | 40,000 | 25+ | Oct 2014 - 18 | 2014 - present |
| Virginia (SSN-774) Block IV | 10 plan | 114.8 m (377 ft) | 10.1 m (33 ft) | xxxx (surf), >7,800 (sub) | S9G | 40,000 | 25+ | 1 st in 2019 | |
| Virginia (SSN-774) Block V | 10 + 2 plan | 136.2 m (447 ft) | 10.1 m (33 ft) | TBD | S9G | 40,000 | 25+ | 1 st in 2023 (est.) | |
| Virginia (SSN-774) Block VI | 6 (plan) | 136.2 m (447 ft) | 10.1 m (33 ft) | TBD | S9G | 40,000 | 25+ | 1 st in 2028 (est.) | |
| Virginia (SSN-774) Block VII | 2 (plan thru 2030) | 136.2 m (447 ft) | 10.1 m (33 ft) | TBD | S9G | 40,000 | 25+ | 1 st in 2038 (est.) | |
| SSN(X) / Improved Virginia | TBD | TBD | TBD | TBD | TBD | TBD | 25+ | After 2035 | |

Nautilus (571)



Skate (578)-class



Skipjack (585)-class



Triton (586)



Permit (594)-class



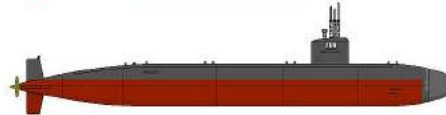
Tullibee (591)



Sturgeon (637)-class



Los Angeles (688)-class



Improved Los Angeles (688i)-class



Seawolf (SSN-21)-class



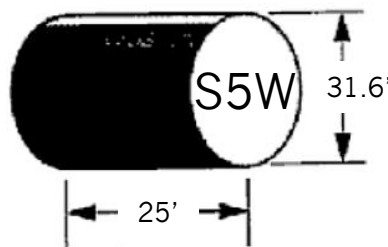
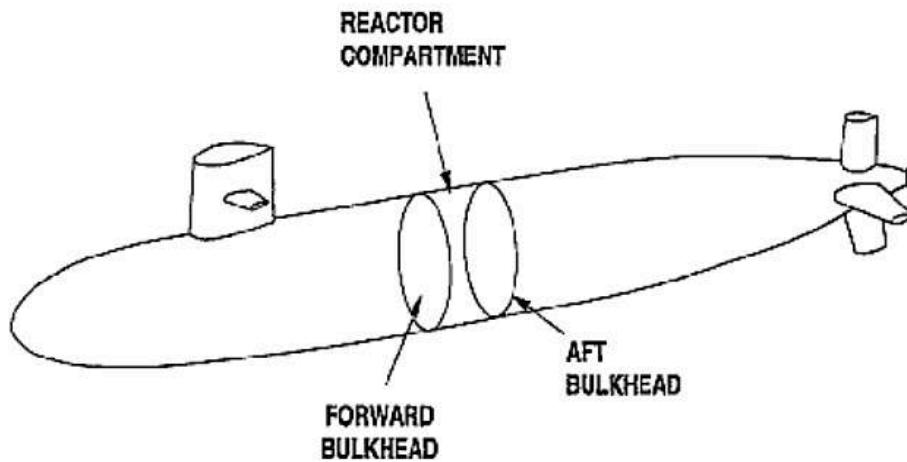
Virginia (774)-class



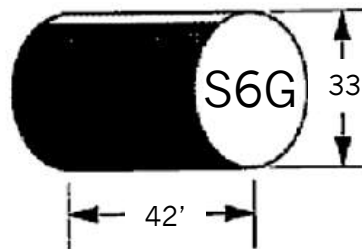
Evolution of US Navy SSNs

Submarine reactor compartments

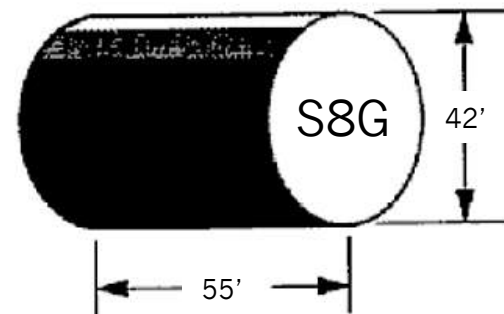
Except for *USS Triton*, all US submarines have a single reactor in a shielded reactor compartment located between the aft engineering / propulsion spaces and the forward operations / weapons / living spaces. Approximate dimensions and weights of the reactor compartment are shown in the diagrams.



Pre LOS ANGELES
Class
Submarine – about 110
(1130 tons)



LOS ANGELES
Class
Submarine – 62
(1680 tons)



OHIO Class
Submarine – 18
(2750 tons)

Source: adapted from <http://fas.org>

The shrinking US SSN fleet

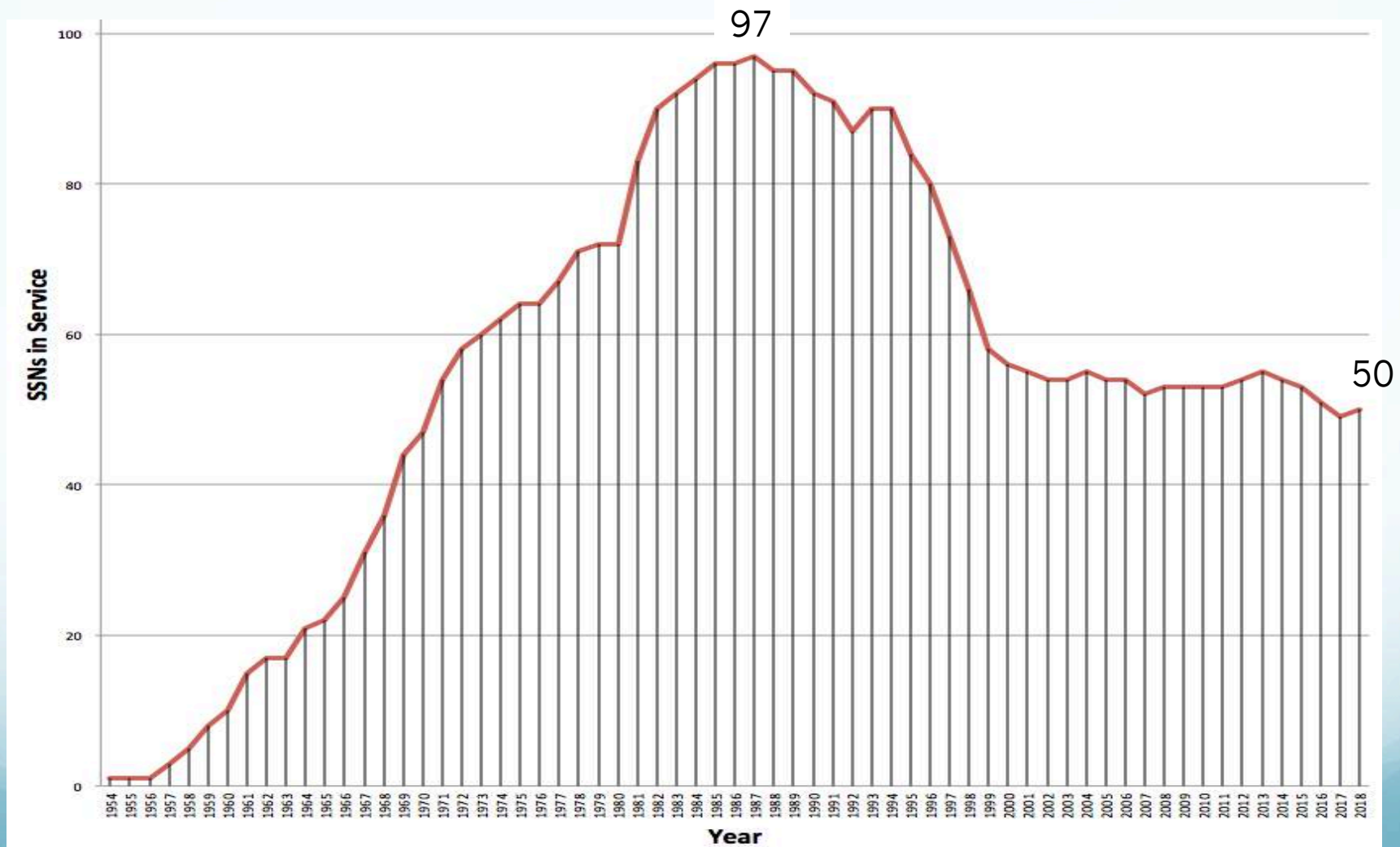
- **1988:** The Navy's requirement for SSNs, as dictated by the Navy's maritime strategy, was 100 SSNs. After the dissolution of the Soviet Union in 1990 – 1991, the Navy's need for SSNs was greatly reduced.
- **1991:** Under the base force concept, the Navy reduced its fiscal year 1995 SSN force level requirement to 80.
- **Prior to 1993:** The Navy took several measures to reduce the SSN force structure, including:
 - Accelerating the retirement of the Sturgeon (SSN-637)-class SSNs so that the entire class (except for two special operations ships) would be retired by the end of 1999,
 - Removing five improved Los Angeles (SSN-688i)-class submarines from the Navy shipbuilding plan, and
 - Truncating the Seawolf (SSN-21)-class shipbuilding program after construction of the second submarine (SSN-22). SSN-23, *USS Jimmy Carter*, was added back later.
- **1992:** The Deputy Secretary of Defense directed the Joint Chiefs of Staff to conduct a comprehensive examination of the submarine forces needed to meet the future threats to American interests.
- **April 1993:** The Joint Chiefs concluded that 51 to 67 SSNs were needed to satisfy the National Military Strategy's requirements.
- **1994:** The Defense Department's bottom-up budget reviews determined that the Navy should maintain a force of 45 to 55 SSNs.

Source: GAO/NSIAD-95-16, "Attack Submarines: Alternatives for a More Affordable SSN Force Structure," October 1994

The shrinking US SSN fleet

- **Between 1995 – 1999:** 11 Los Angeles Flight I SSNs were decommissioned early after their mid-life reactor refuelings were cancelled.
- **2014:** The Navy's Force Structure Assessment (FSA) requirement was for a 308 ship fleet with 48 SSNs.
 - The FSA SSN quantities include multi-mission SSNs that also serve as replacements for the 4 retiring Ohio-class SSGNs.
 - Operationally, the Navy currently expects to have 10 SSNs deployed on a day-to-day basis.
 - Peak projected wartime demand is about 35 SSNs deployed within a unspecified amount of time.
- **December 2016:** The Navy's updated FSA requirement called for a 355 ship fleet with 66 SSNs.
- **2018 and beyond:** As the Navy SSN fleet shrinks in size, the 2016 FSA SSN targets become unrealistic and the projected wartime demand will be difficult to meet.
 - In 2018, the US SSN fleet consisted of 50 boats.
 - The Navy Shipbuilding Plan for 2017 estimates that the size of the SSN fleet will decline to 41 boats in 2029 and then slowly start increasing in the following years.
 - Without a significant increase in SSN production rate (currently 2 per year), the Navy will have fewer SSNs for the next 30 years than it has in 2018.

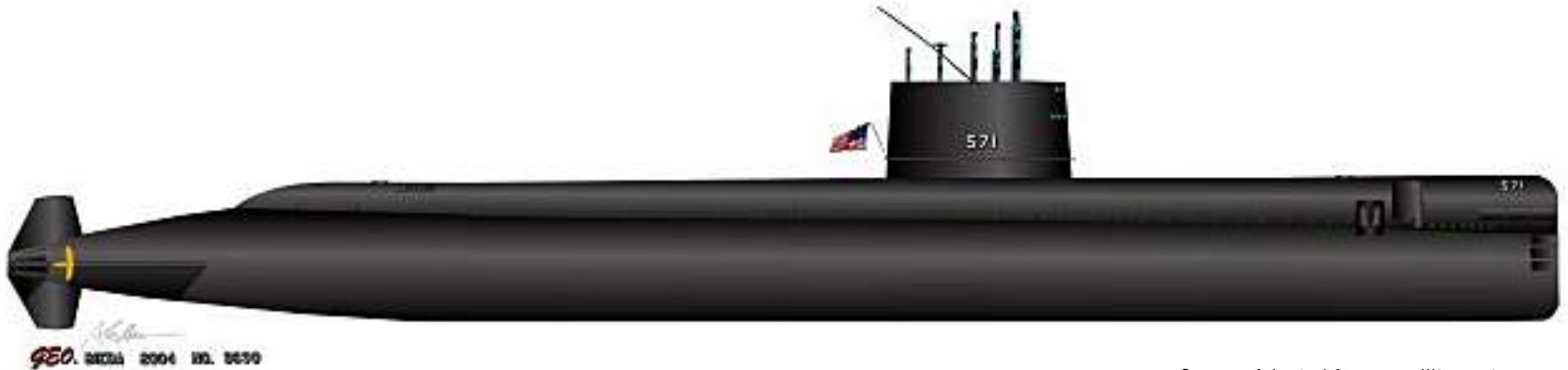
Historical size of the US SSN fleet 1954 - 2018



Source: Adapted from data at <https://www.history.navy.mil/research/histories/ship-histories/us-ship-force-levels.html>

USS Nautilus (SSN-571)

World's 1st nuclear-powered vessel

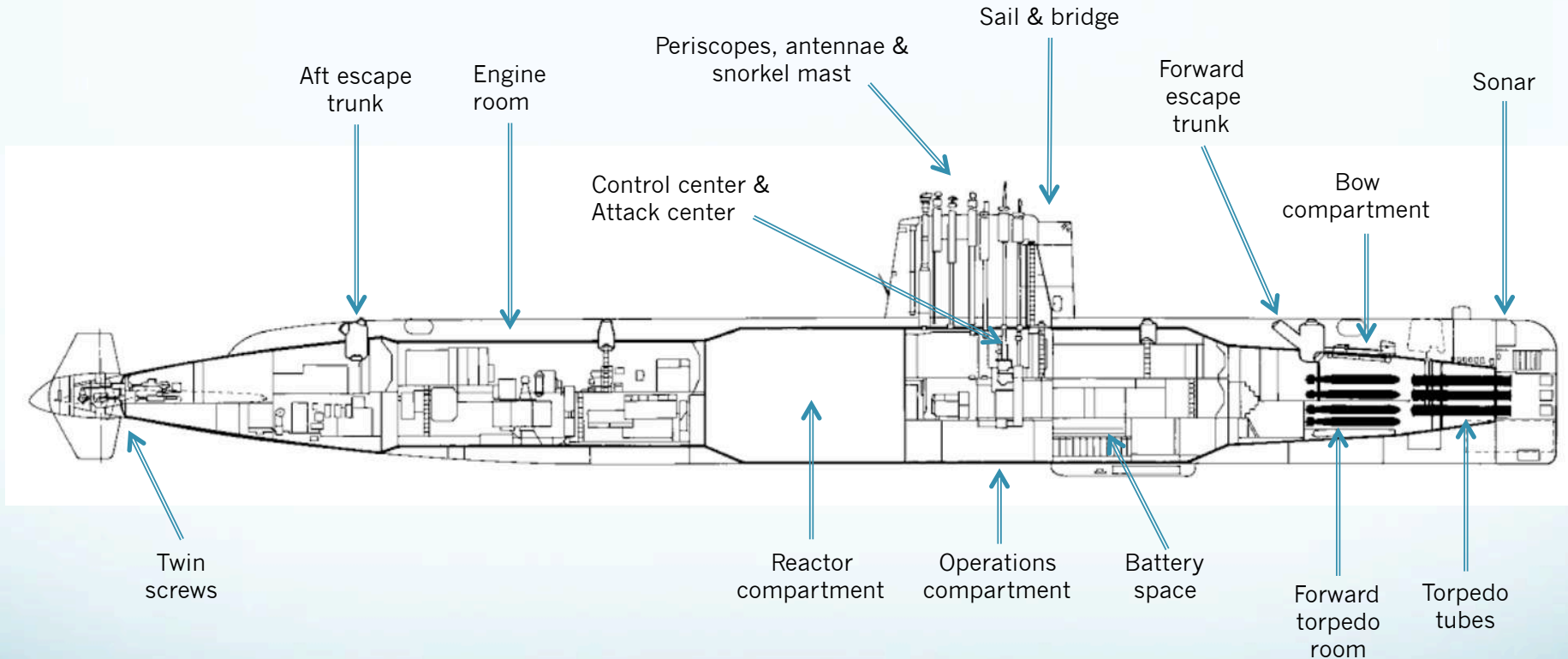


Source: Adapted from usmilitaryart.com

- The basic hull form was very similar to WW II German Type XXI subs and the latest US diesel-electric subs [i.e., *USS Tang* (SS-563)].
- From project approval to underway on nuclear power in less than 5 years:
 - Aug 1949: Chief of Naval Operations establishes a January 1955 "ready-for-sea" date for development of a submarine nuclear propulsion plant
 - Aug 1950: President Truman signs Public Law 674 authorizing construction of the 1st nuclear sub
 - July 1951: Congress funds construction
 - 14 Jun 1952: Keel laid by President Truman at Electric Boat Co, Groton, CT
 - 21 Jan 1954: Launched by First Lady Mamie Eisenhower
 - 30 Sep 1954: Commissioned, remained dockside to complete outfitting.
 - 20 Dec 1954: Initial criticality
 - 5 Jan 1955: Full power dockside test
 - 17 Jan 1955: 1st underway on nuclear power

USS Nautilus (SSN-571)

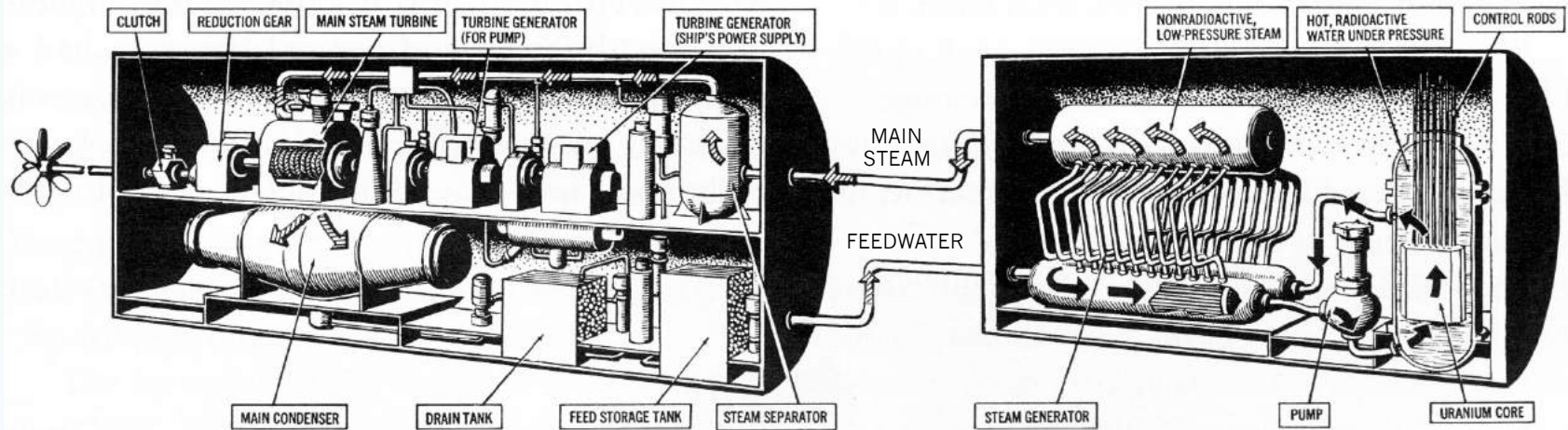
World's 1st nuclear-powered vessel



Source: Adapted from A.D. Baker III / N. Polmar & K. Moore, "Cold War Submarines: The Design and Construction of US and Soviet Submarines," Brassey's Inc., 1994

USS Nautilus (SSN-571)

Notional arrangement of the S2W nuclear propulsion plant



Engine room, showing one of two secondary coolant loops. Each secondary loop establishes a steam flow path from a steam drum in the reactor compartment to a turbine generator, a main propulsion turbine and various auxiliary steam systems. The steam is expanded in the turbines to produce electricity and propulsion power and then condensed in a main condenser, which dumps waste heat to the ocean via a seawater cooling loop. The condensed water is pumped to higher pressure and then returned as feedwater to the steam generator in the reactor compartment. Main steam and feedwater isolation valves are not shown.

Reactor compartment, showing the reactor and one of two primary coolant loops. Each primary loop establishes a coolant (pressurized water) flow path from the reactor vessel to a steam generator where the coolant flows through the inside of horizontal U-tubes and then back to the reactor vessel via the main coolant pump. Secondary coolant (feedwater) on the outside of the U-tubes is heated to produce steam, which rises to a steam drum for delivery to the engine room. Loop isolation valves and the pressurizer are not shown.

Source: Adapted from drawing by Philbeck in N. Polmar, "Atomic Submarines," D. Van Nostrand Company, Inc., 1963, pp. 74 - 75

USS Nautilus (SSN-571)

- Propulsion: 1 x S2W Westinghouse PWR rated @ 70 MWt (est.); 2 x main steam turbines delivering a total of 13,400 hp (10 MW) to 2 x screws
- Armament: 6 x 533 mm (21") bow torpedo tubes. No stern tubes.
- Operational matters:
 - Capt. Eugene P. Wilkinson was the first commanding officer of the *USS Nautilus*.
 - Initial criticality was achieved on 20 Dec 1954.
 - The S2W developed full power alongside the pier on 3 Jan 1955.
 - The famous message, "UNDERWAY ON NUCLEAR POWER," was sent by flashing light signal to Commander Submarine Forces Atlantic on 17 Jan 1955.
 - Capt. Wilkinson was responsible for post-commissioning trials, which provided a first look at the greatly expanded capabilities of a nuclear-powered submarine and were instrumental in the development of early nuclear-powered submarine tactics.

| U. S. NAVAL DISPATCH | | | |
|--|--|----------------------|-------------------|
| FROM: USS NAUTILUS SSN 571 | | CLASSIFICATION: UNCL | PRIORITY: ROUTINE |
| ACTION: COMSUBLANT | | | |
| INFO: | | | |
| NJOF DE NWCL -T-YZZF -R-171601Z -FM NWCL -TO YZZF OR 1/ BT | | | |
| UNDERWAY 1133R ON NUCLEAR POWER BT.... | | | |
| 700 / 1133R F.L. / 1133R JBR | | WU/ELT | |
| 1133R 17 JAN 55 171601Z | | 171601Z | |

Source: US Navy



Capt. Wilkinson. Source: US Navy.

USS Nautilus (SSN-571)

- Operational matters (continued):
 - February 1955: *USS Nautilus* conducted a 1,381 mile (2,222 km) “shakedown cruise” from New London, CT to Puerto Rico, transiting submerged at an average speed of 16 kts. This was the 1st long-distance, high-speed transit ever made by a submarine.
 - August 1957 – August 1958: *USS Nautilus* conducted three missions under the arctic ice, including the first underwater crossing of the North Pole in August 1958.
 - Fall 1962: *USS Nautilus* participated in the naval quarantine of Cuba.
 - Nautilus* was refueled four times in its 25 year service life. See details below.

| Core # | Operating period | Core life | Distance traveled | Cum distance traveled | Refueling # | Refueling period | Notes |
|--------|--------------------|-----------|--|--|-------------|-----------------------|--|
| 1 | Jan 55 – Feb 57 | 2.1 yr | 62,562 mi (100,684 km) | 62,562 mi (100,684 km) | 1 | Feb 57 | Refueled at Electric Boat. Half of miles steamed were submerged. |
| 2 | Apr 57 – May 59 | 2.1 yr | 91,324 mi (146,972 km) | 153,886 mi (247,656 km) | 2 | 29 May 59 – 15 Aug 60 | 1 st ever nuclear ship overhaul; at Portsmouth Naval Shipyard |
| 3 | Jun 59 – Jan 64 | 4.6 yr | 130,713 mi (210,362 km) | 284,599 mi (458,018 km) | 3 | 17 Jan 64 – Spring 66 | 2 nd overhaul at PNSY. 220,714 total mi (355,205 km) submerged to date. |
| 4 | Spring 66 – Aug 72 | 6.4 yr | 115,401 mi (185,720 km) (approx) | 400,000 mi (643,738 km) (approx) | 4 | Aug 72 – 15 Jan 75 | 3 rd overhaul; this one was at Electric Boat. |
| 5 | Jan 75 – Mar 80 | 5.2 yr | 113,550 mi (182,741 km) (approx) | 513,550 mi (826,478 km) | | | Decommissioned 3 March 1980 |

1st Arctic missions to the North Pole

- [illegible]

Nautilus' route through the Arctic. Source: <http://www.navalhistory.org/category/arctic>

Source: <http://www.navy.mil/navydata/>

USS Nautilus (SSN-571)



Source, above: Photomate Wlkewitz, October 2016



Source: <https://en.wikipedia.org/>

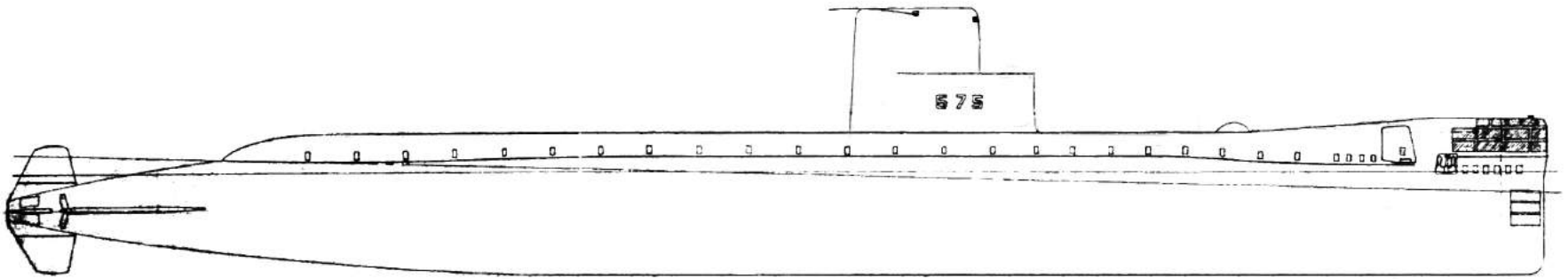


Source, above: Leolook Graves, August 2017

April 1986: *USS Nautilus* opened as a museum ship at the Submarine Force Museum, Groton, CT.

USS Seawolf (SSN-575)

1st submarine with a sodium-cooled reactor



Source: Adapted from Seawolf plans on <http://www.subguru.com>

- This one-ship class was the 2nd nuclear-powered sub built by the US Hull design was based on *USS Nautilus*, with modifications primarily to the bow (to provide better seakeeping on the surface) and sail. The keel was laid in September 1953, 15 months after *USS Nautilus*, at Electric Boat, Groton, CT.
- Propulsion:
 - Originally, 1 x S2G General Electric sodium-cooled Submarine Intermediate Reactor (SIR, Mark B) rated @ 78 MWt (est.); 2 x steam turbine generators delivering a combined 15,000 hp (11 MW) to 2 x screws
 - Replaced in 1959 by 1 x S2Wa Westinghouse PWR rated @ 70 MWt (est.); 2 x main steam turbines delivering a total of 15,000 hp (11 MW) to 2 x screws
- Armament: 6 x 533 mm (21 inch) bow torpedo tubes.

USS Seawolf (SSN-575)

- Operational matters, with S2G reactor:
 - April 1956: Fuel installed
 - 20 August 1956: Full-power dockside tests were conducted and superheater leaks developed during the test. Rickover reported that tube plugging to isolate the leaks resulted in a loss of about 10% of heat exchanger capacity, limiting reactor power and *Seawolf's* top speed to about 90%.
 - February 1957: Start of initial sea trials
 - 30 March 1957: *Seawolf* commissioned
 - It has been reported that *Seawolf* operated with the steam generator superheaters bypassed, with reactor power limited to 60 - 80%, and the steam turbines operating on lower-pressure saturated steam.
 - Even with the reduced capabilities of the S2G propulsion plant, *Seawolf* demonstrated the ability of nuclear subs to make long, independent deployments
 - 25 Sep 1957: *Seawolf* completed a submerged voyage of 6,331 nautical mi (11,725 km) and then embarked President Dwight D. Eisenhower off Newport, RI for a short demonstration cruise.
 - 7 Aug - 6 Oct 1958: *Seawolf* conducted a 61-day submerged voyage of over 13,700 nautical miles (25,372 km).
 - December 1958: *Seawolf* returned to Electric Boat at end-of-core-life, after steaming a total of 71,000 nautical miles in about two years.
 - December 1958: At end-of-core-life, *Seawolf* was turned over to Electric Boat.
 - 2 - 22 January 1959: *Seawolf's* S2G core was defueled dockside at Electric Boat.

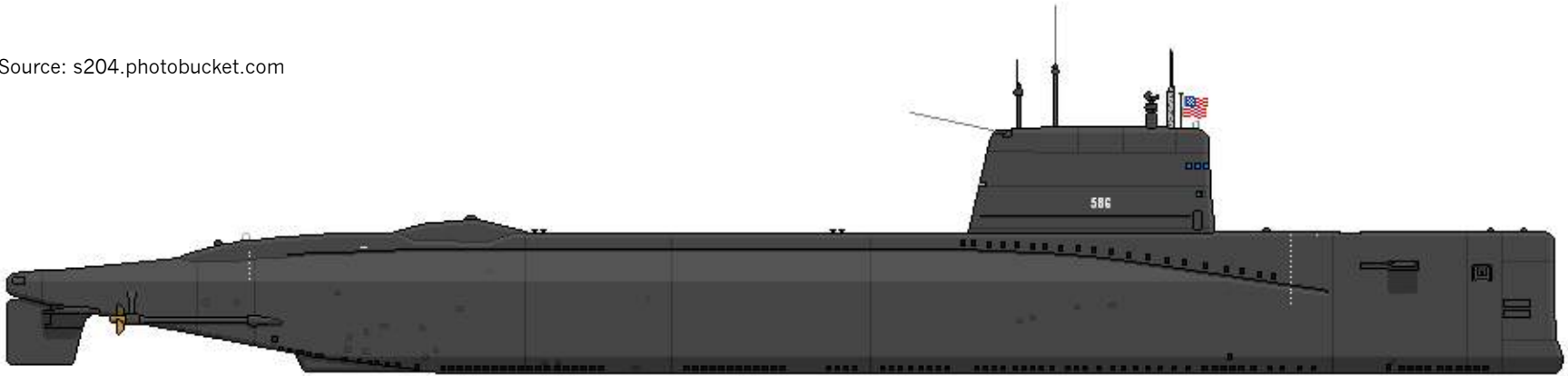
USS Seawolf (SSN-575)

- Operational matters, with S2Wa reactor:
 - December 1958 to September 1960: *Seawolf* was in the Electric Boat shipyard having her S2G propulsion plant removed and replaced with an S2Wa PWR propulsion plant, which also powered *Nautilus*.
 - With S2Wa installed, *Seawolf* was re-commissioned on 30 September 1960.
 - In 1963, *Seawolf* operated with the Navy's all-nuclear Task Force One, which consisted of the aircraft carrier *USS Enterprise* (CVN-65), guided missile cruiser *USS Long Beach* (CGN-9), and guided missile frigate *USS Bainbridge* (DLGN-25). *Seawolf* did not accompany TF1 on *Operation Sea Orbit*.
 - 1971 – 73: In Mare Island Naval Shipyard for modifications for special operations missions, including installation of a new “special projects” hull section. See section, “*Nuclear-powered special operations submarines*,” for more details on this phase of *Seawolf*'s service life.
 - *Seawolf* served as a special operations sub until 1987, when she was decommissioned.

USS Triton (SSRN/SSN-586)

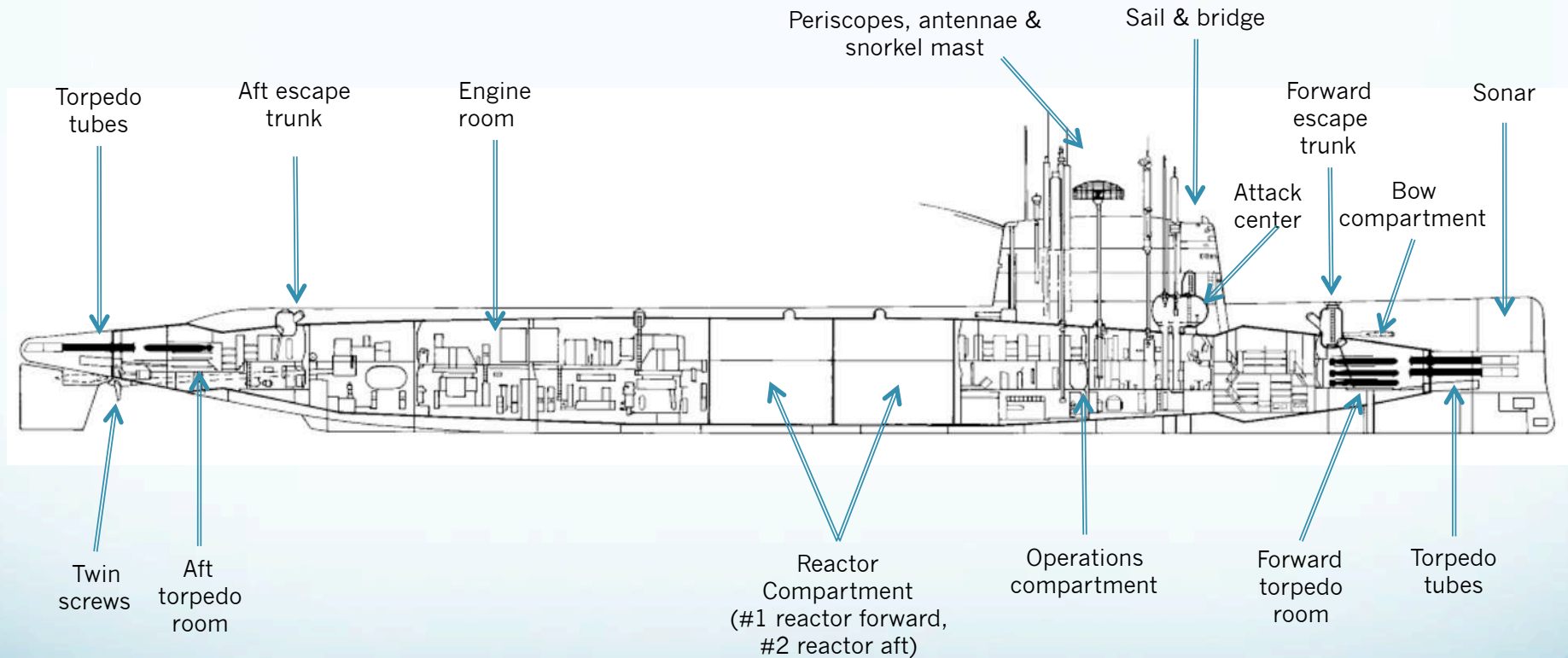
1st nuclear sub to circumnavigate the globe submerged

Source: s204.photobucket.com



- *Triton* was to be the lead ship of a proposed class of nuclear-powered radar picket submarines (SSRNs). A December 1955 long-range naval planning report envisioned five carrier strike groups, each supported by two radar picket submarines.
 - *Triton* was built at Electric Boat, Groton, CT as a nuclear-powered counterpart to two purpose-built diesel-electric radar picket subs, *Sailfish* (SSR-572) and *Salmon* (SSR-573).
 - This role became outdated with the introduction of carrier-based airborne early warning aircraft: Grumman E-1 Tracer
 - *Triton* became a one-ship class, originally with the AN/SPS-26 electronically scanned, three-dimensional (3-D) radar system mounted on a hull design that was similar to its diesel-powered SSR counterparts.
 - Hull design was intended to provide good surface sea-keeping qualities for the radar picket role. In comparison to other US nuclear subs, *Triton* had high reserve buoyancy (30%).

USS Triton (SSRN/SSN-586)

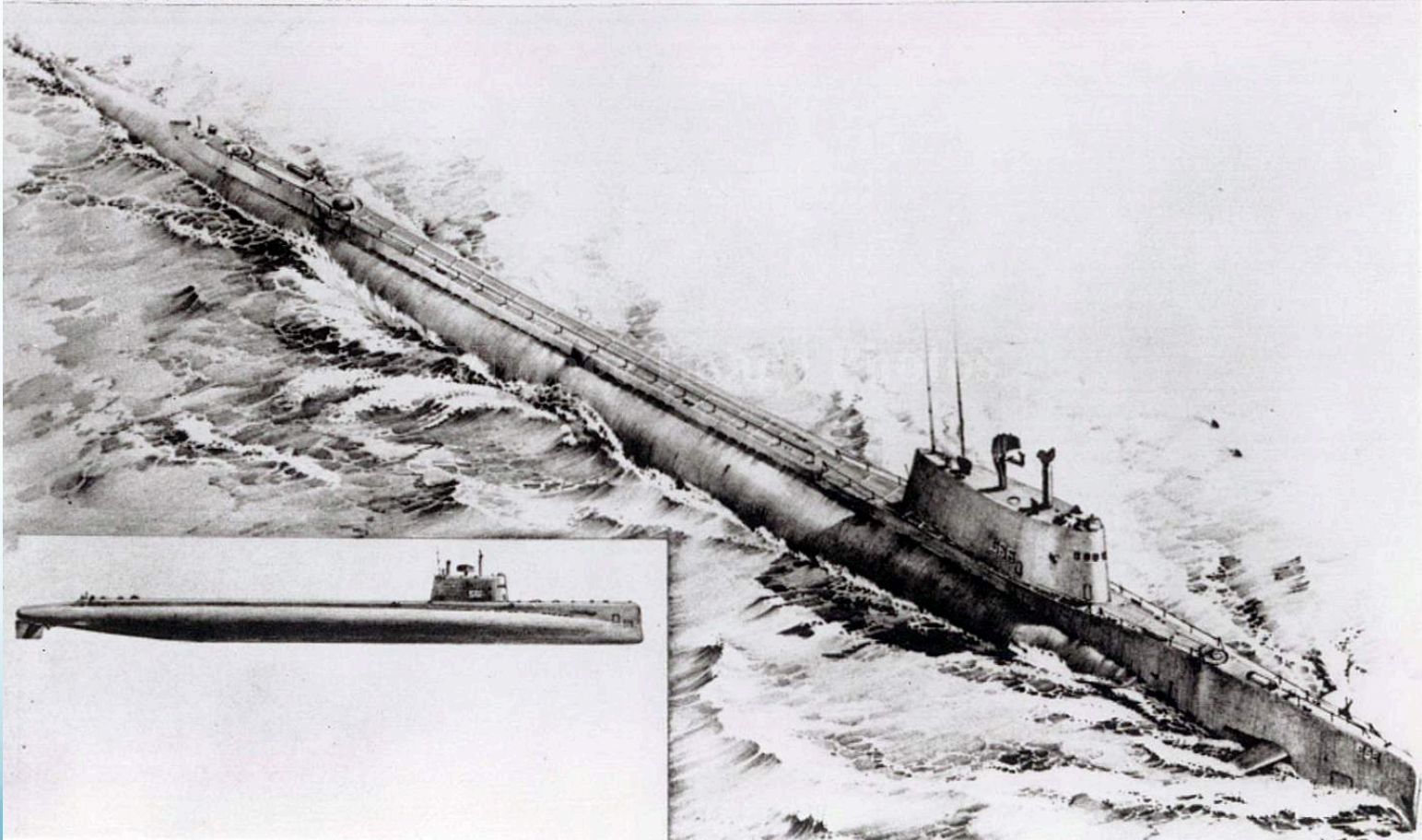


Source: Adapted from A.D. Baler III / also N. Polmar & K. Moore, "Cold War Submarines: The Design and Construction of US and Soviet Submarines"

USS Triton (SSRN/SSN-586)

1958 concept drawing

WAP-062615-6/26/58-WASHINGTON: This is an artist's conception of the USS Triton, the largest submarine ever built. Powered by twin nuclear reactors and displacing 5,450 tons, Triton is the Navy's first nuclear powered radar picket submarine. The giant Triton, third vessel to bear the name, will be launched 8/1958 at Groton, Conn. DEFENSE DEPT. PHOTO FROM UNITED PRESS INTERNATIONAL TELEPHOTO rtf



Source: US Navy

USS Triton (SSRN/SSN-586)

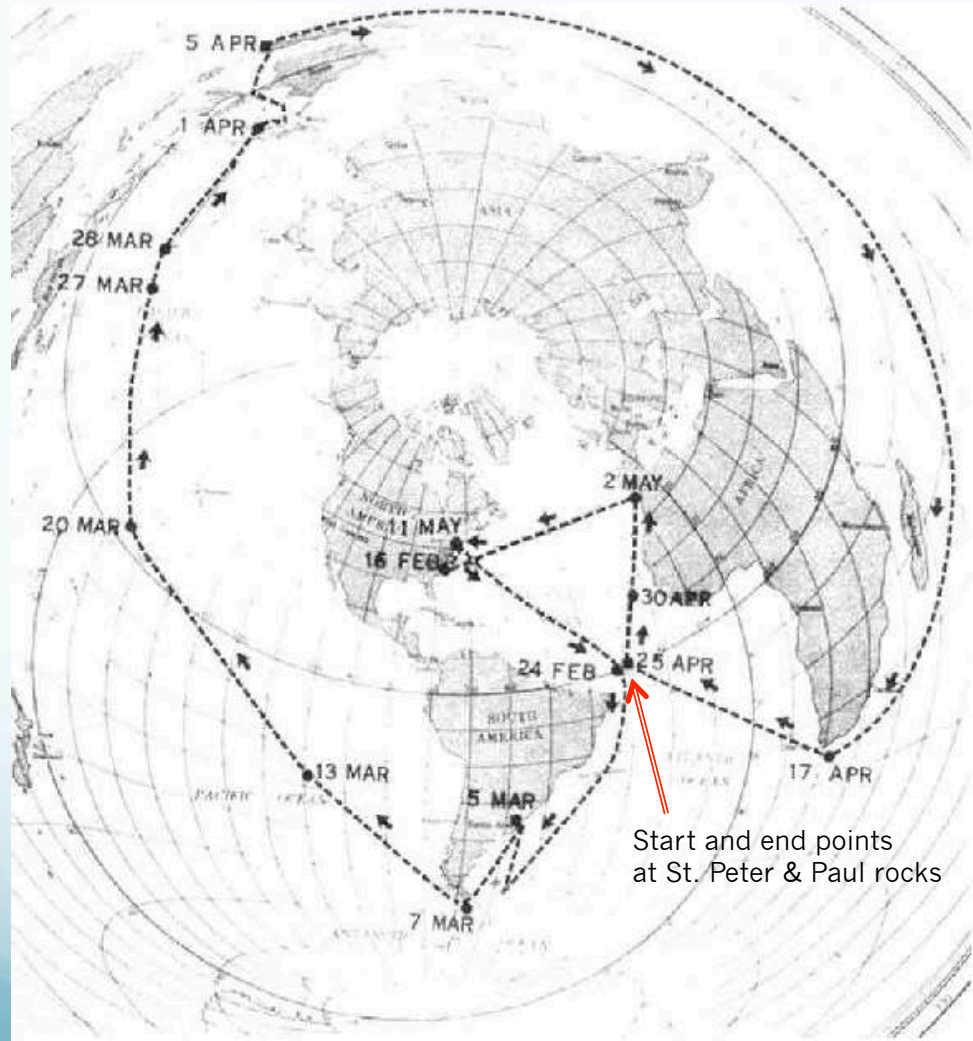
- Propulsion: 2 x S4G General Electric PWRs rated @ 78 MWt, arranged fore-and-aft in the hull; 2 x steam turbines rated @ a combined 30,000 hp (est.), driving 2 x shafts
 - *Triton* was the only US sub with two reactors.
 - Both reactors were located in the same reactor compartment. The #1 (forward) reactor supplied steam to the forward engine room and the starboard propeller shaft. The #2 (aft) reactor supplied steam to the aft engine room and the port propeller shaft.
 - The two steam plants could be cross-connected if required.
- Armament: 6 x 533 mm (21") torpedo tubes; 4 x bow tubes, 2 x stern tubes.
- Operational matters:
 - Launched 11 August 1958; Commissioned November 1959.
 - 24 Feb – 25 Apr 60: In *Operation Sandblast*, *Triton* circumnavigated the globe submerged.
 - 1 March 1961: *Triton* was re-classified as an SSN.
 - Refueled during her Sep 1962 – Jan 1964 overhaul.
 - 3 May 1969: *Triton* was decommissioned early, largely due to its high operating cost with two reactors and low tactical value as an SSN; 1st US nuclear sub to be taken out of service.



Source: [http://content.wow.com/wiki/USS_Triton_\(SSRN-586\)](http://content.wow.com/wiki/USS_Triton_(SSRN-586))

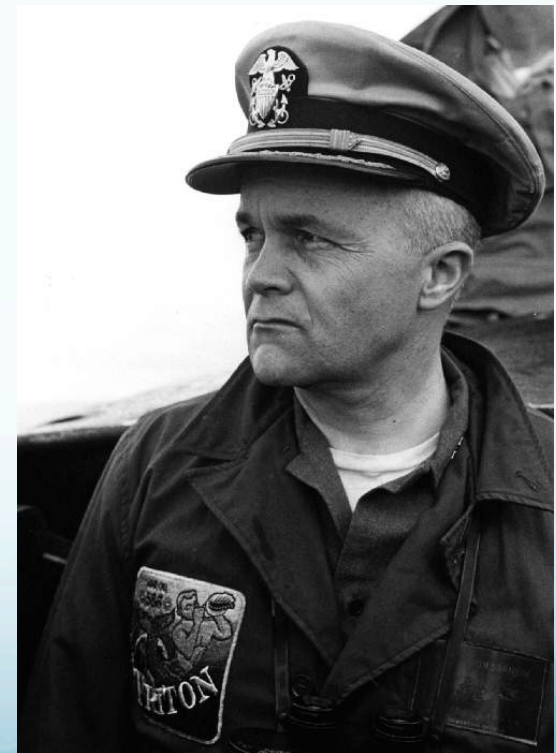
Operation Sandblast

USS Triton, 1st submarine to circumnavigate the globe submerged



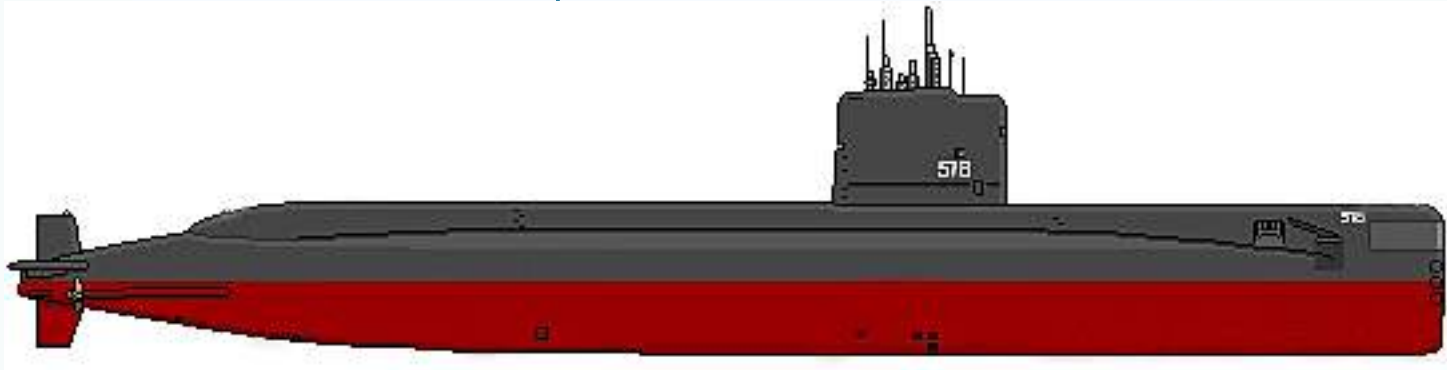
24 Feb – 25 Apr 60,
30,752 mi (49,491 km;),
in 60 days and 21 hours,
average speed 18 knots.

Triton CO: Capt. Edward L. Beach



Skate (SSN-578) class

1st series-produced nuclear subs

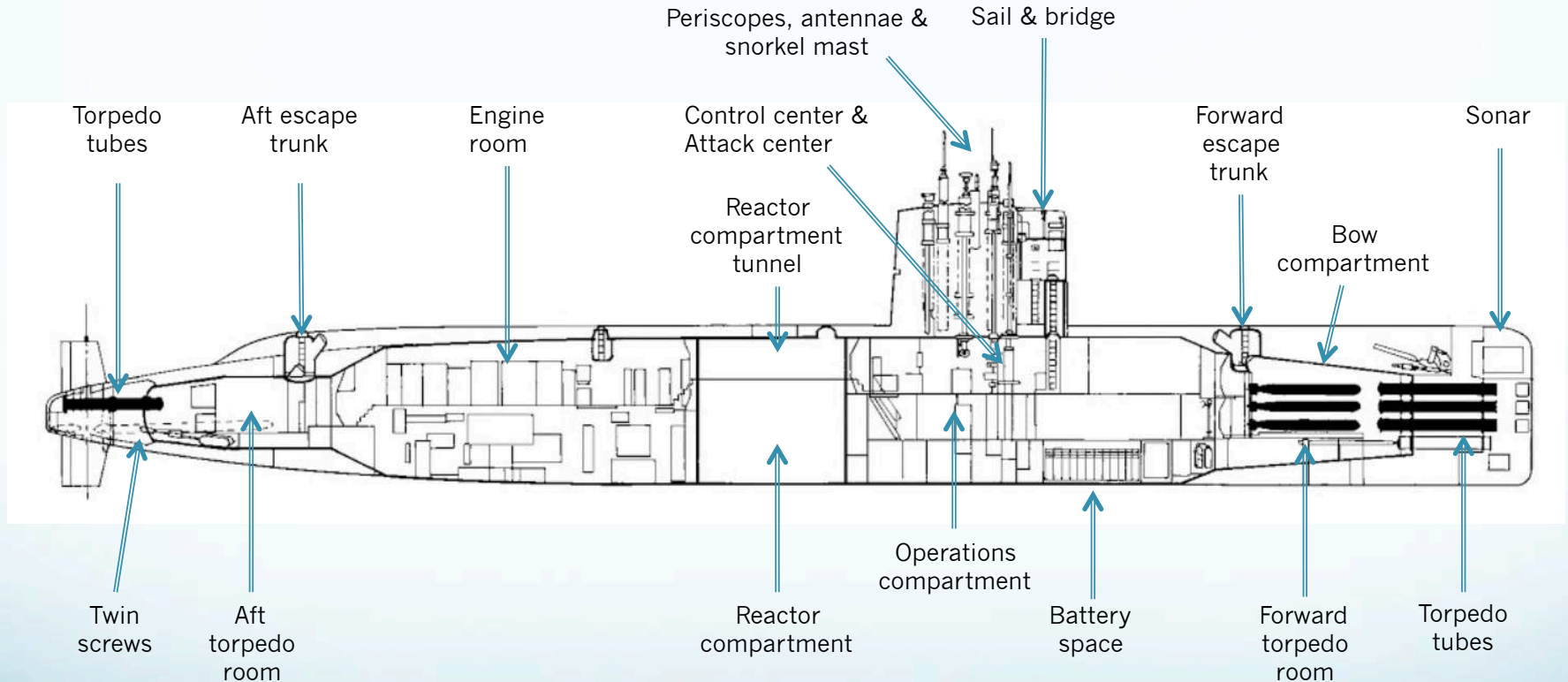


Source: <http://warshipsresearch.blogspot.com>

- This was the first series-produced US nuclear sub: 4 boats in this class.
 - *Skate* (SSN-578) & *Seadragon* (SSN-584) were built by Electric Boat in Groton, CT; *Swordfish* (SSN-579) was built at Portsmouth Naval Shipyard, and *Sargo* (SSN-583) was built at Mare Island Naval Shipyard. All were delivered between December 1957 and April 1958.
 - This hull design was an evolution of the post-WW II Tang-class diesel-electric sub.
- Propulsion
 - *USS Skate* & *USS Sargo*: 1 x S3W Westinghouse PWR rated @ 38 MWt (est.); 2 x main steam turbines delivering a total of 7,300 hp (5.4 MW) to 2 x screws.
 - *USS Swordfish* & *USS Seadragon*: 1 x S4W (with an S3W reactor core) PWR primary system, which featured an alternate equipment arrangement, and similar secondary propulsion plant.
 - During overhauls, the S4W plant was replaced with the S5W.
 - The S3W reactor plant in *Skate* and *Sargo* had a shielded tunnel for fore-and-aft access above the reactor compartment. The other two boats had a shielded deck above the more compact S4W reactor plant.

Skate (SSN-578) class

1st series-produced nuclear subs



Source: Adapted from A.D. Baler III / also N. Polmar & K. Moore, "Cold War Submarines: The Design and Construction of US and Soviet Submarines"

Skate (SSN-578) class

- Armament: 8 x 533 mm (21") torpedo tubes; 6 x bow tubes & 2 x short stern tubes (for Mk-37 torpedoes).
- Operational matters:
 - All subs in this class were Arctic-capable (hardened sail, under ice sonar, inertial navigation, steel propellers)
 - *USS Skate* (SSN-578) was the first sub to surface at the North Pole on 17 March 1959.
 - The other three subs in this class, *USS Swordfish* (SSN-579), *USS Sargo* (SSN-583) & *USS Seadragon* (SSN-584), all reached the North Pole and played an important role in mapping the Arctic Ocean and developing practices for safe under-ice operation.
 - In 1961, *USS Sea Dragon* conducted its first Westpac deployment and became the first US nuclear sub to conduct a SpecOp along the eastern coast of the Soviet Union. In 1964, *USS Seadragon* was the first nuclear sub to visit Hong Kong and Japan (port of Sasebo).
 - In 1967, *USS Skate* was the first nuclear sub to complete the extensive modifications required under the SUBSAFE program, which was instituted after the loss of the *USS Thresher* (SSN-593) in 1963.
 - By the time *USS Seadragon* was decommissioned in 1984, it had been in service for 24 years, steamed over 500,000 nautical miles (926,000 km) with more than 90% of that submerged, and undergone three major overhauls, each of which included reactor refueling.

USS Sargo (SSN-583) in drydock



Note 4-bladed propellers and two aft torpedo tubes.
Source, two photos: <http://www.navsourc.org>

USS Skate (SSN-578)

11 Aug 1958: 2nd submarine under the North Pole

17 March 1959: 1st submarine to surface at the North Pole



Capt. James Calvert

Source: US Navy



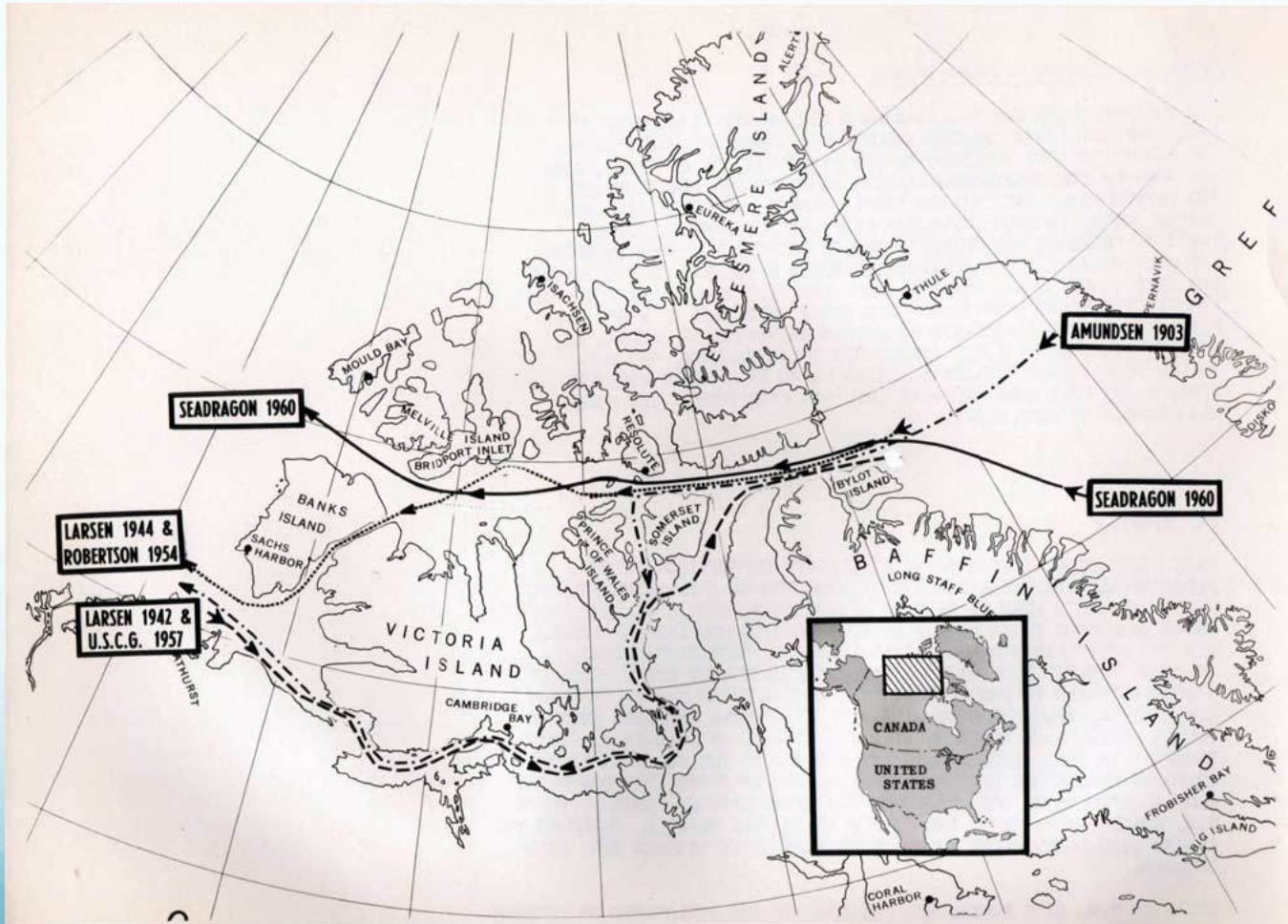
USS SKATE AT NORTH POLE, MARCH 17, 1959

Source: <http://archive.constantcontact.com>

The crew held a ceremony for the late Arctic explorer Sir Hubert Wilkins and spread his ashes at the North Pole. *USS Skate* made three more voyages to the Arctic in 1962, 1969 and 1971.

USS Seadragon (SSN-578)

15-21 August 1960: 1st submarine transit of the Northwest Passage



USS Seadragon was the first ship to transit the Parry Channel through the Canadian Archipelago.

Approaching from the Atlantic, *Seadragon* entered the Parry Channel 15 Aug 1960 at Lancaster Sound, proceeded westward through Melville Sound and McClure Strait and completed the channel passage on 21 Aug 1960. *Seadragon* then continued northward to the North Pole, and then on to Hawaii. This chart shows prior successful expeditions that navigated the archipelago on the surface.

Skipjack (SSN-585) class

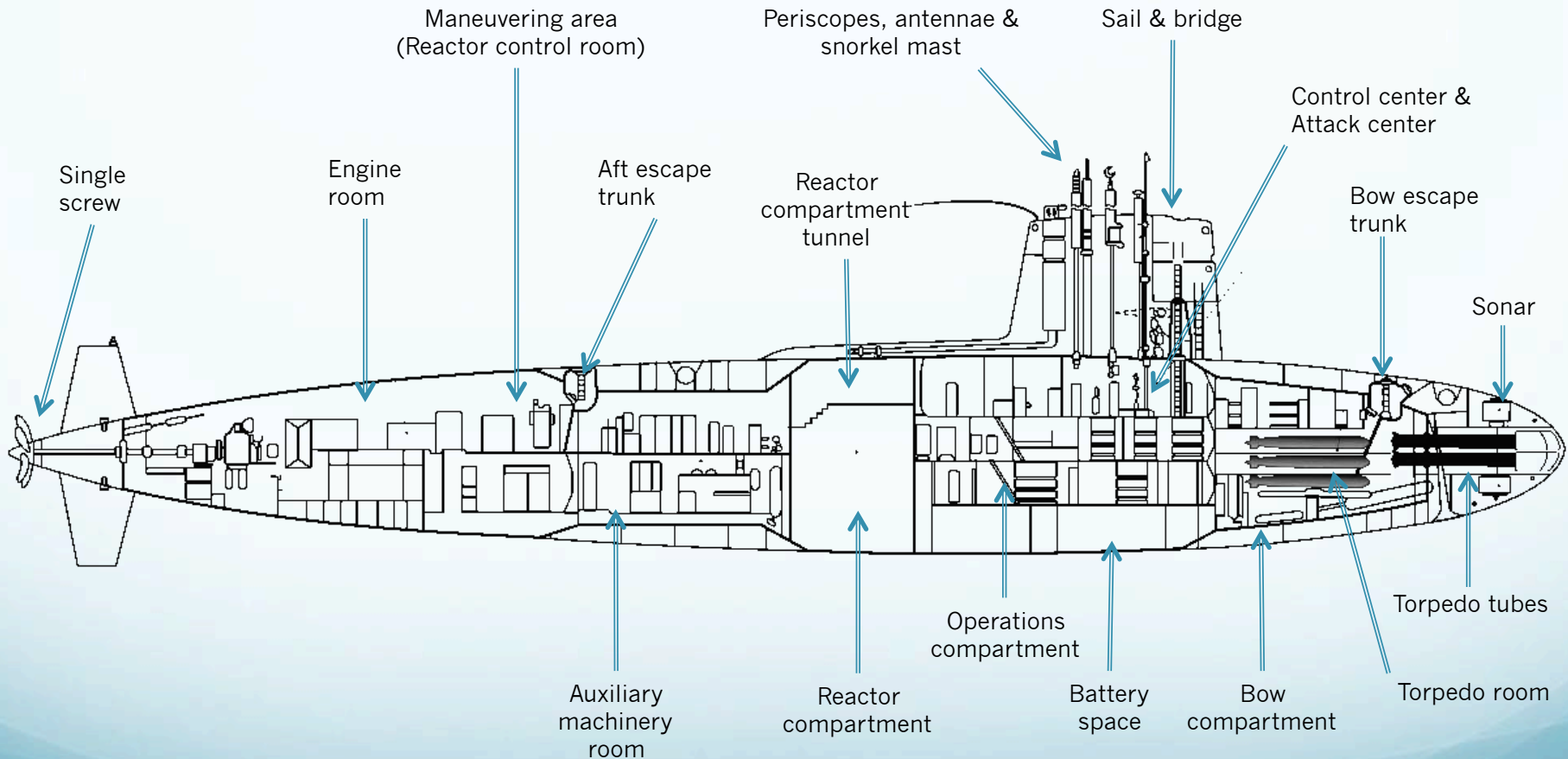


Source: www.subsim.com

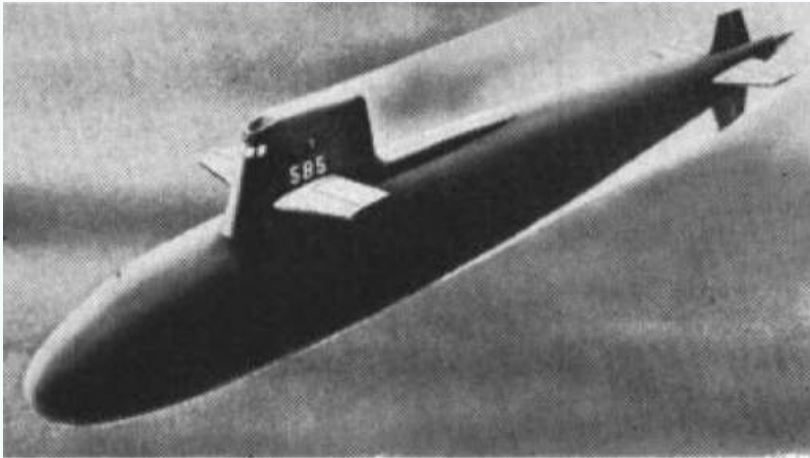
- The six boat Skipjack-class was built at four different shipyards: Electric Boat, Newport News Shipbuilding, Ingalls Shipbuilding & Mare Island Naval Shipyard.
 - All Skipjack-class subs were commissioned in a 3-year period: 1959 – 1961.
 - Original unit price was about \$40 M.
 - Service life of the boat was 30 years, with the last boat being decommissioned in 1990.
- Novel hull design:
 - 1st nuclear sub with a streamlined Albacore-style “body-of-revolution” hull, which greatly improved underwater performance, but reduced sea-keeping on the surface.
 - 1st use of high-strength HY-80 steel in hull construction. Single-hull, with a double hull containing the ballast tanks only around the bow torpedo room and the mid-ship Auxiliary Machinery Room.
 - 1st sub built with sail planes instead of conventional bow planes. This arrangement cut down on flow-induced noise near the bow sonar arrays. This feature was used on all US nuclear submarines until the Improved Los Angeles (688i)-class in 1988.

Skipjack (SSN-585) class

Notional internal arrangement



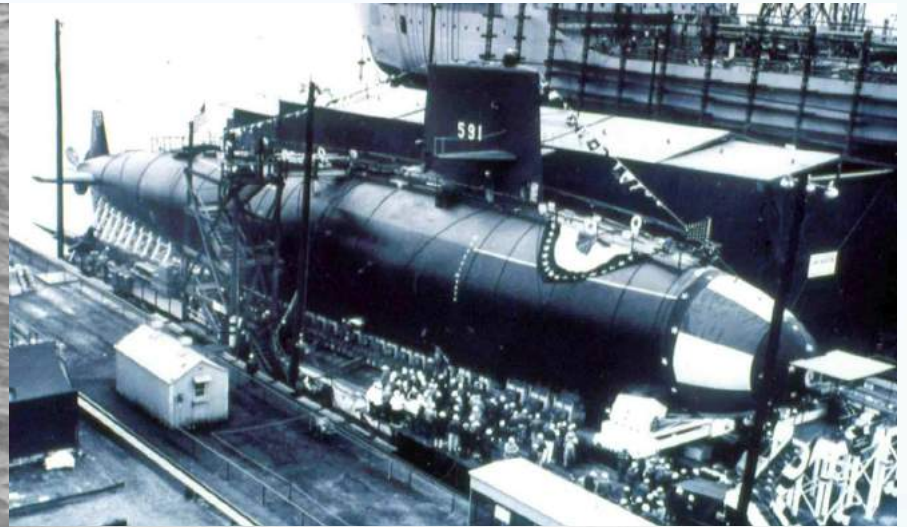
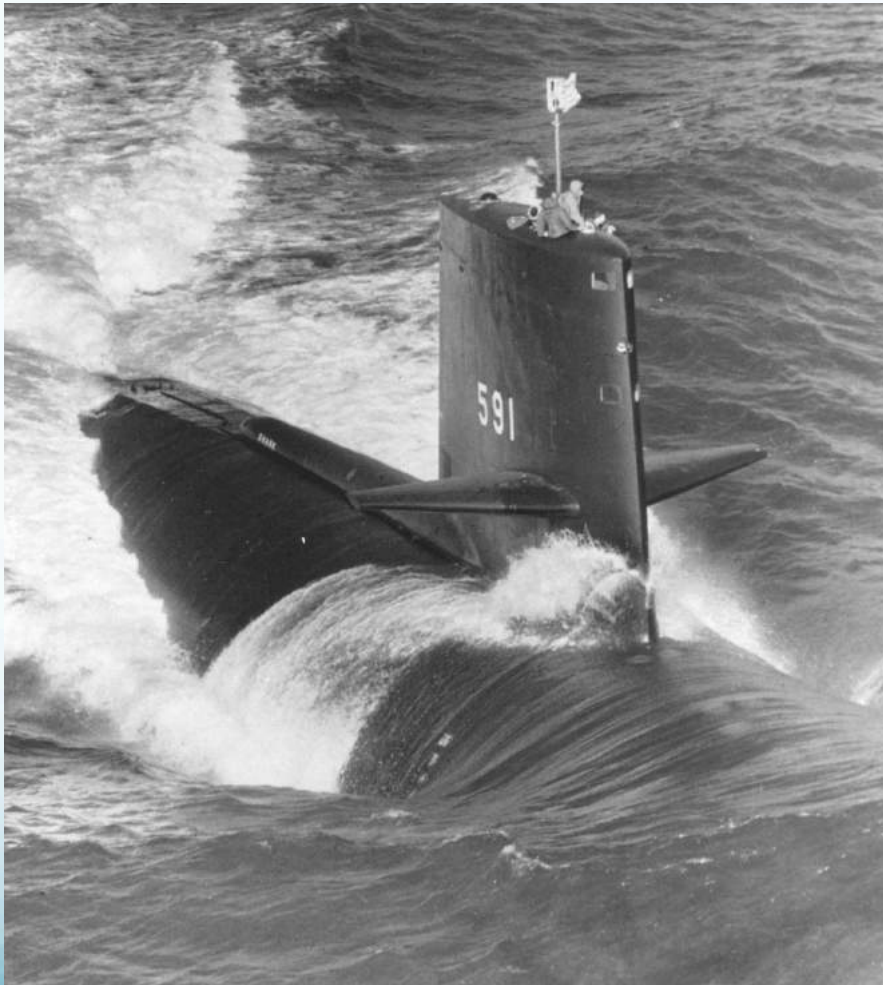
Skipjack (SSN-585) class



Skipjack concept drawing. Source: US Navy, All Hands magazine, Nov 1957

- Propulsion: 1 x S5W reactor rated @ 78 MWt; 2 x main steam turbines delivering a combined 15,000 shaft horsepower (11.19 MW), originally driving a single 5-bladed propeller.
 - This was the 1st class of subs to use the S5W reactor.
 - Original core life was about 5,500 EFPH, which would have provided a steaming range well in excess of 100,000 miles (161,000 km).
- Armament: 6 x 533 mm (21 inch) bow torpedo tubes; Mk 14, Mk 16, Mk 37 & Mk 48 conventional torpedoes; Mk 45 ASTOR nuclear torpedoes; mines
 - Maximum weapon load was 24 torpedoes, or a mix of torpedoes and mines.
- Operational matters:
 - The original hull for the partially-complete *USS Scorpion* was redesigned and used to speed completion of the 1st Polaris missile submarine, *USS George Washington* (SSBN-598).
 - Original max. speed exceeded 30 kts. Skipjack-class boats were the fastest US nuclear subs until Los Angeles-class SSNs joined the fleet in the mid-1970s.
 - Skipjack-class boats received a 7-bladed “skewback” propeller during refits between 1973 and 1976, enabling quieter operation but at reduced speed.
 - *USS Scorpion* (SSN-589) was lost at sea in the Atlantic on 22 May 1968.

Skipjack (SSN-585) class



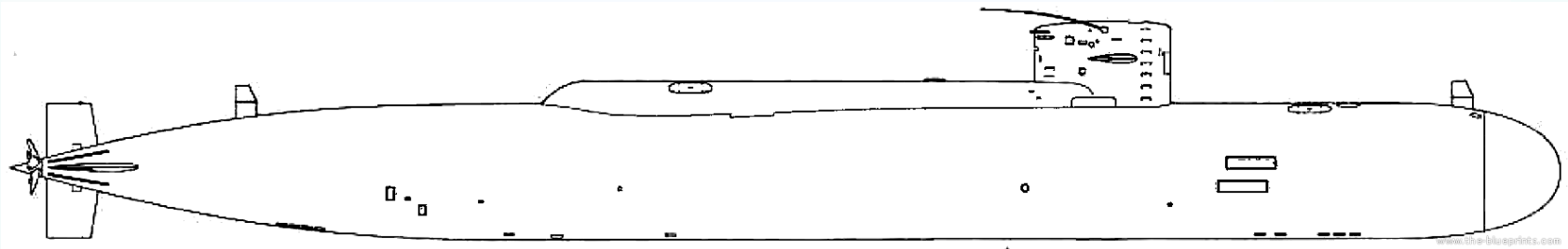
USS Shark (SSN-591) and USS Skipjack (SSN-585). Source: three photos: www.navsource.org/archives

Loss of the *USS Scorpion*

- *USS Scorpion* (SSN-589) sank on 22 May 1968 in the mid-Atlantic, southwest of the Azores, while returning from a Mediterranean deployment.
 - Water depth is about 9,800 ft (3,000 m).
- Numerous acoustic events subsequently associated with the sinking were recorded by multiple stations.
- The 1968 Navy Court of Inquiry offered findings of fact and opinions, including:
 - There is no incontrovertible proof of the exact cause of *Scorpion's* loss.
 - There is no evidence that loss of *Scorpion* was the result of an unfriendly act.
 - Gamma radiation readings taken at the ocean floor and of a bottom core sample taken at *Scorpion's* location, gave only normal background readings. Water samples taken in close proximity to the reactor compartment gave only normal background readings.
 - Evidence supports the finding that no radiological hazard resulted from the loss of *Scorpion*.
- Numerous theories for the loss of *Scorpion* have been proposed.
- US Navy has acknowledged that it periodically visits the site to conduct testing for the release of radioactive material from the S5W reactor core or the two Mk 45 ASTOR nuclear torpedoes still in the wreckage, and to determine whether the wreckage has been disturbed.

USS Tullibee (SSN-597)

1st turbo-electric drive nuclear sub



Source: <https://www.the-blueprints.com/>

- This one-ship class built by Electric Boat, Groton, CT, is a result of recommendations from the 1956 Naboska Study, which emphasized the need for deeper-diving, ultra-quiet ASW submarine designs using long-range sonar.
 - 1st sub with a bow-mounted spherical sonar array and torpedo tubes located amidships, angled out from the hull. These features were being built concurrently in the Permit-class SSNs and became the US standard in following classes of SSNs.
 - Smallest SSN built by the US; comparable in size to the French Rubis / Amethyst-class 1st-generation SSNs, which also have a turbo-electric drive.
 - Maximum speed: about 15 kts submerged; 13 kts surfaced
- Propulsion:
 - 1 x S2C PWR rated @ 13 MWt (est.); 2 x steam turbine generators delivering a combined 1.86 MW (2,500 shaft horsepower) to the electric drive for a single propeller.
 - 1st sub with turbo-electric drive with no reduction gear; not repeated on an SSN until *USS Glenard P. Lipscomb* (SSN-685).

Comparison of *USS Tullibee* with French Rubis (Améthyste)-class SSN

Source: <http://warshipsresearch.blogspot.com>



Dessin : Yannick LE BRIS

Source: <https://defence.pk/>

USS Tullibee:

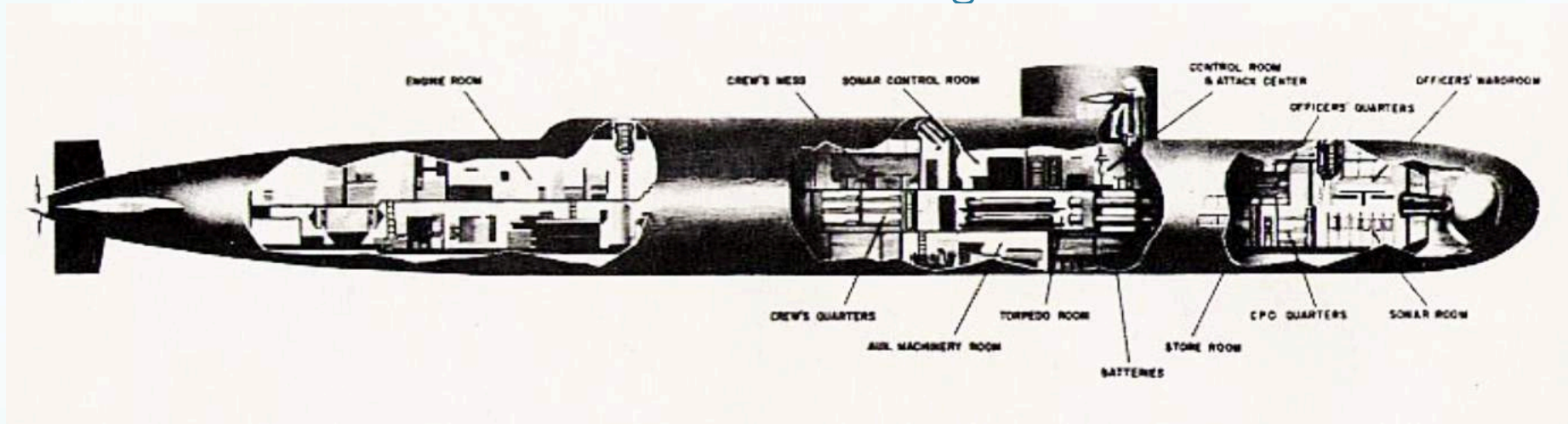
- Length: 273 ft (83 m)
- Hull beam: 23.6 ft (7.2 m)
- Submerged displacement: 2,649 tons
- Test depth: about 700 ft (213 m)
- Submerged speed: 14.8 knots
- Propulsion: Turbo-electric

Rubis (Améthyste)-class SSN:

- Length: 241.5 ft (73.6 m)
- Hull beam: 24.9 ft (7.6 m)
- Submerged displacement: 2,670 tons
- Test depth: about 1,640 ft (500 m)
- Submerged speed: 25 knots
- Propulsion: Turbo-electric

USS Tullibee (SSN-597)

Notional internal arrangement



Source: www.navsource.org/archives, *USS Tullibee Welcome Aboard booklet*

Note: Bow sonar sphere and mid-ship torpedo tubes.

USS Tullibee
5-bladed prop



Source: Marco Brigandi

USS Tullibee (SSN-597)

Operational matters:

- Quietest of the early generation US nuclear subs.
- Operated extensively in the Atlantic & Mediterranean, including numerous fleet exercises and sonar development activities.
- S2C reactor was refueled three times.

| Core # | Operating period | Core life | Refueling # | Refueling period |
|--------|------------------|-----------|-------------|----------------------|
| 1 | Nov 60 – Oct 64 | 3.9 yr | 1 | 28 Oct 64 – 2 Jan 68 |
| 2 | Jan 68 – Feb 73 | 5.1 yr | 2 | Feb 73 – Aug 74 |
| 3 | Aug 74 – Aug 79 | 5.0 yr | 3 | Aug 79 – Oct 82 |
| 4 | Oct 82 – Jun 88 | 5.7 yr | | |

- Decommissioned in June 1988 after 28 years of service and traveling about 325,000 nautical miles (602,000 km).



Source: www.navsource.org/archives/



Source: <https://www.militaryfactory.com/>

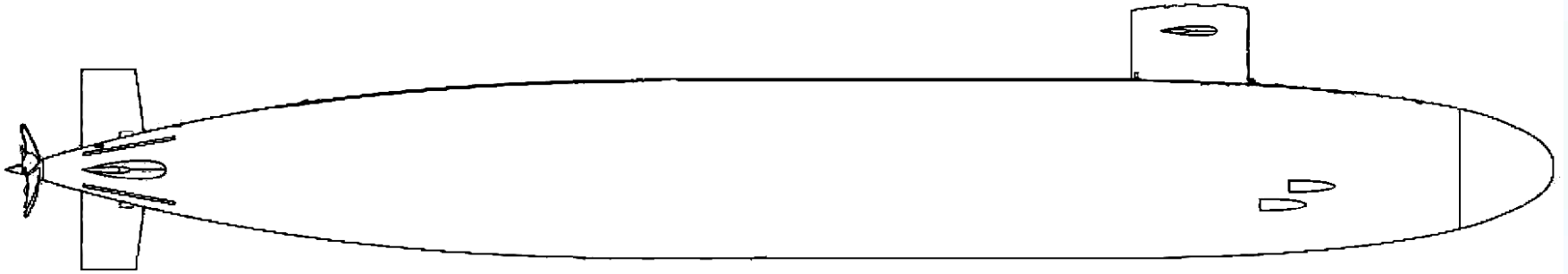
USS Tullibee (SSN-597)

- Designated AN/BQG-4, the three vertical fins housed the PUFFS (Passive Underwater Fire-control Feasibility Study) sonar sensors, which enabled long-range passive detection of targets.
 - Primarily fitted on conventional submarines. Tullibee was the only nuclear-powered sub to receive PUFFS
 - PUFFS also was planned for Thresher and Sturgeon-class nuclear submarines, but was not installed.
- Functionally, PUFFS was a predecessor of modern, passive wide-area arrays (WAA).



Tullibee with PUFFS sensors. Source: www.navsourc.org/archives/

Permit (SSN-594) class



Source: Adapted from <http://www.the-blueprints.com/>

- The 14 boat Permit-class was built by five different shipyards: Electric Boat, Newport News Shipbuilding, Ingalls Shipbuilding, Mare Island Naval Shipyard & Portsmouth Naval Shipyard.
 - Originally named the Thresher-class, after the lead boat, *USS Thresher* (SSN-593), which was lost with all hands due to flooding during deep-dive testing in the Atlantic east of Cape Cod, MA on 10 April 1963.
 - The Permit-class boats were commissioned in a 7-year period from 1961 – 1968.
- Propulsion: 1 x S5W reactor rated @ 78 MWt; 2 x main steam turbines delivering a combined 15,000 shaft horsepower to a single propeller.
 - This was the same propulsion plant used in Skipjack-class SSNs.

Permit (SSN-594) class

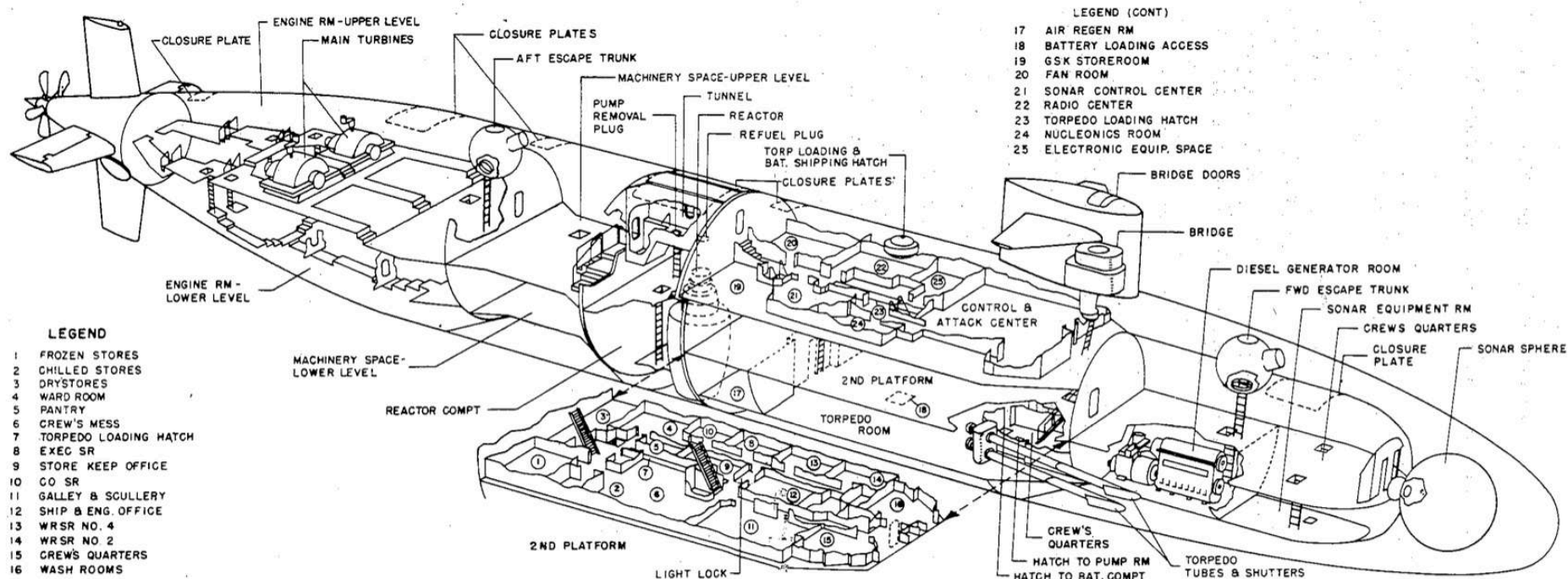
- Significant improvements over Skipjack-class:
 - Longer, cylindrical hull shape; improved hull design with HY-80 steel yielded a greater test depth.
 - This basic hull design became the standard shape for later generations of US nuclear subs.
 - Small sail for reduced hydrodynamic drag, but only one periscope & few electronic masts. This limited intelligence-gathering capability.
 - BQQ-2 bow sonar sphere and mid-ship torpedo tubes, similar to the arrangement on *USS Tullibee* (SSN-597), which was built concurrently.
 - Acoustic-quieting improvements over Skipjack-class:
 - 1st US nuclear subs to mount heavy rotating machinery on “rafts” that were supported from the hull on sound isolation mounts.
 - *USS Permit* was the 1st sub to use of 7-bladed “skewback” propeller for quieter operation, but at the expense of a lower top speed of 28 - 29 knots. In comparison, *USS Thresher* demonstrated a maximum speed of 33 knots with a 5-bladed symmetrical propeller, similar to the propellers used on Skipjack-class SSNs.
- Armament: 4 x 533 mm (21 inch) mid-ship torpedo tubes; initially Mk-37 & later Mk-48 conventional torpedoes; Mk-45 ASTOR nuclear torpedoes; SUBROC anti-submarine nuclear missile; Harpoon anti-ship cruise missiles; mines
 - 1st submarine class fitted with the Mark 113 fire control system that enabled the use of SUBROC.
 - Maximum weapon load was 23 torpedoes/missiles or up to 42 Mk-57, -60, or -67 mines. Any mix of mines, torpedoes, and missiles could be carried.

Notional internal arrangement



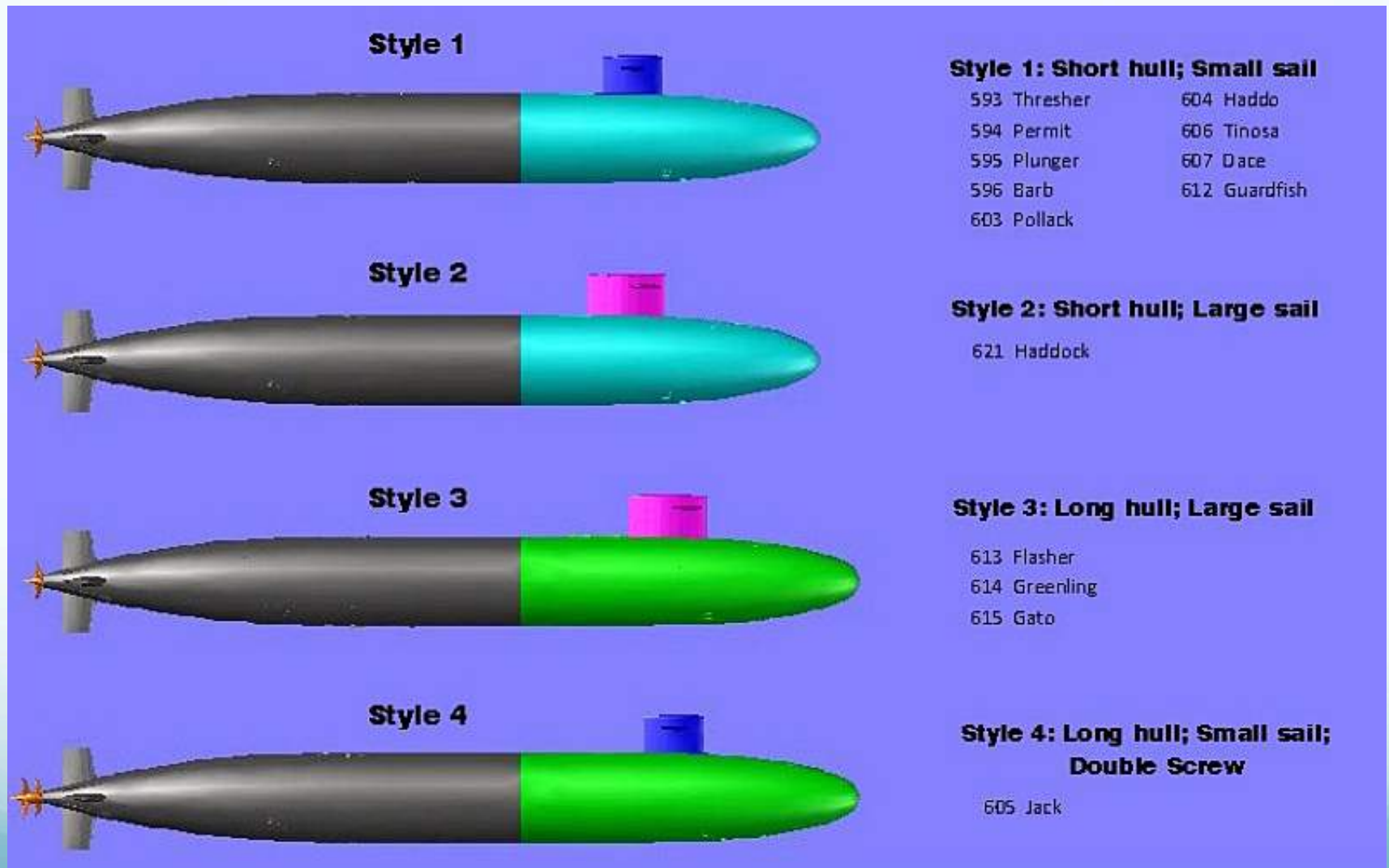
Permit (SSN-594) class

Notional internal arrangement



Source: <http://navsource.org/archives/>

Permit (SSN-594) class variations



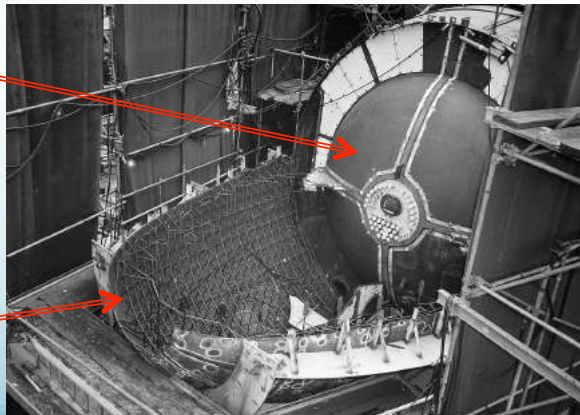
Permit (SSN-594) class

- Operational matters:
 - *Flasher*, *Greenling* and *Gato* were fitted with a larger sail to house additional masts. Their hulls were 10 feet (3 meters) longer than the earlier Permit-class boats to provide more space for SUBSAFE features, additional reserve buoyancy, more intelligence gathering equipment and improved crew accommodations.
 - *Jack* (SSN-605) was a one-of-a-kind modification of the basic Permit-class design to test a propulsion system with counter-rotating propellers, which had been demonstrated successfully on the *USS Albacore* (AGSS-569).
 - Mid-life upgrades included BQQ-5 sonar suite with retractable towed-array, Mk-117 fire control system.
 - The last Permit-class boat was decommissioned in 1996. Average service life was 26 years.

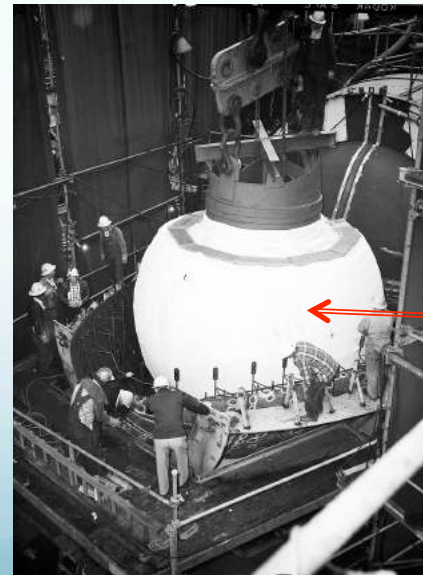
Installation of the *USS Permit*
bow spherical sonar array

Submarine bow
compartment
pressure hull

Submarine bow
dome structure



Source, two photos: navsource.org/archives/



BQQ-2 spherical
sonar array in
the free-flood
area that will be
enclosed by the
bow dome
structure.

Loss of the *USS Thresher*

- *USS Thresher* (SSN-593) sank in 8,500 ft (2,438 m) of water in the Atlantic, about 220 miles (354 km) off of Cape Cod, on 10 April 1963 during a deep dive test being monitored from the Navy submarine rescue vessel *USS Skylark*.
- With *Thresher* initially at about ½ test depth, at relatively low speed:
 - 9:03 AM: Underwater telephone message from *Thresher* reports, "Experiencing minor problem. Have positive angle," and then, "Attempting to blow." For the next 10 minutes *Skylark* attempts to make contact with *Thresher*, but there is no reply.
 - 9:17 A.M. *Skylark* receives a garbled message that ends with the distinct words: "...test depth." *Thresher's* underwater telephone remains open and *Skylark's* navigator hears the distinctive groans and clanks as *Thresher* starts to break up.
- Although the full transcript of the Navy Court of Inquiry (NCOI) still has not been released as of mid-2018, the basic accident scenario reported by NCOI is as follows:
 - An initial leak most likely occurred in a silver-braided joint in an engine room seawater system.
 - Saltwater spray on electrical components caused short circuits, reactor shutdown, and loss of propulsion power.
 - *Thresher* did not have enough forward momentum to drive to the surface using its planes.
 - An "emergency blow" was initiated to rapidly blow all main ballast tanks. However, as the high-pressure air expanded, it cooled, and moisture in the compressed air froze on in-line strainers in the emergency blow lines. This slowed or stopped the emergency blow.
 - Propulsion was not restored and the ship sank deeper as flooding continued.
 - The *Thresher* broke up and all 129 persons aboard were lost.

SUBSAFE Program

- A Judge Advocate General (JAG) Court of Inquiry into the *Thresher* accident was conducted.
 - The JAG report contained 166 Findings of Fact, 55 Opinions, and 19 Recommendations.
 - The recommendations were technically evaluated and incorporated into the Navy's newly-established SUBSAFE design and operational requirements, which were applied to all operating and new-construction subs and continue to be applied to all new design subs.
- The purpose of the SUBSAFE Program is to provide maximum reasonable assurance of watertight integrity and recovery capability.
 - The SUBSAFE boundary is defined on a per-boat basis in the SUBSAFE Manual and depicted diagrammatically in the SUBSAFE Certification Boundary Books.
- The Navy's first task was to systematically establish SUBSAFE culture at all levels.
- A SUBSAFE certification process was established for all items related to the SUBSAFE boundary.
 - This resulted in substantive changes to ship systems, equipment, and operating procedures
- A SUBSAFE certification maintenance process was established to ensure the continuing integrity of the SUBSAFE boundary throughout the operating life of each boat.
- An Audit process provides the necessary confidence that the SUBSAFE Program is meeting its intended purpose and may identify opportunities for improvement.

Deep Submergence Rescue Vehicle (DSRV)



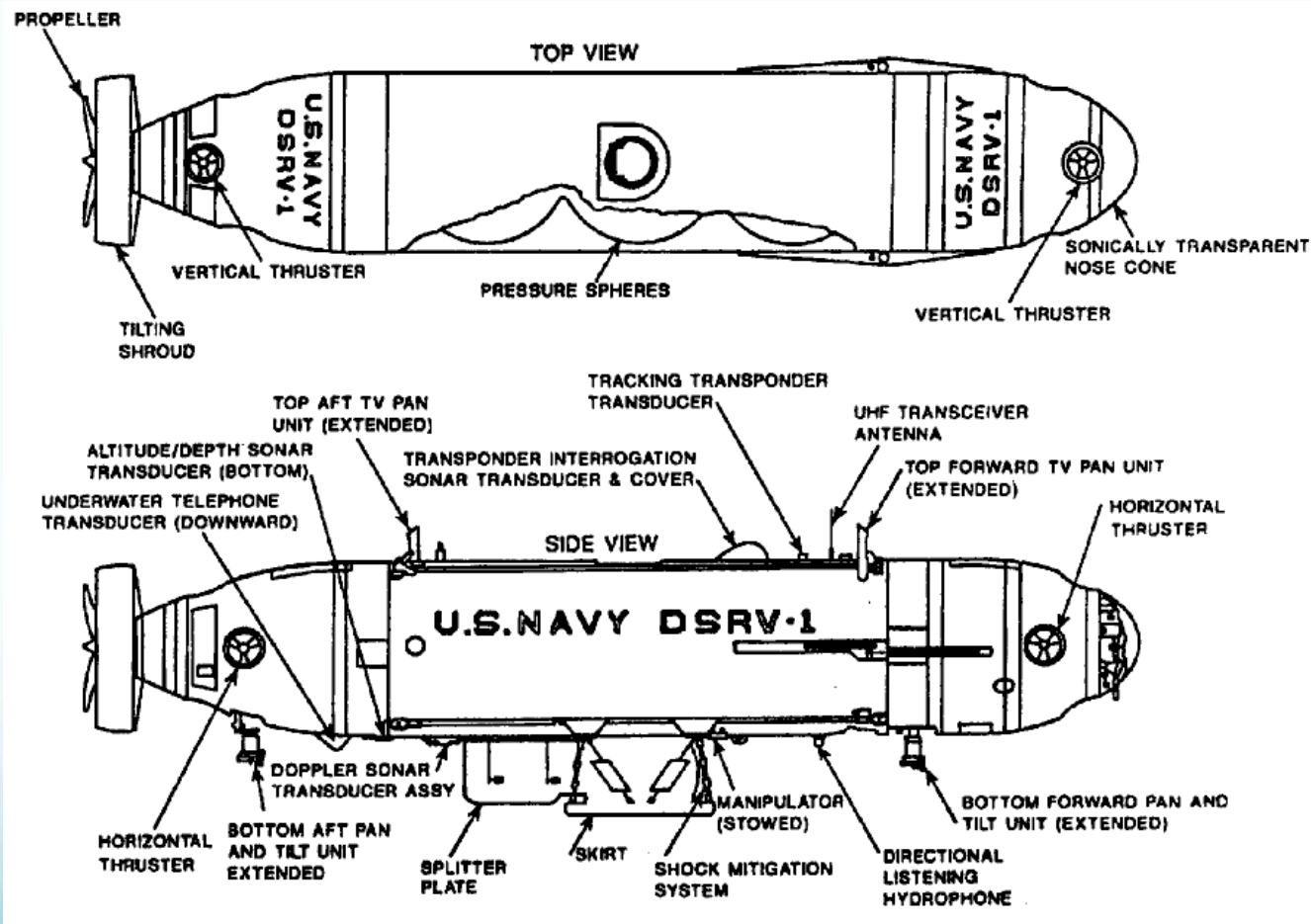
Source: www.navy.mil



Source: www.murdoconline.net

- Development of the DSRV was a reaction to the Thresher accident.
- Two DSRVs, *Avalon* & *Mystic*, were commissioned in the early 1970s.
- The two air-transportable, battery-powered DSRVs were 50 feet (15 m) long, 8 feet (2.4 m) in diameter, and weighed 37 tons.
- DSRVs were capable of descending to 5,000 feet (1,500 m) below the surface and could carry 24 passengers at a time in addition to its crew.
- Many US nuclear subs were configured to carry a DSRV to a rescue location or other operations site.
- The DSRVs were never required to conduct an actual rescue operation. *Avalon* was retired in 2000 and *Mystic* in 2008.

Deep Submergence Rescue Vehicle (DSRV)



Source: www.globalsecurity.org

Sturgeon (SSN-637) class

Source: usnavymuseum.org



- The 37 Sturgeon-class boats were built by seven different shipyards and commissioned in a 7-year period from 1967 – 1975.
 - Same hull as the “long-hull” Permit-class (i.e., *USS Flasher*), but with a bigger sail.
 - These were all capable of operating in ice-covered Arctic waters.
 - Original service life was 20 years with three reactor cores, but was later extended to 24 and 30 years with longer-life reactor cores, with a possible extension to 33 years on a case-by-case basis.
- There were two basic versions:
 - 28 x “short-hull” (last was SSN-677, *USS Drum*), and 9 x “long-hull” boats incorporating a 10 foot (3 meter) hull extension, starting with SSN-678, *USS Archerfish*.
 - Six long-hull boats were equipped to handle a Dry Deck Shelter (DDS) for special operations forces.
 - One long-hull boat (SSN-683, *USS Parche*) was further modified to take over the special operations missions conducted by *Halibut* and *Seawolf*.

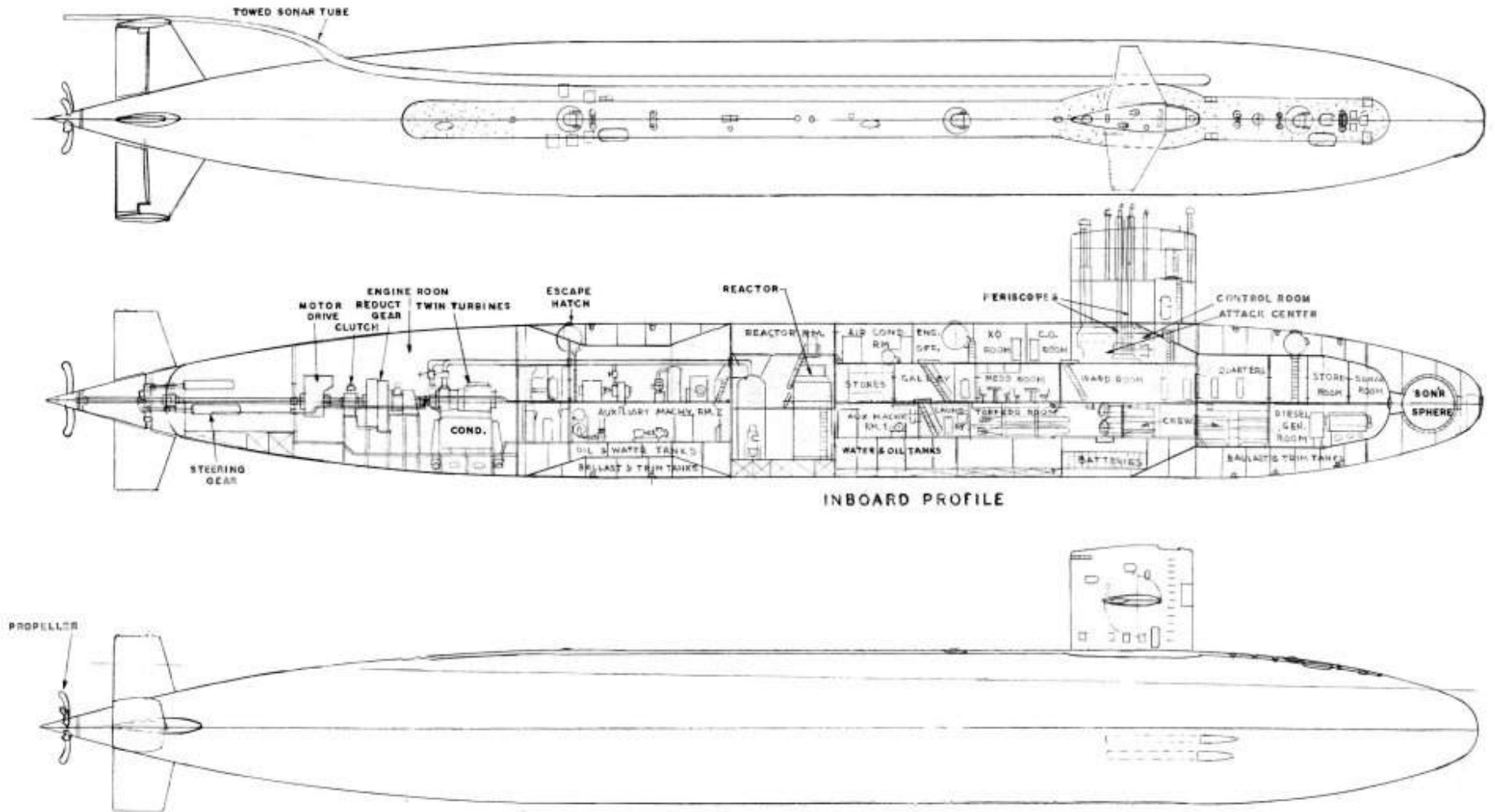
Sturgeon (SSN-637) class

- Propulsion: 1 x S5W reactor rated @ 78 MWt; 2 x main steam turbines delivering a combined 15,000 shaft horsepower to a single propeller.
- Armament: 4 x 533 mm (21 inch) mid-ship torpedo tubes; Mk-37 & Mk-48 conventional torpedoes, Mk 45 ASTOR nuclear torpedoes; SUBROC anti-submarine nuclear missile; Harpoon anti-ship cruise missiles, or Tomahawk land attack cruise missile; also Mark 60 CAPTOR or Mark 67 mines
 - Maximum weapon load was 21 torpedoes/missiles or a mix with mines.
- In 1968, the unit price of a Sturgeon-class SSN was about \$83 M vs. \$79 M for a Permit-class SSN.
- Operational matters:
 - Arctic capable, with hardened sails, under-ice sonar, and fairwater planes that rotated vertical for penetrating the Arctic icepack.
 - Sturgeon-class subs tested the first Harpoon and Tomahawk cruise missiles, towed-array sonar, digital sonar signal analyzer, and satellite communication antenna.
 - 36 Sturgeon-class subs were decommissioned between 1991 – 2001 with an average service life of 26 years. *USS Parche* continued its role as a special operations SSN until 2005, completing almost 31 years of service.



Source: www.pbs.org

Sturgeon (SSN-637) class



Driving a Sturgeon-class SSN

Ship control station
in the Control Room

Engineering control station
in the Maneuvering Room

Ballast Control Panel



Source: Wikimedia commons /
Philwong5176

Source: <http://www.emmitsburg.net/>



Fairwater (bow) plane,
stern plane &
rudder controls,
engine order telegraph

Throttle
Control
Panel
(TCP)

Reactor
Plant
Control Panel
(RPCP)

Electric
Plant
Control Panel
(EPCP)

Submarine Radiated Noise

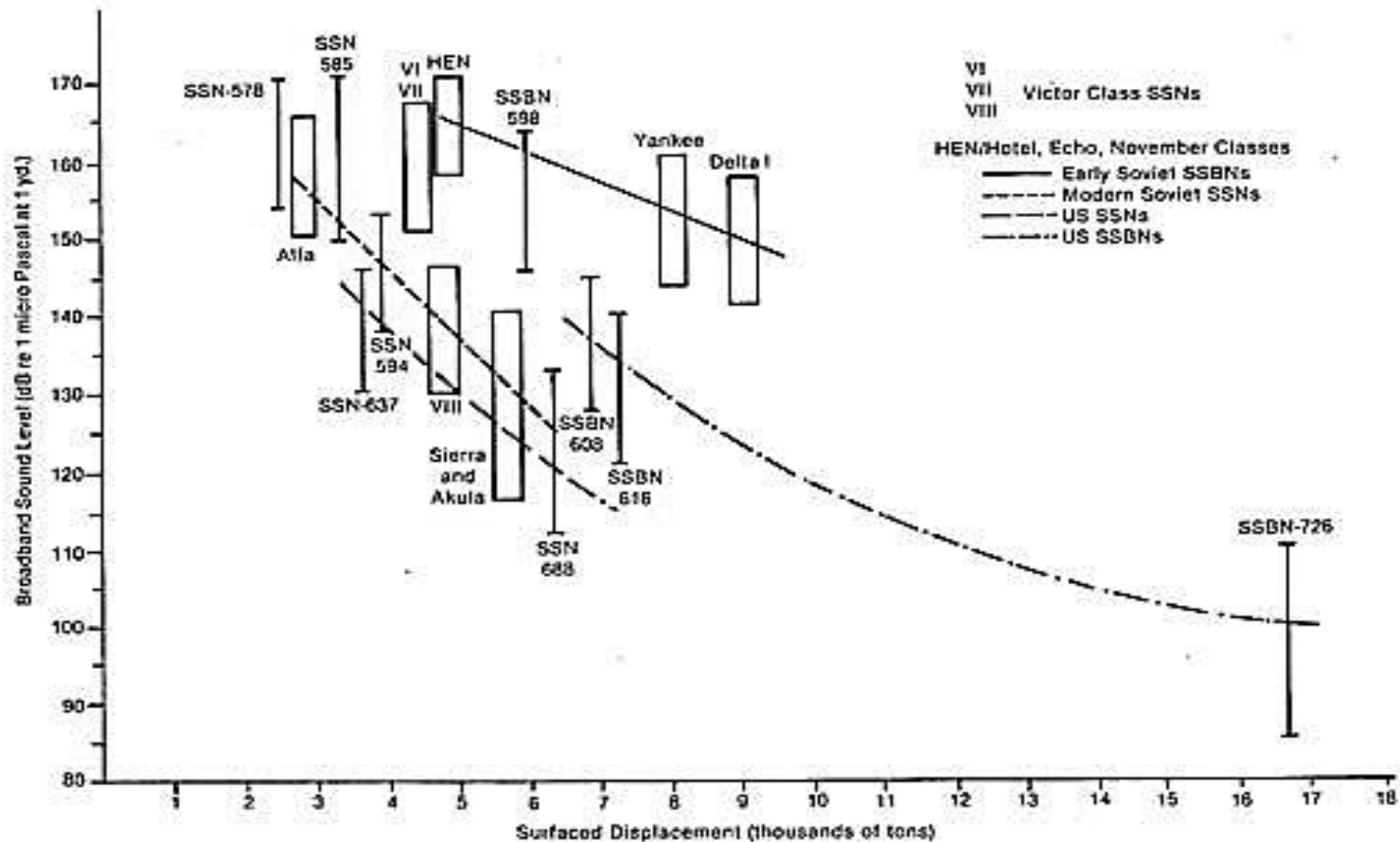
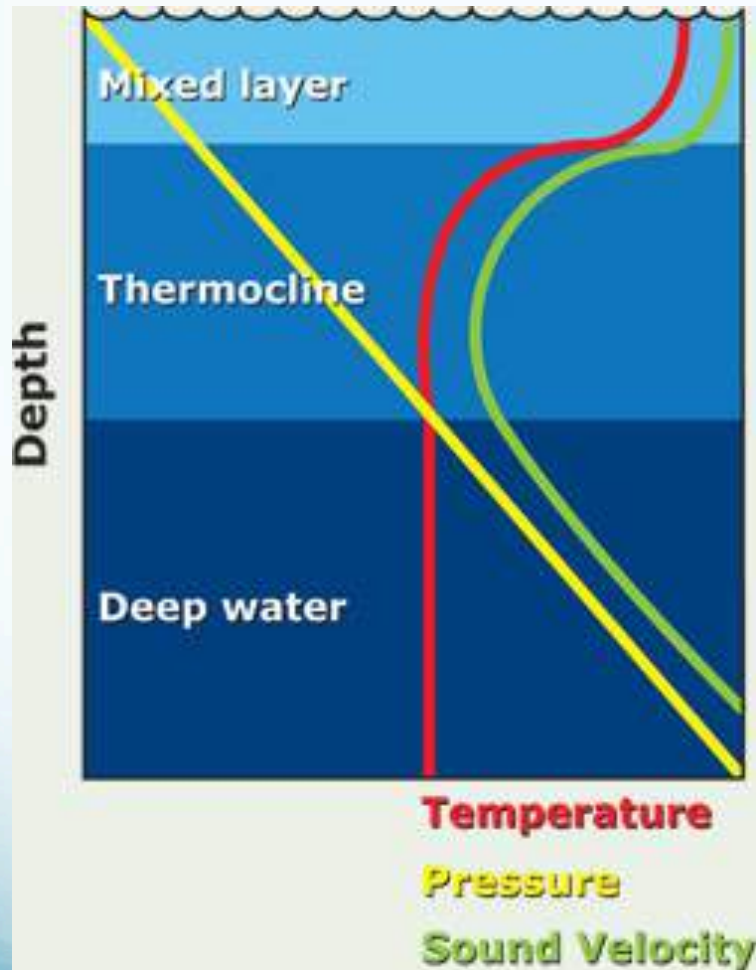


Figure A6-7. Broadband sound level versus surfaced displacement.

Note: Trend lines for different generations of quieting technology are identified.

Sound velocity profile (SVP) creates the deep sound channel

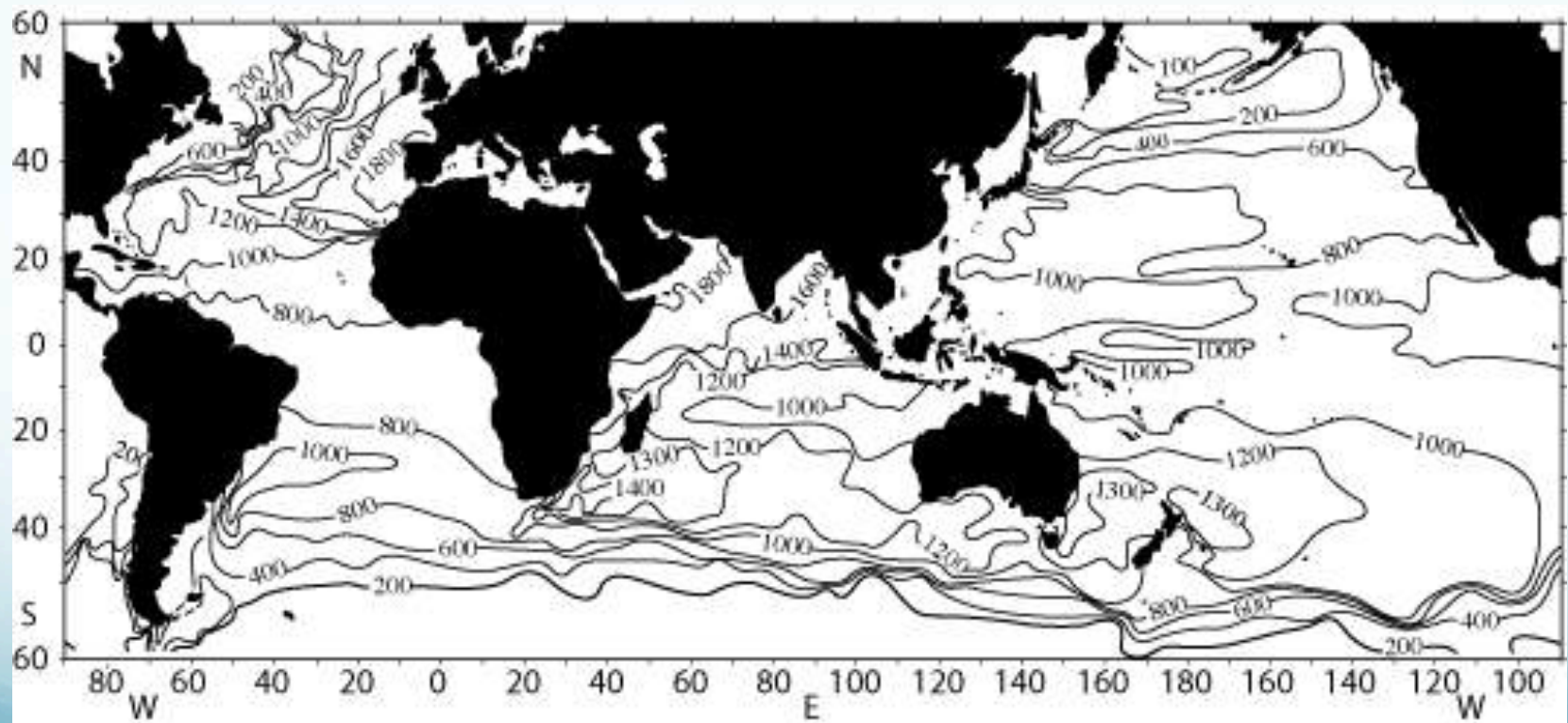


Source: <http://www.divediscover.whoi.edu>

- The speed of sound in the ocean varies because of the combined effects of water temperature and pressure, as shown in the adjacent vertical Sound Velocity Profile (SVP) chart.
- In this example SVP, there are two areas where sound travels relatively faster:
 - In warmer water near the surface, and
 - In deep water where temperature is almost constant and pressure keeps increasing with depth.
- Between these two layers is the thermocline, where temperature changes rapidly over a depth of 500 to 1,000 meters and creates a local minimum sound velocity in the SVP.
 - Acoustic waves from a source in the thermocline are refracted as they radiate away from the source.
 - As acoustic waves approach the surface they are bent back toward the bottom, and as they approach the ocean bottom they are bent back toward the surface.
- Sound travels a great distance in the deep ocean where it gets trapped in this “deep sound channel”, which acts as an acoustic wave guide and conducts sound very efficiently; particularly low frequency sound.

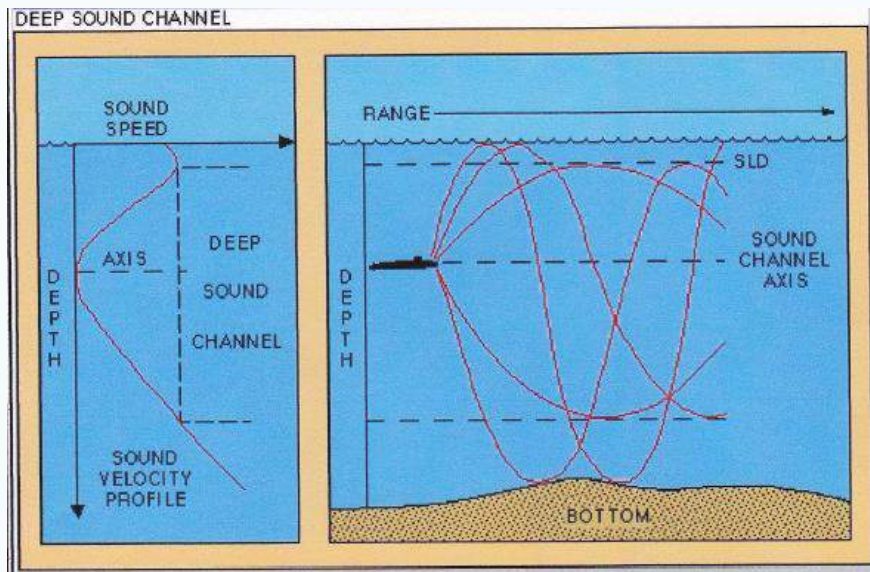
Depth of the axis of the deep sound channel (SOFAR channel)

- The axis of the deep sound channel is at the minimum velocity in the SVP.
- In low to middle latitudes, the deep sound channel is between 600 and 1200 meters below the sea surface. It is closer to the surface in higher latitudes, and at latitudes greater than about 60°N/S, it reaches the surface.



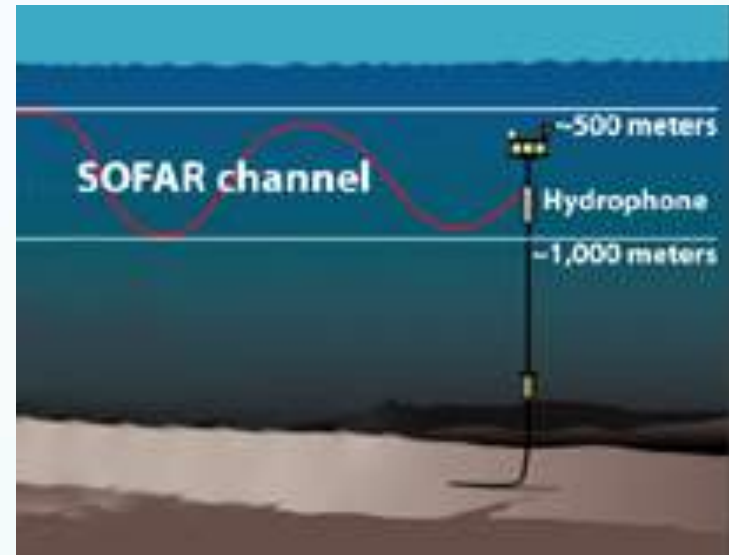
Source: <http://www.dosits.org/science/soundmovement/sofar/variability/>

Sound Surveillance System (SOSUS)



Source: <http://www.oc.nps.edu/~bird/oc2930/acoustics/soundchannel.html>

Source: <http://www.divediscover.whoi.edu/>



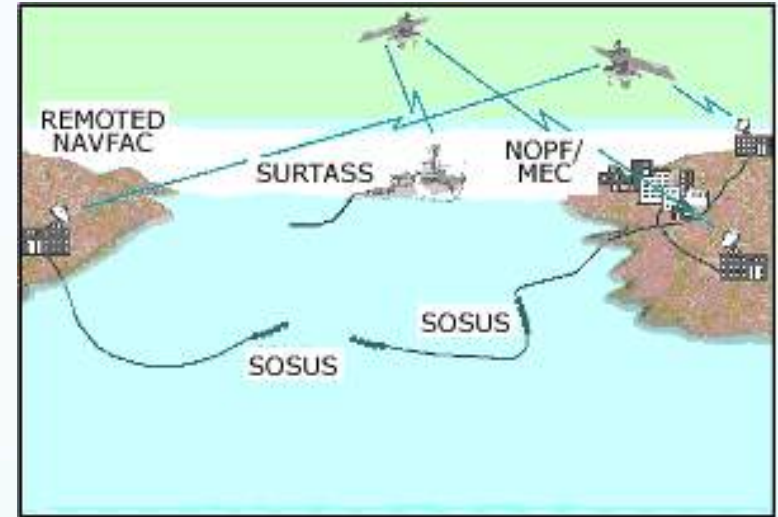
- SOSUS was a highly-classified global network of fixed hydrophone arrays that formed the backbone of the US long-range anti-submarine detection capability.
- Started in 1951 with Project Jezebel, which proved the practicality of SOFAR (SOund Fixing and Ranging) with hydrophones in the deep sound channel (SOFAR channel).
- Operational hydrophone arrays were first installed along the US east coast starting in 1952. By 1981, thirty-six stations had been installed in many locations.

Sound Surveillance System (SOSUS)

- SOSUS arrays and signal processing:
 - Very long (1,000 foot) hydrophone arrays could detect even the lowest frequencies being generated by submarines at ranges of hundreds of miles.
 - Some of the arrays were positioned to monitor natural “choke points” for transiting Soviet submarines (i.e., the Greenland-Iceland-UK gap; Straits of Gibraltar).
 - Low Frequency Analysis and Ranging (LOFAR) involved spectral analysis of the low-frequency tonals embedded in the broadband noise from a submarine.
 - These tonals form acoustic signatures that are characteristic of particular submarines.
- Examples of early SOSUS tracking capabilities:
 - 1961: The east coast SOSUS array tracked the *USS George Washington* (SSBN-598) as she transited for one of her first deterrent patrols.
 - 1962: SOSUS station in Barbados detected a Soviet Hotel/Echo/November (HEN)-class sub as it passed through the Greenland-Iceland-United Kingdom (GIUK) gap.
 - 1968: SOSUS data detected the sinking north of Hawaii of Soviet Golf-class submarine K-129.
 - SOSUS data facilitated the discovery of the wreckage site by the *USS Halibut* and the subsequent clandestine retrieval attempt conducted under *Project Azorian*.
 - 1968: SOSUS data helped find the *USS Scorpion* (SSN-589), which sank in the mid-Atlantic.
 - Wreckage was found about 3 miles from where SOSUS computers had predicted.

Sound Surveillance System (SOSUS)

- Challenges to SOSUS:
 - Starting with the Soviet Delta-class SSBNs, which were equipped with very long range strategic missiles, the SSBN patrol areas could be in the Arctic Ocean, away from SOSUS arrays.
 - Information leaked to the Soviet Navy by the Walker/Whitworth spy ring enabled the Soviets to make substantial gains in reducing the radiated noise from their later modes subs such as the Victor III and Akula-class SSNs.



Source: <http://www.dosits.org/technology/>

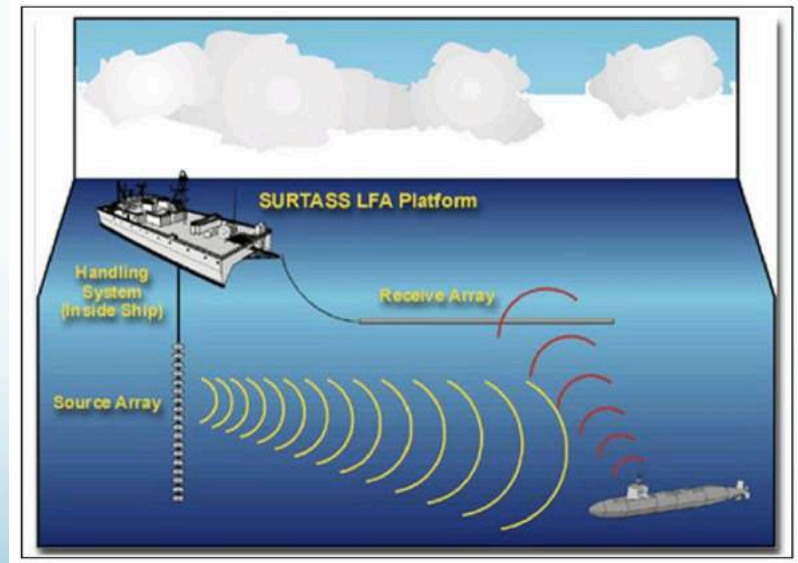
- SOSUS was supplemented with Surveillance Towed Array Sensor System (SURTASS) ships starting in 1984.
- With the end of the Cold War, the US Navy offered the civilian scientific community “dual use” of SOSUS for use in ocean environmental monitoring.
- The total investment in SOSUS is estimated at more than \$16 billion.
- The number of operating SOSUS hydrophone arrays and land stations (NAVFACs) has been reduced from the Cold War peak.
- SOSUS remains a component of the Integrated Undersea Surveillance System.

Surveillance Towed Array Sensor System (SURTASS)

- SURTASS/CLFA is a low frequency, passive and active acoustic surveillance system installed on Tactical Auxiliary General Ocean Surveillance Ships (T-AGOS) as a component of the Integrated Undersea Surveillance System (IUSS).
 - SURTASS provides passive detection of quiet nuclear and diesel subs and enables real-time reporting of surveillance information to fleet commanders.
 - CLFA is a low-frequency active sonar system for active detection of quiet submarines operating in environments that support active sonar use.



Source: <https://en.wikipedia.org>



Source: <http://www.surtass-lfa-eis.com>

New technologies tested on one-of-a-kind operational SSNs:

Counter-rotating propellers: *USS Jack* (SSN-605)

- 1st nuclear sub with a directly-coupled main turbine (no reduction gear) driving contra-rotating propellers on concentric shafts.
- Commissioned in March 1967 at Portsmouth Naval Shipyard.
- 20 feet (6.1 m) longer than standard Permit-class SSN to accommodate the new main turbine and drive train. Propeller configuration likely similar to the final *USS Albacore* (AGSS-569) configuration.
- Performance improvement did not meet expectations based on good *USS Albacore* test results.



USS Albacore final contra-propeller configuration.

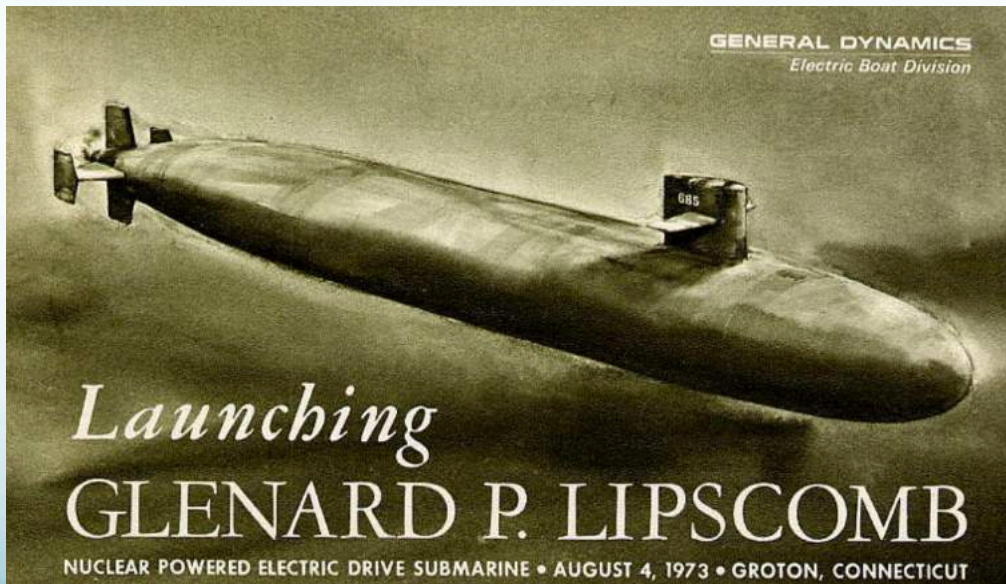
Source: Author photo

- Adequate shaft sealing (i.e., keeping seawater from leaking along the rotating shafts and into the sub), was an on-going problem.
- Decommissioned in July 1990 after 23 years of service.
- This drive train technology was not used in later US nuclear subs, which adopted single, large, seven-bladed “skewback” propellers until the introduction of pump-jet propulsors in the Seawolf and Virginia-class SSNs.

New technologies tested on one-of-a-kind operational SSNs:

Turbo-electric drive (TED): *USS Glenard P. Lipscomb* (SSN-685)

- One-ship class based on Sturgeon-class hull. 2nd-generation turbo-electric drive (*USS Tullibee* was the 1st generation).
- Commissioned in December 1974 at General Dynamics Electric Boat.
- This turbo-electric drive technology, which required substantially larger and heavier machinery, demonstrated relatively lower reliability than the conventional steam turbine mechanical drive on Sturgeon-class SSNs.



Source: General Dynamics Electric Boat Division

- This operating experience led to the turbo-electric drive not being adopted for Los Angeles-class SSNs.
- Decommissioned in July 1990 after 15.5 years of service.
- An improved turbo-electric drive is expected to be used on the new Columbia-class SSBNs.

New technologies tested on one-of-a-kind operational SSNs:

Natural circulation reactor: *USS Narwhal* (SSN-671)

- One ship class. S5G is 1st natural circulation reactor in an operational submarine.
 - Commissioned in July 1969 at General Dynamics Electric Boat
 - Reactor rated @ 90 MWt, with small main coolant pumps used only for high-power operation. The reactor was refueled twice.
- Larger hull diameter than Sturgeon-class (33 ft. vs. 31.6 ft.) to house natural circulation reactor; interior layout provided better accessibility than earlier Sturgeon-class boats; full-diameter pressure hull around the mid-ship machinery area aft of the reactor compartment (Sturgeon-class SSN pressure hull had reduced diameter surrounded by a free-flood area here).
- Directly-coupled, single main turbine (no reduction gear) delivered 17,300 shp to a single propeller.
- 1st (and maybe only) US sub to use “scoop” seawater injection for cooling water (this feature is used on several Russian subs).
- Quietest US submarine until Ohio-class SSBNs and Seawolf-class SSNs.
- Decommissioned in July 1999 after 30 years of service.
- Natural circulation reactor technology is employed in S8G for Ohio-class SSBNs and the S9G for Virginia-class SSNs.



Source: US Navy

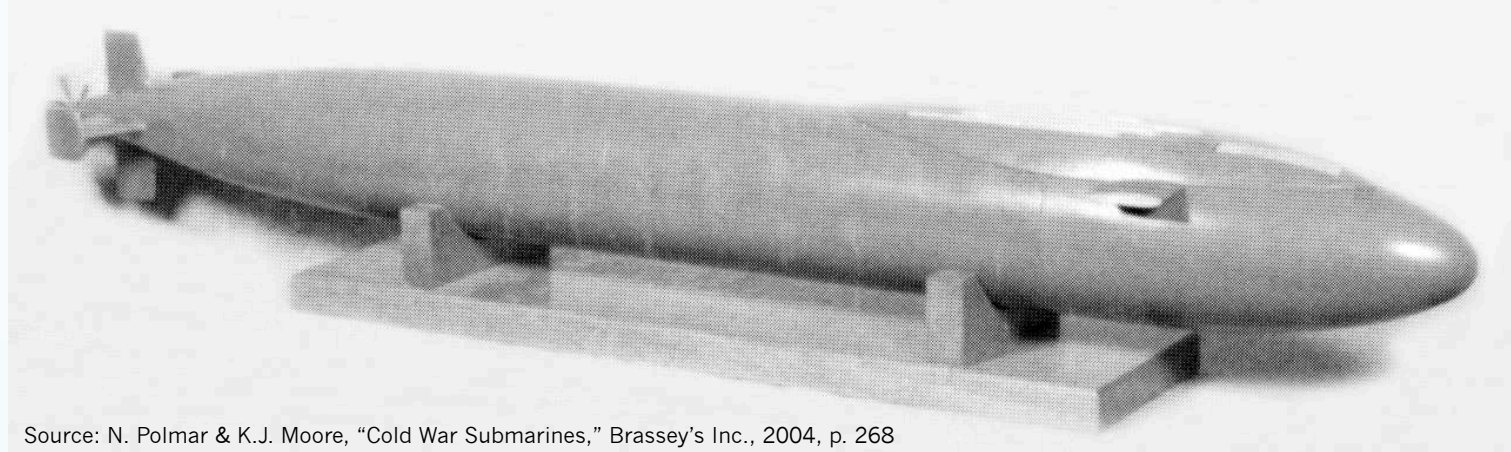
New technologies tested on one-of-a-kind operational SSNs:

Polymer injection: *USS Jack* (SSN-605) & *USS William H. Bates* (SSN-680)

- This technology involved injecting a liquid polymer at the nose of a submarine to temporarily reduce the flow drag on the hull and / or reduce radiated noise.
- The *USS Albacore* (AGSS-569) tested this technology with positive results in 1970 – 1972.
- Two nuclear submarines tested the use of polymer injection:
 - *USS Jack* (SSN-605) trials focused on noise reduction.
 - *USS William H. Bates* (SSN-680) trials focused on drag reduction.
 - A basic problem was the limited supply of polymer.
- Subsequent laboratory tests at Pennsylvania State University demonstrated the effectiveness of polymer injection for drag reduction.
 - The Navy reported, “The new advanced polymers and injection system is projected to achieve submerged speed increases on 20%. Quieter operation at tactical speeds are also expected from its use.”
- A follow-up full-scale test on a Los Angeles-class SSN was planned, but was cancelled in the early 1990s.
- Use on polymer injection on Seawolf-class SSNs appears to have been considered, but not implemented.

CONFORM SSN

(CONcept FORMulation)

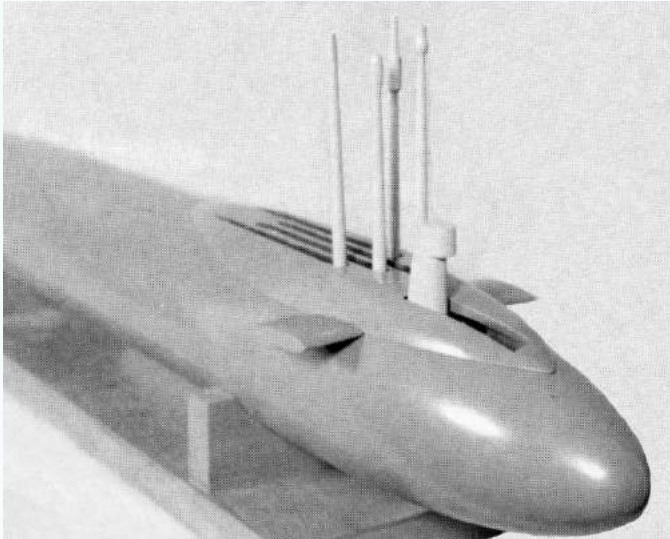


Source: N. Polmar & K.J. Moore, "Cold War Submarines," Brassey's Inc., 2004, p. 268

- CONFORM was a Naval Sea Systems Command program that was formally chartered on 22 September 1967 to develop a preferred design concept for a lighter, faster, quieter, cost-effective attack submarine. The CONFORM SSN was conceived as an alternative to a larger, more powerful SSN envisioned by Naval Reactors (ultimately the NR design would become the Los Angeles-class SSN).
- NAVSEA's CONFORM program was led by Capt. Donald H. Kern, a Massachusetts Institute of Technology-trained naval architect. By 1968, the program produced 36 design concepts that were evaluated against five SSN mission profiles.
 - Design trade-offs included: type of reactor (S5W, S5G derivative & D1G derivative), number of reactors, number of main propulsion turbines, propeller type (single, contra-rotating), test depth (same as Sturgeon, deeper, or shallower), number of weapons, number of torpedo tubes & tube diameter (533 mm or larger), sonar suite, sail size (including no sail, with periscopes and masts that folded down flush onto the hull rather than retracting vertically into the hull), and degree of automation.

CONFORM SSN

(CONcept FORMulation)



- The “signature” CONFORM SSN design with folding masts and periscopes reduced the number of pressure hull penetrations, provided more flexibility in the internal arrangement of the control / attack center, and eliminated the need for a sail. A small bridge structure could be raised when surfaced and then folded down flush onto the hull for submerged operation.
- Study results:
 - A CONFORM SSN would cost more than Sturgeon-class SSNs then being produced, but less than NR’s planned D1G-powered fast SSN.
 - Powered by a derivative of the S5G natural circulation reactor.
 - 20,000 shaft horsepower driving counter-rotating propellers would yield a submerged speed of more than 30 knots for a CONFORM SSN hull approximately the same size as a Sturgeon-class SSN (about 4,800 tons submerged).
- Work on the CONFORM SSN was abandoned in 1969 after the Navy decided to procure the SSN-688 Los Angeles-class SSN.

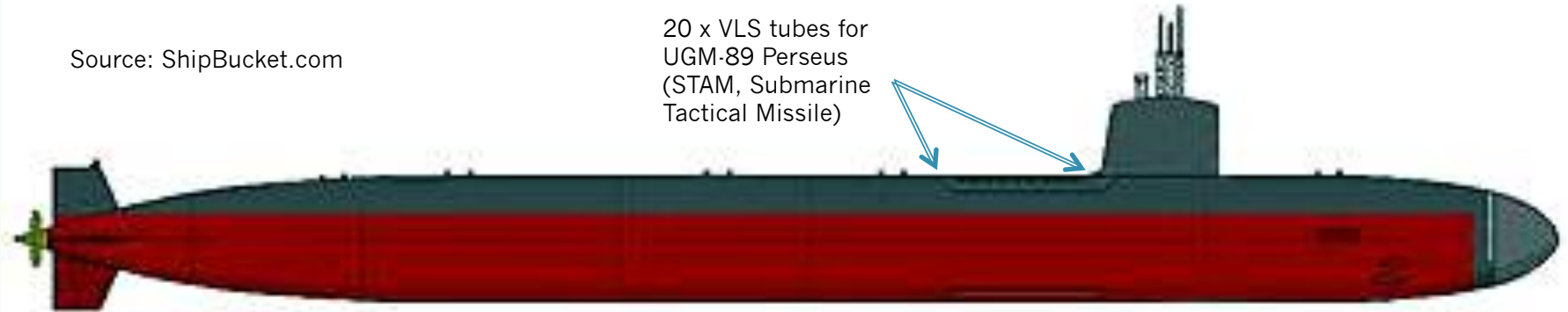
Source, top left: N. Polmar & K.J. Moore, “Cold War Submarines,” Brassey’s Inc., 2004, p. 268

Source, bottom left: <https://www.shapeways.com/>

APHNAS

(Advanced Performance High-speed Nuclear Attack Submarine)

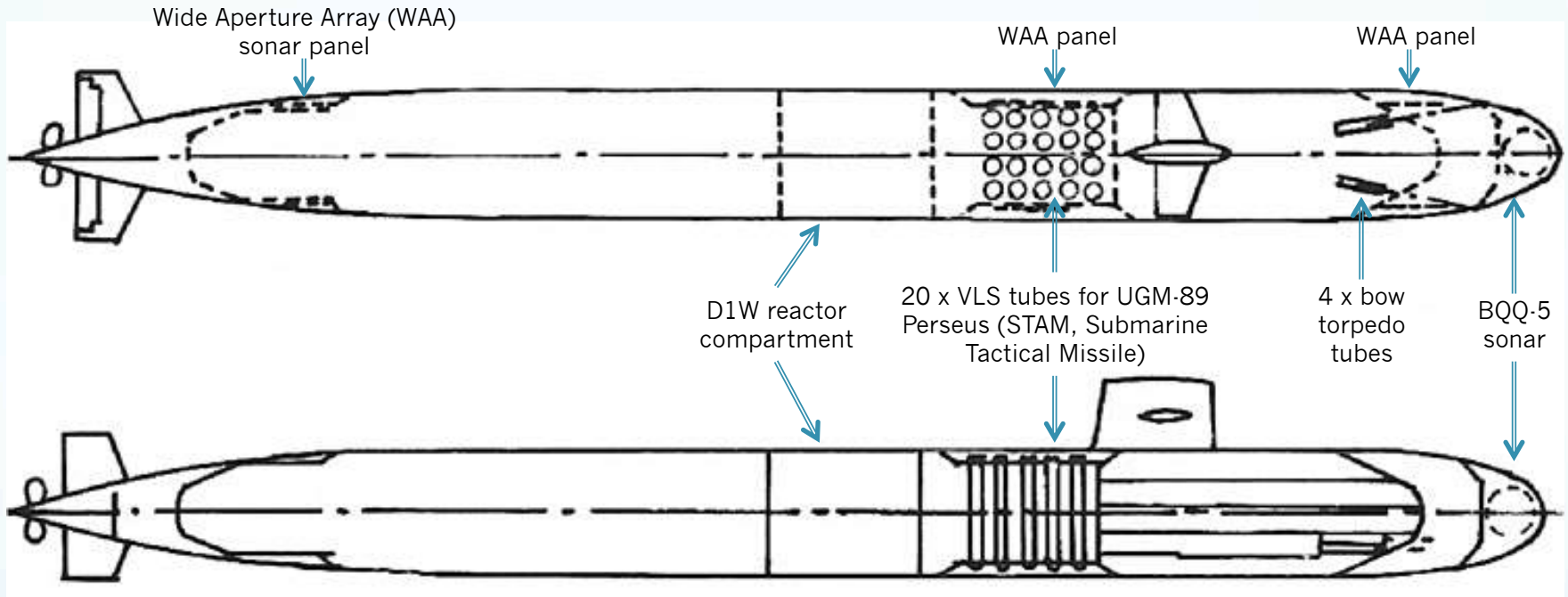
Source: ShipBucket.com



- APHNAS was the product of a 1971 – 1972 design study for an SSN capable implementing ocean area control through the use of standoff missiles targeted against newer, quieter Soviet submarines and surface fleets.
 - The sub was designed for detecting targets passively at long range and then obtaining an entirely passive fire control solution using a towed array sonar. The sonar suite also included a new wide aperture array (WAA) with three, large, planar passive sonar arrays along the flanks of the submarine hull and a large bow active sonar.
- 26 June 1971: APHNAS concept report was presented to the Chief of Naval Operations (CNO), who then requested a preliminary design by 18 August 1971.
- Propulsion
 - 1 x D1W reactor rated @ 300 MW (est.), 2 x main steam turbines delivering a combined 60,000 shp (44.7 MW) (est.) to a single propeller.
- Armament:
 - 20 x anti-ship and anti-submarine versions to the STAM (Submarine TACTical Missiles, aka UGM-89 Perseus) in vertical launch system (VLS) tubes (four rows of five tubes) aft of the sail.
 - 4 x 533 mm (21 in) mid-ship torpedo tubes

APHNAS

(Advanced Performance High-speed Nuclear Attack Submarine)



Source: N. Friedman, "US Submarines Since 1945," Naval Institute Press, 1994, p. 170

- Larger hull diameter (40 ft, 12.2 m) required to accommodate the D1W reactor.
- Crew of 111: 12 officers, 15 CPOs and 84 enlisted.
- 1972 cost estimate: \$500 - 600 M for lead boat, \$300 - 400 M for follow-on boats.
- The APHNAS and STAM were cancelled by CNO Admiral Elmo Zumwalt in 1973. This action assured continuing production of the Los-Angeles-class SSN.
- The WAA was developed further for use on Seawolf-class SSNs.

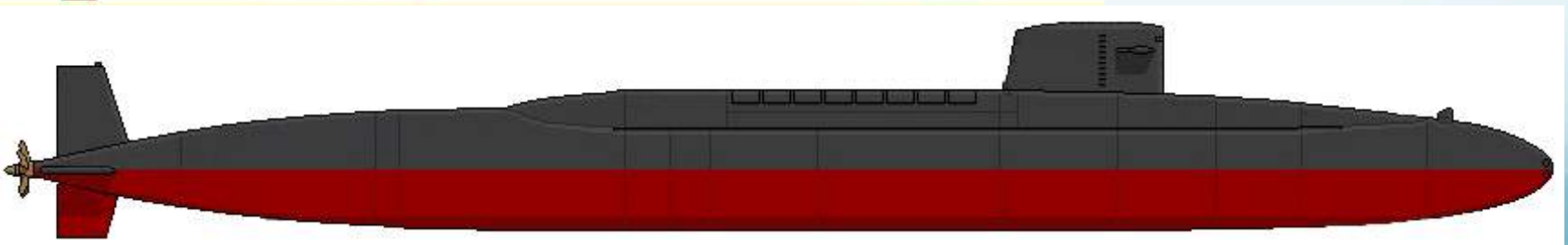
“Slow attack” SSNs

(Early Polaris SSBN conversions to SSN)

- To comply with the SALT II treaty limits and to make room for the new Ohio-class SSBNs, several early Polaris strategic missile subs were withdrawn from SSBN service, had their strategic systems removed and replaced by a tactical fire control system, and were re-designated as SSNs.
 - Three George Washington-class SSBNs, *George Washington* (SSBN-598), *Patrick Henry* (SSBN-599) and *Robert E. Lee* (SSBN-601), were re-designated as SSNs in 1982. The last boat retired in 1985.
 - All five Ethan Allen-class SSBNs were re-designated as SSNs in 1981. Two became special operations force (SOF) SSNs, while *Ethan Allen* (SSBN-608), *Thomas Edison* (SSBN-610) and *Thomas Jefferson* (SSBN-618) became “slow attack” SSNs. The last SSN retired in 1985 and the last SOF operated until 1992.
 - The SSBN conversion subs had less capable sonar suites than the contemporary Sturgeon-class SSNs and did not have “rafted” engineering systems for quieter operation. They were retained primarily for training, anti-submarine warfare exercises, and other secondary duties.
- Two Ben Franklin-class SSBNs were converted in 1992 – 1994 to SSNs for SOF duty: *Kamehameha* (SSN-642) and *James K. Polk* (SSN-645). The last of these two boats, *Kamehameha*, retired in 2002.



Relative size of a Sturgeon-class SSN (292 ft, 89 m) & a Polaris SSBN conversion to SSN (410 ft, 125 m). Both had 15,000 shp S5W propulsion plants.



Source: Adapted from <https://www.the-blueprints.com/blueprints/ships/submarines-us/>

Los Angeles (SSN-688) class

Source: usnavymuseum.org



- In the mid-1960s, Naval Reactors began working with General Electric to develop a submarine version of the D1G nuclear propulsion plant for use on a large, high-speed SSN with twice the shaft horsepower of the Sturgeon-class SSN then being built (30,000 shp vs. 15,000 shp). This evolved into the S6G reactor plant.
- The early studies identified the need for significant weight-saving design changes to deliver a maximum speed of about 32 knots. This translated into a thinner HY-80 steel hull to save 900 - 1,000 tons, but at the expense of reducing test depth relative to the Sturgeon-class SSNs.
- March 1968: Chief of Naval Operations, Admiral Moorer, organized a panel of submarine commanders to assess the design for the new high-speed SSN. The panel recommended the S6G reactor, new digital fire control and sonar systems, and the reduced test depth.
- June 1968: The Navy formally proposed this version of the D1G-powered SSN. The design was funded in the FY 1970 budget: \$234 M for the lead ship and \$156 M for each follow-on boat.

Los Angeles (SSN-688) class

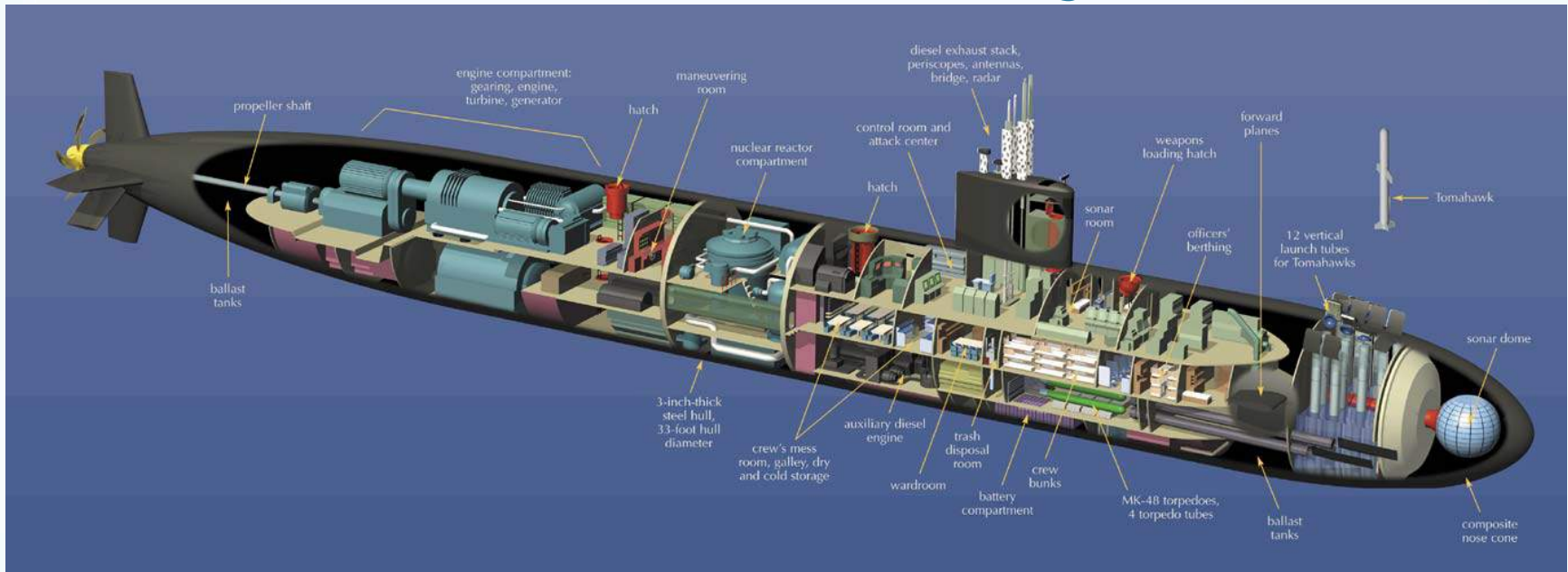
- The resulting SSN-688 Los Angeles-class, with 62 boats, became the largest class of US nuclear subs.
 - Originally designed for a 30 year service life.
- Built by two different contractors, General Dynamics Electric Boat Division (33 boats) and Newport News Shipbuilding Co. (29 boats), and commissioned in a 20-year period from 1976 – 1996.
- Three variants:
 - Flight I (31 boats, IOC 1976):
 - Relative to Sturgeon-class: faster, quieter, improved weapons system, larger diameter hull, fewer masts and less surveillance capability.
 - Flight II (8 boats, IOC 1985):
 - Added 12 x Vertical Launch System (VLS) launchers in the bow, in the free-flood area forward of the pressure hull.
 - Improved, life-of-the-boat D2W reactor core installed.
 - Improved 688i (23 boats, IOC 1988):
 - 12 x VLS launchers in the bow & D2W reactor core, as on Flight II boats.
 - Improved sonar: BSY-1
 - Relocated forward diving planes from the sail to the hull.
 - Hardened sail for Arctic operations.

Los Angeles (SSN-688) class

- Propulsion:
 - 688 Flight I boats:
 - 1 x S6G reactor plant with a D1G-2 reactor core rated @ 150 MWt. One mid-life refueling was required.
 - 2 x main steam turbines delivering a combined 30,000 shaft horsepower (22 MW) (est.) to a single propeller.
 - In 20 of the 31 Flight I boats, the D1G-2 core was replaced with the more powerful D2W core during mid-life refueling. The remaining 11 Flight I boats did not receive a mid-life refueling and were retired early.
 - 688 Flight II and 688i boats:
 - 1 x S6G reactor plant with a D2W reactor core rated @ 165 MW. D2W was designed to be a life-of-the-boat reactor core.
 - 2 x main steam turbines delivering a combined 33,500 shp (25 MW) (est.) to a single propeller.
- Armament:
 - 4 x 533 mm (21 inch) mid-ship torpedo tubes; storage in the torpedo room for 21 weapons: Mk-48 torpedo; Harpoon anti-ship cruise missiles; Tomahawk land-attack cruise missile (TLAM). The only submarine-launched mine currently available is the Mark 67 SLMM mine.
 - Flight II and 688i boats also have 12 x vertical launch system (VLS) launchers in the bow free-flood area (outside the sub's pressure hull), for Tomahawk cruise missiles.
 - Originally carried nuclear-armed UUM-44 SUBROC anti-submarine missiles, which were retired in 1989 and the nuclear-armed UGM-109A TLAM-N, which was removed from all Navy ships in 1992. Also capable of handling the Mark 60 CAPTOR mine, which was retired in 2001.

Improved Los Angeles (SSN-688i) class

SSN-751 to -773 internal arrangement



Source: <http://americanhistory.si.edu/subs/>

- There are 12 x VLS tubes in the bow, outside the pressure hull, primarily for Tomahawk cruise missiles (similar to Flight II boats).
- Capable of carrying a Dry Deck Shelter on the top deck, docked to the sub via the hatch (emergency escape trunk) behind the sail, for special operations forces and their equipment.
- The forward auxiliary machinery spaces and the diesel engine are on the lowest level, below the crew's mess and galley.
- Underway access to the engineering spaces is by means of a shielded tunnel running along the inside of the hull, from the mid-deck crew's mess area to a mid-deck in the engine room.

Los Angeles (SSN-688) class

Mark-45 Vertical Launch System (VLS)



Source, 4 photos: <http://www.seaforces.org/wpnsys/SUBMARINE/Mk-45-vertical-launching-system.htm>

Los Angeles (SSN-688) class

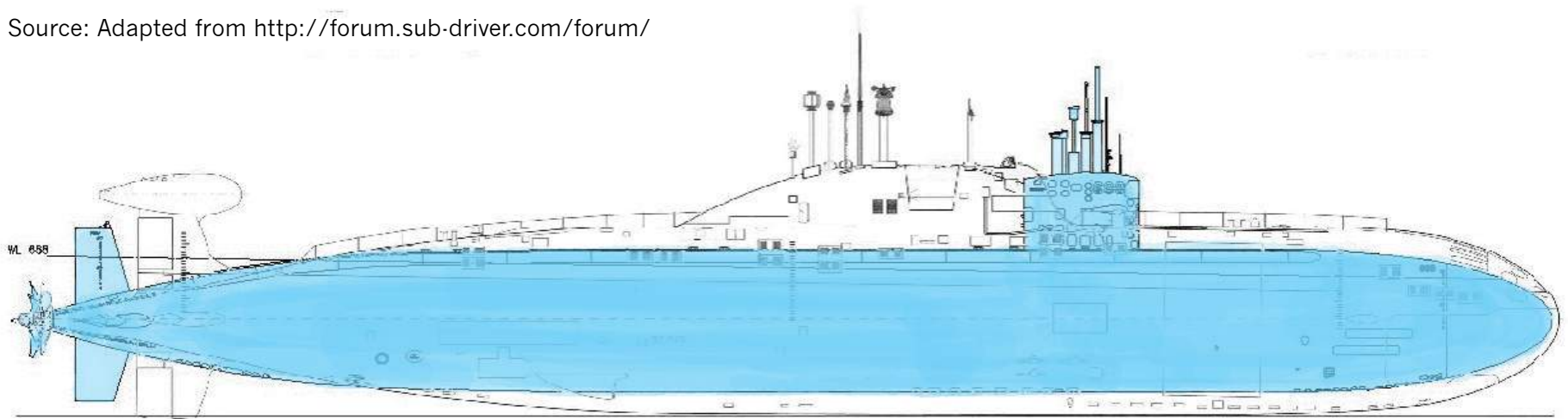
- Operational matters:
 - 1986 - 1989: Manufacturing and welding technology for higher-strength HY-100 steel was demonstrated on hull inserts installed during the construction of *USS Miami* (SSN-755) and *USS Scranton* (SSN-756) at EB and NNS. This de-risked the choice of HY-100 for the Seawolf-class SSN hull. The keel for *USS Seawolf* was laid in 1989.
 - 17 Jan 1991: *USS Louisville* (SSN-724) fired the 1st submarine launched Tomahawk cruise missiles in combat during *Operation Desert Storm*, after a 14,000 mile (22,531 km) transit from San Diego, CA.
 - 1995 – 1999: 11 Flight I boats were decommissioned early after their mid-life reactor refuelings were cancelled. These boats had an average of 13 years of life remaining on their 30 year service life. The cost of a refueling overhaul for each boat reportedly exceeded the cost to inactivate the boat by about \$210M.
 - 1997 – 2003: The Acoustic Rapid COTS Insertion (A-RCI) program was implemented on all 688-class SSNs, transforming their existing sonar systems (AN/BSY-1, AN/BQQ-5, or AN/BQQ-6) to a more capable and flexible integrated system that implemented commercial off-the-shelf (COTS) hardware in an open system architecture (OSA), facilitating future rapid insertions of new technologies.

Los Angeles (SSN-688) class

- Operational matters (cont'd):
 - 2000: SSN-688 class service life was extended from 30 to 33 years. (NAVSEASYS COM letter 4700 Ser 392A34/0146 dated 13 October 2000).
 - 2004: NR developed an improved generic reactor plant instrumentation & control (I&C) system, which was installed first on Los Angeles-class SSNs and later on Ohio-class SSBNs / SSGNs. The goal was to establish a common reactor plant I&C architecture for all of these subs.
 - January 2005: *USS San Francisco* (SSN-711) collided with a seamount while transiting at high speed and moderate depth in the Pacific.
 - 2012: While in Portsmouth Naval Shipyard, 688i-class *USS Miami* (SSN-755) was severely damaged by an arson fire in the forward part of the boat. The ship was decommissioned in 2014.
 - The last 688i-class boats currently are scheduled to retire by 2029, at the end of their 33-year service life.
 - A May 2017 Congressional Research Service report (RL32418) indicated that the Navy is considering extending the service life of these boats to 36 – 37 years to help mitigate the impending fleet shortfall in SSNs.
 - As of early 2018, three refueled 688 Flight I boats still were in active service, all having have served for more than 34 years. Two are scheduled to be retired in 2018, when the oldest will have a service life of 37 years. The last will be retired in 2019 after a 38 year service life. At least from the perspective of the submarine systems, the feasibility of life extension has been demonstrated.

Comparison of Los Angeles & Russian Akula-class SSNs

Source: Adapted from <http://forum.sub-driver.com/forum/>



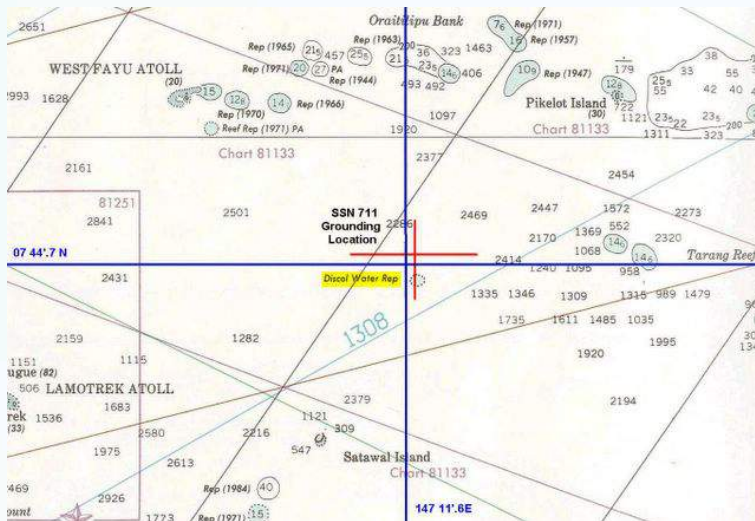
Los Angeles-class SSN:

- Length: 362 ft (110 m)
- Hull beam: 33 ft (10 m)
- Submerged displacement: 7,685 tons (6,927 tonnes)
- Test depth: about 950 ft (290 m)

Akula II & III-class SSN:

- Length: 372 ft (113.3 m)
- Hull beam: 45 ft (13.5 m)
- Submerged displacement: 13,400 – 13,800 tons
- Test depth: about 1,710 ft (520 m)

USS San Francisco (SSN-711) collision with a seamount in the Pacific



Source: lubbers-line.blogspot.com

- 8 Jan 2005: While transiting at flank (maximum) speed and submerged to 525 feet, Los Angeles Flight I-class SSN *San Francisco* hit a seamount in the Pacific that did not appear on the chart being used for navigation. However, other charts in *San Francisco's* possession displayed a navigation hazard in the vicinity of the grounding.
- One crewman was killed. The sub recovered from the collision and was able to return to port. It was repaired, returned to service, and later converted to a Moored Training Ship (MTS).



Source: <https://www.flickr.com/photos/tth91722/3539664246>



Seawolf (SSN-21) class

Source: www.shipbucket.com



- Designed to operate autonomously against the world's most capable submarine and surface threats. When the sub was designed in the 1980s, its primary mission was to destroy Soviet SSBNs before they could attack US targets. It is an ASW sub.
- Originally, 29 Seawolf-class subs were planned. Designed jointly by Electric Boat and Newport News Shipbuilding. Only three were built by Electric Boat after program cuts that were due primarily to high program cost and the perception of a decreased threat level following dissolution of the USSR in 1991.
- An early program cost estimate in the 1980s was \$38 billion for 29 boats (\$1.31 billion per boat). By 1999, the program cost estimate was \$16 billion of three boats (\$5.3 billion per boat), and that estimate was made while the last boat, *USS Jimmy Carter*, was under construction (and not completed until 2005).

Seawolf (SSN-21) class

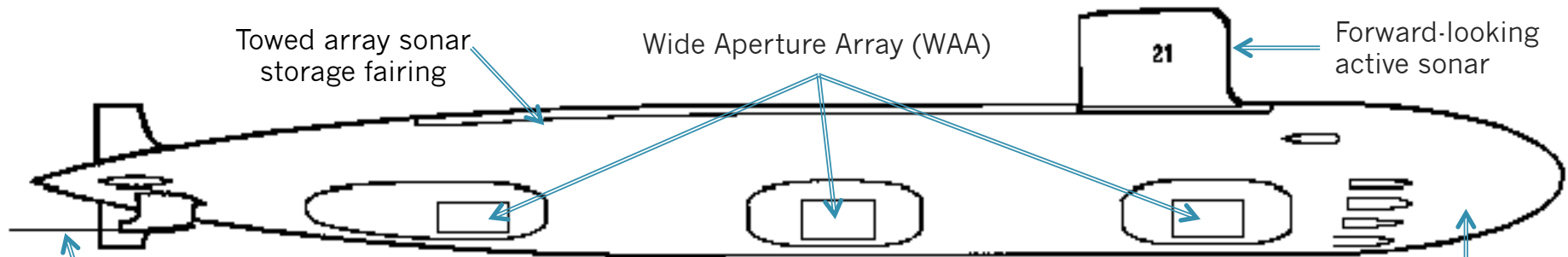
- Important design features:
 - High-strength HY-100 steel hull, first tested on two 688i subs. Original plans called for HY-130 steel, but manufacturing and welding technologies were not sufficiently advanced to use this higher-strength steel.
 - Larger diameter hull than previous SSNs (42.3 feet, 12.9 m, similar to Ohio-class SSBN / SSGN).
 - The hull is coated with cast-in-place anechoic material to help reduce the sub's noise signature.
 - 1st use of a pump-jet propulsor on a US sub.
 - Strengthened sail, designed to permit operations under the Arctic ice..
 - Capable of operating deeper and faster than 688-class SSNs, which were limited to 950 feet (290 meters).
 - Extremely quiet at all speeds. Tactical speed (the speed at which a submarine is still quiet enough to remain undetected while tracking enemy submarines effectively) is rumored to be as high as 25 kts.
- Propulsion:
 - 1 x S6W reactor rated @ 220 MWt (est.), designed for the 30 year service life of the boat without refueling.
 - 2 x steam turbines delivering a combined 45,000 shaft horsepower (34 MW) to a single pump-jet propulsor.

Seawolf (SSN-21) class

- Armament:
 - 8 x 660 mm (26 in) mid-ship torpedo tubes arranged on two decks. Tubes have sleeves for handling smaller-diameter 533 mm (21 inch) weapons or other devices.
 - Torpedo room has space for up to 52 torpedoes or other similar size devices. Typical load is about 40 x 533 mm (21 inch) Mk 48 ADCAP torpedoes.
 - Seawolf-class subs currently do not carry Harpoon anti-ship cruise missiles or Tomahawk land-attack cruise missiles, although these subs are capable of employing these weapons. The only submarine-launched mine currently available is the Mark 67 SLMM mine.
 - There are no separate vertical launch system (VLS) tubes in the bow free-flood area, as found on 688 Flight II, 688i, and all Virginia-class SSNs.
- Special-operations force (SOF) capabilities:
 - Dry Deck Shelter (DDS): can be attached to the top deck of the sub and used to store and launch a swimmer delivery vehicle and combat swimmers
 - Combat Swimmer Silo: an internal lock-out chamber that can deploy up to eight combat swimmers and their equipment at one time.

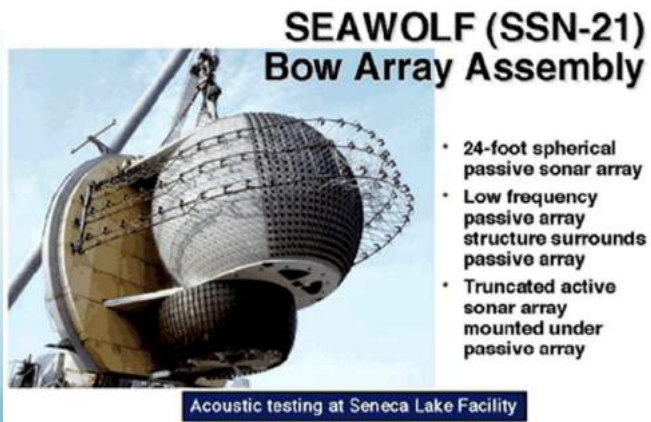
Seawolf (SSN-21) class

- Sonar systems:
 - Spherical passive bow sonar array surrounded by a low-frequency passive array
 - Chin-mounted active sonar array mounted under the spherical array
 - Three Wide Aperture Array (WAA) panels mounted along both sides of the hull
 - Towed array sonar, stowed in external fairing along the top of the hull when retracted
 - Forward-looking sail-mounted active sonar for close-in detection (ice, mines)



Towed array sonar (deployed)

Source, above line drawing:
Adapted from GlobalSecurity.org



Source (above photos): fas.org



Bow sonar arrays

Seawolf (SSN-21) class

- Operational matters:
 - The established 30 year service life for SSN 21 class submarines derives from OPNAVINST C9010.332A (NOTAL).
 - One boat in this class, *USS Jimmy Carter* (SSN-23), received a 100 ft (30.5 m) hull extension containing a “Multi-Mission Platform” (MMP) to support special operations (see the section, “*Nuclear-powered special operations submarines*,” for more details on SSN-23).
 - All three Seawolf-class SSNs currently are assigned to Submarine Development Squadron 5 and are based at Naval Base Kitsap – Bangor in Washington state.
 - Submarine Development Squadron 5 describes its mission as including responsibility for the Navy’s ocean engineering systems and as the tactical development authority for UUVs (unmanned undersea vehicles), undersea acoustic arrays, and Arctic warfare.
 - Significant logistic problems exist because these three subs have a great deal of unique equipment not found in other US subs and weaknesses have developed in the supply chain since the last sub, *USS Jimmy Carter*, was commissioned in 2005.
 - When spares have been exhausted and the original vendor no longer manufactures the item, replacement items are “borrowed” from the sub with the lowest priority (i.e., probably from the sub undergoing maintenance at the time).
 - *USS Jimmy Carter* gets the highest priority.

Seawolf (SSN-21) class

USS Connecticut (SSN-22)



Source, two photos: <http://www.seaforces.org/usnships/>

USS Seawolf (SSN-21)



Fairing for storing a retracted towed array sonar

Driving a Seawolf-class SSN



Traditional helmsman, planesman, chief-of-the-watch and diving officer

Source: US Navy

Virginia (SSN-774) class



Source: www.the-blueprints.com

- Designed as a multi-mission attack submarine, working independently or in consort with a battle group or other ships.
 - The Navy identified seven “core missions”: anti-submarine warfare, anti-ship warfare, covert intelligence, covert strike, covert mine-laying, battle group support, and special operations.
 - Slower and not as deep-diving as Seawolf-class SSNs.
 - Virginia-class SSNs retain the silencing features of Seawolf-class SSNs.
- As of early 2018, 48 Virginia-class SSNs in seven variants, Block I to Block VII, have been ordered or planned
 - 15 Block I, II & III subs have been delivered.
 - Current unit price is about \$2.6 B for a Block III boat delivered in 2018.
 - The Navy has a goal to reduce per unit procurement price to \$2.0 B.
- Service life is 33 years, as defined in Virginia-class Submarine Operational Requirements Document, Rev. A, Change 2 dated 27 October 2009.

Virginia (SSN-774) class

- Design features:
 - Emphasis on littoral (close-to-shore) operations; fly-by-wire ship control system improves shallow-water control.
 - Traditional optical periscopes have been replaced by two photonics masts that house high-definition (HD) color, black and white & infrared digital cameras on top of telescoping masts that do not penetrate the pressure hull.
 - Control room and attack center has been moved down one deck. This provides more room for an improved layout for better situational awareness.
 - Improved automation to reduce crew size. For example: the traditional helmsman, planesman, chief-of-the-watch and diving officer were replaced by just two stations manned by Chief Petty Officers.
 - Modular construction of the entire vessel, with manufacturing distributed between Electric Boat and Newport News Shipbuilding.
 - Open-architecture data systems; greater use of commercial off-the-shelf (COTS) equipment to enable simpler future upgrades.
 - Improved support for special operation forces:
 - Torpedo room can be reconfigured to house a large number of special operation forces & equipment.
 - Large internal lock-in/lock-out chamber can deploy up to nine combat swimmers and equipment at a time; compatible with a Dry Deck Shelter mounted to the deck, behind the sail (similar to Seawolf SSN).

Virginia (SSN-774) class

- Powerplant:
 - 1 x S9G reactor rated @ 210 MWt (est.). Designed for the service life of the boat, 33 years, without refueling.
 - NR states that S9G is “the first true life of the ship core – designed to provide full-power, unrestricted operation throughout the design life of a new class of ship without refueling.” (NR’s FY2003 Congressional Budget Request)
 - S9G incorporates the New Concept Steam Generator with improved corrosion performance while also improving plant quietness.
 - Secondary steam plant delivers a combined 40,000 shaft horsepower (29.8 MW) to a single pump-jet propulsor.
- Armament:
 - All Virginia-class SSNs have a similar torpedo room configuration with 4 x 533 mm (21 inch) mid-ship torpedo tubes with storage for 27 torpedoes or combinations of torpedoes, missiles and mines.
 - Mk-48 ADCAP torpedo
 - Harpoon anti-ship cruise missiles.
 - The only submarine-launched mine currently available is the Mark 67 SLMM mine.
 - Virginia-class SSNs have additional vertical launch system (VLS) tubes in various configurations, depending on the production block of the sub.

Virginia (SSN-774) class

Variants

- Block I: 4 boats; IOC 2004; all commissioned
 - Built in 10 modular hull segments with each submarine requiring roughly 7 years (84 months) to build.
 - 12 x individual Mark-45 Vertical Launch System (VLS) cells for Tomahawk land-attack cruise missiles or similar sized weapons / devices in the bow free-flood area (similar to Mark-45 VLS installations on Los Angeles-class Flight II and 688i boats).
- Block II: 6 boats; IOC 2008; all commissioned
 - Similar to Block I. Built in four modular hull segments. Construction improvements saved \$500 M and 15 months construction time on each boat.



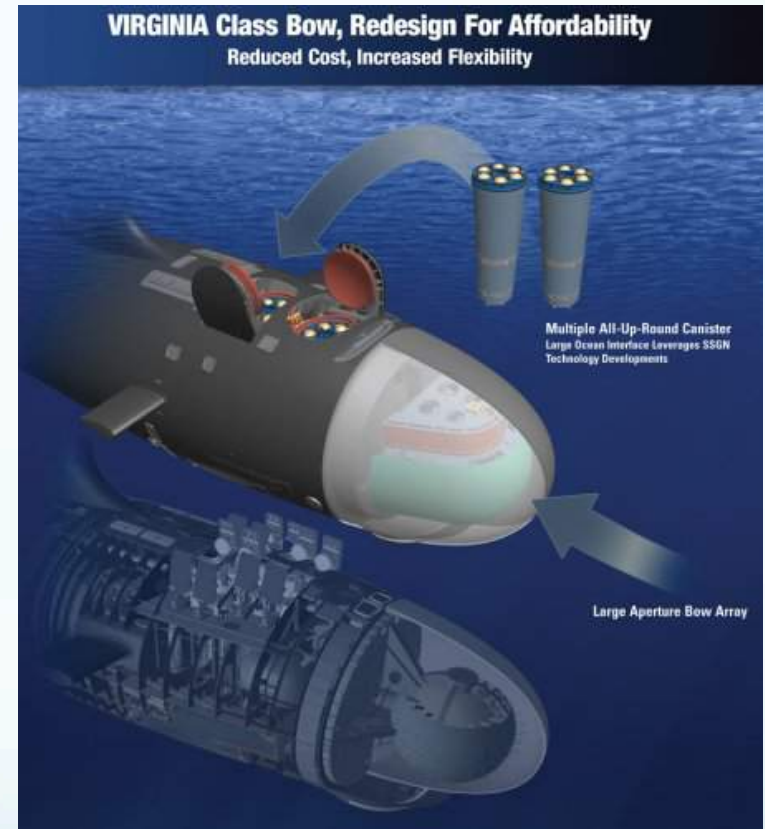
Block I *USS Virginia* (SSN-774). Source: <http://www.seaforces.org/>

Virginia (SSN-774) class

Variants

Blocks III & IV

- Block III: 8 boats ordered; construction started 2012; IOC 2014; 5 of 8 commissioned by mid-2018.
 - The 12 individual bow VLS tubes were replaced by two 87 inch (221 cm) diameter Multiple All-up Round Canisters (MACs), each housing six Tomahawk SLCMs or other weapons / devices.
 - Introduced the Large Aperture Bow (LAB) array sonar.
 - *USS Colorado* (SSN-788) construction cost is expected be \$2.6 B when delivered in 2018.
- Block IV: 10 boats ordered; construction started in 2017
 - Equipment & system improvements to reduce the number of major maintenance periods from 4 to 3 during the lifetime of the boat.
 - *USS South Dakota* (SSN-790) will be equipped with a new propulsor incorporating the Hybrid Multi-Material Rotor (HMMR), which is intended to reduce the cost and weight of the propeller/rotor as well as improve overall acoustic performance.
 - Otherwise similar to Block III



Source: NAVSEA

Virginia (SSN-774) class

Block III *USS Colorado* (SSN-788)



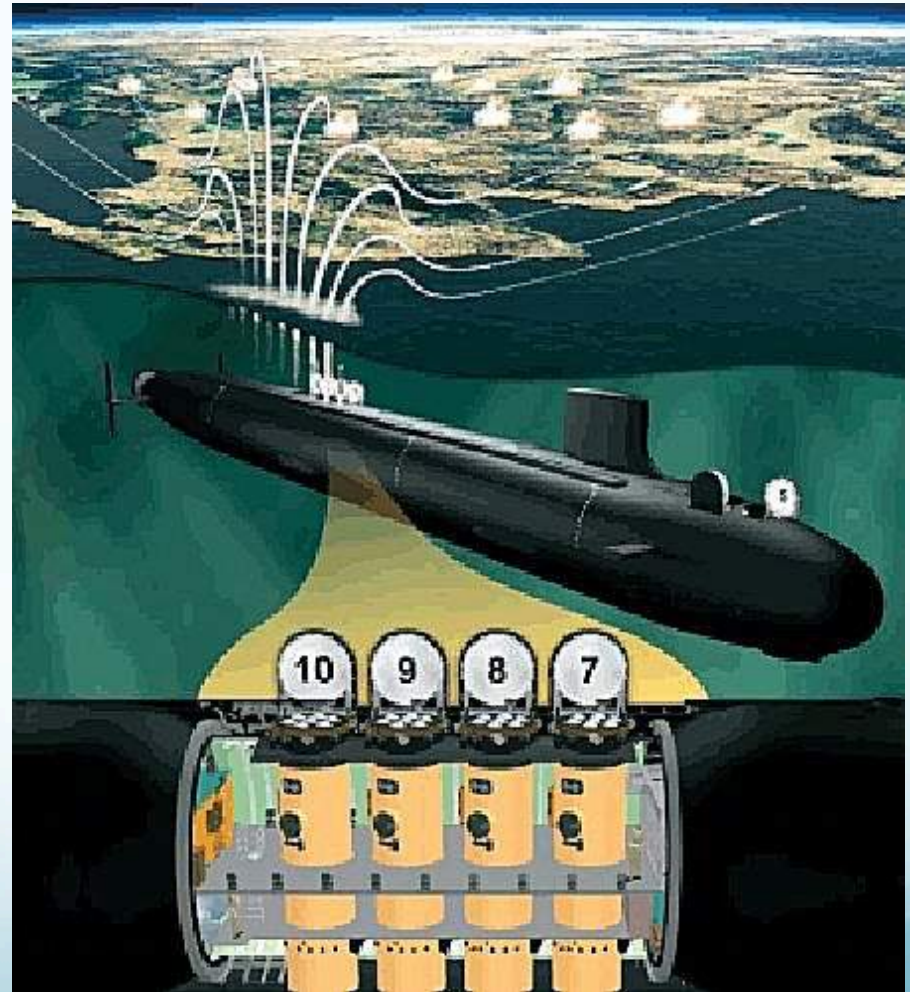
MAC doors open. Source: US Navy photo via <https://www.dvidshub.net/image/4223276/uss-colorado-ssn-788>

Virginia (SSN-774) class

Variants

Block V

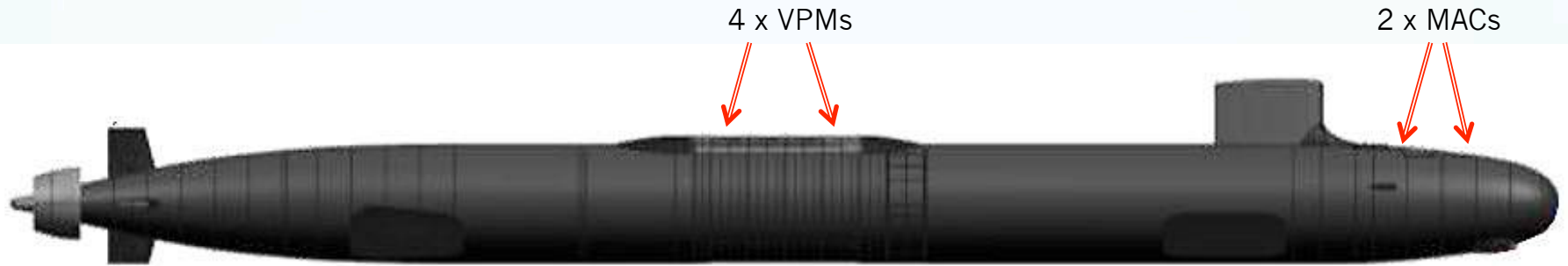
- Block V: 10 boats planned, construction expected to start in 2019
 - 2 x bow MACs as in Blocks III & IV
 - Aft of the sail, a 70 ft (21.3 m) section will be added to house four new vertical cells called Virginia Payload Modules (VPMs).
 - The design approved in October 2014 keeps the same 33 ft (10.1 m) diameter pressure hull and houses the machinery for the doors of the new VPM tubes in a small dorsal fairing.
 - MACs and VPMs can carry a total of 40 cruise missile or similar sized devices.
 - Will start replacing Ohio-class SSGNs in the mid-2020s.



Source: NAVSEA / General Dynamics

Virginia (SSN-774) class

Variants



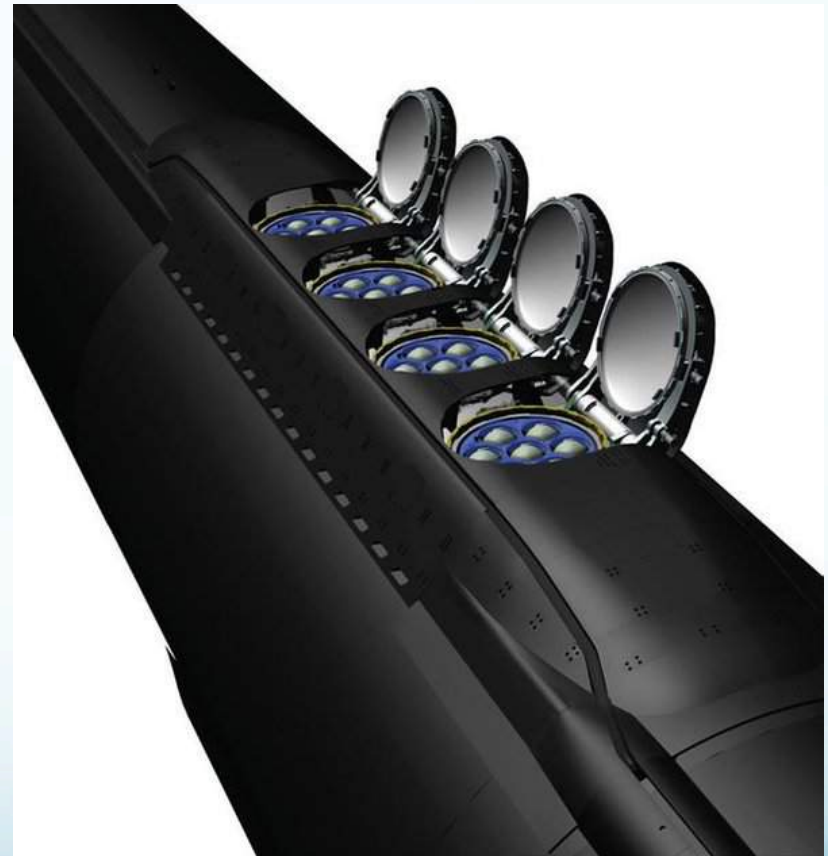
Virginia-class Block V, VI and VII SSN. Source: adapted from NAVSEA

- Two more block purchases of Virginia-class SSNs are identified in the Navy's 2017 Submarine Shipbuilding Plan. The design is expected to be similar to Block V, with two MACs in the bow and four VPMs aft of the sail.
 - Block VI: 5 boats planned; procurement of 1st unit is expected in FY2024.
 - Block VII: 2 boats currently planned thru FY2030, but expected to be a five-boat block; procurement of 1st unit is expected in FY2029.
- The Navy's recently-announced plans to increase fleet size to a 355 ships. This likely will result in additional Virginia-class SSNs being procured.
- Delays in the SSN(X) / Improved *Virginia* program also may result in additional procurement of Virginia-class SSNs.

Virginia (SSN-774) class

Virginia Payload Module (VPM)

- The large diameter (87 inch, 2.1 m) of the Virginia Payload Module (VPM) provides a volume that can be reconfigured for a wide range of missions.
- VPMs are capable of supporting:
 - Seven land-attack and/or anti-ship cruise missiles
 - UUV / UAV storage / deployment / retrieval systems
 - Special Operations Force (SOF) equipment & personnel deployment / retrieval
- Electric Boat is using a construction technique, called “tube and hull forging” to expedite building and lower costs. This involves connecting the top section of the VPM tube to the pressure hull as one integral piece, similar to the construction technique for the Common Missile Compartment (CMC) for the Columbia-class SSBN.

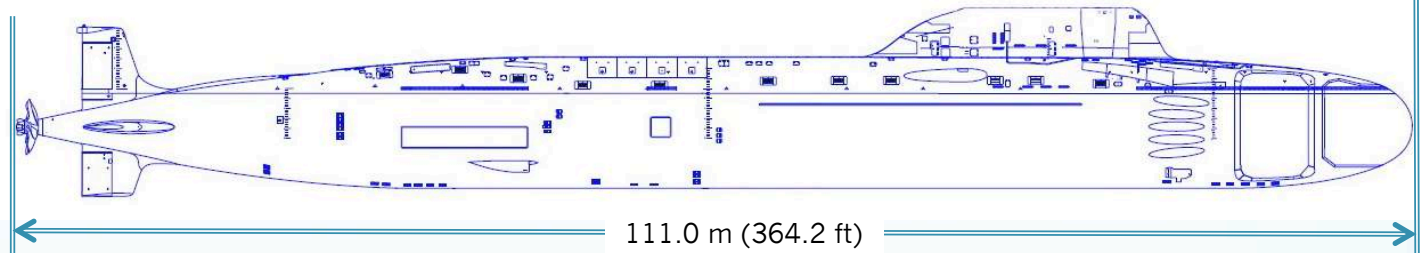


Artist's concept of VPMs. Note the raised hull fairing for the VPM hatches. Source: WhiteFleet.net, 2016

Comparison of Virginia & Russian Yasen-class SSNs



Above: Virginia-class Block I, II and III SSN. Source: www.the-blueprints.com



Above, Russian Yasen SSN / SSGN. Source: adapted from <http://www.russiadefence.net/>



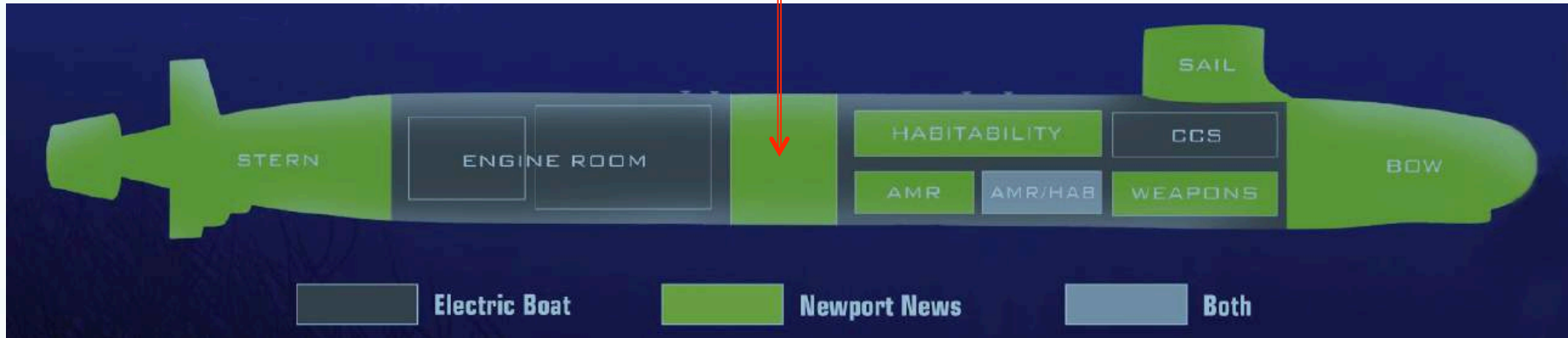
Above: Virginia-class Block V, VI and VII SSN / SSGN. Source: adapted from NAVSEA

Building a Virginia-class SSN

Work breakdown between Electric Boat & Newport News

Reactor
compartment

Source: Newport News Shipbuilding



Notes:

CCS = Command & Control Center

AMR = Auxiliary Machinery Room



Source: <https://www.sinodefenceforum.com/>

Building a Virginia-class SSN

Installing an equipment raft in a hull section



Source: navylive.dodlive.mil

Building a Virginia-class SSN

Rolling out a completed hull forward section



Block III USS *Washington*, SSN-787 bow section. Source: usswashingtoncommissioning.org

Building a Virginia-class SSN

Shipping a hull forward section from Virginia to Connecticut

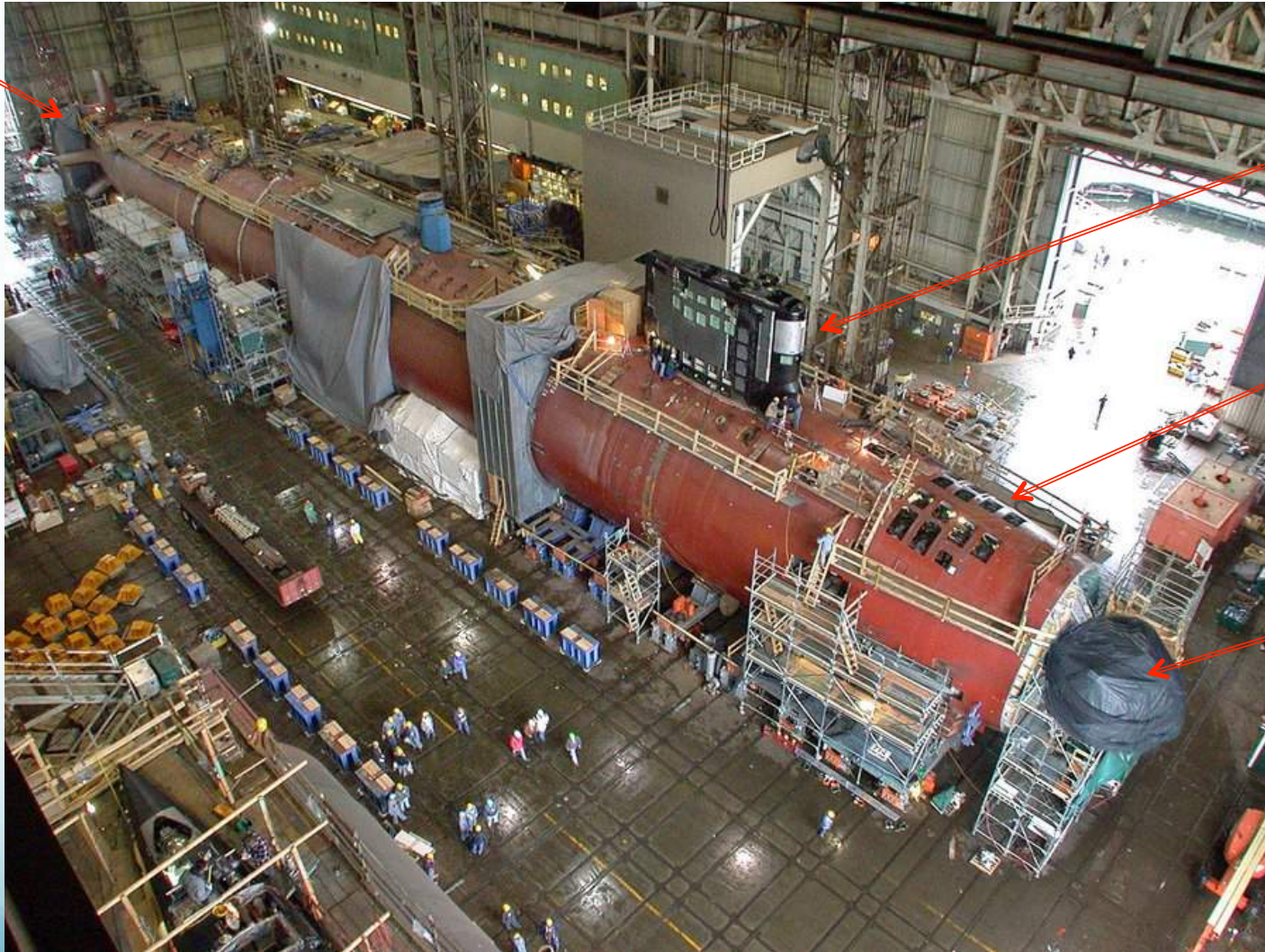


Block III *USS Colorado* (SSN-788) bow section being shipped from Newport News Shipbuilding to Electric Boat.
Source: Asian Defense News

Building a Virginia-class SSN

Hull assembly in progress

Pump-jet
propulsor



Sail-mounted
HF sonar
(under ice
& mine
detection)

12 x VLS
missile
tubes

Sonar
spherical
passive
array

Block I USS Virginia (SSN-774). Source: US Navy

Building a Virginia-class SSN

Assembly nearing completion



Block III *USS Illinois*, SSN-786.
Source: Electric Boat

Lightweight Wide Aperture Array
(LWAA) passive sonar (3rd
hydrophone panel not visible aft)

Torpedo tubes
Bow plane rigged out

Chin mounted active sonar
Bow dome over Large
Aperture Bow (LAB) array

Building a Virginia-class SSN

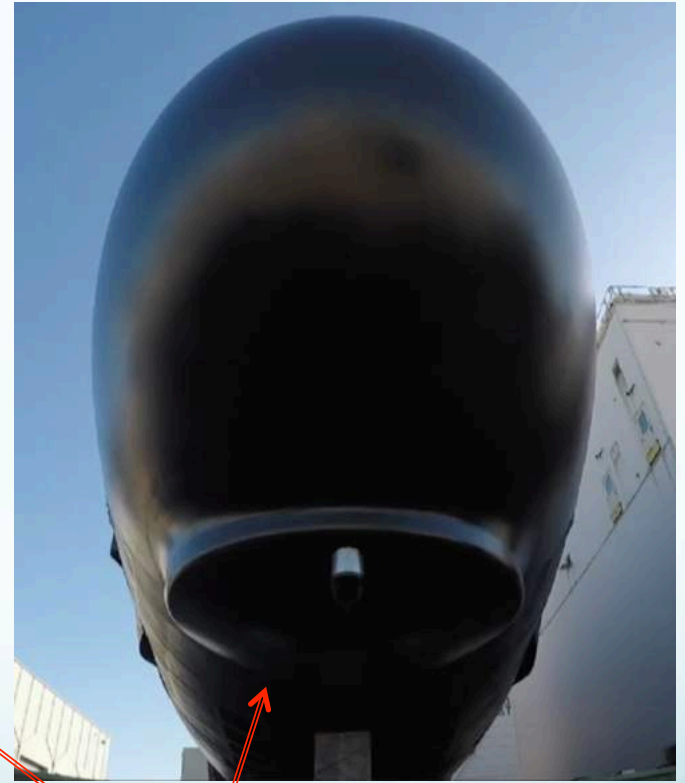
Moving out of the assembly building

Torpedo tubes



Block III *USS Washington*, SSN-787.

Source: screenshots from Newport News Shipbuilding video



Chin mounted active sonar

Building a Virginia-class SSN

Ready for launch



Block I *USS Texas*, SSN-775.
Source: Electric Boat

Building a Virginia-class SSN

Flooding up the drydock in preparation for launch

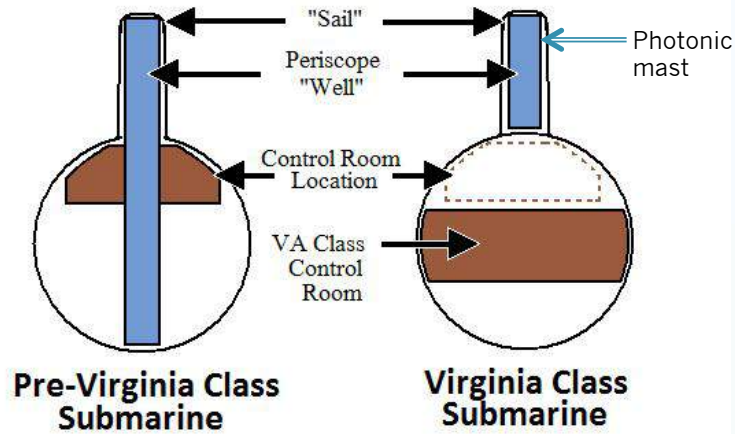


Block III *USS Washington*, SSN-787.

Source: screenshots from Newport News Shipbuilding video

Large control room

Enabled by moving the control room down one level and eliminating the conventional periscopes



Source: Naval Submarine League San Diego



Source: US Navy



Source: US Navy

Layout of the Virginia-class control room



Source: US Navy

Driving a Virginia-class SSN



Eliminated the traditional helmsman, planesman, chief-of-the-watch and diving officer by combining them into two stations manned by two Chief Petty Officers

Source: US Navy

Universal Modular Mast (UMM) and the photonic sensor package



Both photonic masts raised in above photo. Source: US Navy



Source: Naval Sea Systems Command

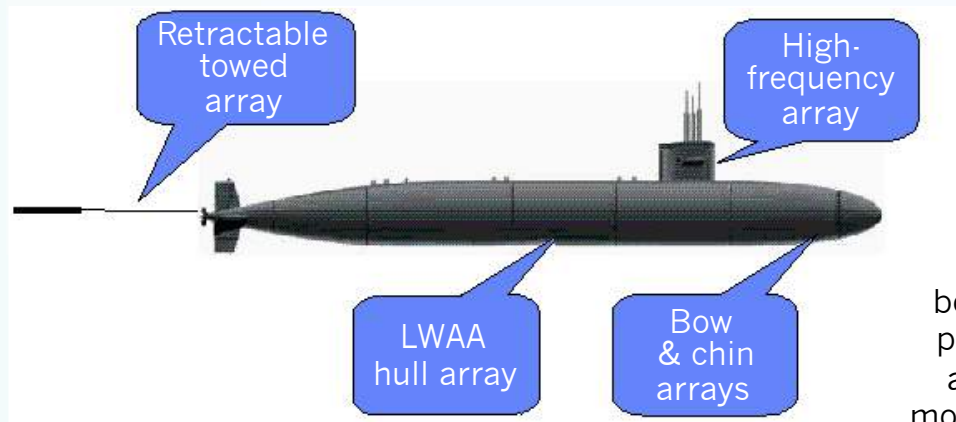
- UUM telescopic hardware is entirely within the sail. The mast does not penetrate the submarines hull, like conventional periscopes.
- Replaces conventional periscopes on Virginia-class SSNs.

- Photonic sensor package provides HD color & thermal IR video cameras, laser rangefinder, ESM, communications & GPS functions.
- Big, but designed to reduce detectability.



Source: L3 KEO

Virginia-class SSN sonar arrays



Block I & II
bow spherical
passive sonar
array & chin-
mounted active
array



Source (above): adapted from <http://www.navy.mil/>



High-
frequency
array active
sonar for
under-ice
operation
& mine
detection

<http://www.sygwestinc.com/>



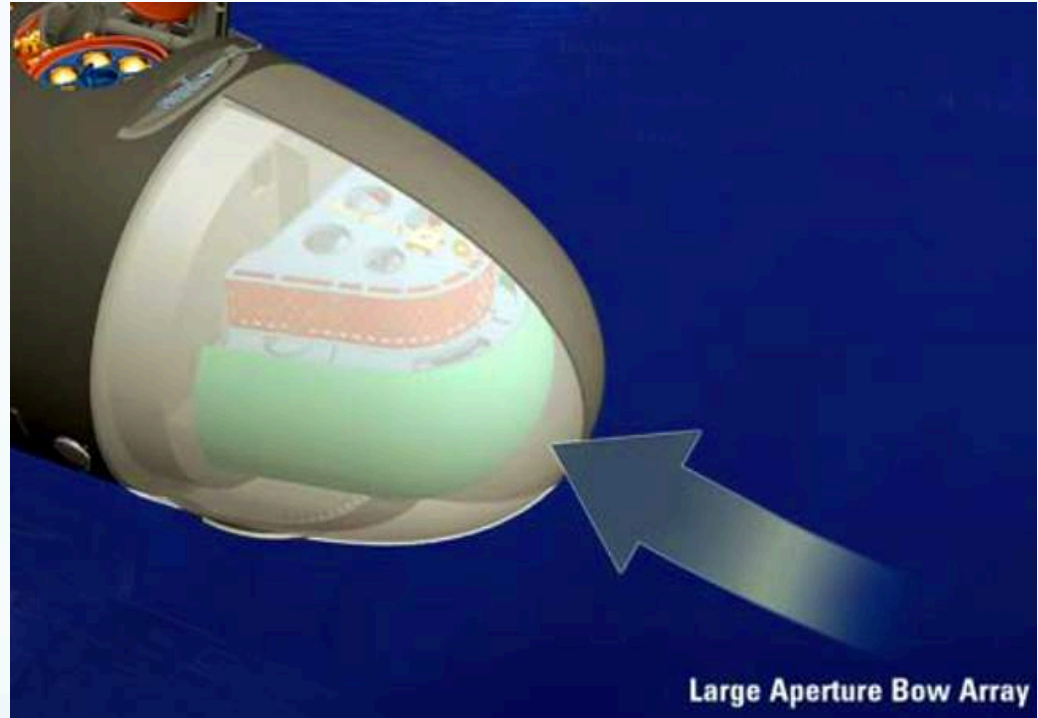
Conformal
lightweight
wide aperture
array (LWAA)

<http://lubbers-line.blogspot.com/2005>

Large Aperture Bow (LAB) array

Introduced in Virginia Block III

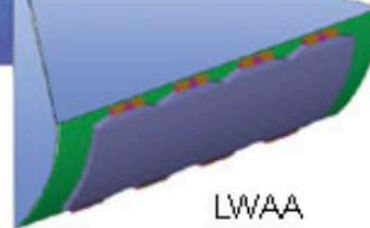
- The LAB water-backed horseshoe-shaped passive array replaces the air-backed spherical array in Virginia Block I and II boats and eliminates hundreds of SUBSAFE hull penetrations.
- Air-backed bow spherical arrays have been used in all Los Angeles, Sturgeon & Permit-class SSNs dating back to the 1960s.
- LAB also includes a medium-frequency active array.
- LAB has life-of-boat sensors similar to Seawolf-class SSNs. Sensors on Block I & II spherical arrays require mid-life replacement.
- The Columbia-class SSBN is expected to use a scaled-up version of LABs.



Source: US Navy

Lightweight Wide Aperture Array

1st submarine fiber optic acoustic sensor array

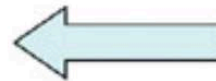
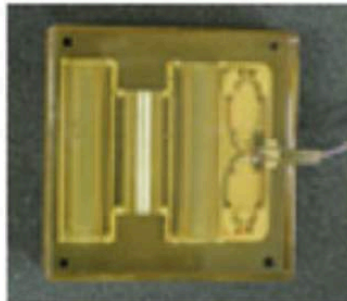


Fiber Optic LWAA

- 6 arrays (three per side)
- -450 hydrophones per array
- Provides ranging capability without maneuvers
- Passive acoustics

LWAA

All-Optical Hydrophones



Virginia-class LWAA, also expected to be used on the Columbia-class SSBN.

Source: A. Dandridge, A.B. Tveten & C.K. Kirkendall, "Development of the Fiber Optic Wide Aperture Array: From Initial Development to Production," NRL, 2004

SSN(X) / Improved *Virginia* class

- This program was initiated in 2014, with original plans that the 1st boat would be authorized in 2025. Those plans have been significantly delayed.
- Current plans call for a study phase thru 2024, when an “analysis of alternatives” should be issued. The analysis will consider:
 - The threat environment expected in the 2040 - 2050 timeframe.
 - Newer technologies that could be implemented in the design, such as:
 - Better submarine integration with other military sea, air and land platforms.
 - Advanced weapons, UUVs / UASs, and sensors.
 - Advanced nuclear reactor; beyond the TTC / NGR core developed by Naval Reactors for late-model Virginia-class SSNs. No mention has been made of possible use of a low-enriched uranium (LEU) reactor core.
 - Advanced secondary (power conversion) plant: One concept being studied by NR uses the supercritical carbon dioxide (S-CO₂) energy conversion cycle in place of the Rankine steam cycle that has been used in all US nuclear submarines. The S-CO₂ cycle potentially offers a major step change in propulsion plant technology, including a significantly smaller, simpler, more automated, and more affordable secondary plant.
 - Quieter, advanced propulsor, possibly something beyond the electric motor & conventional main propulsion shaft-driven pump-jet propulsor being implemented on the Columbia-class SSBN. Possibilities may include a shaftless electric drive (i.e., a podded drive or a “rim” drive) or an electromagnetic drive.
 - Affordability, including construction & life-cycle operating cost.
- 1st SSN(X) boat could be authorized by 2034 with an IOC date of 2044.

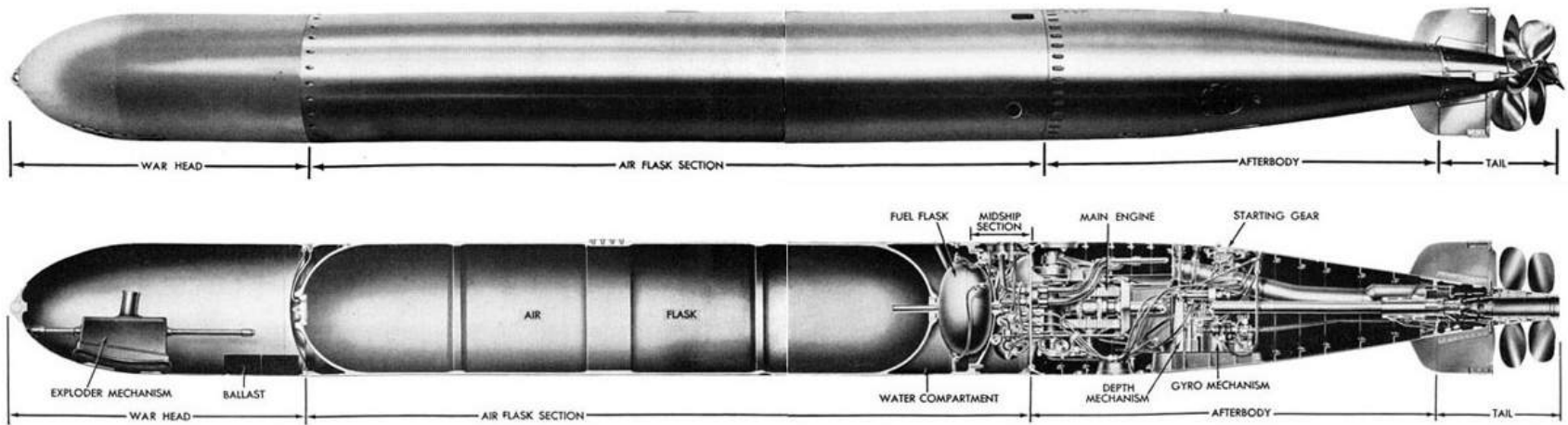
Submarine-launched
torpedoes,
anti-submarine
missiles & mines

US submarine-launched torpedoes

| Weapon | Years in service | Weight | Length | Diam | Speed / Propulsion | Range / guidance | Warhead |
|--|-------------------------------|--------------------------------|------------------------------|-------------------|---|---|---|
| Mk-14 Anti-ship torpedo | Pre-WW-II to about 1980 | 1,490 kg (3,280 lb) | 6.25 m (20.5 ft) | 530 mm (21 in) | 46 knots Ethanol + compressed air driving a turbine | 4,500 yards (4.1 km) Guidance: gyro | Conventional high-explosive (Torpex), 292 kg (643 lb) |
| Mk-37 Anti- submarine torpedo | 1956 – mid-1970s | Mod. 0 650 kg (1,430 lb) | Mod. 0 3.4 m (11.3 ft) | 480 mm (19 in) | Two speeds, 17 or 26 knots | 23,000 yards (21 km) @ 17 kts, or, 10,000 yards (9.1 km) @ 26 kts | Conventional high-explosive, 149.7 kg (330 lb) |
| | | Mod. 1 750 kg (1,660 lb) | Mod. 1 4.1 m (13.4 ft) | | Electric motor | Guidance: gyro + passive / active acoustic homing | |
| Mk-45 ASTOR Anti- submarine torpedo | 1963 - 76 | 1,089 kg (2,400 lb) | 5.76 m (18.9 ft) | 480 mm (19 in) | 40 knots Electric motor | 3.2 – 12.9 km (2 – 8 miles) / Guidance: gyro + wire guided | W34 nuclear @ 11 kT |
| Mk-48 ADCAP Heavyweight anti-sub / anti-ship torpedo | 1972 - present | 1,663 kg (3,695 lb) | 5.79 m (19 ft) | 530 mm (21 in) | 55 knots (est) Otto fuel II + “swashplate” engine | 38 km (24 mi) (est) Guidance: wire guided + passive / active acoustic homing | Conventional high-explosive, 292.5 kg (650 lb) |

Mark 14 torpedo

Anti-ship torpedo



Mark 14 external and interior views. Source: <https://en.wikipedia.org/>

- Until the IOC of the Mark 48 heavyweight torpedo in 1972, the 530 mm (21 inch) Mark 14 was the standard anti-ship torpedo in the US submarine fleet from before WW-II into the Cold War.
- Combustion of 180 proof ethanol and compressed air drove a turbine and contra-rotating propellers. At a maximum speed of 46 knots, range was 4.1 km (4,500 yards).
- A gyroscope provided guidance on a pre-set straight course to the target.
- The 292 kg (643 lb) high-explosive Torpex warhead could be detonated by a contact fuse or a magnetic influence exploder, which allowed the torpedo to be set to detonate under the keel of the target vessel.
- The Mark 13 torpedoes were withdrawn from service between 1975 - 1980.

Mark 37 torpedo

Anti-submarine torpedo



Mark 37 Mod 0 torpedo. Source: <https://en.wikipedia.org/>

- Development began in 1946; testing was conducted from 1955 - 56; IOC in 1957.
- Powered by a silver-zinc battery driving a two-speed electric motor, which provided operating speeds of 17 or 26 knots. Capable of operating to a depth of 330 m (1,000 ft).
- The 480 mm (19 inch) torpedo was launched by “swimming out” of a 533 mm (21 inch) torpedo tube.
- Gyroscope + passive sonar homing system provided initial guidance, switching to Doppler-enabled active sonar homing during the last 640 m (700 yards) to the target.
- Effective against submarine targets with speed < 20 knots and depth < 305 meters (1,000 ft). The advent of faster, deeper diving Soviet nuclear submarines greatly reduced the effectiveness of the Mark 37.
- Served as the primary US submarine-launched ASW torpedo for 25 years until it was replaced by the Mark 48 heavyweight torpedo starting in 1972.
- The Mark 67 Submarine-Launched Mobile Mine (SLMM), which was first deployed in 1983, was a modified Mark 37 torpedo body with a mine warhead.
- The NT-37 torpedo, developed in the early 1970s, was a complete rework of the Mark 37 except for its hull. The electric drive was replaced with an Otto fuel II engine (similar to Mark 48), greatly improving speed and range. NT-37 versions remained in international naval service until the early 1990s.

Mark 45 ASTOR

Anti-Submarine TORpedo



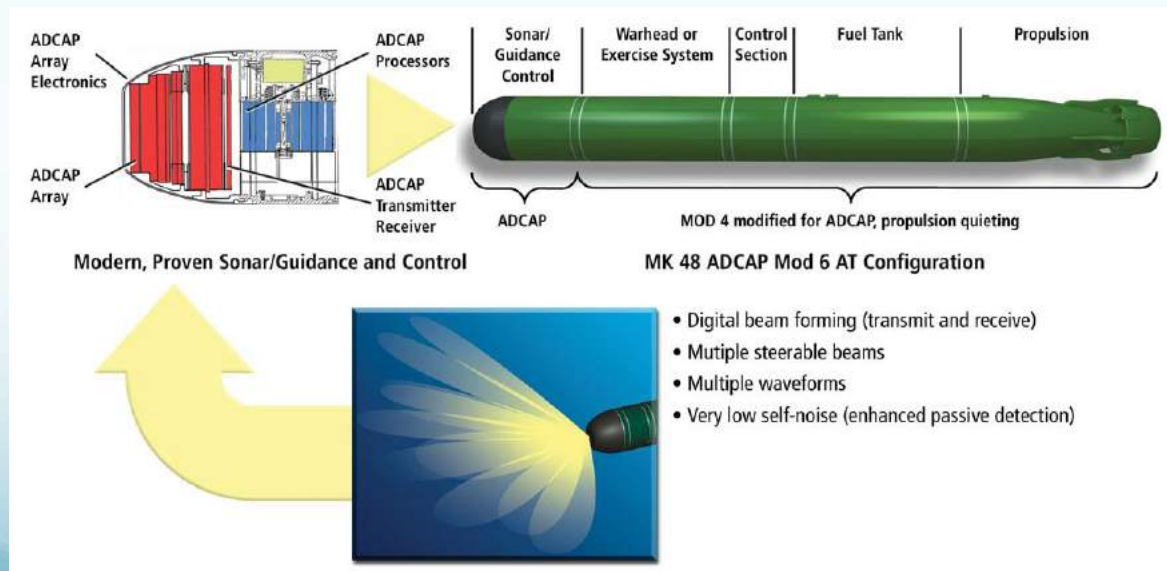
Source: <https://en.wikipedia.org/>

- Development recommended by the 1956 Naboska Study. Design was completed in 1960; IOC was in 1963.
- Powered by a seawater battery and a 160 hp electric motor; the ASTOR had a maximum speed of 40 knots.
- The 480 mm (19 inch) torpedo was launched by “swimming out” of a 533 mm (21 inch) torpedo tube.
- Gyroscope + wire-guided; the torpedo had no on-board homing capability.
- W34 nuclear warhead with a yield of 11 kT was detonated only by a command sent over the guidance wire (for positive control of the nuclear warhead). There was no contact or influence fuse.
- 600 ASTORs were produced by Westinghouse Electric.
- Withdrawn from service in 1976 and replaced by conventionally-armed Mark 48 torpedo.

Mark 48 ADCAP torpedo

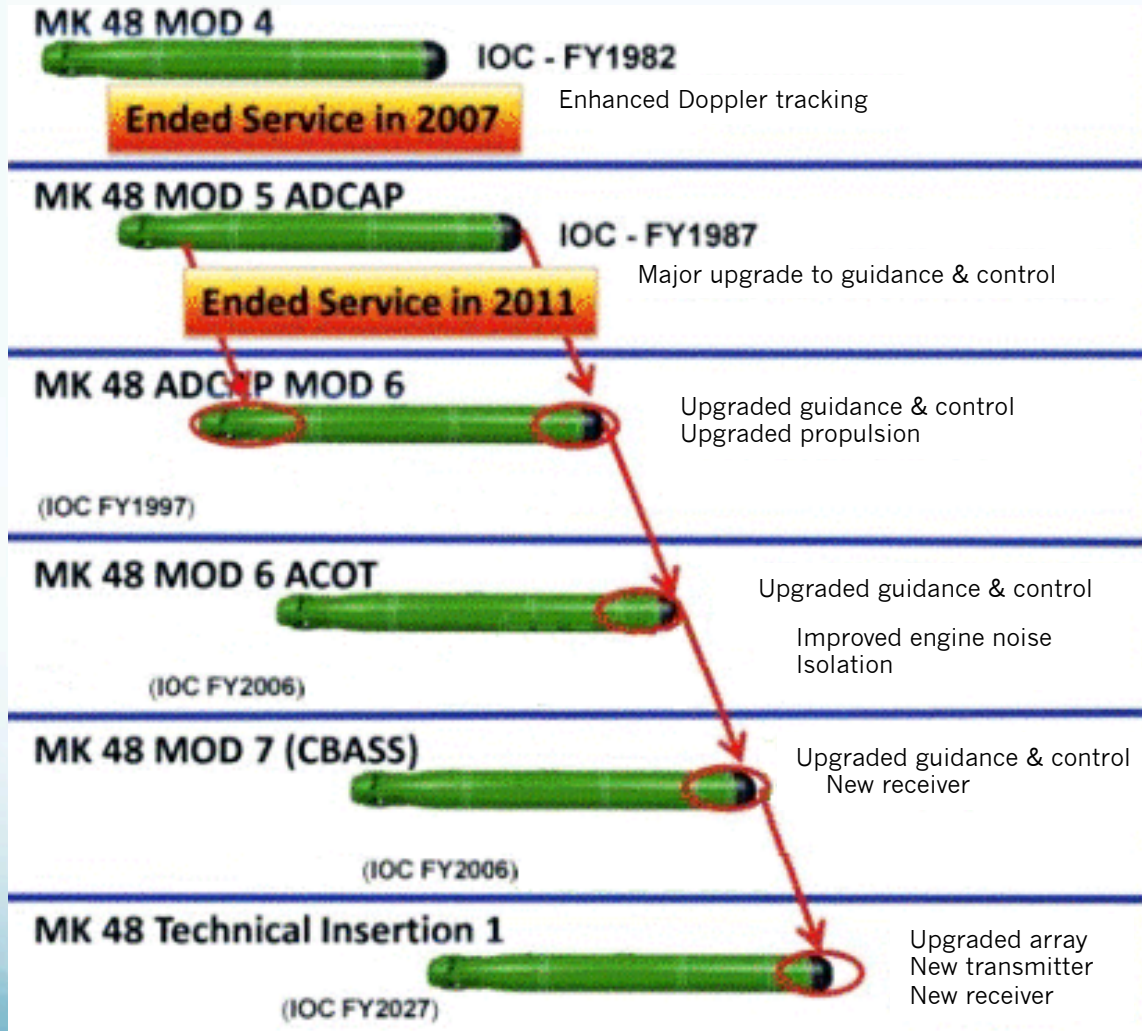
Heavyweight submarine-launched torpedo

- This is the standard heavyweight, long-range, acoustic homing torpedo carried on all US submarines; designed for use against fast, deep-diving submarines and high-performance surface ships. Also used by several other nations.
 - Performance is considered adequate for dealing with 30+ knot, deep-diving targets. Navy acknowledges depth capability > 366 m (1,200 ft); industry estimates suggest 800 m (2,600 ft).
- The Mk-48 (Mod 1) originally was produced by Gould, Inc. Initial Operating Capability (IOC) was in 1972, when the Mk-48 started replacing the Mk-14 and Mk-37 torpedoes.
 - Driven by a “swashplate” piston engine fueled by Otto fuel II monopropellant.
 - 290 kg (650 lb) high-explosive warhead
- The IOC for the first major update, the Mk-48 Mod 4 ADvanced CAPability (ADCAP) torpedo, was in 1982. This version was manufactured by Hughes Aircraft.



Mark 48 ADCAP torpedo

Evolutionary ADCAP upgrades since 1982



- A series of evolutionary ADCAP upgrades have introduced new technologies that improved Mk-48 performance and kept it a modern weapon for the past 35 years.
- The current Mk-48 Mod 7 Common Broadband Advanced Sonar System (CBASS) torpedo is optimized for both deep ocean and littoral waters and has advanced counter-countermeasure capabilities.
- Lockheed-Martin is the current manufacturer.

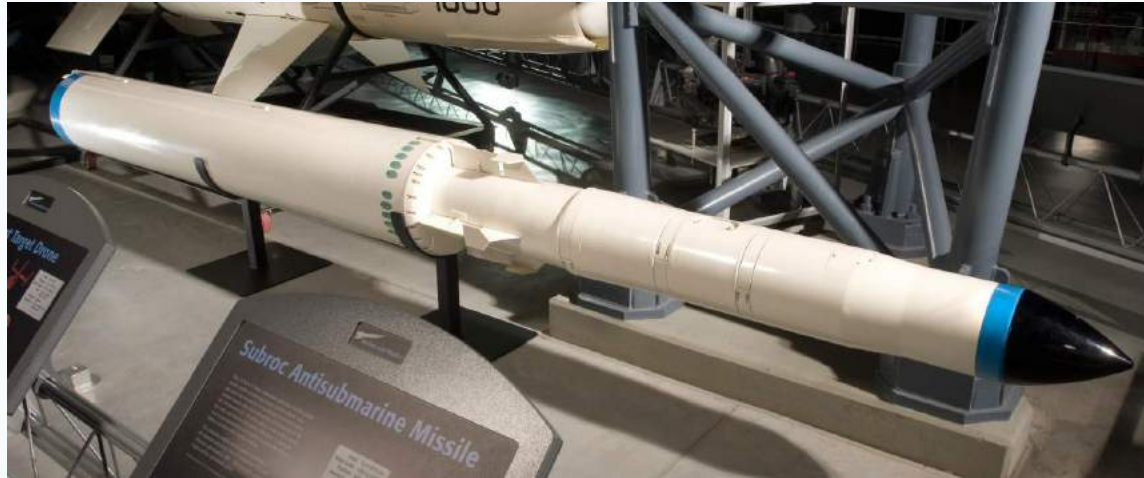
Source: Adapted from NAVSEA

US submarine-launched anti-submarine missiles

| Weapon | Years in service | Weight | Length | Diam | Speed / Propulsion | Range / guidance | Warhead |
|---|--------------------------|--------------------------------|------------------|----------------|---------------------------|---|---|
| SUBROC (UUM-44) anti-sub rocket | 1964 - 89 | 1,814 kg (4,000 lb) | 6.7 m (22 ft) | 530 mm (21 in) | Supersonic / Solid rocket | 40.2 – 80.5 km (25 - 50 miles) / Inertially guided | W55 thermonuclear @ 1 - 5 kT (or 250 kT) depth charge |
| Perseus (UGM-89, STAM) anti-sub / anti-ship rocket | Design phase, circa 1971 | 5,180 kg (11,420 lb) OA launch | 8.64 m (28.3 ft) | 864 mm (34 in) | Mach 2.0 / Solid rocket | Initially, 9 - 55 km (5.5 – 34 miles) | Conventional warhead, homing torpedo |
| Sea Lance (UUM-125, Common ASW Standoff Weapon) | Design phase 1980 - 90 | 1,400 kg (3,086 lb) | 6.25 m (20.5 ft) | 530 mm (21") | Solid rocket | UUM-125A 185 km (115 miles) / inertially guided UUM-125B 65 km (40 nm) / inertially guided | UUM-125A: W89 thermonuclear depth charge @ 200 kT UUM-125B: conventional warhead, Mk 50 homing torpedo |

UUM-44 SUBROC

SUBmarine-launched anti-submarine ROcket



Source (above): Smithsonian National Air & Space Museum

- Development of a long-range, submarine-launched, nuclear-armed ASW weapon was recommended by the 1956 Naboska Study.
- SUBROC consisted of a solid fuel booster rocket with a W55 nuclear depth charge warhead. Yield has been reported variously as 1 – 5 kT or 250 kT.
- Development by Goodyear Aerospace began in 1958; technical evaluation completed in 1963; Initial Operating Capability (IOC) aboard *USS Permit* in 1964.
- Production ended in 1968 with a total of 285 W55 warheads produced.
- Operational on Permit, Sturgeon and Los Angeles-class SSNs.
- SUBROC was retired in 1989.



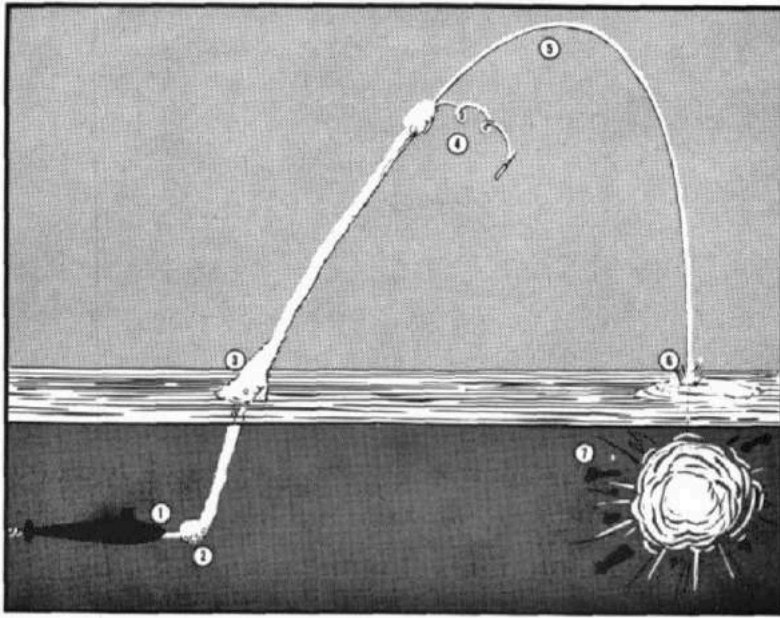
SUBROC handling on *USS Permit*.
Source: GlobalSecurity.org/

UUM-44 SUBROC

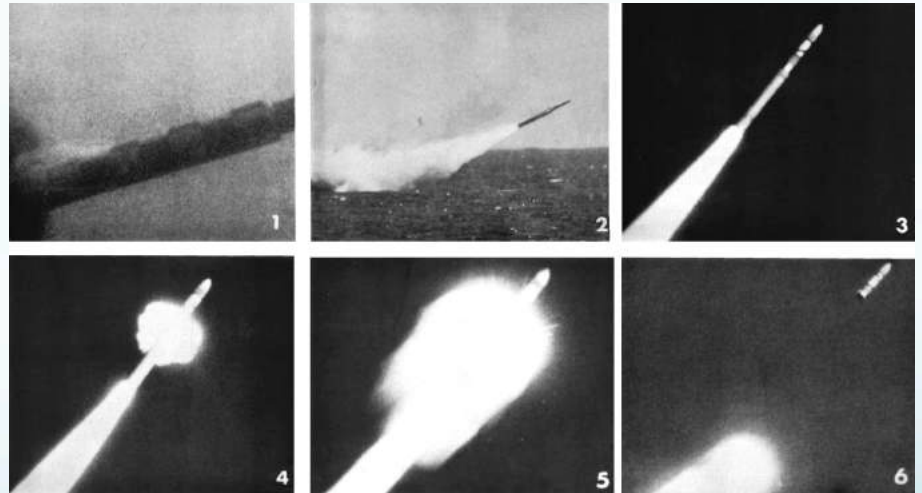
SUBmarine-launched anti-submarine ROCKET

Below: SUBROC mission profile showing:

1. SUBROC is ejected from an SSNs torpedo tube
2. Solid rocket motor fires underwater, propelling SUBROC to the surface
3. SUBROC breaks the surface
4. Warhead separates from the rocket booster
5. Warhead continues on a ballistic trajectory toward the target
6. Warhead reenters the ocean near the target
7. Nuclear warhead detonates, destroys the target



Source: All Hands magazine, Dec 1964



Above: SUBROC launch from a torpedo tube (photo 1) and subsequent flight sequence through separation of the nuclear depth charge warhead from the rocket booster (photos 2 – 6).
Source: <https://en.wikipedia.org/>

UGM-89 Perseus

Submarine Tactical Missile (STAM)

- In March 1969, the US Navy issued a requirement for the STAM (Submarine Tactical Missile), which was to be a submarine-launched dual role (anti-sub/anti-ship) attack missile.
 - Also referred to as Submarine Anti-ship Weapon System (STAWS) and Perseus (UGM-89).
 - Original missile payload was a new 533 mm (21 in) high-performance homing torpedo to be developed in parallel with the missile.
 - Original range was between 9 - 55 km (5.5 - 34 miles).
- This missile system was to be the primary armament on the proposed Advanced Performance High-speed Nuclear Attack Submarine (APHNAS), which was designed to perform an ocean area control mission through the use of standoff missiles targeted against newer, quieter Soviet submarines and surface fleets.
 - STAM was too large for standard 533 mm (21 in) torpedo tubes. It was carried in 20 x vertical launch system (VLS) tubes housed within the hull, in a separate missile compartment located between the submarine's operations and reactor compartments, behind the sail of the APHNAS sub.
 - In 1969, the original VLS launch tubes had a diameter of 76.2 cm (30 inches) and a length of 7.62 m (300 inches).
 - APHNAS was championed by then-Vice Admiral Hyman G. Rickover.

UGM-89 Perseus

Submarine Tactical Missile (STAM)

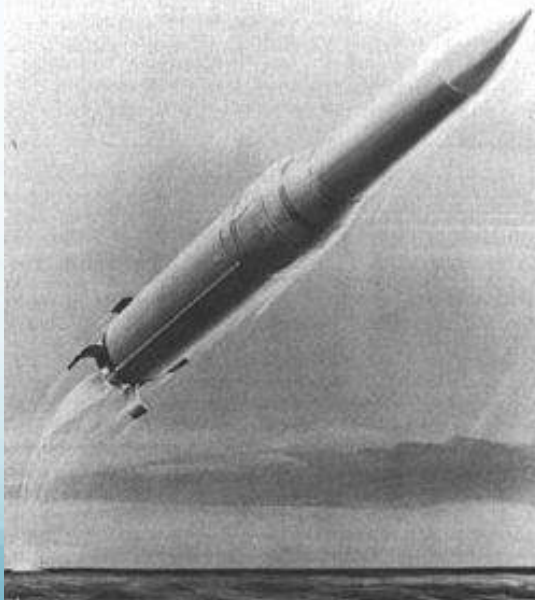
- By 1971, Lockheed Missiles & Space Co. had evolved STAM into a long-range Advanced Cruise Missile (ACM) program with three missile versions:
 - Supersonic anti-ship / ASW: medium range, conventional ASW torpedo warhead
 - High subsonic anti-ship: medium range, conventional armor-piercing warhead
 - Strategic nuclear strike: long range (3,334 km, 2,071 mi), nuclear warhead
- The missile size grew to a diameter of 86.4 cm (34 inches) and a length of about 8.64 m (28 ft), requiring larger launch tubes on the the APHNAS submarine, with a diameter of 101.6 cm (40 inches) and length of 10.16 m (33.3 ft).
- STAM and the APHNAS submarine were cancelled in 1973, in favor of purchasing Los-Angeles-class SSNs.
 - The Flight II Los Angeles-class SSNs, which entered the fleet in 1985, were the first US submarines to deploy with VLS launchers for tactical missiles.
- The ASW component of the UGM-89 Perseus would later serve as the baseline for the proposed UUM-125A Sea Lance stand-off ASW missile system.

UUM-125A / B Sea Lance

Submarine-launched, stand-off ASW missile



Above: Sea Lance launch capsule



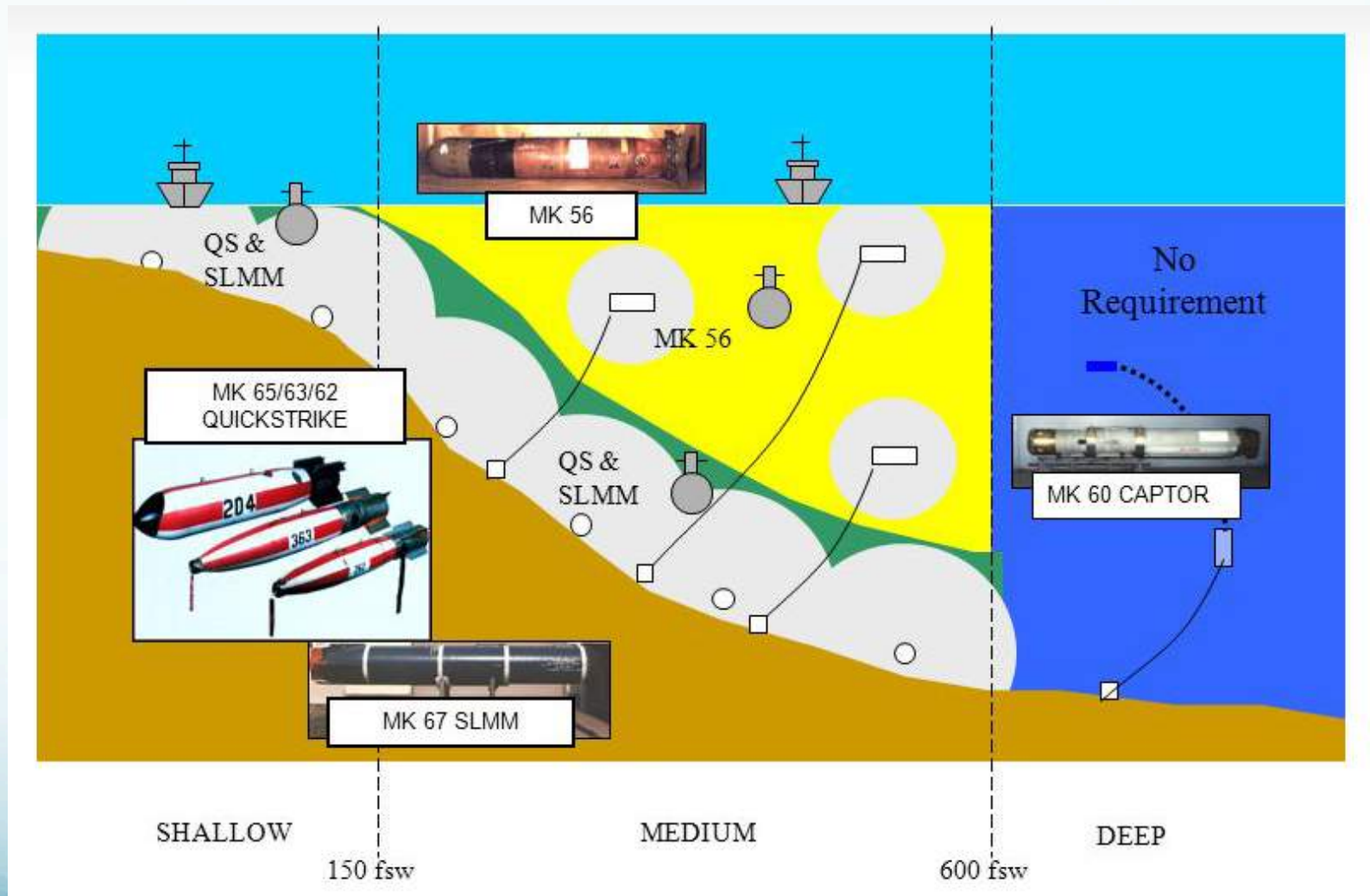
Source, two images : US Navy / Wikipedia

- Sea Lance was an evolutionary development of the larger anti-submarine version of the Submarine Tactical Missile (STAM), UGM-89 Perseus, which was cancelled in 1973.
- Sea Lance was intended to replace SUBROC on Los Angeles and Seawolf-class SSNs. In addition, there was a version intended to replace ASROC on surface ships (RUM-125).
- The submarine version was an encapsulated weapon launched from a torpedo tube. After the capsule floated to the surface in a vertical attitude, the solid fuel booster rocket ignited. The surface ship version was to be deployed in a vertical launch system (VLS).
- Near the target area, the warhead separated from the booster, deployed a parachute, and decelerated before landing to the ocean.
- The A version carried a W89 200 kiloton warhead had a lethal radius against submarines of about 10 km (6.2 miles). Maximum range was about 185 km (100 nm).
- The B version carried a Mk 50 Barracuda torpedo, known as ALWT (Advanced Light-Weight Torpedo). Because of the limited search range of the torpedo, effective range of the B version would be reduced to about 65 km (35 nm).
- Boeing started full-scale development in 1986.
- The nuclear-armed A version was cancelled first while development continued on the conventional B version. The entire program was cancelled in 1990.

US submarine-deployed mines

| Weapon | Years in service | Weight | Length | Diam | Speed / Propulsion | Range / guidance | Warhead |
|--|------------------|----------------------------|----------------------------|-------------------|---|--|---|
| Mark 57 Submarine-laid moored ASW mine | 1964 IOC, | 934 kg (2,059 lb) | 3.08 m (10.1 ft) | 530 mm (21 in) | Mine moored to the bottom | Mine moored to the bottom | High-explosive charge of 154 kg (340 lb) of HBX-3 |
| Mark 60 CAPTOR (Encapsulated mine-torpedo) | 1979 to 2001 | 935 kg (2,056 lb) | 3.35 m (11 ft) | 530 mm (21 in) | Mine moored to the bottom Torpedo: 45 knots / Otto fuel II engine | Mine moored to the bottom Torpedo: Range 8,000 yards (7,300 m) / Active or passive / active homing | Mark 46 homing torpedo with 45.4 kg (100 lb) HE warhead |
| Mark 67 Submarine Launched Mobile Mine (SLMM) | 1987 to present | 754 kg (1,658 lb) | 4.1m (13.4 ft) | 480 mm (19 in) | Similar to Mark 37 torpedo: Electric motor | Max standoff range: 23,000 yards (21 km, 13 mi) | Conventional warhead |
| Mark 76 Improved Submarine-Launched Mobile Mine (iSLMM) | Not deployed | Similar to Mark 48 torpedo | Similar to Mark 48 torpedo | 530 mm (21 in) | Similar to Mark 48 torpedo: Otto fuel II engine | Max standoff range: 38 km (24 mi) (est) | Two mines with conventional warheads |

US naval mine deployment zones

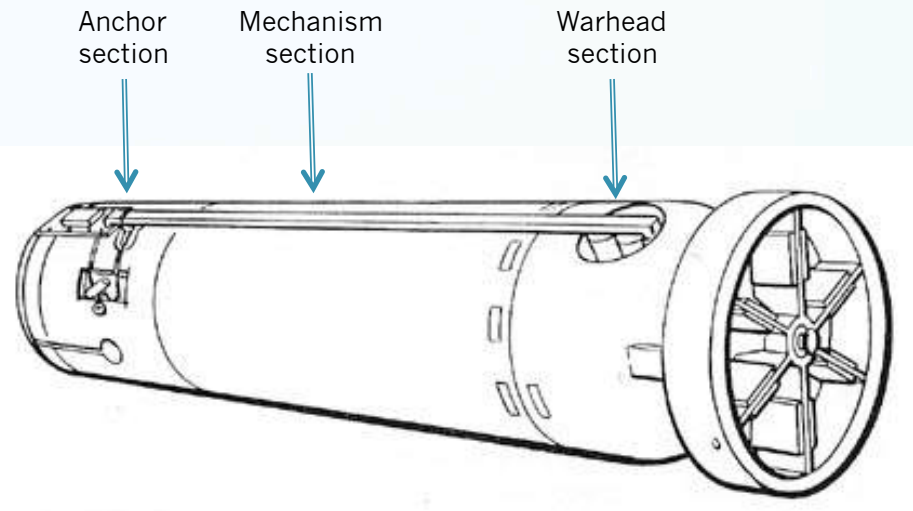


The Mark 57 submarine-launched moored mine is similar to the Mark 56 mine shown in the above diagram. The Quickstrike mines are all air-dropped mines. Source: Program Executive Office, Mine and Undersea Warfare

Mark 57 submarine-laid moored ASW mine

- The moored mine is deployed where water is too deep for bottom mines.
- The Mark 57 was designed for use against high-speed and deep-water subs. IOC was in 1964. It was similar to the air-dropped Mark 56 mine.

- The Mark 57 consisted of three major sections in a fiberglass case.
- The 340 lb (154 kg) HBX-3 warhead had a total-field magnetometer-type magnetic influence firing device.
- It was deployed from a standard 21 in diameter (530 mm) torpedo tube.
- It could be deployed in water up to 1,200 feet (366 m) deep.



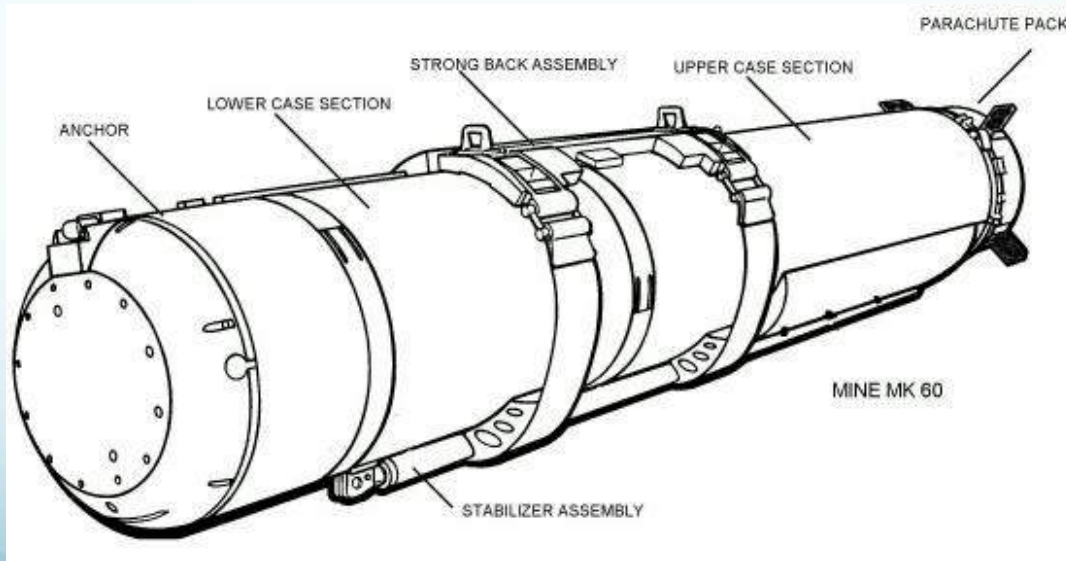
Source: <http://www.hartshorn.us/Navy/navy-mines-09.htm>

- Upon deployment, the mine sinks to the bottom where the anchor and mechanism section separate from the warhead section, which starts to float toward the surface while still connected to the anchor by a cable. Warhead depth is determined by a cable-measuring device in the anchor. When the preset depth has been reached, an electrical signal is sent to an explosive device, which locks the cable to prevent further payout.
- If the mine becomes separated from its mooring cable, the mine will fill with water automatically and neutralize itself to prevent detection and possible hazards to friendly ships.
- The Mark 57 ASW mine has been withdrawn from service.

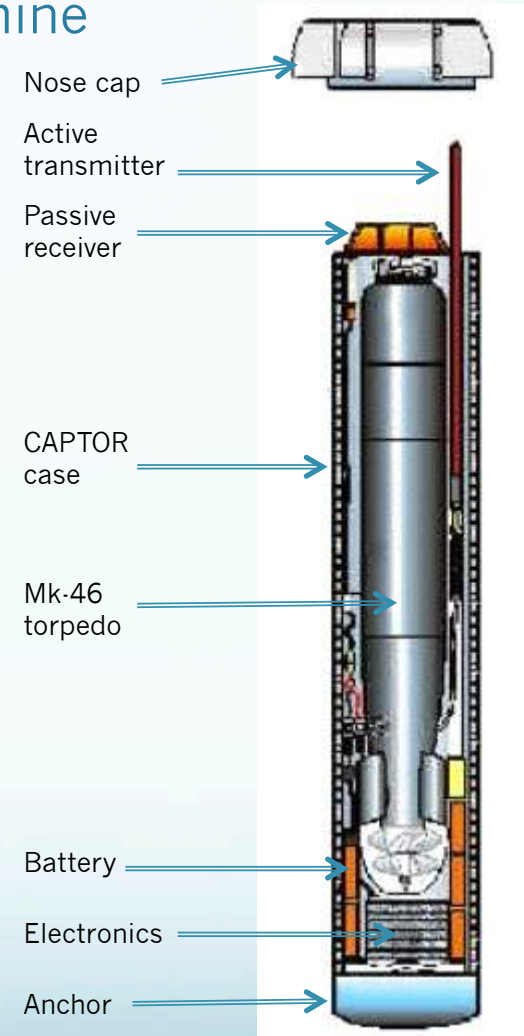
Mark 60 CAPTOR

enCAPsulated TORpedo mine

- CAPTOR was a deep water moored mine that was designed in the 1970s for use against the high-speed, deep-operating submarines of the day.
- Manufactured by Goodyear Aerospace. IOC was in 1979. CAPTOR retired in 2001.
- CAPTOR was comprised of two major elements:
 - A watertight aluminum casing containing sonar, electronics, a battery, and an anchor, and
 - A Mark 46 lightweight homing torpedo



CAPTOR external arrangement. The Mk-46 torpedo is inside.
Source: <http://minemen.org/CaptorMk60.htm>



CAPTOR cross-section view. Source: Adapted from
<https://aquellasarmasdeguerra.wordpress.com/>

Mark 60 CAPTOR

enCAPsulated TORpedo mine



Mark 60 CAPTOR in a handling cradle.

Source: http://www.navweaps.com/Weapons/WAMUS_Mines.php



Relative size of the Mk-46 lightweight torpedo use in CAPTOR and the Mk-48 heavyweight torpedo.

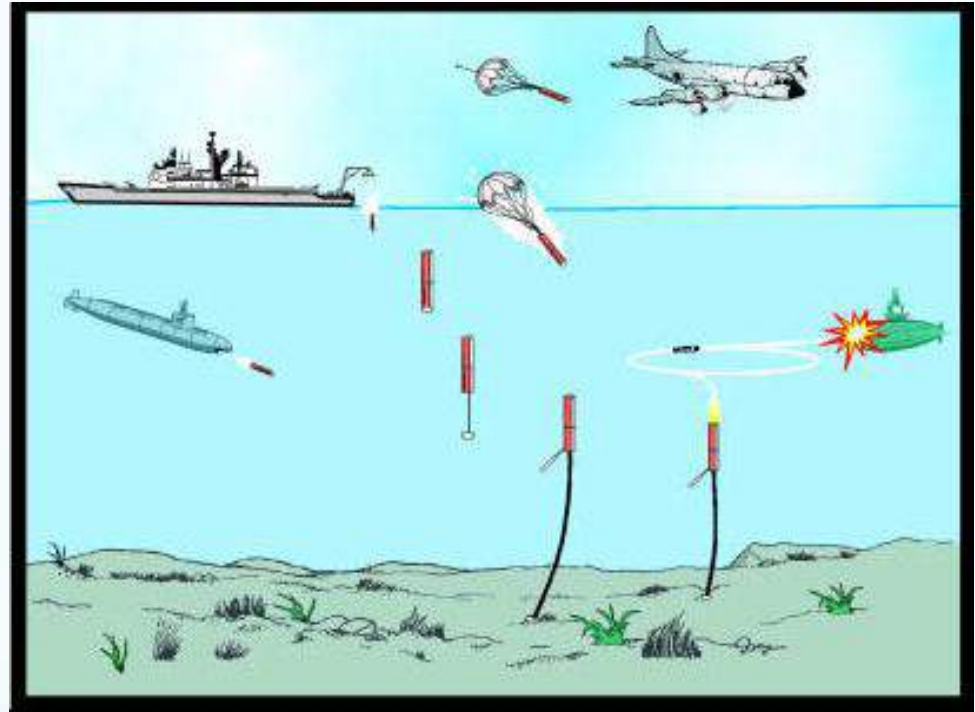
Source: <http://www.navy.gov.au/weapon/mark-46>

- CAPTOR characteristics (submarine-laid version):
 - Dimensions: 21 in x 11 ft (533 mm x 3.35 m)
 - Weight: 2,056 lbs (935 kg)
 - Max. deployment depth: 1,000 ft (305 m)
- Mark 46 Mod 5 (NEARTIP) torpedo characteristics:
 - Dimensions: 12.7 in x 8.5 ft (324 mm X 2.6 m)
 - Weight: 517 lb (234.5 kg)
 - Range: 8,000 yards (7.3 km) @ 45 knots
 - Homing: Active or passive / active
- The Littoral Sea Mine (LSM) was proposed as a replacement for the Mark 60 mine for use against surface or subsurface targets in intermediate water depths of 150 to 600 ft. Like the Mark 60, LSM was to have been air-, surface-, or submarine-deployed. There has been no recent LSM funding for continued development or acquisition.

Mark 60 CAPTOR

enCAPsulated TORpedo mine

- Deployed from submarines, surface ships or aircraft.
- Vertically moored on the seabed after deployment. Mission lifetime could be several weeks to months.
- Passive acoustic sensors listen using Reliable Acoustic Path (RAP) sound propagation methods for a target having specified signal characteristics.
- When a viable target was detected, CAPTOR pinged on the target to establish that it was within kill range.
- If all requirements were met, then CAPTOR opened its hatch and launched its Mark 46 acoustic homing torpedo, which circled to acquire the target and then homed in to attack.
- The 44 kg (97 lb) high-explosive (PBXN-103) torpedo warhead was capable of damaging or sinking a submarine.
- CAPTOR could be remotely controlled by acoustic signals.

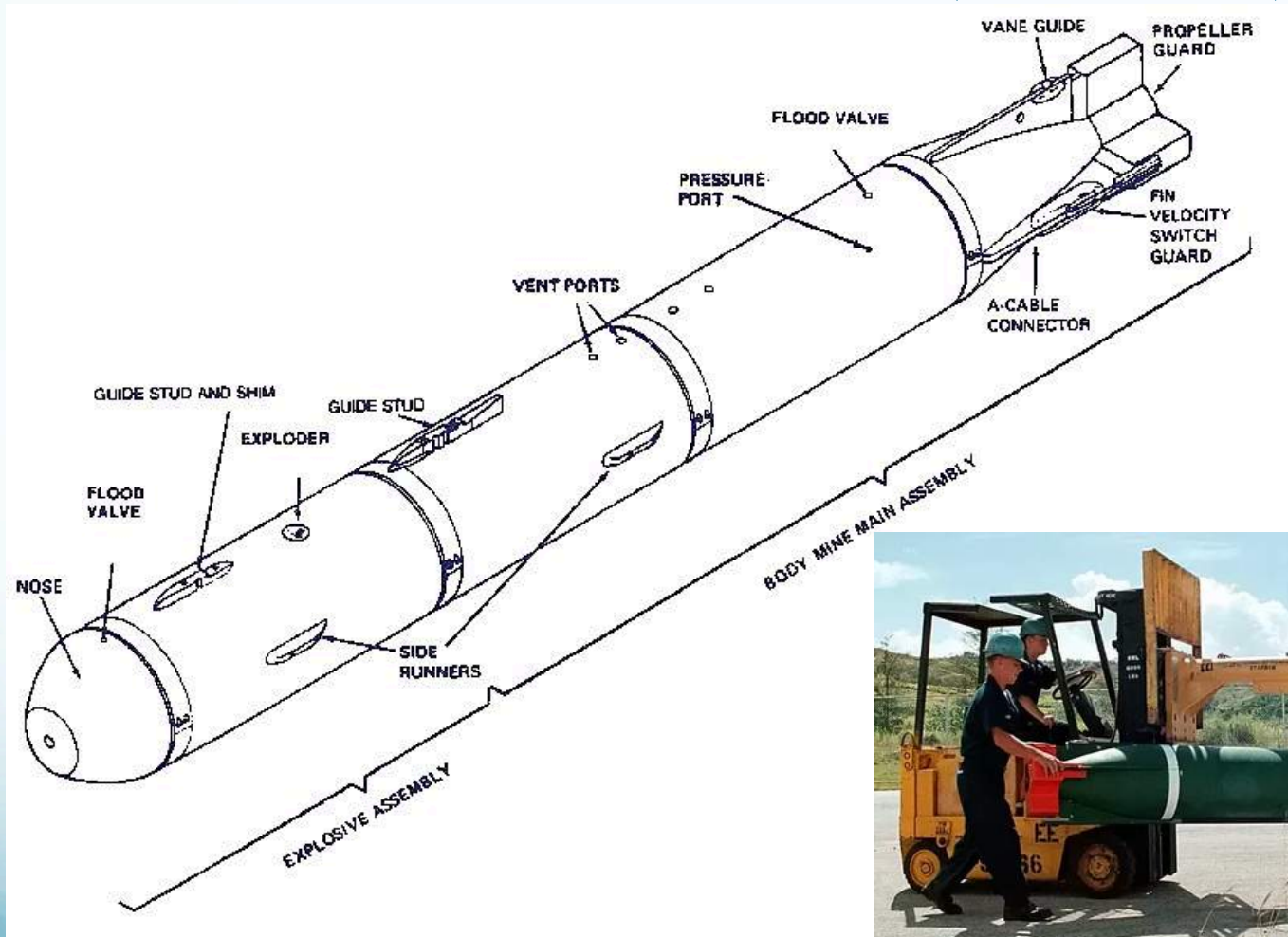


Mark 60 CAPTOR deployment and mission profile.
Source: <http://www.warships.ru/usa/Weapons/Mines/>

Mark 67 Submarine Launched Mobile Mine (SLMM)

- SLMM is a multi-purpose (anti-submarine and anti-surface) mobile mine intended to be used for destruction of enemy ships and/or disruption of enemy ship traffic in areas that are inaccessible for other mine deployment techniques or for clandestine deployment in hostile environments.
 - IOC was in 1987.
 - Mark 67 currently is the only mine in the Navy stockpile that can be covertly delivered from standoff range.
- The Mark 67 mobile mine combines a modified Mark 37 torpedo with a mine casing.
 - Dimensions: 19 in x 13.4 ft (48.5 cm x 4.1 m)
 - Weight: 1,658 lbs (754 kg)
 - Launched by “swimming out” of a 21 inch (533 mm) torpedo tub
 - Maximum range: maximum of 23,000 yards (21 km, 13 mi)
 - Explosives: 515 lbs (234 kg) PBXN-103
 - Trigger: magnetic/seismic or magnetic/seismic/pressure
- The Navy conducts 2 – 5 SLMM Exercises (SLMM-Ex) per year in shallow water off the coast of Kauai at the Pacific Missile Range Facility (PMRF). The goal of these exercises is to provide practice for SSN crews with the techniques and hardware for effectively deploying the Mark 67 SLMM. Inert exercise mines are used. Divers from Mobile Diving and Salvage Unit (MDSU) One are tasked with recovering the exercise mines.
- There have been unconfirmed reports of work to modify the Mark 67 SLMM to be deliverable by Large Displacement Unmanned Underwater Vehicles.
- At one time, the Navy had plans to replace the Mark 67 SLMM with a similar weapon known as the Improved SLMM (iSLMM), which was to be based on the Mark 48 heavyweight torpedo.

Mark 67 Submarine Launched Mobile Mine (SLMM)

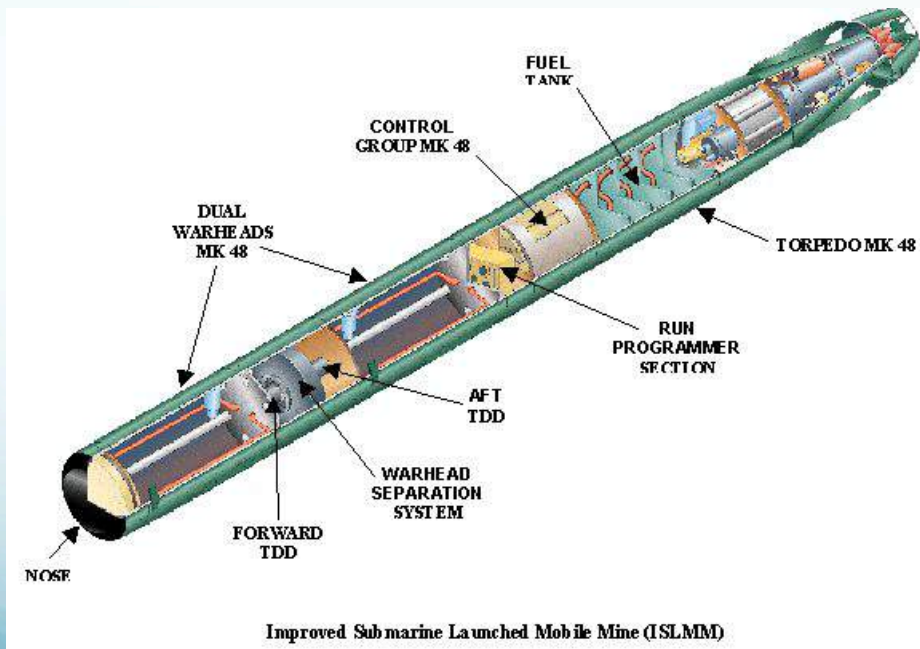


Source, above: <http://minemen.org/SLMM67.htm>

Right: <https://www.quora.com/Does-the-US-Navy-still-lay-naval-mines>

Mark 76 Improved Submarine Launched Mobile Mine (iSLMM)

- This was a joint program between the US Navy and the Royal Australian Navy to develop a replacement for the obsolescent Mark 67 SLMM. This program intended to convert early-vintage Mark 48 heavyweight torpedoes into dual warhead mobile mines with greater capabilities than the Mark 67 SLMM, including:
 - Modern electronics and other system that would be maintainable well into the future
 - Greater standoff distance and better mine placement accuracy
 - Multiple mine warheads with an improved target detection & discrimination capability

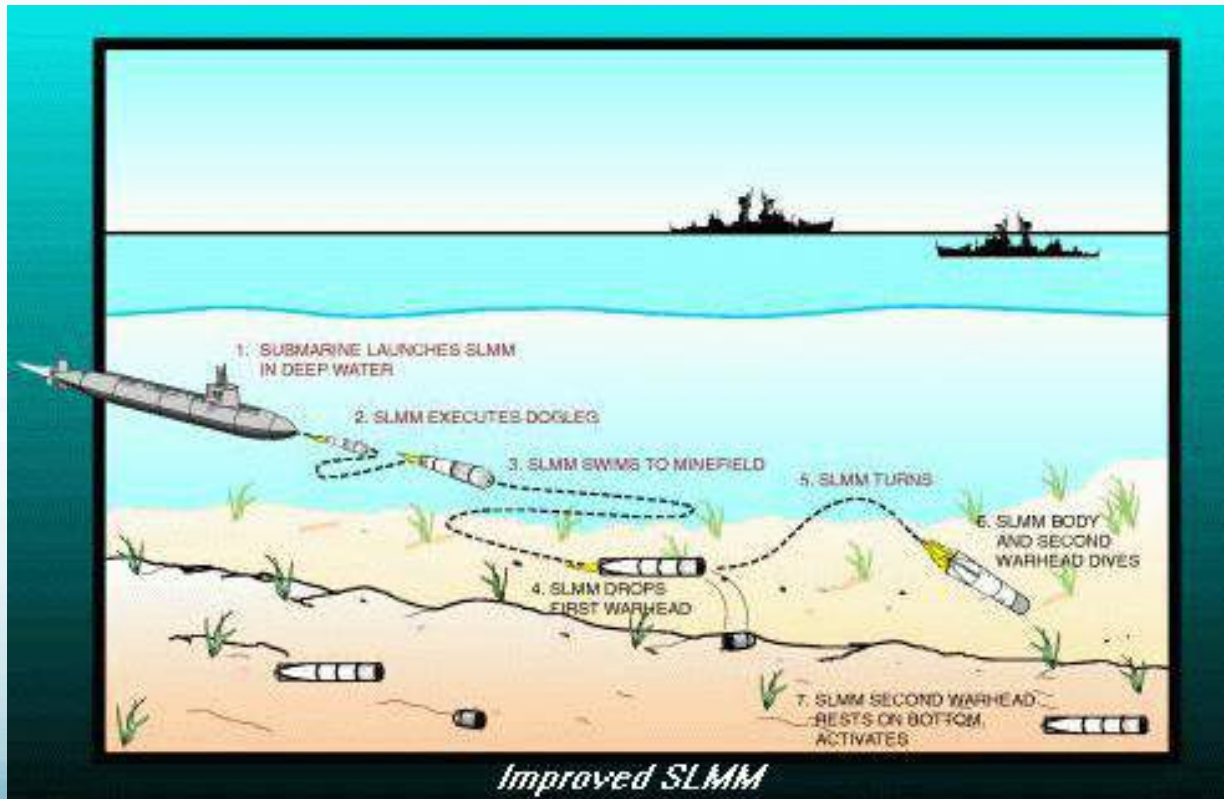


Source: <http://www.navweaps.com/>

- iSLMM would retain the dimensions, propulsion and wire-guidance of the Mark 48 torpedo, thereby enabling it to be launched from any Mark 48 capable submarine.
- Each dual warhead would be equipped with the Target Detection Device (TDD) Mark 71, which used advanced mine algorithms for ship detection, classification and localization against emerging threats (i.e., quiet diesel-electric subs, mini subs, fast patrol boats, air cushion vehicles) that are likely to be encountered in future conflicts. The TDD Mk 71 was developed but not acquired.

Mark 76 Improved Submarine Launched Mobile Mine (iSLMM)

- The Mk-76 iSLMM would be launched from a remote location and then guided to its destination. Each warhead would be dropped in a separate location, allowing iSLMM to attack two separate targets.



- Original plans called for the development phase beginning in FY 2000 followed by a three-year procurement phase starting in FY 2002. Currently, there is no funding for the iSLMM.

Systems to augment submarine operational capabilities

- Unmanned Underwater Vehicles (UUV)
- Unmanned Aerial Systems (UAS)
- Submarine advanced communications

Unmanned Underwater Vehicle (UUV) capabilities

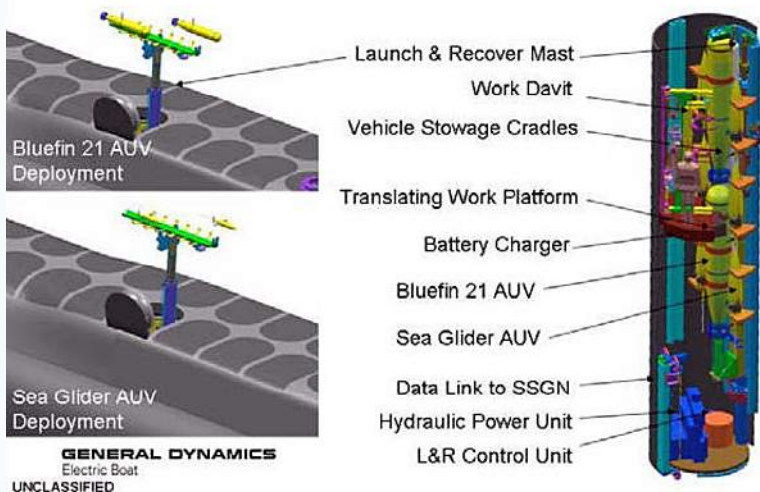


Source: Hydroid

- In July 2015, *USS North Dakota* (SSN-784), a Block III Virginia-class sub, returned to its base in Groton, CT after an almost two-month deployment to the Mediterranean Sea specifically to test a “free-flying” unmanned underwater vehicle (UUV) during military operations.
 - This was the first operational launch and recovery of this type of UUV during a military operation.
 - The drone deployed was a Remus 600, which is a 500-pound, 10-foot-long vehicle that its manufacturer, Hydroid, says can be equipped with video cameras, GPS devices and sonar technology.
 - The Navy declined to say whether the Remus 600 was self-guided or piloted by a member of the submarine's crew.
 - The drone was launched from a Dry Deck Shelter (DDS) attached to the top of the Virginia- class submarine.

UUV onboard storage & handling

Universal Launch and Retrieval Module Can be Adapted to support Heavy Weight and Man Portable AUVs



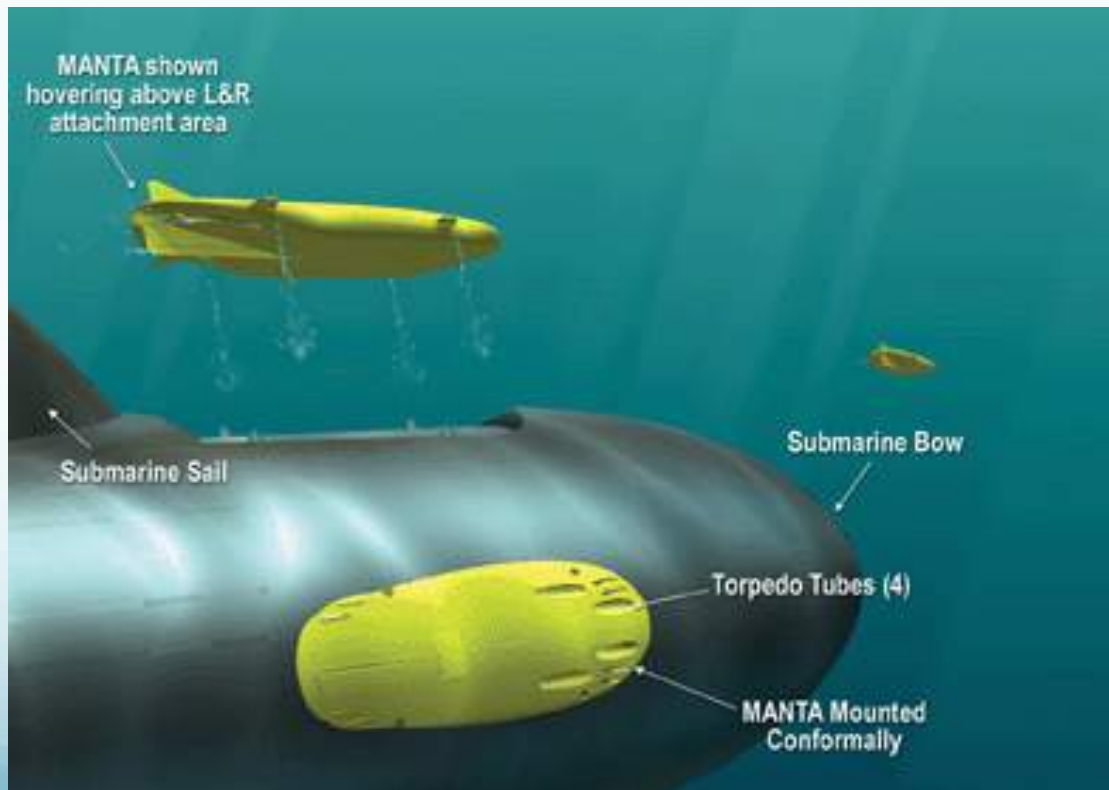
Source, both images: General Dynamics Electric Boat



- UUVs are “force multipliers” that will greatly expand the operational capabilities of the host vessel.
- A variety of UUV deployment and retrieval schemes are being developed. One solution is the General Dynamics Universal Launch and Retrieval Module (ULRM), which can be installed in an Ohio-class SSGN missile tube. ULRM has a telescoping mast and rotating cradle that moves the UUV from a storage position inside the tube to a deployment / retrieval position above the sub. ULRM was tested in 2014.
- In the near future, submarine use of UUVs will become commonplace.

Armed UUV concept

- This large, autonomous UUV concept for the future includes a flexible payload capability such as full-size torpedoes, a greater quantity of lightweight torpedoes, missiles or small UUVs, sensor and communications packages, and towed array sonar.



- Mounted conformally on launch & recovery (L&R) sites on the submarine's hull.
- Naval Undersea Warfare Center has been operating a MANTA Test Vehicle (MTV) since 1999 to develop technology and a concept of operations for this class of UUV.

Source: Naval Undersea Warfare Center

Unmanned Aerial Systems (UAS) launch capabilities

- As an follow-on to a 2013 Joint Capabilities Technology Demonstration (JCTD) program known as Advanced Weapons Enhanced by Submarine UAS against Mobile targets (AWESUM), the Navy is developing the means to launch various UASs from existing submarine systems.
- **Vertical Launch System (VLS):** Individual VLS tubes typically are configured for weapons comparable in size to a Tomahawk cruise missile with booster: diameter 21 in. (533 mm), length 20.5 ft. (6.25 m).
 - An encapsulated UAS could replace weapons in a VLS on a one-for-one basis.
 - The full 88 inch. (224 mm) diameter of an Ohio-class SSGN missile tube or 87 inch (221 cm) diameter of a Virginia-class SSN Multiple All-up Round Canister (MAC) could provide the volume needed for a large UAS.
- **Submerged signal ejectors:** Typically there are two 3 in. (7.6 cm) diameter signal ejectors on each submarine.
 - Traditionally, these are used for launching a variety of devices, including locator flares, SLOT (Submarine-Launched One-way Transmitter) buoys, bathythermographs (to measure ocean vertical temperature profiles), and submarine countermeasure devices (acoustic, bubble generator).
 - In 2012, *USS Mississippi* (SSN-782), a Block II Virginia-class sub, conducted trials of a small *Blackwing* UAS launched via a signal ejector.

Unmanned Aerial Systems (UAS) launch capabilities

- **Trash disposal unit (TDU):** Traditionally used for discharging weighted trash canisters via a downward facing tube connected to the ocean via a ball valve. Trash canisters diameter is 9 in (22.9 cm); length 28.5 in (72.4 cm).
 - Raytheon has developed a Submarine Launch Vehicle (SLV) for TDU launch. The SLV floats to the surface after being ejected via the TDU, then launches a small UAS.
- **Torpedo tube:** Typically configured for weapons comparable in size to a Mk 48 ADCAP torpedo or a Tomahawk cruise missile with booster: diameter 21 in (533 mm), length 20.5 ft. (6.25 m). The Seawolf-class SSNs have larger diameter 26 in. (660 mm) torpedo tubes.
 - An encapsulated UAS could replace weapons in the torpedo room on a one-for-one basis.

In the near future, submarine use of UASs will become commonplace.

UAS launched via a signal ejector



ADVANCED WEAPONS ENHANCED BY SUBMARINE UAS AGAINST MOBILE TARGETS (AWESUM)

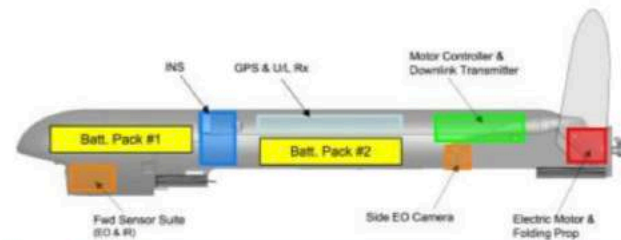


Low cost, submarine-launched, micro-UAVs, optimized for A2AD environment to provide target solution for OTH 3rd party strike.

Technologies:

- Re-packaged UAV for 3-inch countermeasure launch with >1hr endurance
- Timed-release launch with Mission Preload
- Submarine-to-UAV communications via OE-538
- Digital and encrypted comms
- Multiple UAVs daisy chained to increase comms and covertness
- JREAP-C (Link 16 over IP) for OTH 3rd party strike

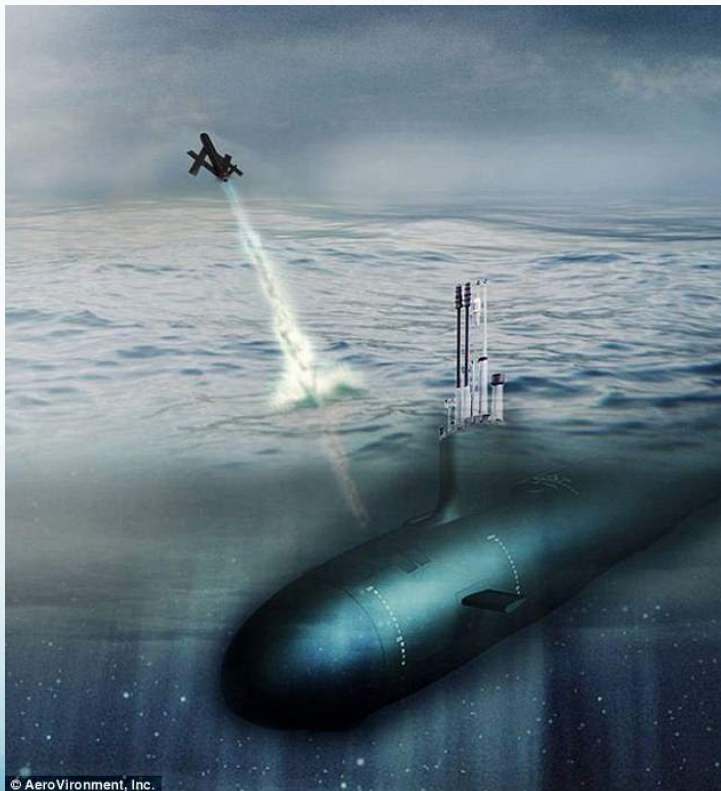
Weaponized version (inert demonstration) as a close-in and littoral self-defense option



Teamed with USAF, SOCOM & PACOM

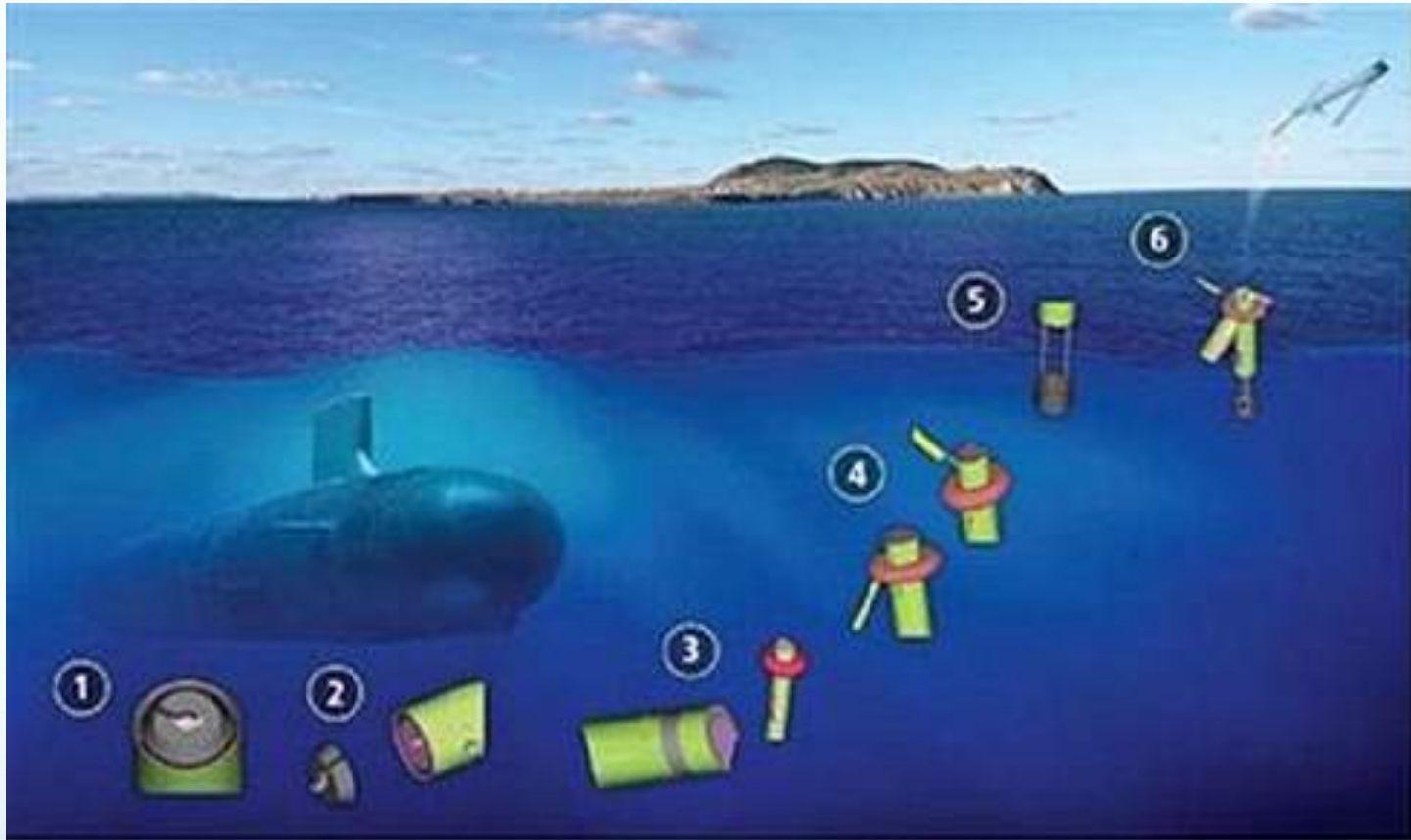
UAS launched via a signal ejector

- Navy has tested the AeroVironment *Blackwing* drone launched from a 3 in (7.6 cm) diameter submarine signal ejector and demonstrated the ability of the *Blackwing* to communicate with surface ships, SSNs and a swarm of UUVs.



Source, both images: AeroVironment

UAS launched via the TDU

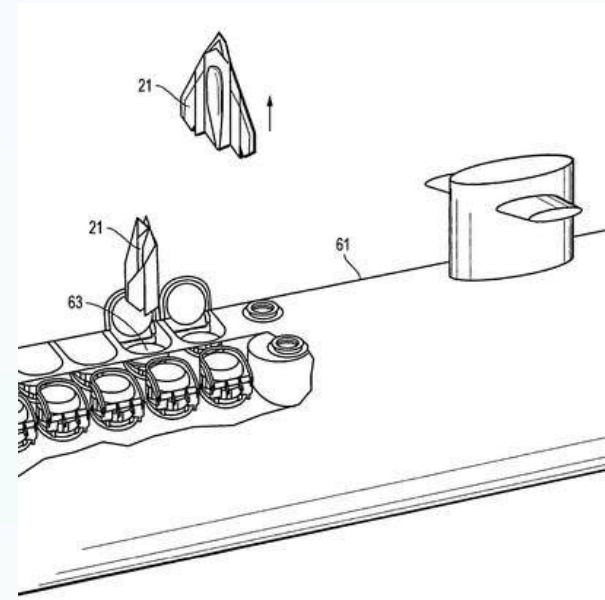


Raytheon Submarine Launch Vehicle (SLV) launches a *Switchblade* UAV via a submarine's trash disposal unit (TDU): 1: UAS packaged in a weighted Submarine Launch Vehicle (SLV) is ejected via the TDU; 2: weight released after SLV clears submarine; 3: UAS canister released from SLV and flotation collar inflates; 4 & 5: UAS canister rises to surface and is readied for launch; 6: UAS launched with canister properly aligned and floating on the surface. Source: Raytheon

UAS launched from a large diameter VLS

Virginia Block V, VI or VII SSN or Ohio SSGN

- Lockheed Martin has proposed a large, submarine launched Multi-Purpose UAV (MPUAV), Cormorant, that uses the full diameter of an SSGN vertical launch tube to store, launch and recover the UAV.
- The folding wing Cormorant is designed for 500 nm (926 km) range at Mach 0.8 with a 1,000 lb. (454 kg) payload.
- Cormorant is designed to land in the ocean after the mission with air inlet and engine exhaust sealed. It would be recovered with the help of a UUV that attaches a cable to the Cormorant that allows the UAV to be winched back into the original launch tube.

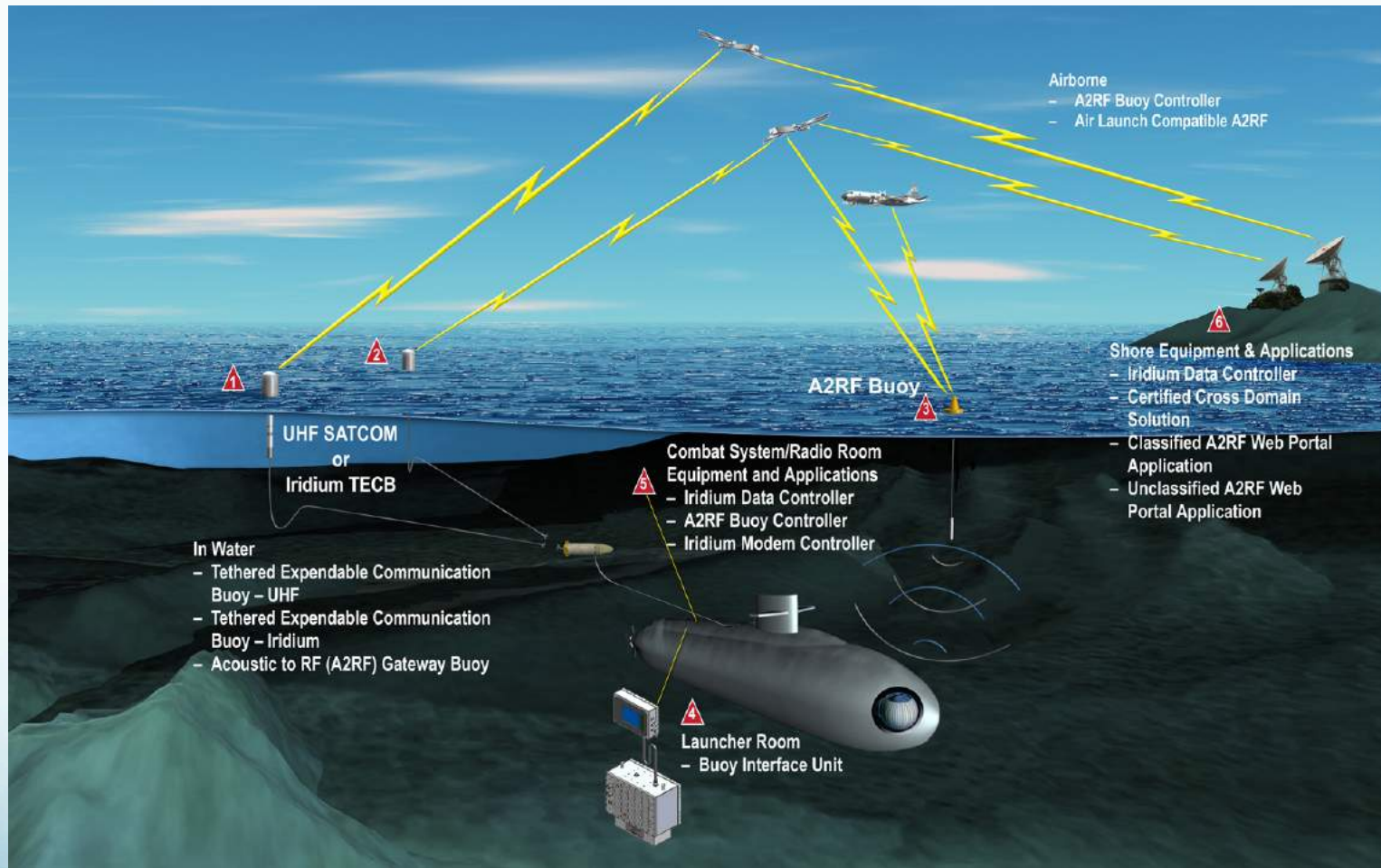


Source, two graphics: Lockheed Martin

Submarine advanced communications capabilities

- To coordinate with other fleet and air assets, exploit UASs, and develop a holistic view of the battle space with information from multiple sources, submarines need advanced, networked communications capabilities. To this end, the Navy is implementing the Consolidated Afloat Networks and Enterprise Services (CANES), with plans to have it installed on 190 surface ships and submarines by 2020. One goal of CANES is to increase operational effectiveness through standardization of a scalable network that is adaptable and easier to maintain and upgrade over its operational lifetime.
- Submarine communications capabilities at speed and depth are being expanded with various devices and systems, including:
 - Tactical Paging Buoy (TPB)
 - Tethered Expendable Communications Buoy (TECB)
 - Recoverable Tethered Communications Buoy (RTCB, which, in concept, would be similar to the recoverable buoy used on *USS Richard B. Russell*, SSN-687)
 - Acoustic-to-radio frequency (A2RF) gateway systems
- These devices and systems are capable of establishing a variety of communications pathways to a submarine operating at speed and depth without revealing the exact location of the submarine.
 - Communications links can be established via UHF and/or via satellite communications using Iridium (commercial SATCOM) or MUOS (military SATCOM).

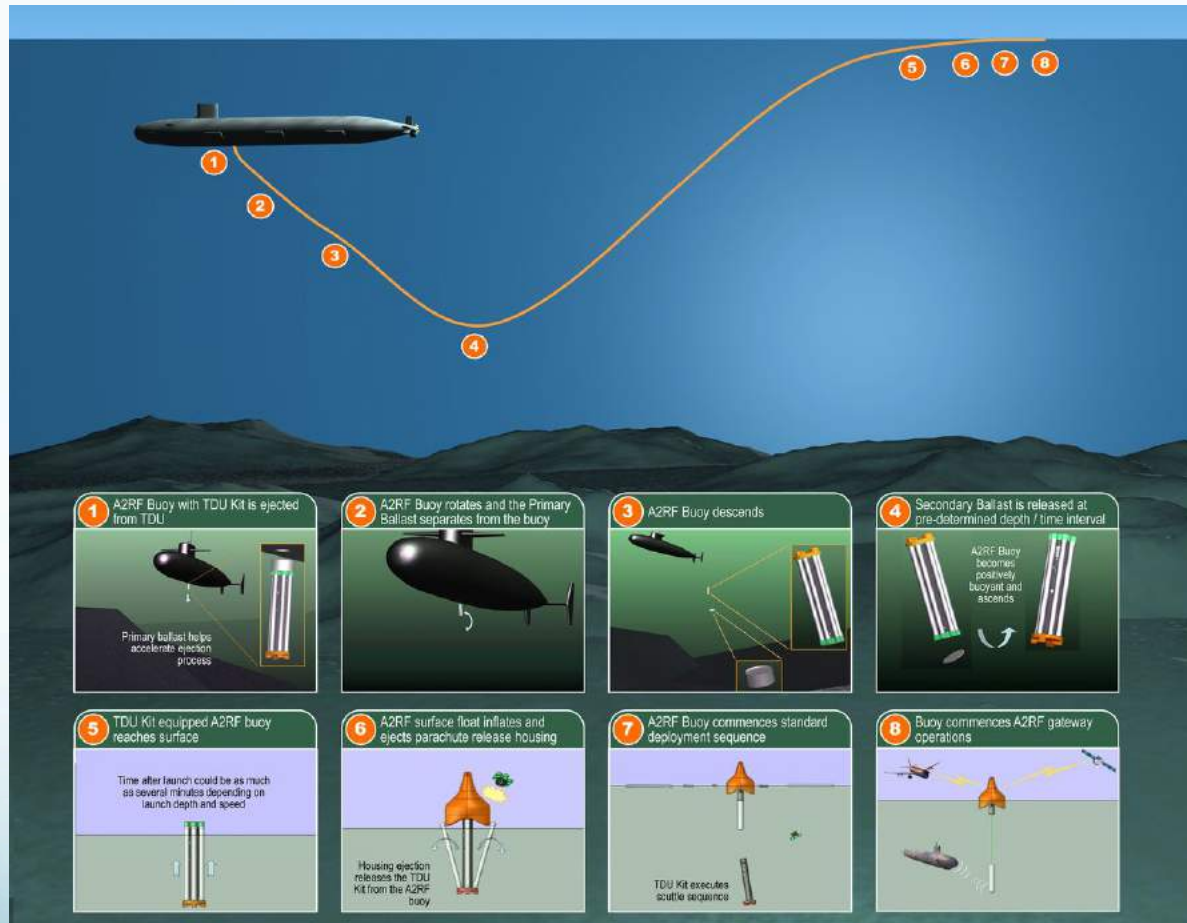
Submarine networked communications concept



Submarine networked communications concept with TECB and A2RF.

Source: Lockheed Martin via <https://www.wired.com/2010/07/>

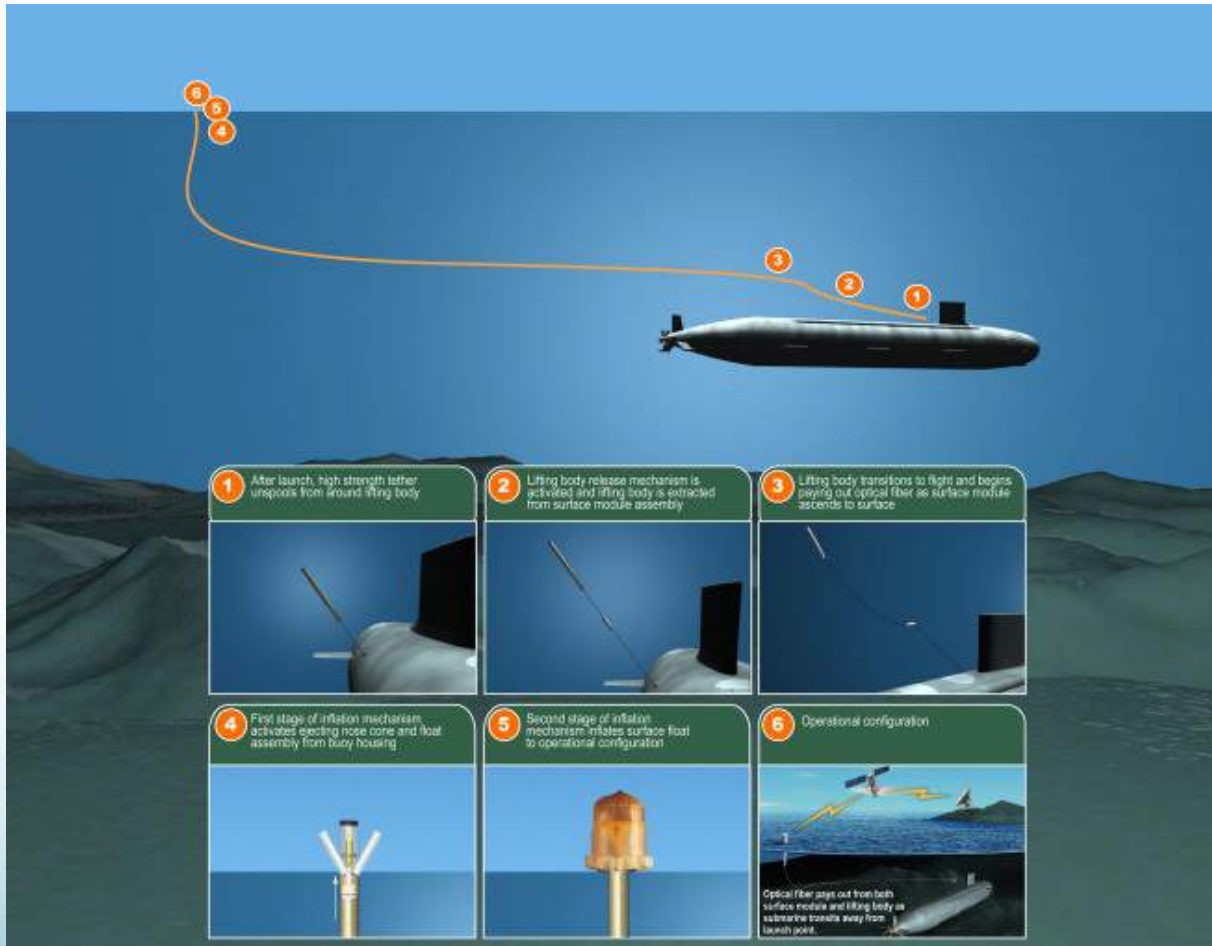
Operational concept for an expendable A2RF buoy



Source: Lockheed Martin via <https://www.wired.com/2010/07/>

- The battery-powered A2RF can be air-dropped or launched via the submarine's trash disposal unit (TDU).
- The A2RF can be equipped for both UHF and Iridium communications. It communicates to the sub via an underwater acoustic transducer.
- When battery power is lost after about 3 days, the A2RF scuttles itself.

Operational concept for a TECB



- The battery-powered TECB is launched via a signal ejector and is tethered to the sub via a fiber optic cable.
- The TECB may be equipped for UHF or Iridium communications.
- When battery power is lost after about 30 minutes, the TECB scuttles itself.
- Operational testing by the Navy began in 2011.

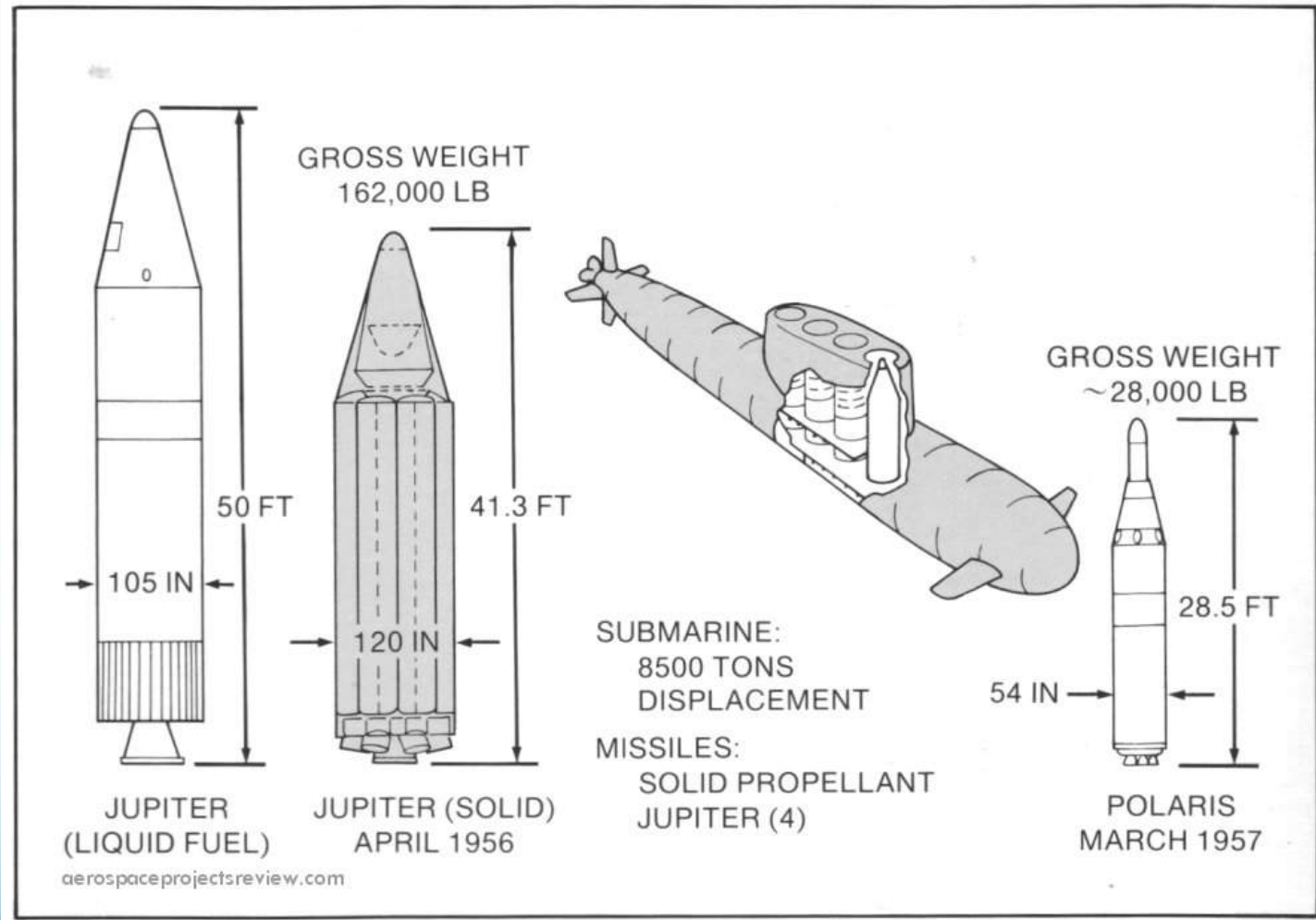
Source: Lockheed Martin via <https://www.wired.com/2010/07/>

Nuclear-powered strategic ballistic missile submarines (SSBN)

Joint Army-Navy Ballistic Missile Committee

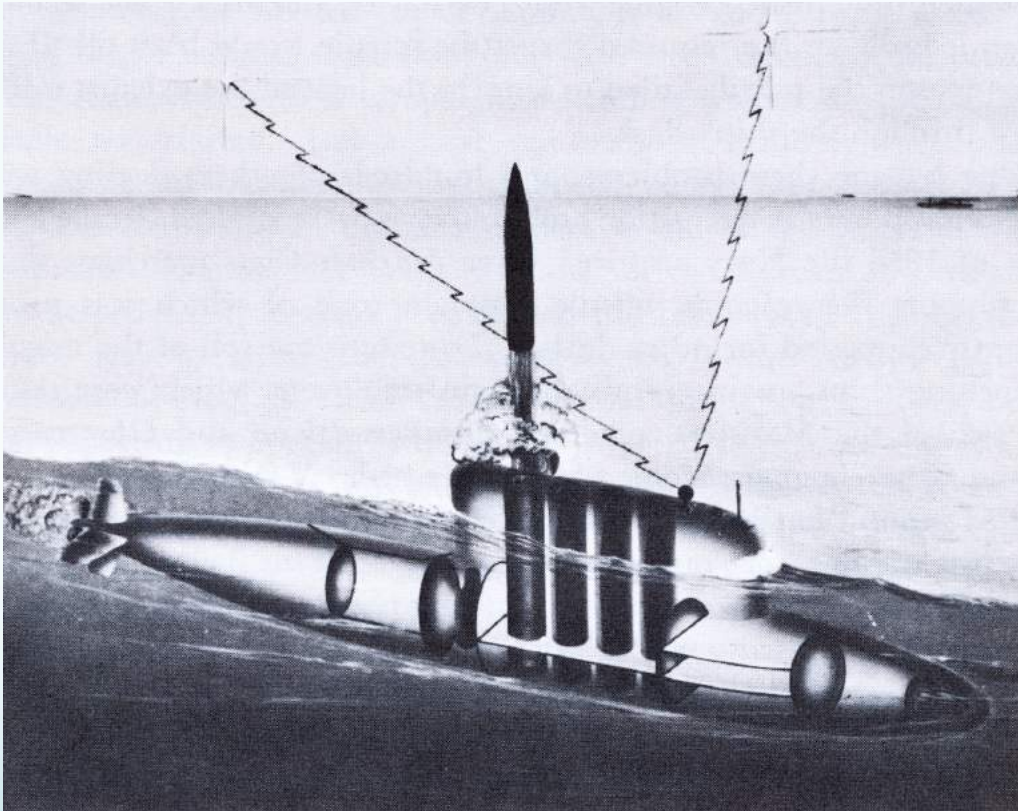
- **1948:** The “*Key West Agreement*” reallocated aviation roles among the three military branches, giving the strategic bombardment mission to the USAF, and limiting the Navy to tactical air roles.
- **1949:** Secretary of Defense Louis A. Johnson's memorandum, “*Assignment of Responsibility for Guided Missiles*,” dated 7 November 1949 confirmed USAF responsibility for land-based missiles for the strategic bombardment mission. It also clarified that the Navy was responsible for, “ship-launched guided missiles which supplement, extend the capabilities of, or replace naval aircraft.....”
- **Early-to-mid 1950s:** The USAF and Army developed competing programs for land-based Intermediate-Range Ballistic Missiles (IRBMs): the USAF's Thor and the Army's Jupiter IRBMs.
- **Summer 1955:** James R. Killian Jr., president of MIT and an advisor to President Eisenhower, proposed that IRBMs also be sea-based.
- **9 Sep 55:** A joint program was established to develop the Army's liquid-fueled Jupiter IRBM for Navy use on submarines & surface ships.
 - The shipboard hazard of liquid fuel was recognized.
- **13 Sep 1955:** President Eisenhower approved the development of a submarine-launched IRBM.
- **Feb 56:** A parallel solid fuel IRBM study (Jupiter S) was initiated with Lockheed.

Early Jupiter missile sub concept



Source: Scott Lowther, Aerospace Project Review

Early Jupiter missile sub concept



Source: N. Polmar, "Atomic Submarines," Van Nostrand Company, Inc., p. 206

- Many design concepts based on variations of the Skipjack SSN hull were developed.
- In this concept, four Jupiter missiles were housed in vertical missile tubes that extend through the hull into an enlarged sail.
- In preparation for a missile launch, the submarine broached (only the top of the sail was exposed above water) and would have to maintain this depth throughout the launch sequence.
- Then a Jupiter missile was raised out of its missile tube, fueled, and launched.
- In the diagram, the sub is acquiring navigation updates from satellites.

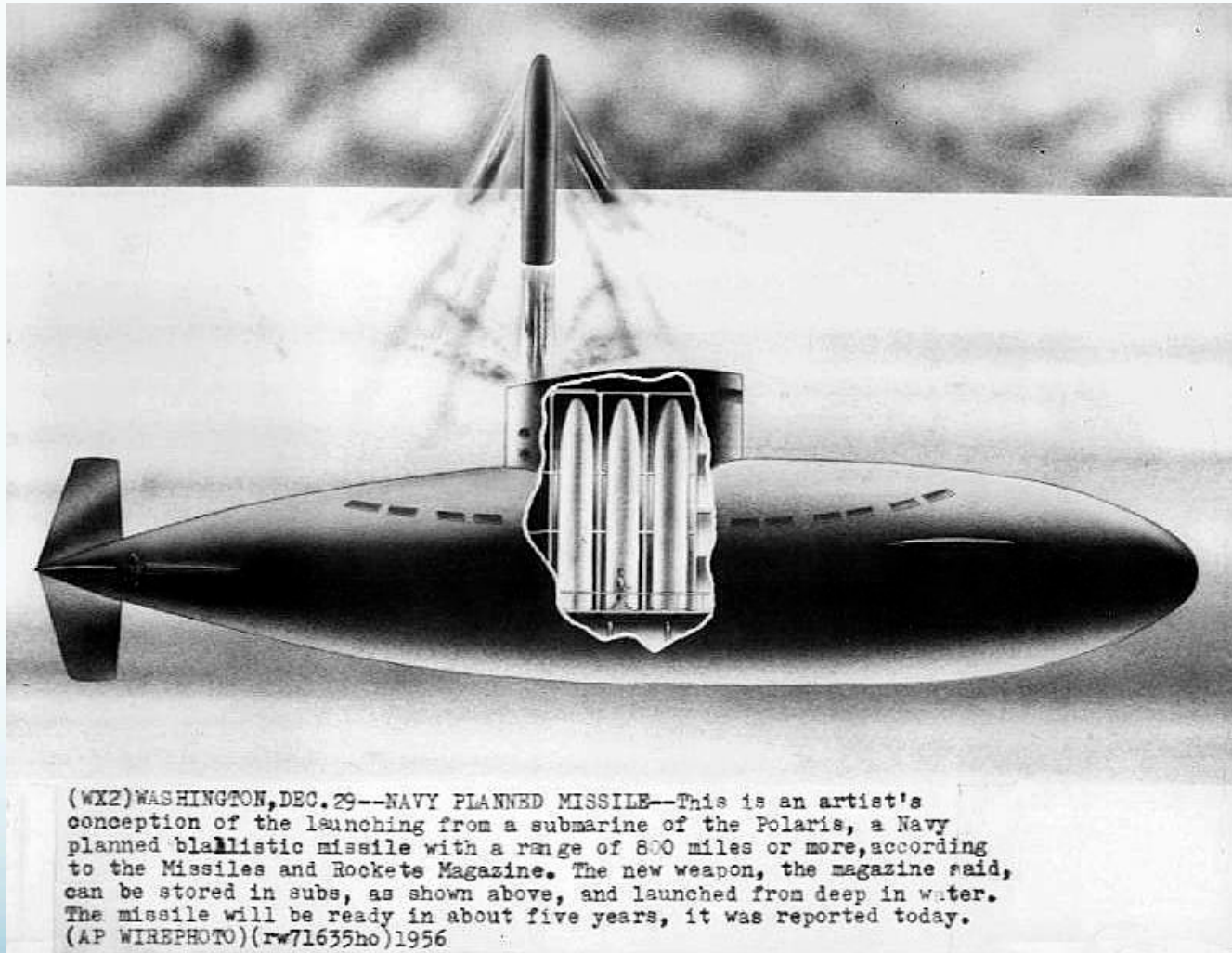
Joint Army-Navy Ballistic Missile Committee

- **Summer 1956:** Project NABOSKA examined application of new technologies to the Navy IRBM:
 - Smaller nuclear warheads predicted (Edward Teller).
 - Smaller inertial guidance systems being developed (MIT Draper Labs).
 - Larger, higher specific impulse solid rocket motors demonstrated (Atlantic Research).
- **Sep 56:** The Atomic Energy Commission (AEC) confirmed NABOSKA warhead predictions; Lockheed & Aerojet confirmed missile size & performance predictions.
- **Sep 56:** RADM William F. “Red” Raborn presented Lockheed’s “Polaris” missile design to Chief of Naval Operations (CNO), then to Secretary of Defense, which included submarine and surface ship launch platforms.
 - Recommended focus on submarine launch.
- **26 Nov 56:** Secretary of Defense Charles E. Wilson’s memorandum, *“Clarification of Roles and Missions to Improve the Effectiveness of Operation of the Department of Defense,”* dated 26 November 1956, defined inter-service roles related to Intermediate Range Ballistic Missiles (IRBMs).
 - The Air Force was responsible for land-based IRBMs; the Navy was responsible for ship-based IRBMs; the Army had no further role in IRBMs.

Joint Army-Navy Ballistic Missile Committee

- **8 Dec 56:** The joint Army-Navy project was terminated and the Navy was authorized to proceed on its own with the solid-fuel Polaris program with concurrent development of required technologies for the Polaris mission.
 - The missile system originally was designed as a second-strike weapon. The initial circular error probable (CEP) for the warhead was not small enough to use Polaris as a first-strike weapon.

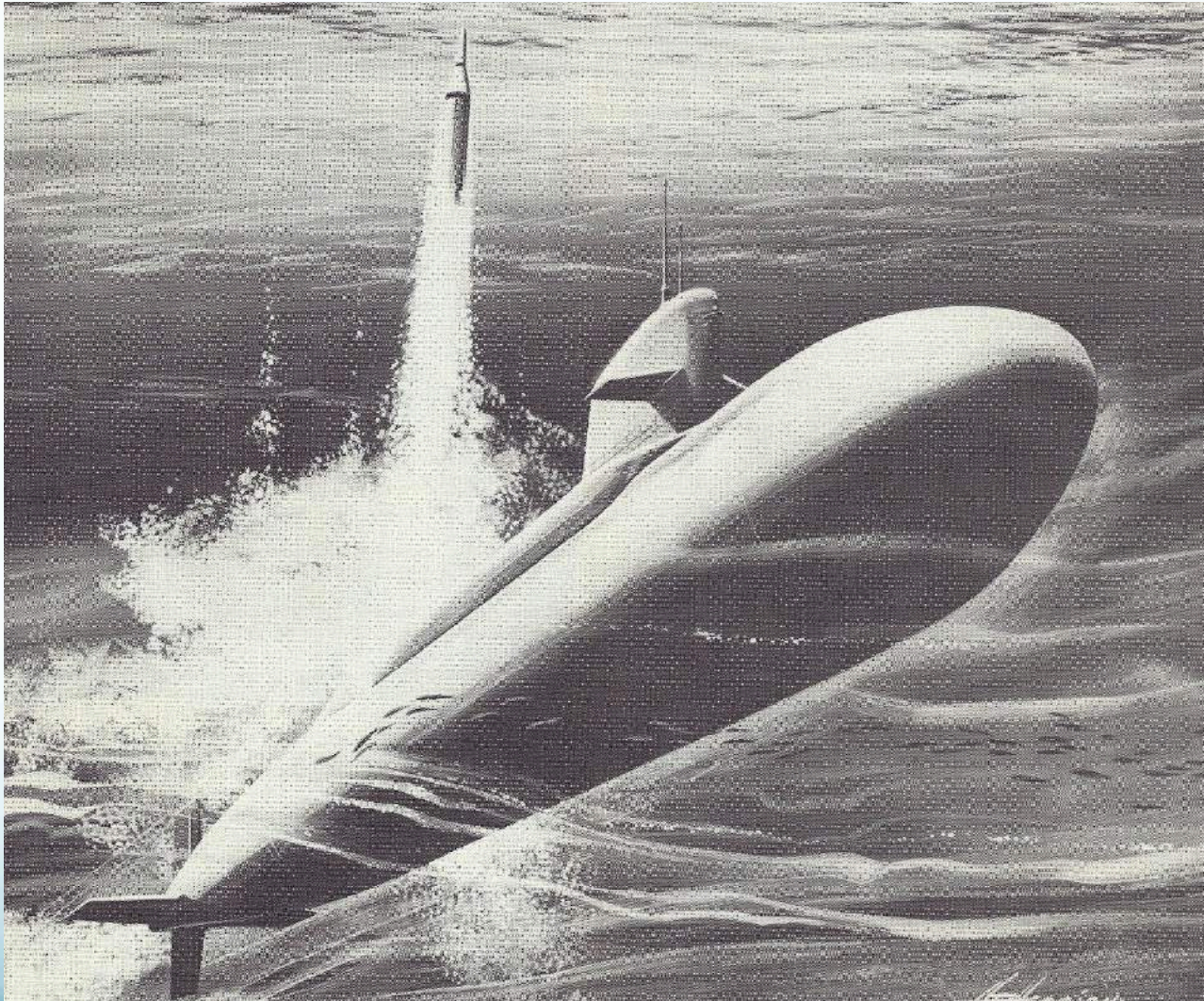
Early Polaris missile sub concept



(WX2)WASHINGTON, DEC. 29--NAVY PLANNED MISSILE--This is an artist's conception of the launching from a submarine of the Polaris, a Navy planned ballistic missile with a range of 800 miles or more, according to the Missiles and Rockets Magazine. The new weapon, the magazine said, can be stored in subs, as shown above, and launched from deep in water. The missile will be ready in about five years, it was reported today. (AP WIREPHOTO)(rw71635ho)1956

Source: Navy news release, 29 Dec 1956, via Scott Lowther, Aerospace Project Review Blog

Final Polaris missile sub design



Source: Navy booklet: "Polaris – The US Navy's Fleet Ballistic Missile Weapon System," circa early 1960s

Polaris on surface ships

- *USS Observation Island* (E-AG-154) conducted the first at-sea test launch of a Polaris A1 missile on 27 August 1959.
- *USS Observation Island* continued serving as a test platform, launching the Polaris A2 in March 1961 and the A3 version in June 1963.
- Original Navy plans included installing Polaris on several US cruisers, including the nuclear powered *USS Long Beach*, which would have had eight Polaris launchers.
- Plans were developed for creation of a NATO Multilateral Force (MLF) consisting of 25 surface ships armed with 200 Polaris missiles. Plans to establish MNF failed.
- Polaris was not deployed on any US or NATO surface ship.



Launch from *USS Observation Island*.
Source: US Navy



Artists concept of a launch from *USS Long Beach* (CGN-9).
Source: US Naval Institute

Polaris on surface ships

The Italian cruiser *Giuseppe Garibaldi* was equipped with four Polaris launch tubes near the stern and conducted test launches of Polaris shapes.



(foto Rotalfoto - Milano - coll. M. Risolo)



Two more Italian Navy cruisers (Andrea Doria-class and *Vittorio Veneto*) were "fitted for but not with" two Polaris missile launchers per ship.

RADM William F. "Red" Raborn

- 8 Nov 1955: as Director of Special Projects at the Bureau of Weapons, tasked to develop a submarine-launched ballistic missile based on the Army's Jupiter IRBM.
 - Raborn was told the new system had to achieve interim capability by early 1963 and full capability by early 1965.
- 8 Dec 1956: Joint project terminated and Navy was authorized to proceed with Polaris program with concurrent development of required technologies.
- Raborn became the Polaris Program Manager. His team successfully coordinated the many concurrent development activities, each of which had to be successful in order to deliver the operational Polaris weapons system.
 - PERT (program evaluation and review technique) was a management tool used widely on the Polaris program
- The *USS George Washington* (SSBN-598), the 1st U.S. nuclear-powered ballistic missile submarine, was commissioned 30 December 1959, fired its first test missile 20 July 1960, and departed on the Navy's first deterrent patrol on 15 November 1960, years ahead of the original program schedule.
- Raborn was awarded the Collier Trophy, presented by President Kennedy, for his leadership on the Polaris program.



Source: US Navy

Concurrent development of required technologies

- Submarine vehicle:
 - Hull: The first Polaris submarine, *USS George Washington* (SSBN-598), was created by cutting the hull of a new-construction SSN, *USS Scorpion* (SSN-589), and inserting a completely new center section with 16 missile launch tubes.
 - Nuclear power plant: The S5W nuclear propulsion section intended for *USS Scorpion* was used without change on *USS George Washington*.
- Command & control communications system:
 - Naval Research Laboratory (NRL) developed a VLF facsimile transmission system, known as “Bedrock”
 - Earliest demonstrations were in 1959 for *USS Skate*’s (SSN-578) voyage to the North Pole, and in 1960 for *USS Triton*’s (SSN-586) circumnavigation of the globe, February-May 1960.
 - This became the first system to provide reliable command and control communication from a single high-power transmitting station in the US to continuously submerged submarines operating in any region of the world.
- Submarine navigation system:
 - Sperry developed the Mk II SINS (Ships Inertial Navigation System), which became the standard on all Polaris subs
 - First deployed in 1960 on *USS Halibut* and for *USS Seadragon*’s Arctic cruise.

Concurrent development of required technologies

- Small (enough) nuclear warhead: 600 kT W-47 Y1
 - Diameter: 18 in (46 cm); length: 47 in (120 cm) long; Weight: 717 lb (326 kg)
 - First nuclear warhead with a new, miniaturized pit
- Re-entry vehicle: Mark 1
 - Mk-1 RV had a beryllium heat-sink heat shield
- Missile system:
 - Polaris solid-fuel missile:
 - Lockheed Polaris A1 (UGM-27A) 2-stage missile airframe
 - Aerojet General solid rocket motors; Polyurethane Ammonium Perchlorate (PU/AP) solid fuel
 - Underwater launch system:
 - Naval Ordnance Test Station (now Space and Naval Warfare Systems Center Pacific) developed a “cold launch” method, where the missile is ejected from the vertical launch tube by high-pressure gas and the missile breaches the surface before the rocket motor ignites.
 - Westinghouse/MIT launch control system activated the high-pressure gas flow.
 - 4 April 1960: First live submerged test launch took place off San Clemente Island
 - Fire control system: General Electric Mark 80 analog / digital fire control system
 - Missile inertial navigation system:
 - Designed by MIT, manufactured by General Electric and Hughes

U.S fleet ballistic missile subs (SSBN)

| Class | # in Class | Length | Beam | Displacement (tons) | Reactor | Shaft hp | Max speed (kts) | Years delivered | Years in service |
|------------------------------|-------------------|--------------------|----------------|-----------------------------|---------|----------|-----------------|-----------------|------------------|
| George Washington (SSBN-598) | 5 ⁽¹⁾ | 116.3 m (381.6 ft) | 10.1 m (33 ft) | 6,000 (surf), 6,880 (sub) | S5W | 15,000 | 20+ | Dec 59 - Mar 61 | 1959 - 1985 |
| Ethan Allen (SSBN-608) | 5 ⁽²⁾ | 125.1 m (410.3 ft) | 10.1 m (33 ft) | 7,070 (surf), 8,010 (sub) | S5W | 15,000 | 20+ | Aug 61 - Jan 63 | 1961 - 1992 |
| Lafayette (SSBN-616) | 9 | 129.5 m (425 ft) | 10.1 m (33 ft) | 7,370 (surf), 8,380 (sub) | S5W | 15,000 | 20+ | Apr 63 - Dec 64 | 1963 - 1994 |
| James Madison (SSBN-627) | 10 | 129.5 m (425 ft) | 10.1 m (33 ft) | 7,440 (surf), 8,370 (sub) | S5W | 15,000 | 20+ | Apr 64 - Dec 64 | 1964 - 1995 |
| Benjamin Franklin (SSBN-640) | 12 ⁽³⁾ | 129.5 m (425 ft) | 10.1 m (33 ft) | 7,250 (surf), 8,250 (sub) | S5W | 15,000 | 20+ | Oct 65 - Apr 67 | 1965 - 2002 |
| Ohio (SSBN-726) | 14 ⁽⁴⁾ | 170.7 m (560 ft) | 12.8 m (42 ft) | 15,275 (surf), 16,800 (sub) | S8G | 35,500 | 20+ | Nov 81 - Sep 97 | Nov 81 - present |
| Columbia (SSBN-826) | 12 | 170.7 m (560 ft) | 13.1 m (43 ft) | 20,815 (sub) | S1B | TBD | 20+ | First in 2031 | |

- (1) Three in this class were converted to an SSN role in 1982 to comply with arms control treaty limits: *George Washington*, *Patrick Henry* & *Robert E. Lee*.
- (2) All in this class were converted to an SSN role in 1982 to comply with arms control treaty limits. Two, *Sam Houston* and *John Marshall*, were further converted as special operations SSNs with 2 x Dry Deck Shelters on the missile deck.
- (3) All were decommissioned by 1995 except *James K. Polk* and *Kamehameha*, which were converted to special operations SSNs with 2 x Dry Deck Shelters on the missile deck. *Polk* was decommissioned in 1999 and *Kamehameha* in 2002.
- (4) Originally 18. Four were converted in 2002 to an SSGN (non-SSBN) role to comply with arms control treaty limits.

41 for Freedom

Five classes of Polaris SSBNs

- 41 Polaris SSBNs were built at an average rate of more than 5 per year and were commissioned in a 7 year period between December 1959 (*USS George Washington*, SSBN-598) and April 1967 (*USS Will Rogers*, SSBN-659).
- Armament:
 - All were armed with 16 solid-fueled SLBMs in a missile compartment located amidships.
 - The particular type of missile (Polaris A1, A2, A3; Poseidon C3; Trident I C4) and nuclear warhead(s) depended on the SSBN class and the missile system upgrades made during major overhauls later in the SSBN's service life.
 - The first two classes (589 and 608) could not be upgraded to carry the Poseidon C3 or Trident I C4 SLBMs.

| Polaris SSBN class | # in class | Service life (avg) | Polaris A1 | Polaris A2 | Polaris A3 | Poseidon C3 | Trident I C4 |
|-------------------------|------------|--------------------|------------|------------|------------|-------------|--------------|
| George Washington (598) | 5 | 23 yr | ✓ | | ✓ | | |
| Ethan Allen (608) | 5 | 22 yr | | ✓ | ✓ | | |
| Lafayette (616) | 9 | 27 yr | | ✓ | ✓ | ✓ | |
| James Madison (627) * | 10 | 29 yr | | | ✓ | ✓ | ✓ |
| Ben Franklin (640) * | 12 | 27 yr | | | ✓ | ✓ | ✓ |

* Only six boats in each of these classes were converted for Trident I C4.

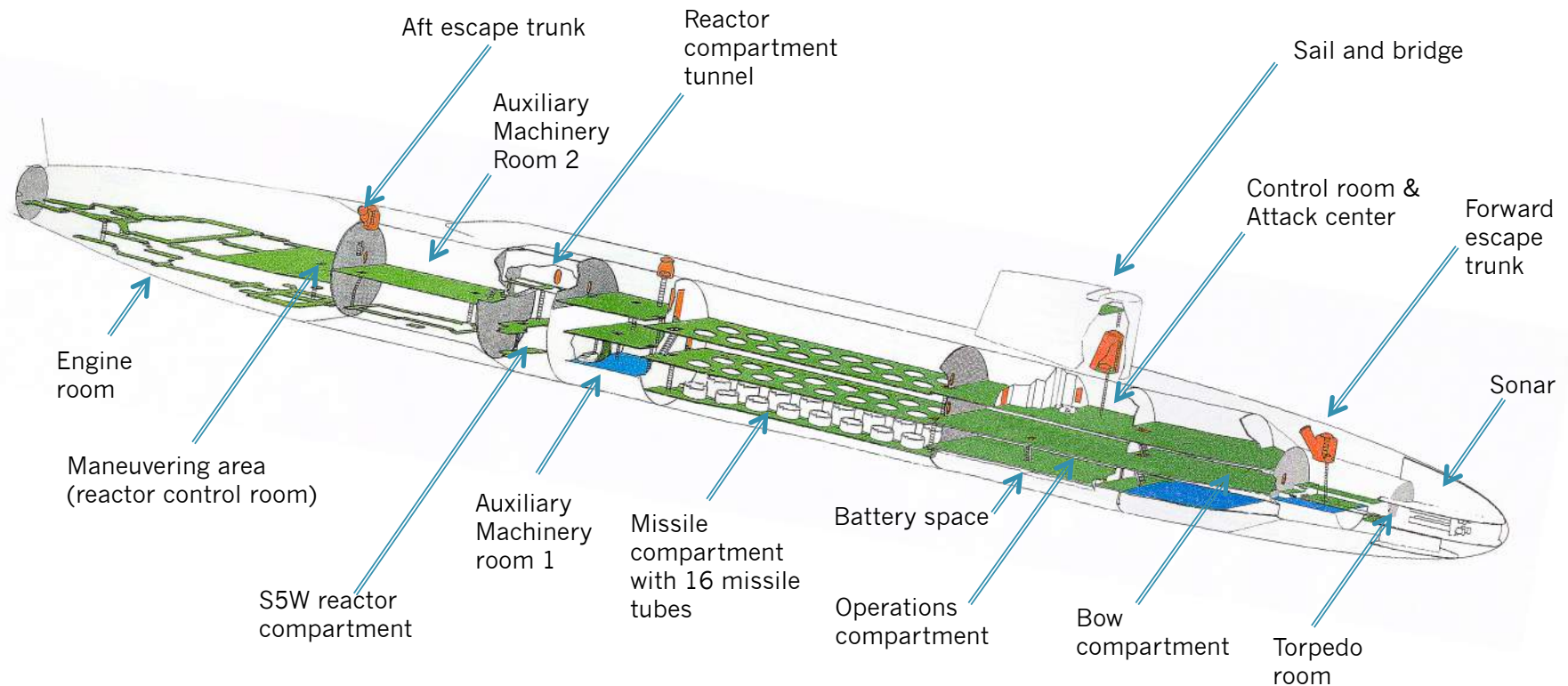
41 for Freedom

Five classes of Polaris SSBNs

- Armament (continued):
 - The George Washington (598)-class SSBNs had 6 x 533 mm (21 in) bow torpedo tubes. The following classes had 4 x 533 mm (21 inch) bow torpedo tubes
- Propulsion:
 - All were powered by similar S5W nuclear propulsion plants: 1 x S5W reactor rated @ 78 MWt; 2 x main steam turbines delivering a combined 15,000 shaft horsepower to a single propeller.
 - All boats were refueled twice during their service life.
- All SSBNs were operated by two crews, Blue & Gold.
 - Several boats were converted to SSNs late in life to comply with arms control treaty limits. Some of these SSN conversions included additional features to support Special Operation Force (SOF) equipment and personnel. All SSN conversion boats had a single crew.
- A total of 1,245 Polaris deterrent patrols were made in a period of about 21 years, from the first Polaris A-1 deterrent patrol by *USS George Washington* starting on 15 Nov 1960, and ending with the last Polaris A-3 deterrent patrol by *USS Robert E. Lee*, which started on 1 October 1981.
 - By then, the remainder of the original Polaris SSBN fleet had transitioned to Poseidon C3 and Trident I C4 SLBMs.
 - Average service life was about 26 in SSBN duty (20 – 31 year range).
- All 41 of the original Polaris SSBNs were replaced by 18 Ohio-class SSBNs, armed initially with 24 x Trident I C4 SLBMs, and later with 24 x Trident II D5 SLBMs.

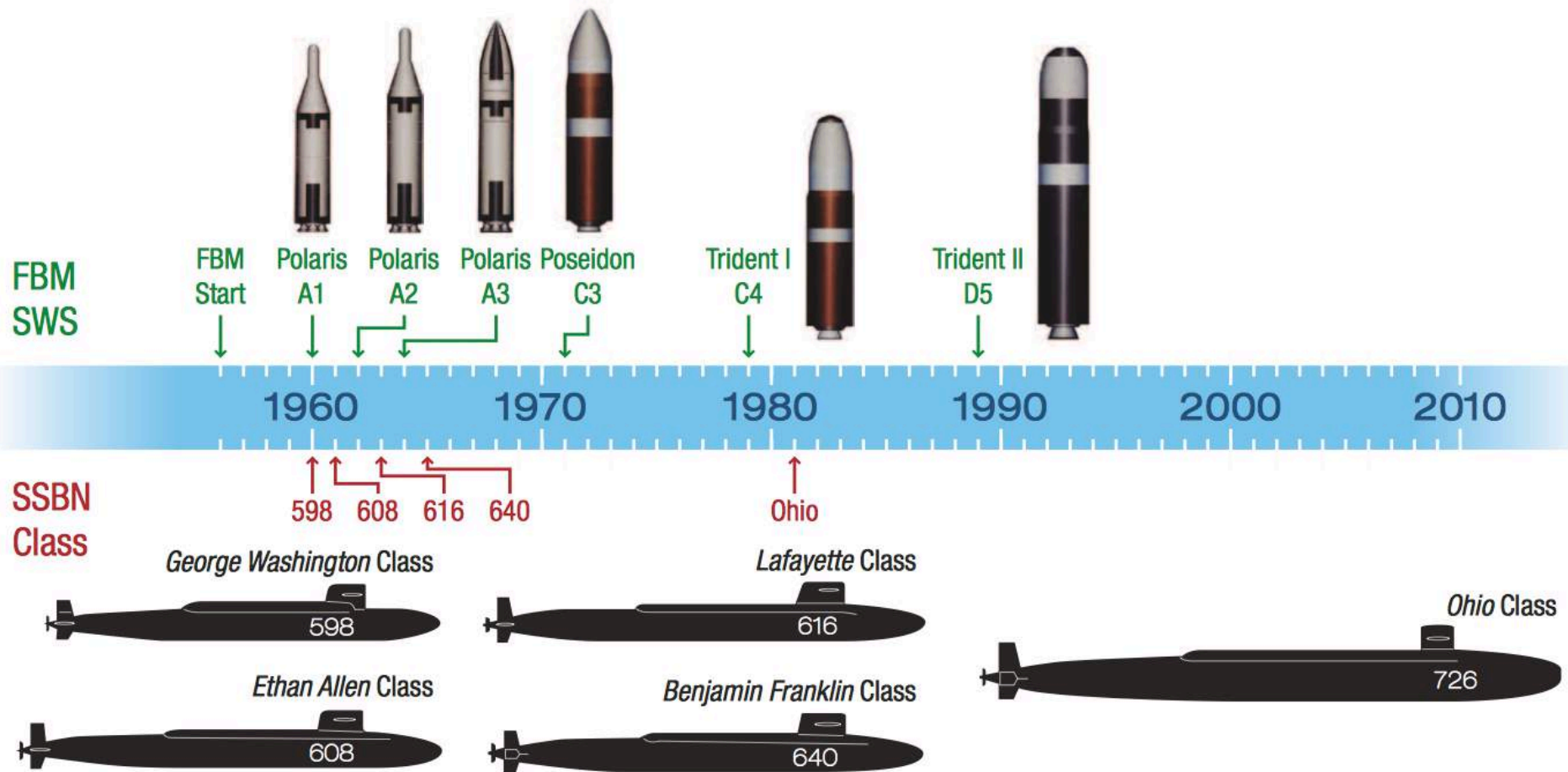
Polaris SSBN

Typical notional internal arrangement



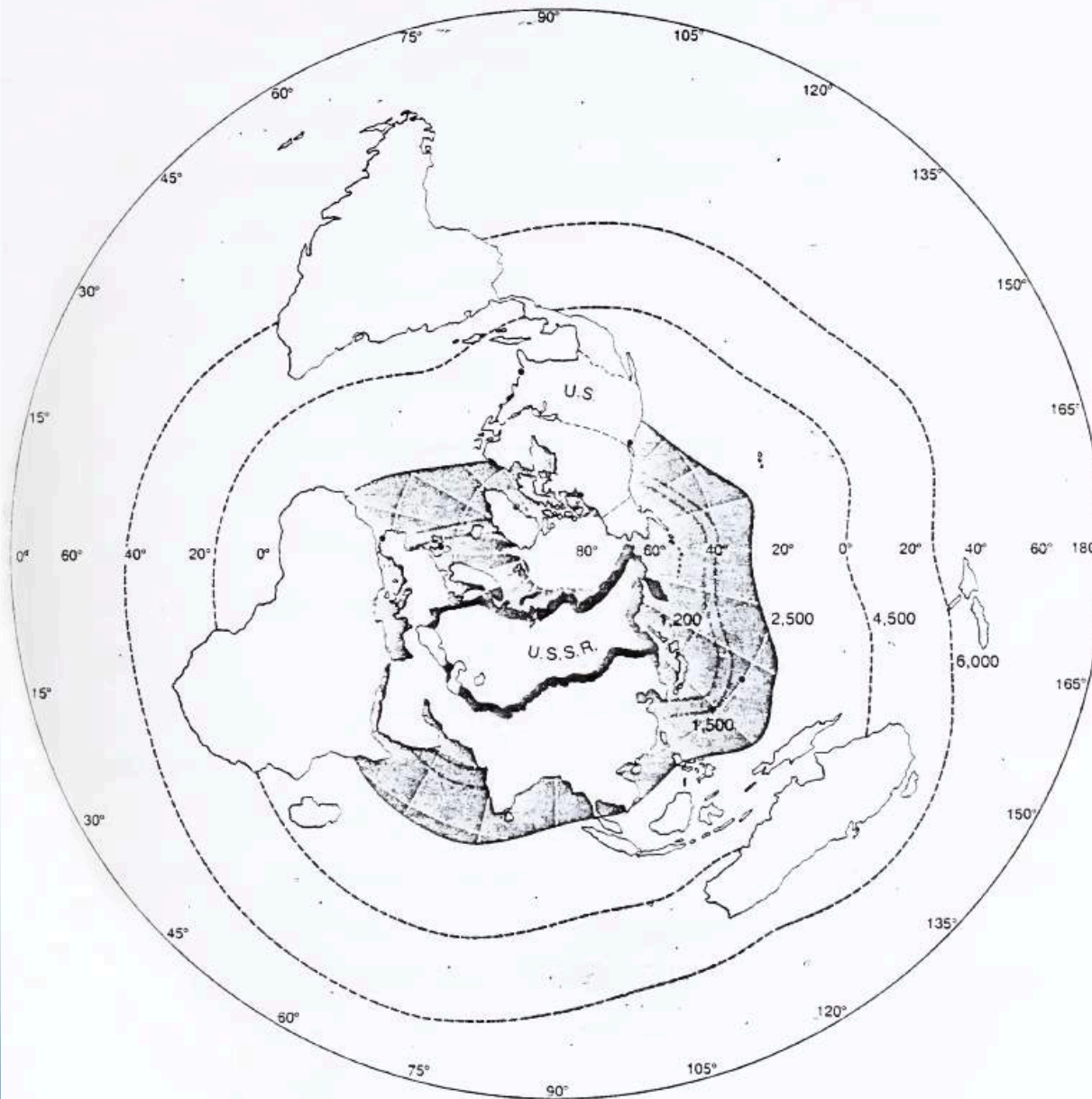
Source: adapted from US Navy

Initial Operating Capability (IOC) dates for US SLBMs and SSBNs



Source: Johns Hopkins APL technical Digest, Volume 29, Number 4 (2011)

SLBM range expands potential US SSBN patrol areas



Source: T.W. Ford,
"Ballistic Missile
Submarines of the
United States and the
Soviet Union:
a comparison of
systems and doctrine,"
December 1982

George Washington (SSBN-598) class

- Five boats in this class. The first three boats in class (*George Washington*, *Patrick Henry* & *Theodore Roosevelt*) originally were laid down as Skipjack-class SSNs (*Scorpion*, *Sculpin* & *Scamp*), but were modified during construction with the insertion of a 130 ft (40 m) ballistic missile section to accelerate SSBN delivery to the fleet.
- A typical SSBN 105-day deployment cycle began with a 3-day “turnover” with the prior crew. After taking over the boat, the new crew performed a 30-day refit and provisioning process assisted by the local tender or sub base, followed by a 70-day deterrent patrol.
- Originally deployed with 5-bladed propellers, converting later to 7-bladed “skewback” propellers first introduced in the Permit-class SSN.



USS *George Washington* (SSBN-598). Source: www.navsource.org/archives

George Washington (SSBN-598) class

- Operational matters:
 - 20 July 1960: The 1st Polaris A1 launch from a submerged submarine was conducted from *USS George Washington* (SSBN-598).
 - 15 Nov 1960: *USS George Washington* started the 1st Polaris nuclear deterrent patrol armed with 16 Polaris A1 ballistic missiles
 - This milestone occurred just 3 years 11 months after the Polaris FBM program was authorized by the Secretary of Defense.
 - The 1st deterrent patrol was completed 66 days later on 21 January 1961.
 - All SSBNs in this class were refitted between June 1964 - October 1965 to carry Polaris A3 missiles. None could be upgraded further to handle the larger diameter Poseidon SLBM.
 - To comply with the SALT II treaty limits and to make room for the new Ohio-class SSBNs, missile tubes in all George Washington-class SSBNs were unloaded.
 - *Robert E. Lee* departed on the last Polaris A3 deterrent patrol on 1 October 1981. On 28 February 1982, *Robert E. Lee* off-loaded its Polaris A3 SLBMs in Bangor, WA. A total of 1,245 Polaris deterrent patrols had been made since the first patrol by *George Washington* in 1960.
 - *George Washington* (SSBN-598), *Patrick Henry* (SSBN-599) and *Robert E. Lee* (SSBN-601) were converted to SSNs in March 1982. The last ship in this group (*George Washington*) was decommissioned in 1985.
 - *Theodore Roosevelt* and *Abraham Lincoln* were decommissioned in 1982.
 - All George Washington-class SSBNs were refueled twice and had an average service life of 22.5 years.

George Washington (SSBN-598) class



USS George Washington (SSBN-598) launched 9 Jun 59.
Source: <https://connecticuthistory.org/>



Polaris A1 handling alongside tender.
Source: <http://users.skynet.be/RonSubCovers/>



SSBN-598 in drydock. Note the 5-bladed propeller.
Source: <https://imgur.com/a/IQBOi>



SSBN-599 in drydock. Note the 7-bladed "skewback" propeller. Source: <http://www.shipmodels.info>

Ethan Allen (SSBN-608) class

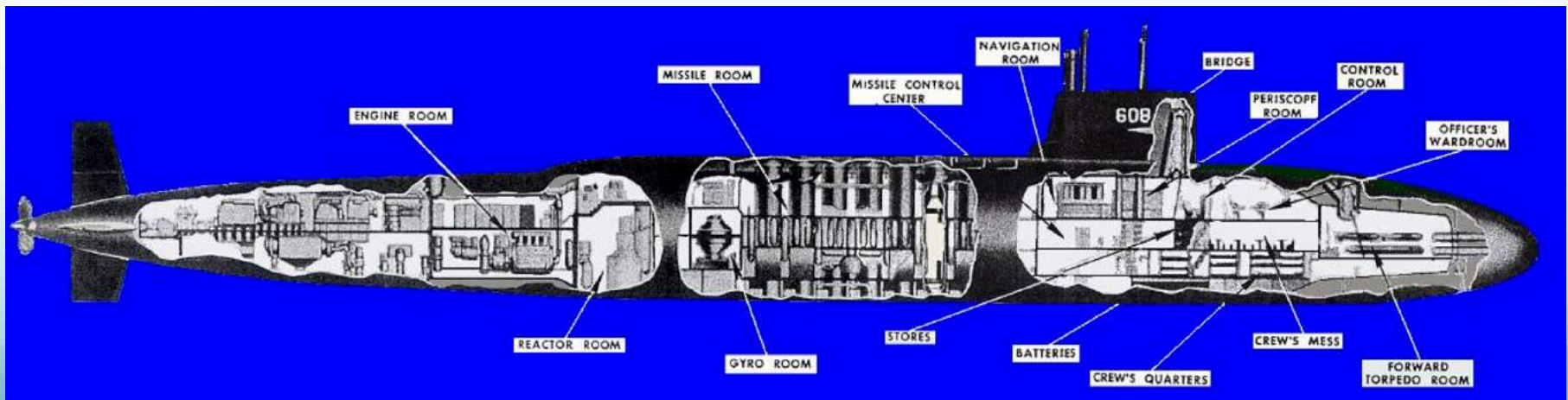
- Five boats in this class.
This was the first submarine class designed from the keel up as an SSBN.
- 23 October 1961: *USS Ethan Allen* (SSBN-608) made the 1st submerged launch of a Polaris A2.
- 6 May 1962: While submerged in the Pacific, *USS Ethan Allen*, operating as a unit of Joint Task Force 8 “*Operation Frigate-Bird*,” launched the only nuclear-armed Polaris missile (an A2) ever tested.
- 26 June 1962: *USS Ethan Allen* started its 1st deterrent patrol armed with Polaris A2 SLBMs.
- All SSBNs in this class were refitted to carry Polaris A-3 missiles in the 1970s. None could not be upgraded further to handle the larger diameter Poseidon SLBM.



USS Thomas Jefferson (SSBN-618). Source: www.navsourc.org/archives

Ethan Allen (SSBN-608) class

- Operational matters:
 - To comply with the SALT II treaty limits and to make room for new Ohio-class SSBNs, missile tubes in all Ethan Allen-class SSBNs were filled with concrete and the Polaris fire control system was removed. These subs were re-designated as SSNs in 1981.
 - *Sam Houston* and *John Marshall* were converted to carry two Dry Deck Shelters and up to 67 special operations force (SOF) personnel. Service life for these two SOF boats was 30 years.
 - The Ethan Allen-class boats not converted for SOF duty, *Ethan Allen*, *Thomas Edison* and *Thomas Jefferson*, were decommissioned between 1983 – 1985. They had an average service life of 21.8 years.



Source: https://fas.org/nuke/guide/usa/slbm/ssbn608_cut.jpg

Lafayette (SSBN-616), James Madison (SSBN-627) & Ben Franklin (SSBN-640) classes

- These three very similar SSBN classes totaled 31 boats.
 - Eight of the nine Lafayette-class boats originally were outfitted with the Polaris A2 SLBM. *USS Daniel Webster* (SSBN-626) was the 1st SSBN to be originally armed with the Polaris A3.
 - The Lafayette-class boats and their successors were equipped with a hovering system to manage trim more effectively when launching missiles; this increased the missile launch rate from one per minute to four per minute.
 - The 10 James Madison-class boats were identical to the Lafayette-class except that they were designed originally to carry Polaris A3.
 - The 12 Ben Franklin-class boats incorporated quieter machinery and originally were designed with SUBSAFE features that were retrofit on the earlier SSBN classes.
- The 2,500 nm (4,630 km) range of the Polaris A3 extended SSBN operations to the Pacific Ocean, providing a larger operating area to offset expanding Soviet anti-submarine capabilities.
 - 25 December 1964: *USS Daniel Boone* (SSBN-629) departed Apra Harbor, Guam and began the 1st deterrent patrol with Polaris A3 in the Pacific.

Lafayette (SSBN-616), James Madison (SSBN-627) & Ben Franklin (SSBN-640) classes

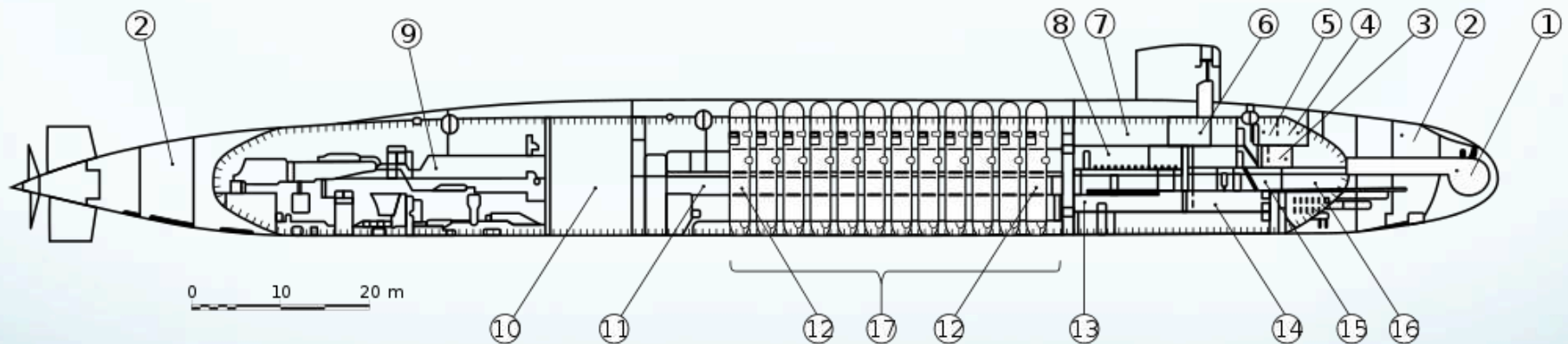
- Operational matters:
 - 20 April 1964: During a series of tests off Cape Canaveral, the Lafayette-class *USS Henry Clay* (SSBN-625) was the first SSBN to launch a Polaris missile (an A-2) while surfaced.
 - All of these SSBNs were overhauled and modernized to handle Poseidon C3 SLBMs.
 - 31 March 1971: 1st Poseidon (C3) deterrent patrol was by James Madison-class *USS Sam Rayburn* (SSBN-635).
 - Six James Madison (627)-class and six Ben Franklin (640)-class boats were modernized again during the late 1970s and early 1980s to handle Trident I C4 SLBMs.
 - 627-class: *James Madison, Daniel Boone, John C. Calhoun, Von Steuben, Casimir Pulaski & Stonewall Jackson*
 - 640-class: *Benjamin Franklin, Simon Bolivar, George Bancroft, Henry L. Stimson, Francis Scott Key & Mariano G. Vallejo*
 - October 1979: 1st Trident I (C4) deterrent patrol was by Ben-Franklin-class *USS Francis Scott Key* (SSBN-657).

Lafayette (SSBN-616), James Madison (SSBN-627) & Ben Franklin (SSBN-640) classes

- Operational matters (cont'd):
 - Most of these SSBNs were decommissioned to comply with SALT II treaty limits as the newer Ohio-class SSBNs entered service.
 - Two boats were converted into Moored Training Ships (MTS):
 - James Madison-class boat *Sam Rayburn* (SSBN-635) was decommissioned in 1989 after 23 years of SSBN service and modified to become MTS-635.
 - Lafayette-class boat *Daniel Webster* (SSBN-626) was decommissioned in 1990 after 26 years of SSBN service and modified to become MTS-626.
 - Two Ben Franklin-class boats were converted in 1992 – 1994 for SSN special operations force (SOF) duty carrying two Dry Deck Shelters and up to 66 special operations force (SOF) personnel: *Kamehameha* (SSN-642) and *James K. Polk* (SSN-645).
 - These two boats had very long careers, with *Polk* serving 33.2 years and *Kamehameha* serving 36.3 years.

Ohio (SSBN-726) class

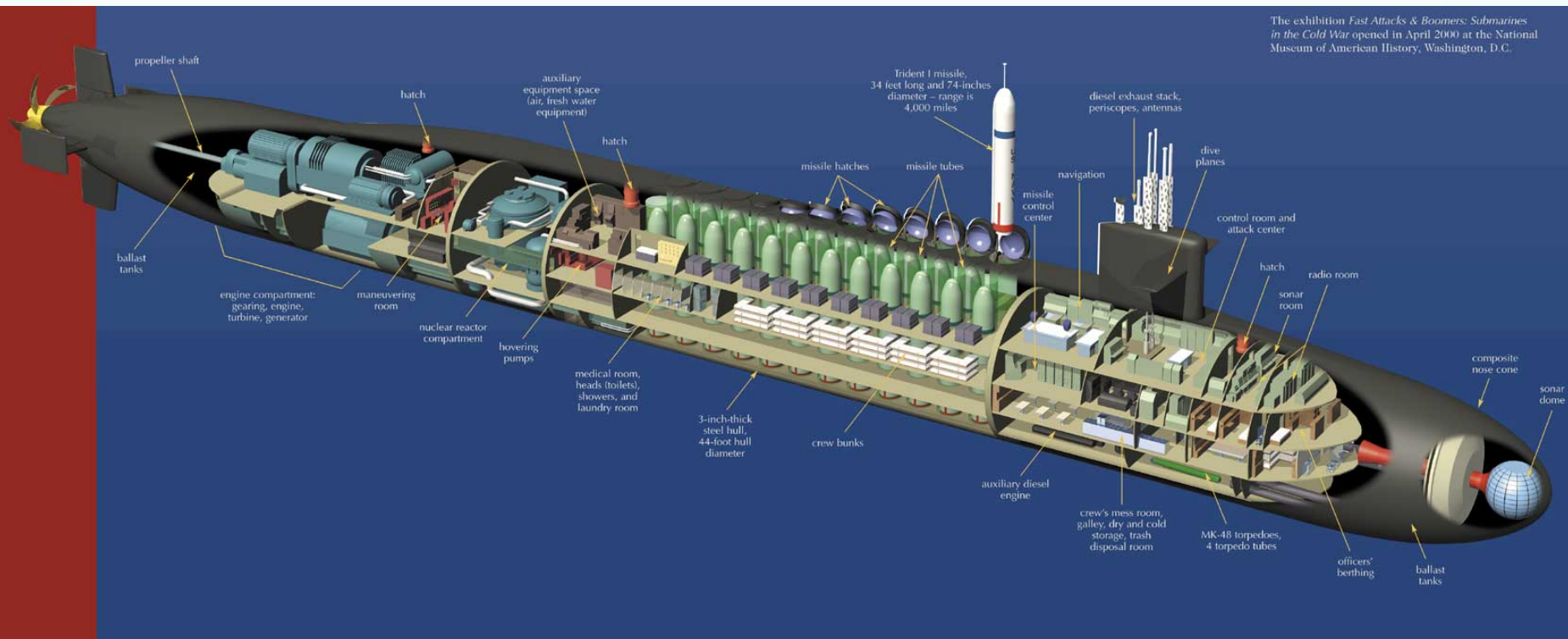
- The 18 Ohio-class SSBNs are the largest subs ever built by the US All were built by Electric Boat, Groton, CT. They entered service in a 19-year period between 1981 – 1997.
 - The first eight Ohio-class submarines initially were armed with 24 x Trident I (C4) SLBMs. During their mid-life refueling overhauls between 2000 – 2005, boats 5 to 8 were updated to handle 24 x Trident II (D5) SLBMs.
 - Beginning with the 9th boat in class, *USS Tennessee* (SSBN-734), the remaining Ohio-class SSBNs were equipped originally to handle the larger Trident II (D5).



Line drawing of the Ohio class in its original SSBN configuration. (1) Sonar dome, (2) Main ballast tanks, (3) Computer room, (4) Integrated radio room, (5) Sonar room, (6) Command and control center, (7) Navigation center, (8) Missile control center, (9) Engine room, (10) Reactor compartment, (11) Auxiliary machinery room no. 1, (12) Crew's berthing, (13) Auxiliary machinery room no. 2, (14) Torpedo room, (15) Wardroom, (16) Chief petty officer quarters, and (17) Missile compartment.

Ohio (SSBN-726) class

Internal arrangement



Source: www.usnavymuseum.org

Ohio (SSBN-726) class

- Nuclear weapons treaties have affected the Ohio-class SSBN fleet:
 - The Clinton administration's Nuclear Posture Review (NPR) 1994 determined that the strategic needs of the US could be met with 14 of the 18 Ohio-class SSBNs. The four oldest Ohio-class boats were removed from SSBN service and converted into guided missile submarines (SSGNs) capable of conducting conventional land attack with cruise missiles and special operations.
 - The SSGN conversion plan was implemented to comply with the SORT treaty, which entered into force on 1 June 2003.
 - The four Ohio-class boats were converted to SSGNs during their mid-life refueling overhauls between 2002 – 08.
 - This conversion eliminated 96 strategic launchers.
 - Starting in 2015, to comply with New START, the Navy began reducing the number of missile tubes on the 14 remaining Ohio-class SSBNs from 24 to 20. This work is scheduled to be completed by 5 Feb 2018, eliminating 56 strategic launchers.
 - The current 14 boat Ohio-class SSBN fleet carries about 50% of the total US active inventory of strategic nuclear warheads.
- Propulsion:
 - 1 x S8G PWR rated at 185 MWt (est.), 2 x main steam turbines with a combined rating of about 35,500 hp (26.5 MW) (est.) driving a single shaft and propeller.
 - Ohio-class subs require a mid-life refueling after about 21 years of operation.

Ohio (SSBN-726) class

- Armament:
 - Originally, 24 x Trident I (C4) or II (D5) SLBMs in vertical launch tubes. Currently, 20 x Trident II (D5) SLBMs each armed with 5 – 6 warheads for New START treaty compliance.
 - 4 x 533 mm (21”) mid-ship torpedo tubes for Mk-48 ADCAP torpedoes.
- Navigation system:
 - The Trident I Ohio-class SSBNs were among the last US subs to use the Ship Inertial Navigation System (SINS), which had been in service since 1960 on all previous Polaris / Poseidon SSBNs.
 - For Trident II, major system changes included:
 - Adoption of the Electrostatically-Supported Gyro Navigator (ESGN) as the inertial navigator (replacing SINS),
 - Addition of the Navigation Sonar System (NSS) with increased capability to measure velocity,
 - Adoption of Global Positioning System (GPS) to replace the aging Navy Navigation Satellite System (NAVSAT), and
 - Installation of a digital interface with the FBM weapon system and other ship systems.

Ohio (SSBN-726) class

- Operational matters:
 - Ohio-class SSBNs are among the very quietest nuclear subs, particularly when the main coolant pumps are off and primary system is operating on natural circulation.
 - Four boats are on station ("hard alert") in designated patrol areas at any given time.
 - As with prior US SSBNs, two crews (Blue and Gold) take alternate deterrent patrols.
 - Ohio-class SSBNs operate on a planned maintenance (PM) strategy based on regular intervals of 112 days, each of which include an at-sea deterrent patrol followed by a 35-day in-port period that starts with ship turnover to the incoming crew, and includes refit, incremental overhaul, appropriate modernization and resupply.
 - To decrease the time for replenishment between deterrent patrols, emergency escape trunks can be removed to create larger diameter resupply openings in the hull.
 - September 1982: 1st Trident I (C4) deterrent patrol, by *USS Ohio* (SSBN-726).
 - March 1990: 1st Trident II (D5) deterrent patrol, by *USS Tennessee* (SSBN-734).
 - Originally designed for a 30 year service life, but in 1998 NAVSEA certified all boats in the Ohio-class for a 42 year service life.
 - The current service life derives from NAVSEASYS COM letter 4700 Ser PMS392A2B/1001 dated 20 January 1998.
 - The first operating cycle (OPCYCLE) lasts 252 months (21 years), followed by an engineered refueling overhaul. An extended refit period (ERP) occurs at 168 month (14 years) into the first OPCYCLE.
 - The OPCYCLE is reset after the engineered refueling overhaul and the second OPCYCLE lasts 240 months (20 years), with an ERP at the midpoint of this OPCYCLE.

Ohio (SSBN-726) class

- Operational matters (cont'd):
 - May 2013: Rear Adm. Richard Breckenridge, Director, Undersea Warfare, OPNAV N97 reported: “....the pace at which our operational SSBNs go to sea in the conduct of the deterrence mission has remained essentially constant and offers no slack”.....“In order to sustain 10 operational SSBNs from now through the introduction of the new SSBN, we must complete refueling overhauls of all 14 Ohio SSBNs and operate the 12 newest of them to their full 42-year extended life.”
 - The long (27-month) mid-life Engineered Refueling Overhaul at the end of the first OPCYCLE can cause as many as four Ohio-class SSBNs to be out of service at the same time, reducing the deployable fleet size to as few as 10 SSBNs for periods of time.
 - The shorter extended refit period in the middle of the second OPCYCLE can cause as many as two Ohio-class SSBNs to be out of service at the same time, reducing the deployable fleet size to 12 SSBNs during this balance of the fleet’s service life.
 - November 2013: Congressional Budget Office (CBO) report, “*Options for Reducing the Deficit: 2014 to 2023*,” identified significant savings from reducing the size of the Ohio-class SSBN fleet & the future Columbia-class SSBN fleet.
 - 5 February 2018: New START treaty limits took effect Congressional Research Service report, “The New START Treaty: Central Limits and Key Provisions,” describes US treaty compliance actions affection the Ohio-class SSBN fleet:
 - No more than 240 operational SLBM launchers by February 2018: (12 SSBNs x 20 SLBM missile tubes per boat).

Ohio (SSBN-726) class

- Operational matters (cont'd):
 - The Navy has determined that certain aging electronic systems on Ohio-class SSBNs are not sustainable and need to be replaced with the Submarine Warfare Federated Tactical Systems (SWFTS), which already has been implemented on SSNs and the four Ohio-class SSGNs, and the Consolidated Afloat Networks and Enterprise Services (CANES), which the Navy plans to install on all classes of ships in the fleet.
 - *USS Rhode Island* (SSBN-740) will be the first SSBN to receive the electronic system modernization during its planned 27-month Engineered Refueling Overhaul (ERO), which started in January 2016.
 - The three younger Ohio-class SSBNs (SSBN-741 to -743) will receive the electronic system modernization during their EROs.
 - The ten older Ohio-class SSBNs that already have completed their EROs (SSBN-730 to -739) may receive the electronic system modernization during their second Engineering Refit Period (ERP), which typically occurs at 32 years of service, or at another time.
 - The oldest Ohio-class SSBN (*USS Henry M. Jackson*, SSBN-730) will reach the end of its service life in 2029, two years before the 1st Columbia-class SSBN is delivered. The youngest Ohio-class SSBN (*USS Louisiana*, SSBN-743) will reach the end of its service life in 2040, two years before the last Columbia-class SSBN is delivered.
 - During this fleet replacement period, the US Navy's SSBN force will fall to 10 submarines between 2032 and 2040, with a deployable fleet (a mix of Ohio- and Columbia-class boats) as small as 8 SSBNs.

Ohio (SSBN-726) class



Source: www.usnavymuseum.org



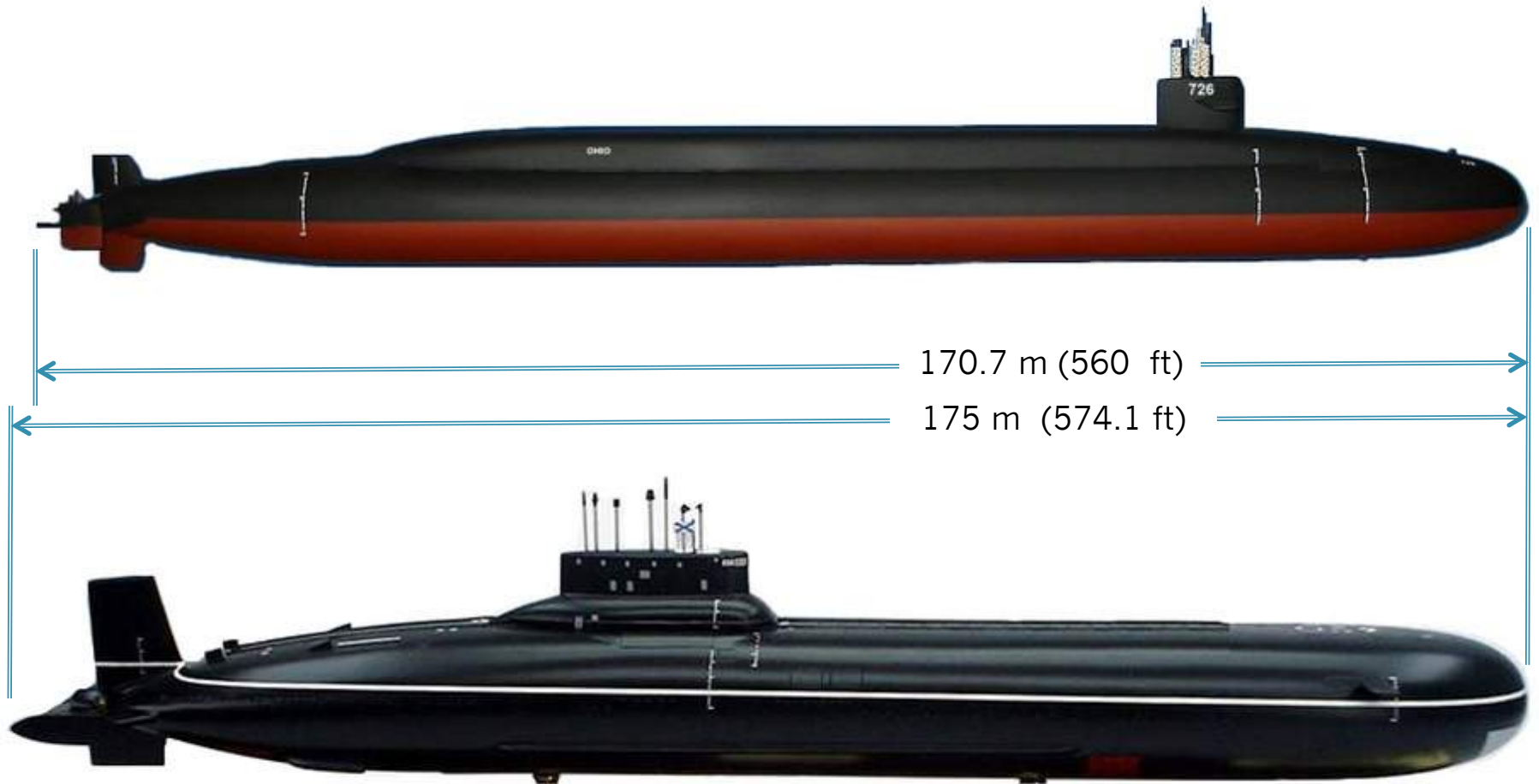
Source: <https://news.usni.org/>



Source: <https://www.defense.gov/Photos/>

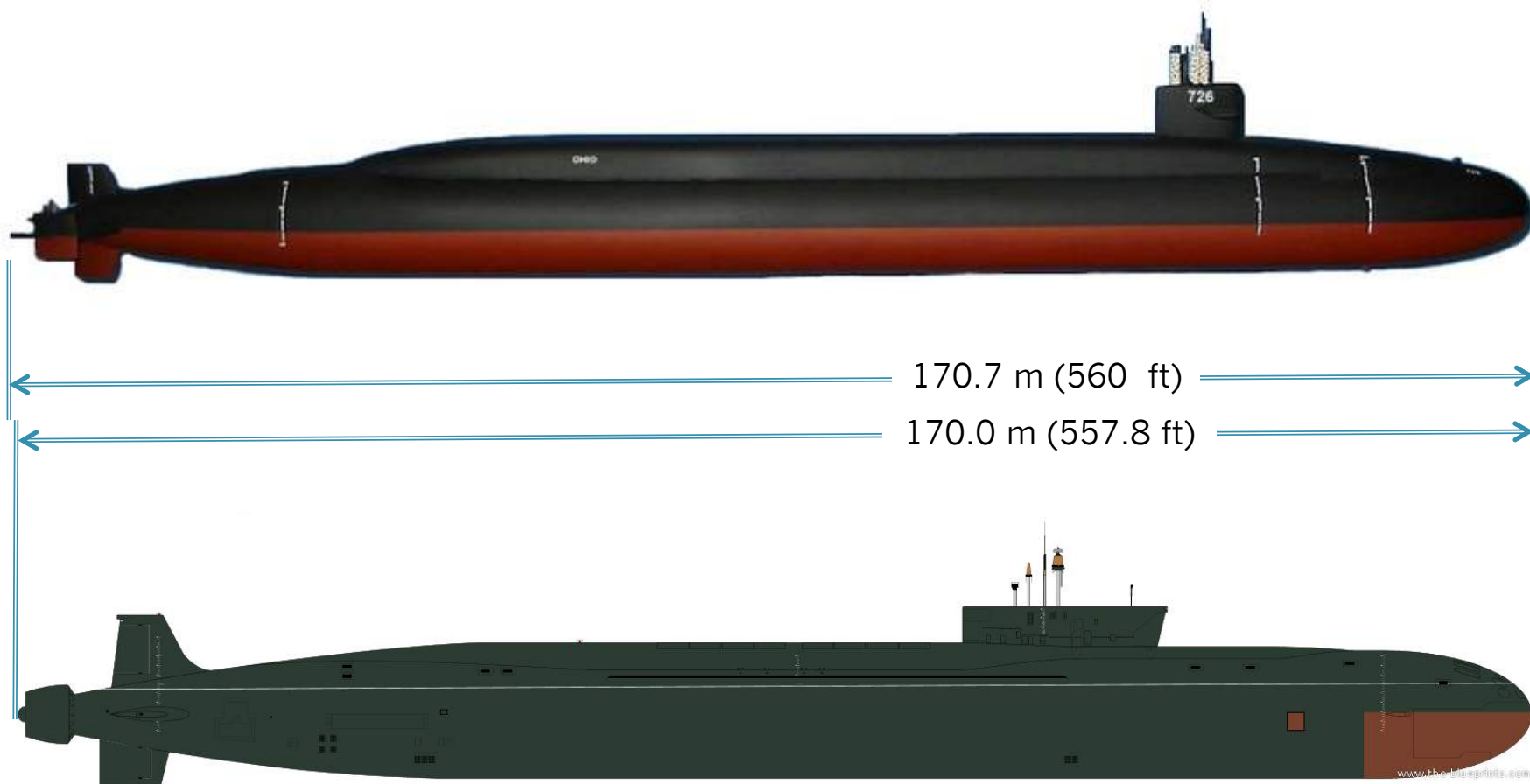
Ohio (SSBN-726) class

Scale comparison with Russian Typhoon-class SSBN



Ohio (SSBN-726) class

Scale comparison with Russian Borei-class SSBN



Driving an Ohio-class sub

USS Florida (SSBN/SSGN-728)

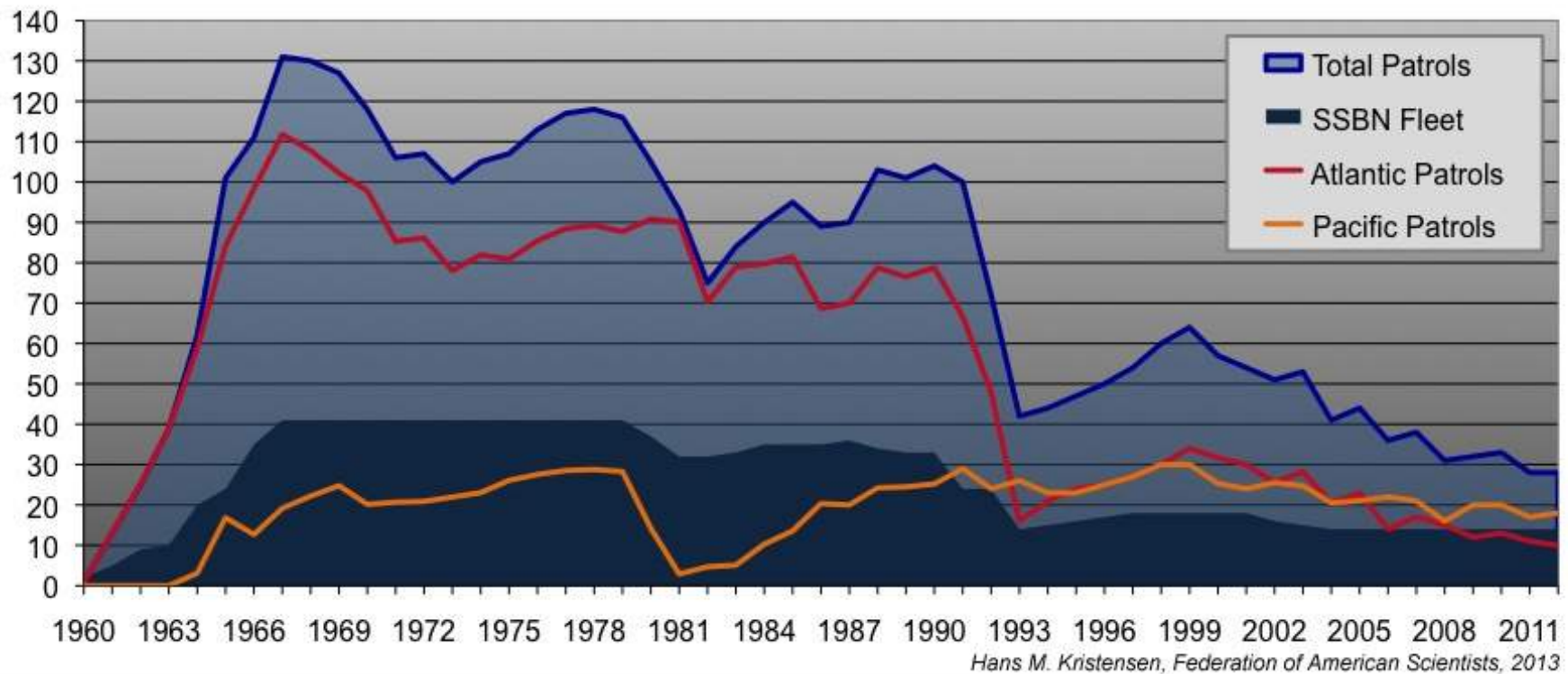


Traditional helmsman, planesman, chief-of-the-watch
and diving officer

Source: US Navy

Trend in number of annual deterrent patrols by US SSBNs

US SSBN Deterrent Patrols 1960-2012



Source: <https://fas.org/blogs/security/2013/04/ssbnpatrols/>

Columbia (SSBN-826) class

- 12 Columbia-class SSBNs will replace the current fleet of 14 Ohio-class SSBNs.
 - The main factor enabling the smaller SSBN fleet is the life-of-the-boat reactor core. The Navy claims that, by eliminating mid-life refueling, the mid-life overhaul is shortened from 4 to 2 years and 12 Columbia-class SSBNs can provide comparable on-station time to 14 Ohio-class SSBNs during the fleet's mid-life overhaul period.
- In FY 2013, the Navy delayed lead ship construction by two years (from FY 2019 to FY 2021) and reactor plant advanced procurement from FY 2017 to FY 2019. Preliminary milestones for the 1st replacement SSBN include:
 - 2021: begin construction of the 1st boat
 - 2027: deliver 1st boat to the Navy
 - 2031: ready to conduct 1st strategic deterrence patrol
- Features of the Columbia-class SSBN include:
 - 42.5 year service life (0.5 year more than Ohio class)
 - Life-of-the-boat reactor core (no refueling)
 - 16 x Trident II (D5) missile tubes, instead of 24 on Ohio-class SSBNs
 - Electric main propulsion motor replaces conventional geared propulsion turbines
 - Pump-jet propulsor, as on Virginia-class SSNs, instead of a propeller
 - X-stern planes instead of conventional cruciform (+) stern planes
 - Sonar suite comparable to Virginia Block III SSN: Large Aperture Bow (LAB) array, flank-mounted passive Lightweight Wide Aperture Array (LWAA), towed-array sonar

Columbia (SSBN-826) class

OHIO Replacement: The US Navy's vision

The US Navy is developing its next generation SSBN with an eye towards cost reductions and an average price per boat of USD4.9 billion. Construction of the first hull is scheduled to start in 2019. The Ohio-class Replacement will leverage technologies from the Virginia-class SSNs as well as innovations that have been tested but never put onboard a production submarine.



| | OHIO | OHIO Replacement |
|------------------------|-----------|------------------|
| HULL LENGTH | 559 ft | TBD |
| HULL DIAMETER | 42 ft | 42 ft |
| MISSILE TUBES | 24 | 16 |
| SUBMERGED DISPLACEMENT | 18,740 LT | 19,737 LT |

- 1 X-stern:**
Aligning aft control surfaces 45 degrees from the horizontal makes it more difficult for a submarine to inadvertently dive, allowing higher speed at greater depth.
- 2 Missile tubes:**
The new SSBN will have four modular 87-inch diameter missile tube quad packs for 16 Trident II D5 SLBMs.
- 3 LAB array:**
The Ohio Replacement will field a scaled-up version of the large aperture bow array designed for the Block III Virginias.
- 4 Hull coating:**
The boat will use anechoic coatings developed for the Virginia class that reduce threats from hostile active sonar.
- 5 Electric drive:**
An integrated power grid will drive the boat via permanent magnet induction motors, instead of a direct mechanical connection.
- 6 Virginia style propulsor:**
A pump-jet reduces cavitation at higher speeds compared to propeller drives, and performs better in shallow water.

Source: adapted from www.shipmodels.info/mws_forum/

For more information, refer to Congressional Research Service report 41129, "Navy Columbia Class (Ohio replacement) Ballistic Missile Submarine (SSBN[X]) Program: Background and Issues for Congress," 12 May 2017

Columbia (SSBN-826) class

- Propulsion:
 - 1 x S1B PWR reactor rated at >185 MWt, 2 x main steam turbine generators with a combined rating of >31 MW, delivering > 26.5 MW (35,500 hp) propulsion power to a single, permanent magnet electric main propulsion motor directly driving the main propulsion shaft and a pump-jet propulsor.
 - Power ratings of the S1B reactor and the electric propulsion train should be comparable to the power ratings of the S8G reactor and mechanical propulsion train on the similarly-sized Ohio-class SSBNs.
- Armament:
 - 16 x Trident II (D5) LE (life extension) SLBMs, each armed with only 5 – 6 warheads for New START treaty compliance.
 - 4 x 533 mm (21 in) mid-ship torpedo tubes for Mk-48 ADCAP torpedoes.
- Estimated unit and program costs:
 - Congressional Research Service report 41129, “*Navy Columbia Class (Ohio replacement) Ballistic Missile Submarine (SSBN[X]) Program: Background and Issues for Congress*,” updated 12 January 2018, reports:
 - The program has an average procurement unit cost “affordability cap” of \$8 B.
 - Lead boat procurement cost: \$8.2 billion in constant 2017 dollars, not including several billion dollars in additional cost for plans for the class
 - Boats 2 through 12: average unit procurement cost of \$6.5 billion in constant FY2017 dollars.
 - Total acquisition cost of the Columbia-class SSBN program is estimated to be about \$100.2 billion in constant FY2017 dollars, including about \$12.6 billion in R&D costs and about \$87.4 billion in procurement costs.

Columbia (SSBN-826) class

- This program is being coordinated with the UK's Dreadnought SSBN (Vanguard replacement) program.
 - Both US and UK SSBNs will use a Common Missile Compartment (CMC). Work on the "quad-pack" modular missile tubes is well advanced. Four CMCs will be used to construct the Columbia missile compartment.
 - Integrated tube and hull design. Each tube measures 86" (2.18 m) in diameter and can accommodate a 44.5 ft (13.58 m) Trident II (D-5) missile.
 - Both US and UK SSBNs are expected to have a common missile fire control system.



CMC "quad-pack." Source: General Dynamics



Source: adapted from NAVSEA

Submarine-launched strategic ballistic missiles (SLBM)

Navy roles & responsibilities for SLBMs

- **1948:** The “*Key West Agreement*,” approved by President Truman on 21 Apr 1948, defined the aviation roles for the three branches of the military service. The Navy was excluded from the strategic bombardment mission, but maintained its naval aviation arm for tactical missions. The “*Key West Agreement*” did not address missiles.
- **1948:** The “*Newport Agreement*,” signed on 21 Aug 1948, clarified inter-service nuclear roles. The Navy gained access to nuclear weapons and a portion of strategic operations planning while the Air Force gained primary oversight of nuclear weapons development programs.
- **1949:** Secretary of Defense Louis A. Johnson's memorandum, “*Assignment of Responsibility for Guided Missiles*,” dated 7 November 1949, was the first DoD document to delineate responsibilities among the three military branches for guided missile development and use.
 - For surface-to-surface missiles, the Navy was responsible for, “ship-launched guided missiles which supplement, extend the capabilities of, or replace naval aircraft.....”
 - At the time, the Navy had no ballistic missiles under development, just cruise missiles.
- **1956:** Secretary of Defense Charles E. Wilson's memorandum, “*Clarification of Roles and Missions to Improve the Effectiveness of Operation of the Department of Defense*,” dated 26 Nov 1956, defined inter-service roles related to Intermediate Range Ballistic Missiles (IRBMs).
 - The Air Force was responsible for land-based IRBMs; the Navy was responsible for ship-based IRBMs; the Army had no further role in IRBMs.
 - At the time, the Navy was participating with the Army in a joint program to deploy the Army's liquid-fuel Jupiter IRBM on Navy submarines and surface ships.
 - On 8 December 1956, the joint Army-Navy project was terminated and the Navy was authorized to proceed on its own with the solid-fuel Polaris IRBM program.

US submarine-launched ballistic missiles (SLBMs)

| SLBM | Years in service (platform) | Weight | Length | Diam | # of stages | Range | Warhead |
|-----------------------|--|--------------------------|----------------------|-------------------|---|-----------------------------|--|
| Polaris A1 (UGM-27A) | Nov 1960 - Oct 1965 (598-class) | 13,063 kg (28,800 lb) | 8.69 m (28.5 ft) | 1.37 m (54 in) | 2 (solid) | 2,222 km (1,200 naut mi) | 1 x W-47 @ 600 kT |
| Polaris A2 (UGM-27B) | Jun 1962 - Sep 1974 (608 & 616-classes) | 14,742 kg (32,500 lb) | 9.45 m (31.0 ft) | 1.37 m (54 in) | 2 (solid) | 2,778 km (1,500 naut mi) | 1 x W-47-Y1 @ 600 kT, upgraded to 1 x W-47-Y2 @ 1 MT |
| Polaris A3 (UGM-27C) | Sep 1964 - Feb 1982 (598, 608, 616, 627 & 640 classes) also Jun 1968 - 1996 UK Resolution-class SSBNs*) | 16,193 kg (35,700 lb) | 9.45 m (31.0 ft) | 1.37 m (54 in) | 2 (solid) | 4,630 km (2,500 naut mi) | Initially 1 x W-47 @ 500 kT, upgraded to Mk 2 RV cluster, 3 x W58 @ 200 kT |
| Poseidon C3 (UGM-73A) | Mar 1971 - 1992 (616, 627 & 640 classes) | 29,484 kg (65,000 lb) | 10.35 m (34.0 ft) | 1.88 m (74 in) | 2 (solid) + post-boost MIRV bus | 4,630 km (2,500 naut mi) | Up to 14 W68 @ 40 kT in Mk 3 RVs |

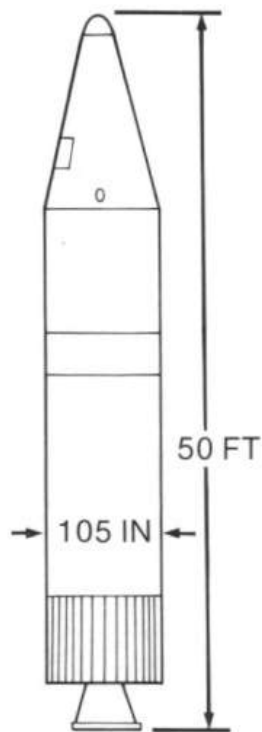
* UK Polaris A3 used UK designed warhead from 1968 - 1982. Upgraded to the A3TK Chevaline with UK-designed multiple reentry vehicle warhead, which was in service from 1982 - 1996.

US submarine-launched ballistic missiles (SLBMs)

| SLBM | Years in service (platform) | Weight | Length | Diam | # of stages | Range | Warhead |
|--|---|------------------------|-------------------|----------------|---------------------------------|-------------------------------|--|
| Trident I C4 (UGM-96) | Oct 1979 -Sep 2005 (627, 640 & 726 class) | 33,112 kg (73,000 lb) | 10.35 m (34.0 ft) | 1.88 m (74 in) | 3 (solid) + post-boost MIRV bus | > 7,408 km (> 4,000 naut mi) | Up to 8 W76 @ 100 kT in Mk4 RVs |
| Trident II D5 (UGM-133) and D5-LE (life extension) | 1990 – present (726 class & future Columbia class) also 1993 – present (UK Vanguard and future Dreadnought-class SSBNs) | 58,967 kg (130,000 lb) | 13.59 m (44.6 ft) | 2.11 m (83 in) | 3 (solid) + post-boost MIRV bus | > 12,000 km (> 6,500 naut mi) | Up to 12 W76-1 @ 100 kT in Mk 4A RVs, or Up to 12 W88 @ 475 kT in Mk 5 RVs, but limited to fewer warheads under arms control treaty limits |

Evolution of US submarine-launched ballistic missiles (SLBMs)

1955
INITIAL
CONCEPT



JUPITER
(LIQUID FUEL)

TRIDENT II
(D5)

TRIDENT I
(C4)

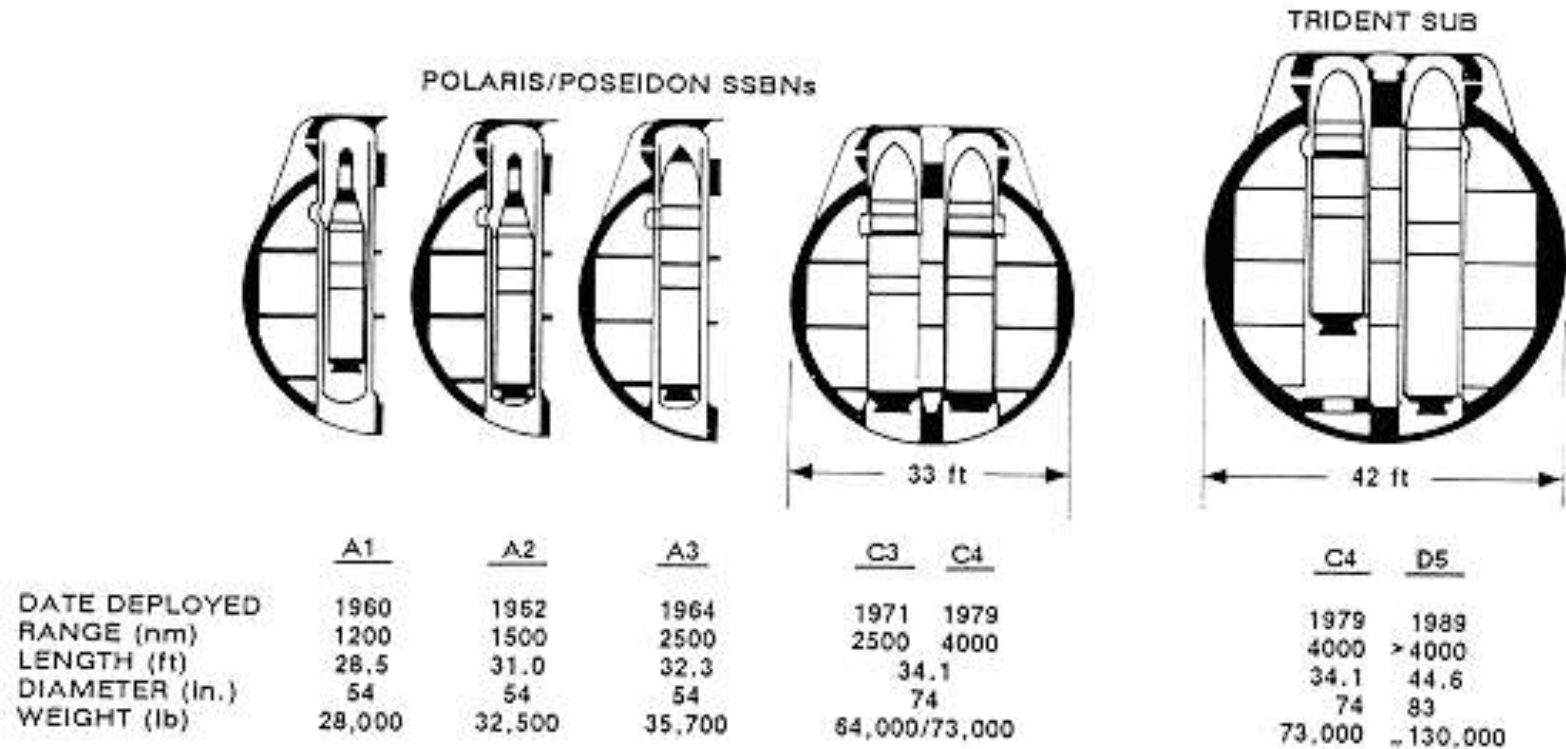
POLARIS A1, A2, A3

POSEIDON
(C3)

| | A1 | A2 | A3 | C3 | C4 | D5 |
|----------------|--------|--------|--------|--------|---------|----------|
| Year | 1960 | 1962 | 1964 | 1971 | 1979 | 1989 |
| Length (ft) | 28.5 | 31.0 | 32.3 | 34.0 | 34.0 | 44.6 |
| Diameter (in.) | 54 | 54 | 54 | 74 | 74 | 83 |
| Weight (lb) | 28,800 | 32,500 | 35,700 | 65,000 | >65,000 | >120,000 |
| Range (nm) | 1,200 | 1,500 | 2,500 | 2,500 | >4,000 | >4,000 |

Source: Johns Hopkins APL technical Digest, Volume 29, Number 4 (2011)

Fitting an SLBM into a submarine hull



FBM Constraints and Growth

Source: <http://fas.org:8080/nuke/guide/usa/slbn/index.html>

Polaris A1 (UGM-27A)

- Carried operationally only aboard the George Washington (598)-class SSBNs.
- Range: 1,200 naut. miles (2,222 km); single W-47 warhead with a yield of 600 kT; CEP: about 2 miles.
- 11 January 1958: A prototype of the Polaris A-1 SLBM made its first flight from a launching pad at Point Mugu, CA.
- 27 August 1959: *USS Observation Island* (E-AG-154) conducted the first at-sea test launch of a Polaris A1 missile.
- 4 April 1960: First live submerged test launch took place off San Clemente Island, CA.
- 20 July 1960: The first submerged launch of a Polaris A1 missile from a submarine. *USS George Washington* launched two Polaris A1 missiles off the coast of Cape Canaveral.
- 15 November 1960: Carrying 16 Polaris A1 missiles, *USS George Washington* started the first operational FBM deterrent patrol, which was completed 66 days later, on 21 January 1961.
- The Polaris A1 was retired from service on 14 October 1965, after about five years of operational service. It was replaced by Polaris A3.



Polaris A1 launch from submarine.

Source: <https://fas.org/nuke/guide/usa/slbm/a-1.htm>

Polaris A1 (UGM-27A)

Underwater testing off San Clemente Island



USS Butternut (AN-9) towing the Polaris Missile Test Cell to San Clemente Island from Long Beach Naval Shipyard, circa 1958. Source: <http://www.navsource.org/>



Polaris missile test shape launched from Polaris Missile Test Cell at San Clemente Island, circa 1958.
Source: Source: <http://www.navsource.org/>



Polaris missile "Pop-Up Variable Depth Launch Facility" at San Clemente Island, circa early 1960s. Source: Aviation Week & Space Technology magazine, 14 August 1961.

- The original Polaris Missile Test Cell (circa 1958) was an underwater tower anchored to the seabed off San Clemente Island. It was used to qualify the Polaris missile launch process. The first live submerged Polaris test launch was made from this facility on 4 April 1960.
- The "Pop-Up Variable Depth Launch Facility" was installed in 1961 for testing advanced Polaris missiles, which could be launched from a wide range of depths. The tower was installed in 170 feet of water. The depth of the launch cell could be adjusted over a range of about 75 feet.

Polaris A1 (UGM-27A)



A UGM-27A Polaris A1 ballistic missile being transferred between the US Navy submarine tender *USS Proteus* (AS-19) and the *USS Patrick Henry* (SSBN-599) at Holy Loch, Scotland (UK), 11 March 1961.
Source: US Navy photo / <https://commons.wikimedia.org/>

Polaris A2 (UGM-27B)

- The Polaris A2 was the original SLBM on all five Ethan Allen (608)-class SSBNs and eight of the nine Lafayette-class boats.
- Range increased to 1,500 naut. miles (2,778 km); higher yield W-47-Y1 warhead, upgraded later to W-47-Y2 version; CEP: about 2 miles.
- 23 October 1961: *USS Ethan Allen* (SSBN-608) made the 1st submerged launch of a Polaris A2.
- 6 May 1962: In the only test of its kind by the US, a Polaris A2 launched from *USS Ethan Allen* carried a live W-47-Y1 nuclear warhead to a target area near Christmas Island. The Polaris A2 is the only US strategic missile to conduct a live nuclear test.
- 26 June 1962: 1st Polaris A2 deterrent patrol aboard *USS Ethan Allen*.
- 20 April 1964: 1st launch of a Polaris missile (an A2) from a submarine on the surface, *USS Henry Clay* (SSBN-625).
- September 1974: Polaris A2 retired after 12 years of operational service; replaced by Polaris A3.



Polaris A2 on surface launch stand.

<https://commons.wikimedia.org/wiki/File:Polaris-A2.jpg>

Operation Dominic

Shot Frigate Bird, 6 May 1962

- Frigate Bird was the only US test of an operational strategic ballistic missile with a live nuclear warhead.
- This test involved firing a Polaris A2 SLBM from the submerged FBM submarine *USS Ethan Allen* (SSBN-608) toward a target area near Christmas Island (Kiritimati).
- The Polaris A2 SLBM was armed with a W-47Y1 warhead in a Mk-1 re-entry vehicle (RV).
 - The Mk-1 RV had a beryllium heat-sink heat shield, and with the 717 lb. warhead, had a gross weight of 900 lb.
 - The warhead had a yield of 600 kt, for a yield-to-weight ratio of 1.84 kT/kg
- The warhead and RV flew 1,020 nm downrange toward Christmas Island before re-entering the atmosphere 12.5 minutes after launch, and detonating in an airburst at 11,000 feet.
 - The missile/RV demonstrated an accuracy on the order of 2,200 yards (about 1.25 mile), which was within the Polaris A2 circular error probable (CEP) of 2 miles.



Source: www.nuclearweaponarchive.org



Source: www.navy.mil

Polaris A2 surface launch

20 April 1964, *USS Henry Clay* (SSBN-625)



Source, three photos: US Navy photos

Polaris A3 (UGM-27C)

- The A3 was the 1st Polaris with a multiple reentry vehicle warhead:
 - 3 x W-58 warheads, each with a yield of 200 kT, in Mk-2 reentry vehicles; CEP about 3,000 feet (910 m).
 - The three warheads were not independently targeted. They would impact around a common target.
- All five classes of US Polaris SSBNs were armed with the A3.
 - Original equipment on James Madison & Ben Franklin-class SSBNs.
 - The three earlier classes were overhauled and modernized to handle the A3.
- 28 Sep 1964: Polaris A3 IOC. *USS Daniel Webster* (SSBN-626) made the 1st deterrent patrol with Polaris A3.
- 25 Dec 1964: *USS Daniel Boone* (SSBN-629) departed Apra Harbor, Guam and began the first Pacific Ocean deterrent patrol.
- 15 Mar 1965: 1st Polaris A3 surface launch by *USS Nathaniel Greene* (SSBN-636).
- The Polaris A3 was retired from US service in February 1982, more than 17 years after IOC. It was replaced by Poseidon C3.



Polaris A3 launched from submarine.
Source: <http://cnls.lanl.gov/>

Polaris A3 (UGM-27C)

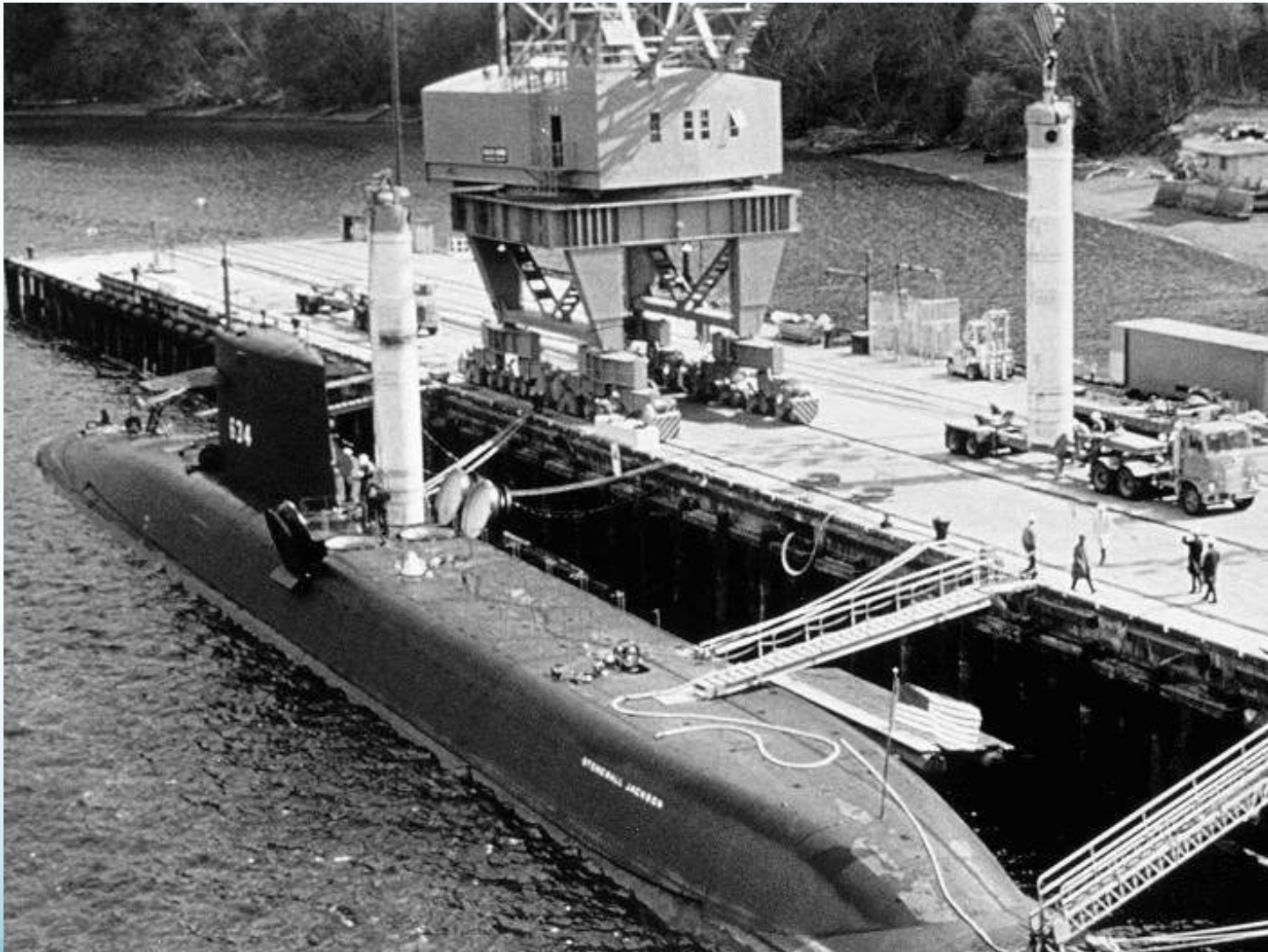
- Polaris A3 missiles were supplied to the UK under the 6 April 1963 *Polaris Sales Agreement* and were operational aboard UK Resolution-class SSBNs, which were comparable to the US Lafayette-class SSBN.
 - 15 February 1968: *HMS Resolution* made the 1st UK launch of a Polaris A3.
 - 15 Jun 1968 – 1982: Resolution-class SSBNs conducted deterrent patrols with 16 x Polaris A3 missiles armed with a UK-designed version of the US W-47 warhead, designated RE.179.
 - 1982 – 1996: When the US SSBN fleet was modernized to use the Poseidon SLBM, the UK continued to operate an improved Polaris model designated A3TK Chevaline, each with two UK-designed warheads.
 - The A3TK Chevaline was retired in 1996 along with the last Resolution-class SSBNs. They were replaced by the Vanguard-class SSBN armed with Trident II D5 missiles.

Poseidon C3 (UGM-73A)

(originally Polaris B3)

- 1st US SLBM with multiple, independently-targetable reentry vehicles (MIRV).
 - Could carry 10 – 14 W68 warheads @ 40 kT yield each, in Mark 3 reentry vehicles.
 - Carrying 14 warheads reduced the missile's range to that of the Polaris A3. For this reason, missiles typically employed 10 warheads.
 - Post Boost Control System (PBCS) managed deployment of the individual warheads.
 - CEP: about 1,800 feet (550 m).
- 16 Aug 1968: 1st test launch from a flat pad at Cape Canaveral, Florida
- 3 Aug 1970: 1st submerged launch was from *USS James Madison* (SSBN 627)
- 31 Mar 1971: Poseidon IOC; 1st deterrent patrol was on *USS Sam Rayburn* (SSBN-635)
- Poseidon eventually was deployed aboard all 31 Lafayette (616)-class, James Madison (627)-class & Ben Franklin (640)-class SSBNs.
- October 1979: Trident I C4 SLBMs started replacing Poseidon SLBMs on 12 James Madison (627)-class and Ben Franklin (640)-class SSBNs.
- The remaining Poseidon-armed SSBNs started retiring in August 1985 to comply with the SALT arms control treaty. The last Poseidon SLBMs were retired in September 1992, more than 21 years after IOC.

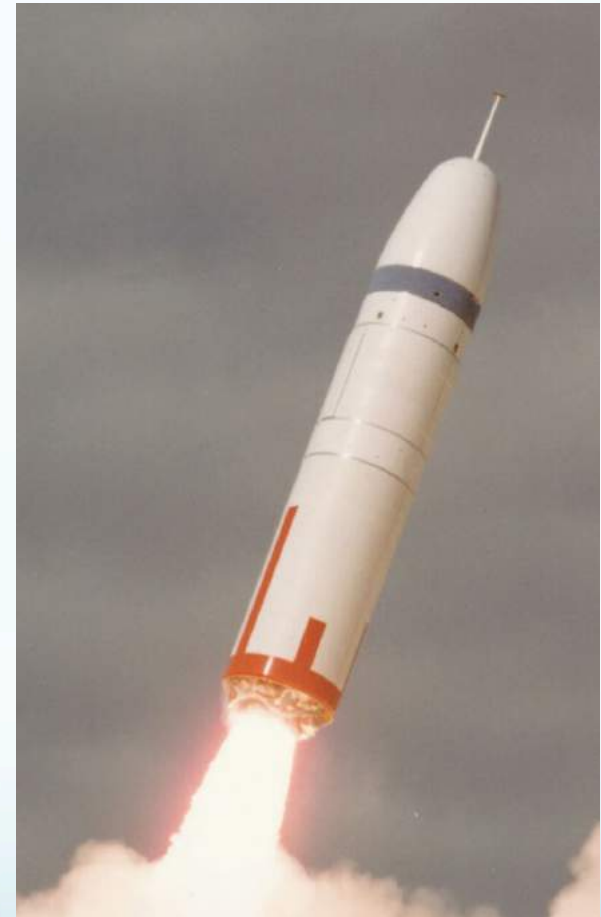
Poseidon C3 (UGM-73A)



USS Stonewall Jackson (SSBN-634) Poseidon SLBM handling dockside.
Source: https://fas.org/nuke/guide/usa/slbm/ssbn634_c3.jpg

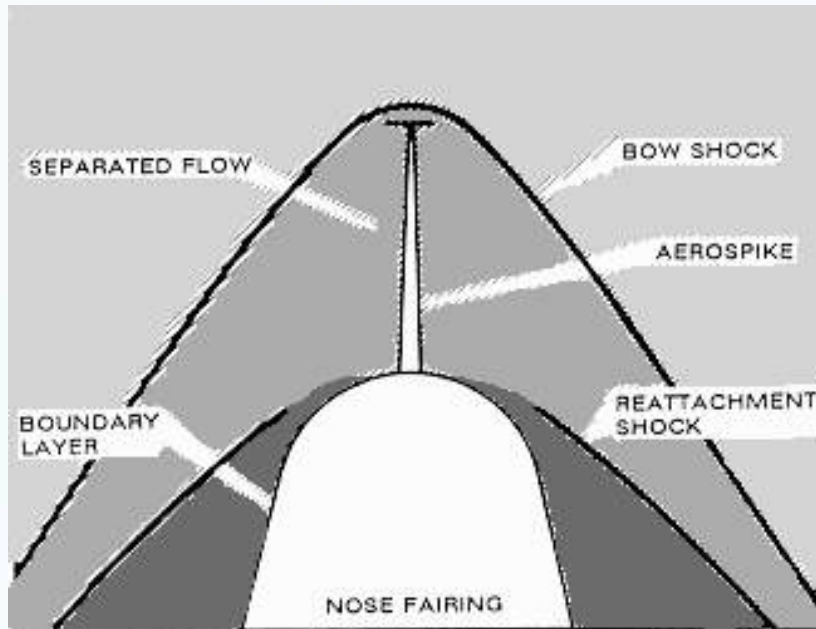
Trident I C4 (UGM-96A)

- 1966: US Navy initiates Undersea Long-range Missile System (ULMS), which would lead to the Trident I (C4) and Trident II (D5) systems
- Trident I was based on the Poseidon missile and was designed to be retrofitted to existing Poseidon subs and deployed on the new Ohio-class SSBNs.
 - Trident I was the last SLBM to use the Ships Inertial Navigation System (SINS).
- Range > 4,000 naut. mi (> 7,408 km); CEP: about 1,250 feet (380 m).
 - Trident I introduced the “aerospike,” which deployed on launch at the nose of the missile and significantly reduced drag. It is estimated to have increased the missile’s range by 297 naut. miles (550 km).
- 14 Sept 71: Secretary of Defense Melvin Laird approved development of ULMS.
- 18 January 1977: 1st Trident I test launch from a flat pad at Cape Canaveral.
- 10 April 79: 1st Trident I launch from a submerged submarine, *USS Francis Scott Key* (SSBN-657).
- 20 October 1979: Trident I IOC. 1st deterrent patrol was on *USS Francis Scott Key*, from Charleston, SC.
- February 1995: *USS Florida* (SSBN-728) launched a test salvo of 6 Trident I missiles in rapid succession.
- Trident I retired in September 2005, 26 years after IOC. It was replaced by Trident II (D5).



Trident I (C4) launch. Note the aerospike deployed. Source: https://en.wikipedia.org/wiki/UGM-96_Trident_I#/

Trident I C4 (UGM-96A)



Aerospike

To help decrease drag from the blunt nose fairing and thereby increase range, Trident I (C4) incorporated a self-deploying aerospike, which was extended shortly after launch. The aerospike reduced frontal drag by approximately 50%. When the missile was launched, a small solid propellant gas generator provided the energy to extend and lock the aerospike into position.

The aerospike also is used on Trident II (D5) SLBMs.



Trident I (C4) missile handling. Source, graphic + photo: <https://fas.org/nuke/guide/usa/slbm/c-4.htm>

Trident II D5 (UGM-133)

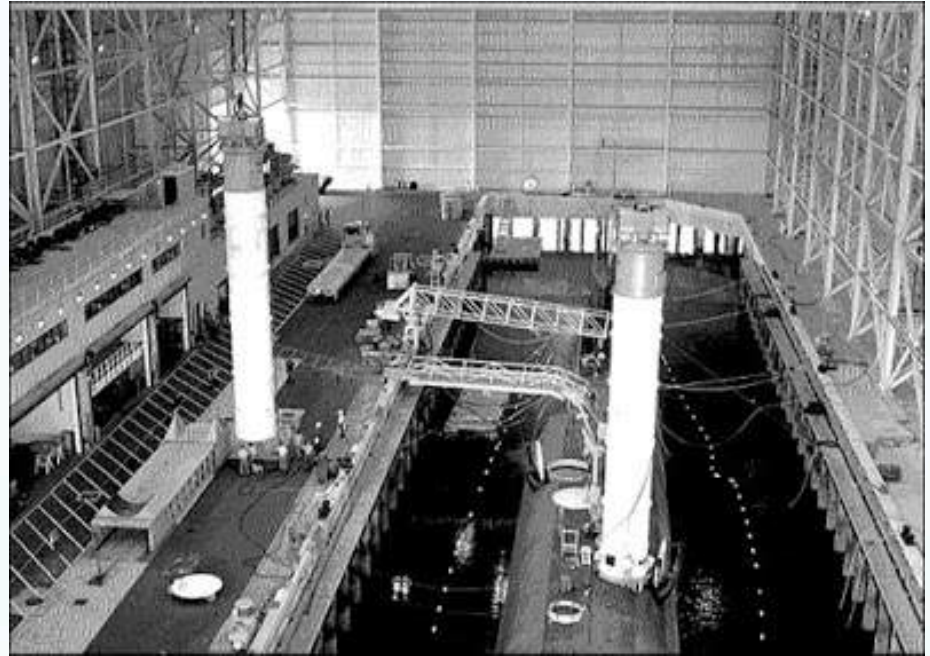
- Deployed on US Ohio-class and UK Vanguard-class SSBNs.
- Range > 6,500 naut. mi (> 12,000 km) with up to 12 warheads:
 - Up to 12 x W88 warheads @ 475 kT in Mk 5 reentry vehicles, or
 - Up to 12 x W76-1 warheads @ 100 kT in Mk 4A reentry vehicles
- Mk 6 Mod 1 astro-inertial guidance system, which is capable of Global Positioning System (GPS) updates; CEP about 100 m (328 ft).
- 21 Oct 83: Navy issued contract to Lockheed to develop Trident II.
- 15 January 1987: 1st Trident II test launch from a flat pad at Cape Canaveral.



Trident II (D5) launch.
Source: [https://en.wikipedia.org/wiki/UGM-133_Trident_II#/](https://en.wikipedia.org/wiki/UGM-133_Trident_II#/media/File:UGM-133_Trident_II_launch.jpg)

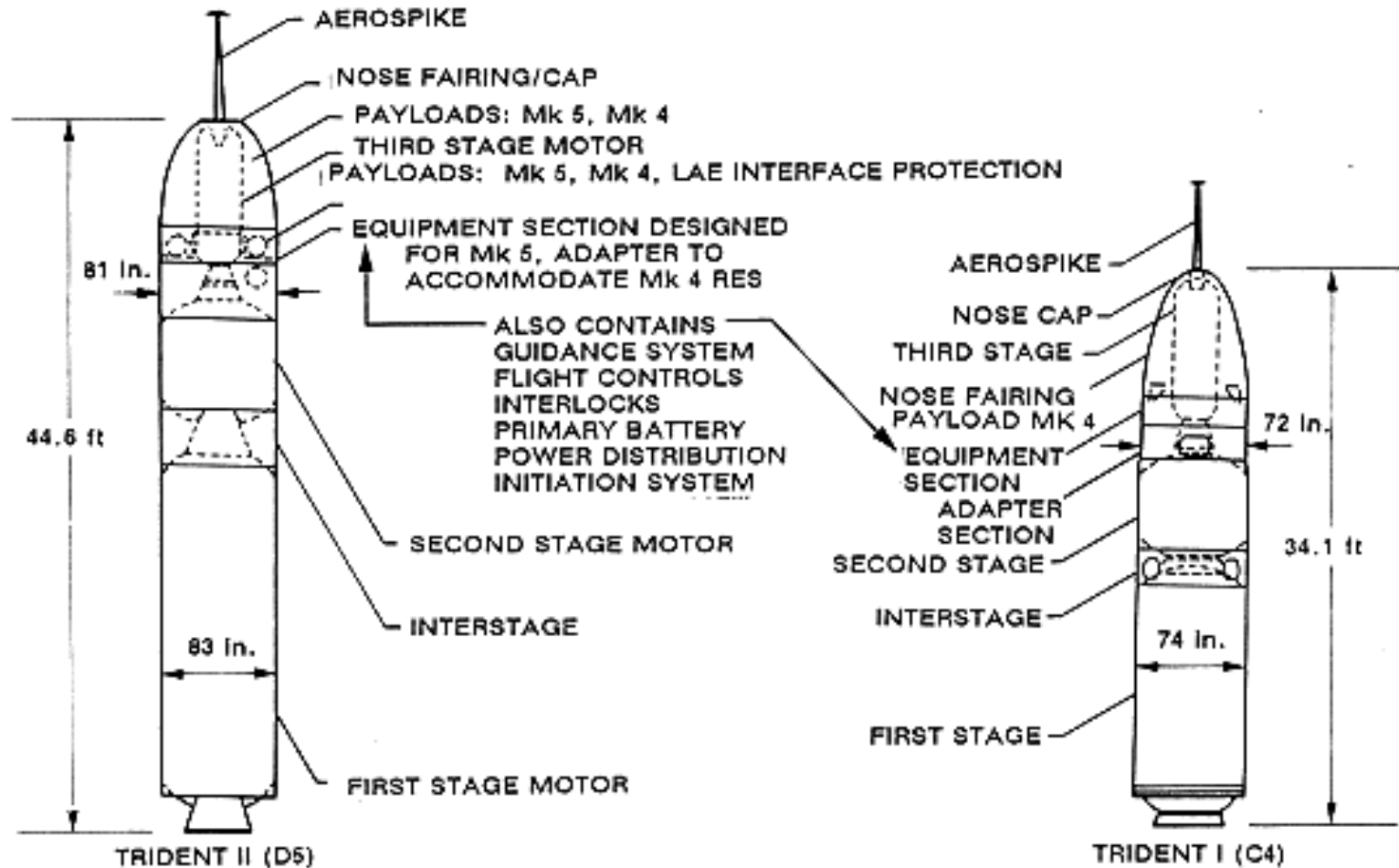
Trident II D5 (UGM-133)

- March 1990: Trident II Initial Operating Capability (IOC). *USS Tennessee* (SSBN-734) was the first Ohio-class boat to deploy with Trident II.
- 485 Trident II missiles currently are in service in the US and UK.
 - US inventory as of January 2018 is 427 total deployed and non-deployed Trident II (D5) SLBMs.
 - Under the March 1982 Trident Sales Agreement, the UK leases a total of 58 Trident II missiles from the US
- The Trident II currently make up 70% of the US nuclear missile deterrent.

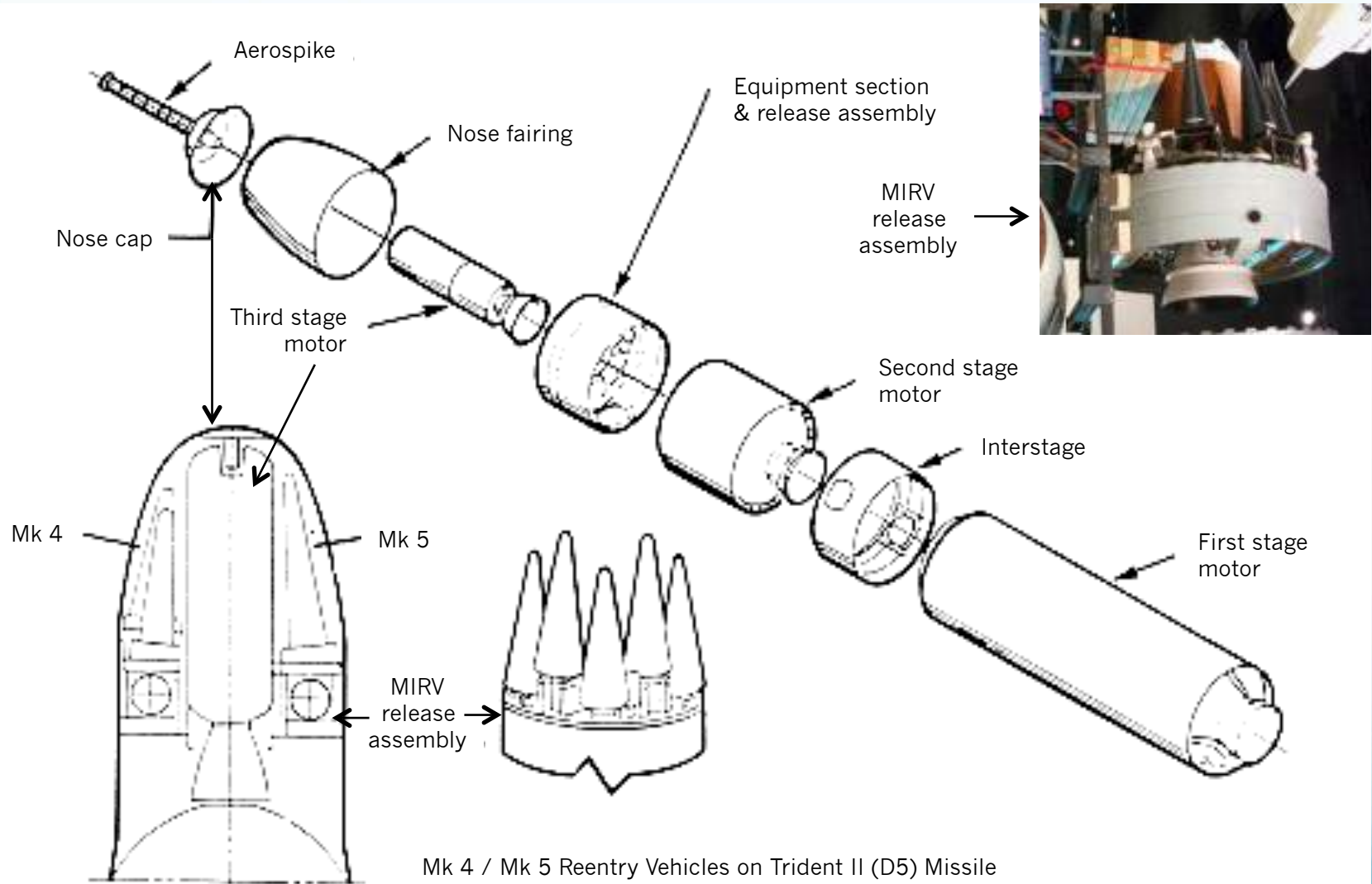


Trident II (D5) handling at Bangor, WA Strategic Weapons Facility Pacific (SWFPAC). Source: <http://www.notnt.org>

Comparison of Trident I C4 & Trident II D5 SLBMs



Trident II D5 details



Source: Line drawing adapted from <https://fas.org/nuke/guide/usa/slbm/d-5.htm>;
Inset photo from: <http://virtualglobetrotting.com>

Trident II D5 life extension (LE)

- The Navy's Strategic Systems Programs (SSP) organization is responsible for maintaining the Strategic Weapons System (SWS) safe, reliable and effective.
 - The SWS is comprised of the Trident II D5 SLBM, the Re-entry System, and shipboard support systems. The SWS originally was designed to have a service life that was compatible with the original Ohio-class SSBN service life: about 30 years.
 - Full funding for life extension efforts started in FY2002.
- The Trident D5LE (life-extension) missile is expected to remain in service until 2042, which is 52 years after IOC and slightly beyond the date when the last Ohio-class SSBN will reach the end of its 42 year service life.
 - The Trident D5LE will be the initial SLBM armament for the new Columbia-class SSBN. The first Columbia deterrent patrol is expected in 2031. The Trident D5LE also will be the initial armament on the UK's new Dreadnought-class SSBN, which is on a similar development and deployment schedule.
- The SSP's Enhanced Ground Test (EGT) program is enabling replacement subsystems to be dynamically tested in environments that replicate actual flight conditions. The EGT provides sufficient confidence in the replacement subsystems to enable missile flight testing to begin with launches from SSBNs rather than ground launch pads.
- Life-extended Trident II D5 missiles (D5LE) were introduced to the SSBN fleet in March 2017.

Trident II D5 life extension (LE)

- All subsystems on Trident D5 missiles, re-entry system, and Trident-related subsystems on the Ohio-class SSBNs were reviewed to identify obsolete components and other supportability issues. Life extension actions include:
 - Missile:
 - The three rocket motor stages have been validated for the service life extension.
 - A modernized guidance system, the Mark 6 Mod 1, was developed by Charles Stark Draper Laboratory.
 - Modernized electronics were developed for the Flight Control Electronics Package and the Command Sequencer.
 - The missile has a structure called a release assembly, which houses and releases the individual re-entry bodies. There is an ongoing effort to engineer a new release assembly that will work with either the Mk-4 or Mk-5 re-entry body.
 - Re-entry System:
 - W76-1/Mk4 re-entry system new arming, fusing & firing systems. Reported to be at 80 percent completion in May 2017.
 - W88/Mk5 re-entry system new arming, fusing & firing systems. Updated Mk-5 RV IOC is expected in 2020
 - Shipboard Support Systems:
 - Modernized the Navigation System with a COTS-based open architecture system, which required only two cabinets of electronics instead of nine.
 - Also modernized the Fire control System with a COTS-based open architecture system.
 - COTS shipboard systems have been put on periodic refresh cycles. The first such cycle rolled out through the SSBN fleet was called Shipboard Integration Increment -1
 - Updated the Northrop-Grumman Underwater Launcher System and continuing the Advanced Launcher Development Program
- The draft Nuclear Posture Review (NPR) 2018 indicated that the Navy will begin studies in 2020 on an SLBM that will replace the Trident D5LE and be deployed on the new Columbia-class SSBN.

Nuclear-powered guided missile submarines (SSGN)

U.S nuclear-powered guided missile subs (SSGN)

| Class | Cruise missile | # in Class | Length | Beam | Displacement (tons) | Reactor | Shaft hp | Max speed (kts) | Years delivered | Years in service |
|---|--|---------------------|------------------|----------------|-----------------------------|---------|----------|-----------------|-----------------|---------------------|
| Halibut (SSGN-575) | Regulus I (RGM-6A), Regulus II (RGM-15A) | 1 | 106.7 m (350 ft) | 8.8 m (29 ft) | 3,655 (surf), 4,000 (sub) | S3W | 7,300 | 20+ | Jan 1960 | 1960 – 65 (as SSGN) |
| APHNAS (Advanced Performance High-speed Nuclear Attack Submarine) * | Perseus (UGM-89 - STAM) | 0 design study only | 143.8 m (472 ft) | 12.2 m (40 ft) | 12,075 (surf), 13,649 (sub) | D1W | 60,000 | 33 - 35 | | |
| Polaris SSGN (former Polaris SSBN conversion) | Tomahawk (UGM-109) | 0 design study only | | | | S5W | 15,000 | 20+ | | |
| Ohio SSGN (former Ohio SSBN conversion) | Tomahawk (UGM-109) | 4 | 170.7 m (560 ft) | 12.8 m (42 ft) | 16,764 (surf), 18,750 (sub) | S8G | 60,000 | 20+ | 2002 - 04 | 2002 - present |
| Virginia SSGN (SSN-774 Block V - VII) * | Tomahawk (UGM-109) | 20 (plan thru 2030) | 136.2 m (447 ft) | 10.1 m (33 ft) | TBD | S9G | 40,000 | 25+ | After 2020 | |
| Future SSGN (possibly based on Columbia-class SSBN) | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | After mid-2030s | |

* APHNAS and Virginia Block V to VII SSNs are included in this SSGN table because they are multi-purpose boats that carry a significant inventory of cruise missiles in mid-ships vertical launch system (VLS) missile tubes and can perform the function of an SSGN along with their SSN functions. See the SSN section of this document for details on these multi-purpose SSNs.

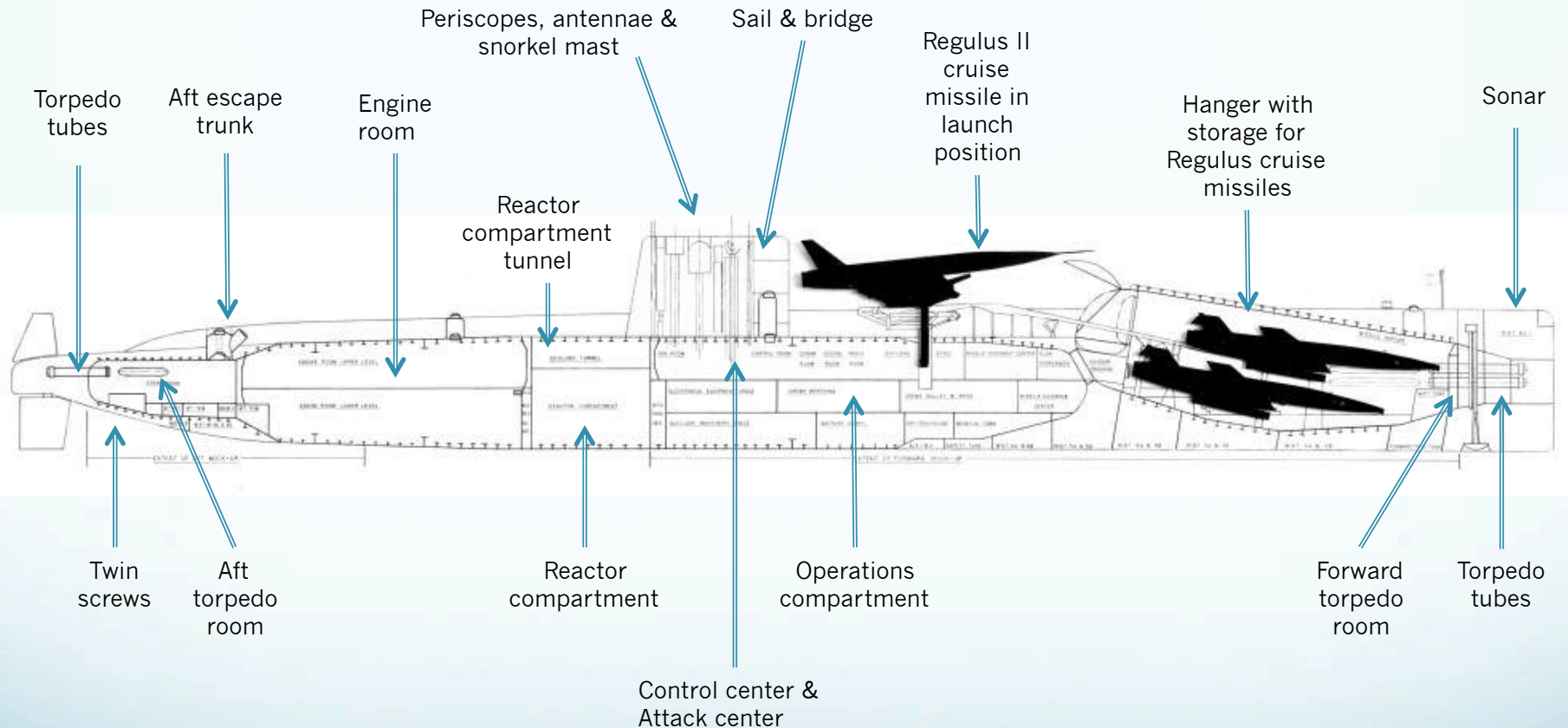
USS Halibut (SSGN-587)



Source: Pinterest

- *USS Halibut* had the distinction to be the first nuclear submarine in the world designed and built from the keel up to launch guided missiles, and was originally intended to carry five Regulus II missiles in a hangar integral with the hull.
 - Regulus II program was terminated just 17 days prior to *Halibut's* commissioning in January 1960. *Halibut* departed for her shakedown cruise on 11 March 1960 equipped with Regulus I missiles.
- Propulsion: 1 x S3W Westinghouse PWR rated @ 38 MWt (est.); 2 x main steam turbines delivering a total of 7,300 hp (5.4 MW) to 2 x screws.
- Armament: 1 x Regulus launcher on deck, forward of the sail; 5 x Regulus I cruise missiles in a watertight hanger; also 6 x 533 mm (21") torpedo tubes; 4 bow tubes, 2 stern tubes.

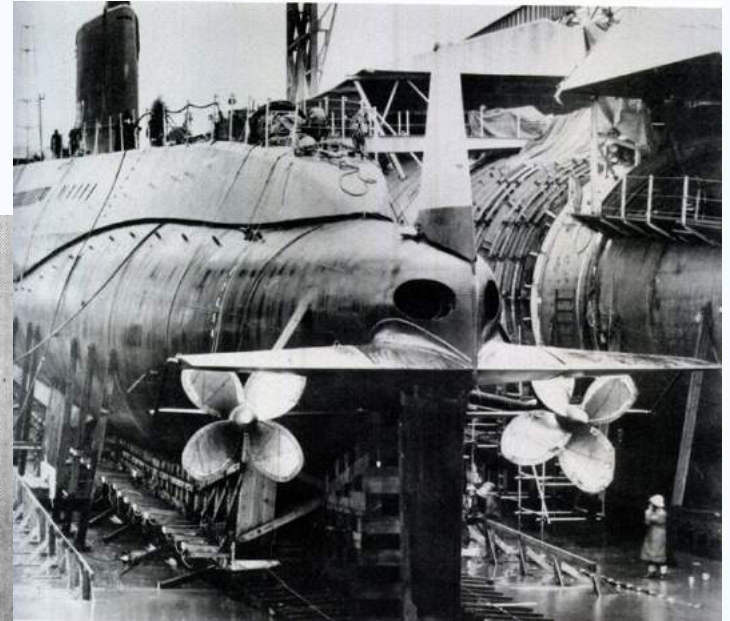
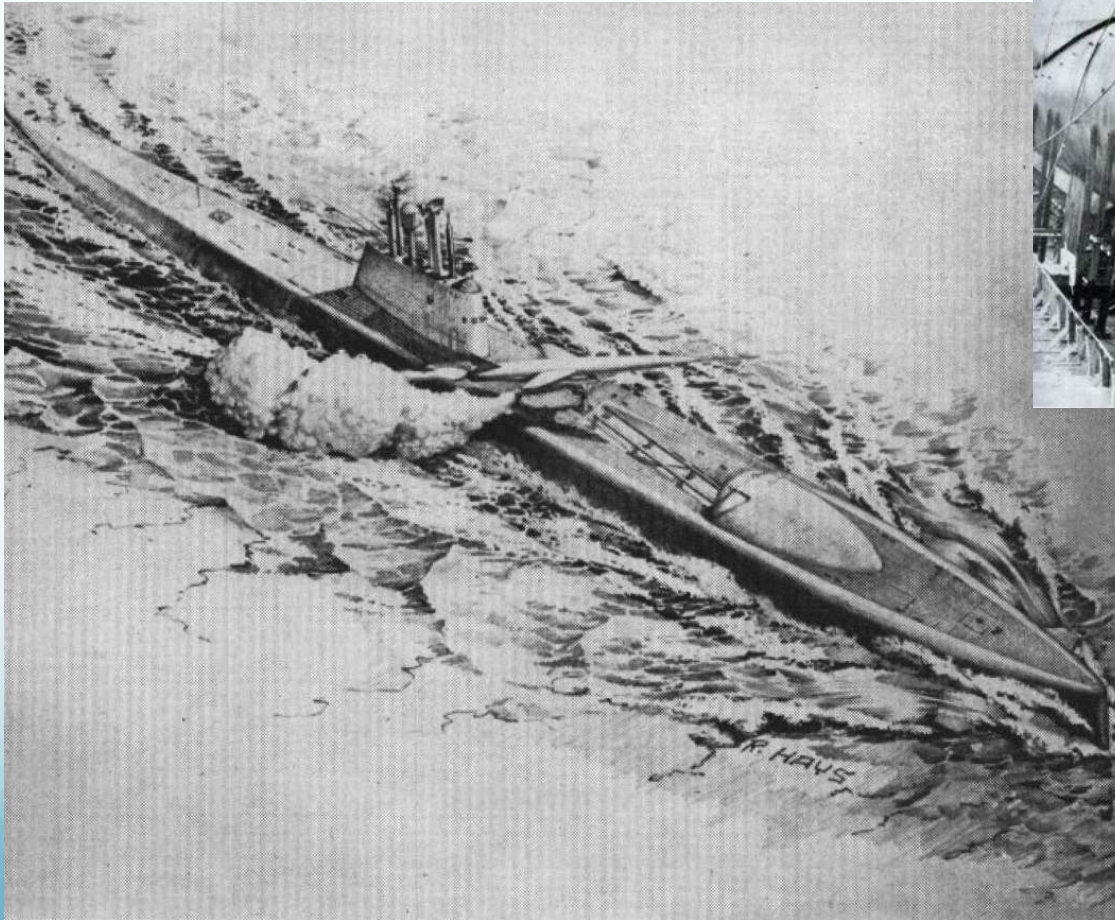
USS Halibut (SSGN-587)



Source: adapted from navsource.org/archives

USS Halibut (SSGN-587)

Below: *Halibut* concept drawing, shown launching a Regulus II cruise missile. Note missile hanger bulge on the foredeck.
Source: US Navy, *All Hands* magazine, Nov 1957



Above: *Halibut* in drydock. Note 4-bladed propellers and two aft torpedo tubes.
Source: <https://imgur.com/a/IQBOi>

USS Halibut (SSGN-587)

- Operational matters:
 - *Halibut* was the first submarine to carry the Sperry Ships Inertial Navigation System (SINS), which was required to align the Regulus II inertial navigation system (but not required for Regulus I).
 - Enroute to the South Pacific, on 25 March 1960, *Halibut* became the first nuclear powered submarine to successfully launch a guided missile (a Regulus I).
 - First nuclear-powered missile-carrying submarine ever to make extended submerged deterrent patrols.
 - Between February 1961 and July 1964, *USS Halibut* made seven Regulus I missile deterrent patrols in the Northwest Pacific Ocean. Her longest deterrent patrol lasted 102 days. These patrols were accomplished with only one crew, not a Blue & Gold crew arrangement as on the later Polaris SSBNs.
 - *Halibut* alternated patrols with four diesel-electric guided missile submarines assigned to cover eastern Soviet targets.
 - Feb 1965 – Sep 1965: At Pearl Harbor Naval Shipyard for a major overhaul. While in the shipyard, *Halibut* was reclassified as an SSN in April 1965 and later converted for special operations missions. See section, “*Nuclear-powered special operations submarines*,” for more details on this phase of *Halibut*’s service life.
 - *Halibut* served as a special operations sub until 30 June 1976, when she was decommissioned.

USS Halibut (SSGN-587)



Halibut made 32 Regulus I missile test launches and 7 deterrent patrols as an SSGN.
Source, all photos: navsource.org/archives

Regulus I deterrent patrols

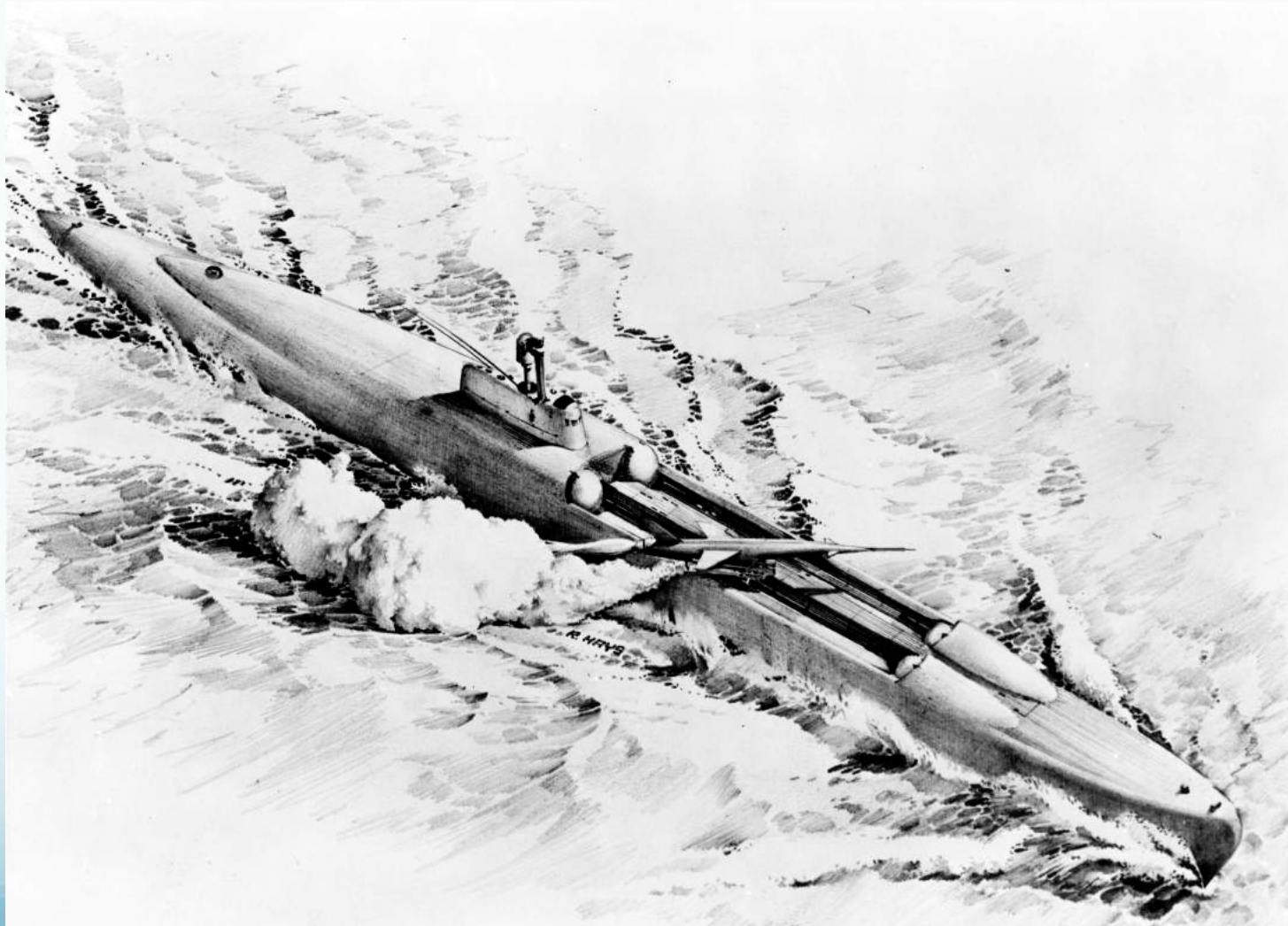
- Deployment on surface ships, 1955 - 1961:
 - First deployed on the heavy cruiser *USS Los Angeles* (CA-135) in 1955 and later on cruisers *Helena* (CA-75), *Toledo* (CA-133), and *Macon* (CA-132).
 - The first three patrolled in the Pacific, and *Macon* patrolled in the Atlantic.
 - *Macon's* last Regulus patrol was in 1958, *Toledo's* in 1959, *Helena's* in 1960, and *Los Angeles's* in 1961.
 - Ten Essex-class aircraft carriers were equipped to launch Regulus, but few missiles were deployed.
 - *USS Randolph* deployed to the Mediterranean carrying three Regulus missiles.
 - *USS Hancock* deployed once to the Western Pacific with four missiles in 1955.
- Deployment on submarines, September 1959 – July 1964:
 - Five submarines were fitted to launch Regulus missiles: diesel-powered *USS Tunny* (SSG 282), *USS Barbero* (SSG 317), *USS Grayback* (SSG 574) and *USS Growler* (SSG 577), and nuclear-powered *USS Halibut* (SSGN 587). 23 other diesel-powered submarines potentially were available for conversion to SSG role.
 - 21 Sep – 12 Nov 1959: 1st Regulus submarine deterrent patrol, *USS Grayback* (SSG-574).
 - 41 Regulus submarine deterrent patrols were made.
 - 7 May – 14 July 1964: Last Regulus submarine deterrent patrol, *USS Halibut* (SSGN-578).

Regulus I deterrent patrols

- In late 1958, with four SSGs and four Regulus cruisers in commission, the Navy moved all of the submarines and three of the cruisers to the Pacific to establish regular deterrent patrols targeting the Soviet Far East.
 - Sub deployment was scheduled so at least four missiles were on station in the Western Pacific at all times
- The Regulus SSGs & SSGN eventually were replaced by Polaris SSBN deterrent patrols, which began with the first deployment of the *USS George Washington* on 15 Nov 1960.

Follow-on Regulus II SSGN

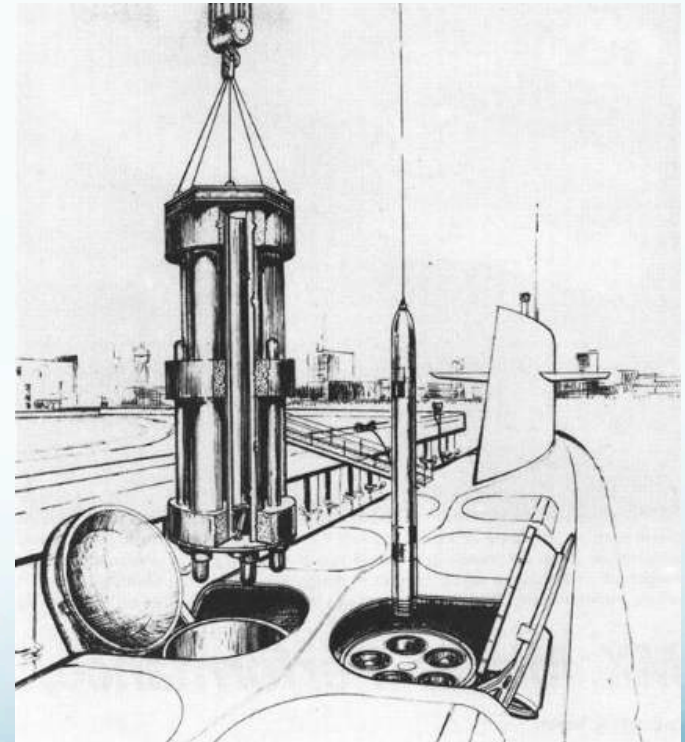
Concept drawing



Source: US Navy drawing by R. Hays / <http://i.imgur.com/J8QTnLA.jpg>

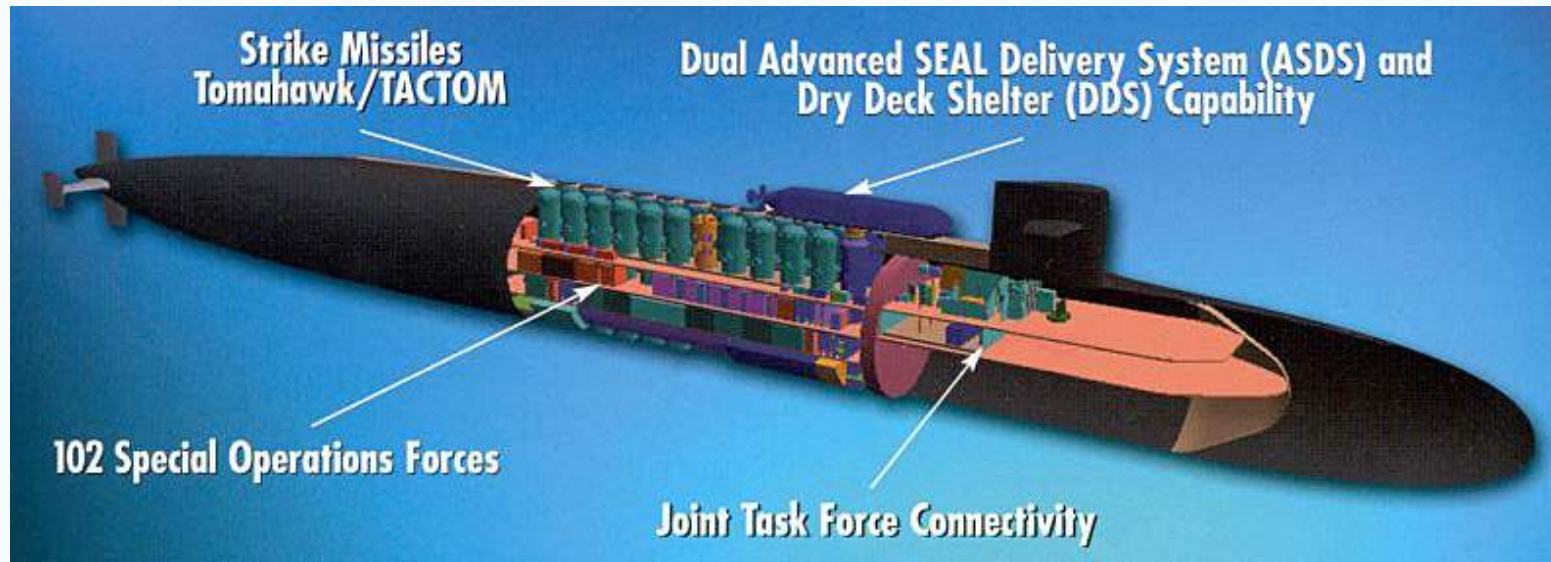
Polaris SSBN conversion to SSGN

- In 1980, the Pentagon developed plans to convert eight Polaris SSBNs (3 x George Washington-class and 5 x Ethan Allen-class) into SSGNs when they were retired from SSBN duty and arm them with Tomahawk nuclear-armed, land-attack cruise missiles (TLAM-N).
- Each former SLBM launch tube would be modified to handle a vertical launch module holding multiple Tomahawk missiles. Each Polaris sub would carry up to 80 Tomahawks.
- The Navy did not support these Pentagon plans, preferring to convert these subs to SSNs for the following reasons:
 - Aided in reaching the Navy's inventory objective of 90 attack submarines.
 - Conversion to SSGN would take significantly more time and money than conversion to SSN.
 - Navy estimated it would cost about \$2 B to convert eight former SSBNs to SSGNs.
 - About \$100 M would be required to produce the new cruise missile multiple weapon launch module.
 - After conversion to SSGN, the subs would have a remaining service life of only 5 – 7 years.
 - The SSGN would require two crews to sustain long-duration forward deployment with the 1,700 mile (2,736 km) range Tomahawk cruise missiles.
- The Navy contracted with Westinghouse to develop the multiple weapon launcher for the proposed Polaris SSGN, with five launch cells per module, including a missile ejection mechanism, shock isolation and salvo launch capability.
- The eight SSBNs were not converted to SSGNs. They completed their service lives as SSNs.



Westinghouse 5 x Tomahawk missile module.
Source: Aviation Week & Space Technology
magazine, 16 June 1980

Ohio SSBN conversion to SSGN



- The Clinton administration's Nuclear Posture Review (NPR) 1994 determined that the strategic needs of the US could be met with 14 of the 18 Ohio-class SSBNs. The four oldest Ohio-class boats (*Ohio*, *Michigan*, *Florida* & *Georgia*) were removed from SSBN service and converted into guided missile submarines (SSGNs) capable of conducting conventional land attack with cruise missiles and special operations.
- The SSGN conversion plan was implemented to comply with the SORT treaty, which entered into force on 1 June 2003.



7 x Tomahawk cruise missile module.
Source, both graphics: <http://www.public.navy.mil/>

Ohio SSBN conversion to SSGN

- The SSGN conversion and engineered refueling overhaul were done at the end of each SSBN's first OPCYCLE, which was at 252 months (21 years) into the boat's 42 year service life.
- Modifications for the SSGN and Special Operating Force (SOF) support roles included:
 - Trident missile tubes 3 – 24 were modified by removing the SLBM gas generator and installing vertical launch modules, each containing 7 x Tomahawk cruise missiles. Maximum cruise missile load is 154 Tomahawks.
 - Trident missile tubes 1 & 2 were modified to be lock-in, lock-out chambers for special operations forces and/or docks for Dry Deck Shelters (DDS).
 - Trident SLBM fire control system was replaced with a tactical fire control system.
 - Accommodations were added for up to 66 SOF personnel.
 - Significant communications upgrades were made, including addition of the Common Submarine Radio Room and two high-data-rate antennas, to enable each SSGN to serve as a forward-deployed, clandestine Small Combatant Joint Command Center.
 - Space for the Small Combatant Joint Command Center was added.
- Average cost to refit the four boats was about \$1 B (in 2008 dollars) per vessel.
- After conversion and refueling, the SSGNs started their second OPCYCLE, which will last 240 months (20 years) with an extended refit period at the mid-point in the cycle.
- The Ohio-class SSGNs re-entered service between 2006 - 2008.
- These SSGNs have two crews, Blue and Gold.

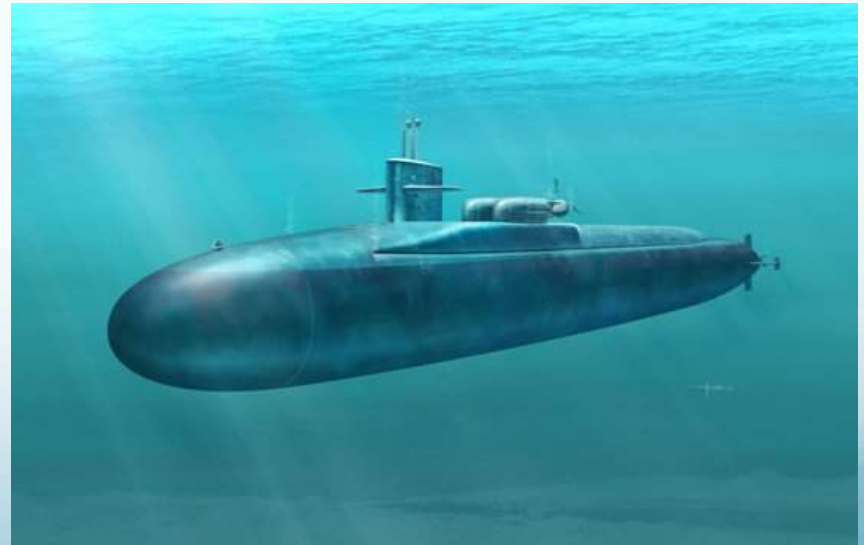
Ohio-class SSGN

- Operational matters:
 - In comparison to the Ohio-class SSBNs, the Ohio-class SSGNs are used in littoral waters rather than open ocean, run at higher speeds and surface and dive more frequently. This operational profile accelerates the aging of the submarine.
 - The Ohio-class SSGNs and SSBNs have the same 42 year service life.
 - Aging lessons identified and resolved first on the older SSGNs are being factored into maintaining the younger Ohio-class SSBNs operational for their full service life.
 - Ohio-class SSGNs operate on a planned maintenance (PM) strategy based on regular intervals of 15 months, each of which includes a 115-day (3.8 month) in-port period to support a major maintenance period (MMP) incremental overhaul, appropriate modernization and resupply (OPNAVINST 3120.33C).
 - In their SOF-support role, the Ohio-class SSGNs were functional replacements for two older Polaris SSBNs that had been converted for SOF-support missions: *USS James K. Polk* (SSN-645) and *USS Kamehameha* (SSBN-642). The *Polk* was retired in 1999 at age 33; the *Kamehameha* was retired in 2002 at age 36.
 - March 2011: During *Operation Odyssey Dawn* against the regime of now-deposed Libyan strongman Muammar Gaddafi, a total of 283 Tomahawk cruise missiles were launched against Libyan positions by US and UK forces. It was reported that *USS Florida* (SSGN-728) launched about 90 of those missiles.
 - The Ohio-class SSGNs are expected to retire between 2026 - 2028.
 - Their SSGN role eventually will be replaced by Virginia Block V, VI and VII multi-mission subs.
 - As Ohio-class SSGNs are retired, and cruise-missile equipped Los Angeles-class SSNs are retired in the same decade, there will be a rapid reduction in the number of land-attack cruise missiles deployed in the US submarine fleet. The submarine fleet's pre-2023 cruise missile inventory will not be restored for more than a decade, until the late 2030s.

Ohio-class SSGN



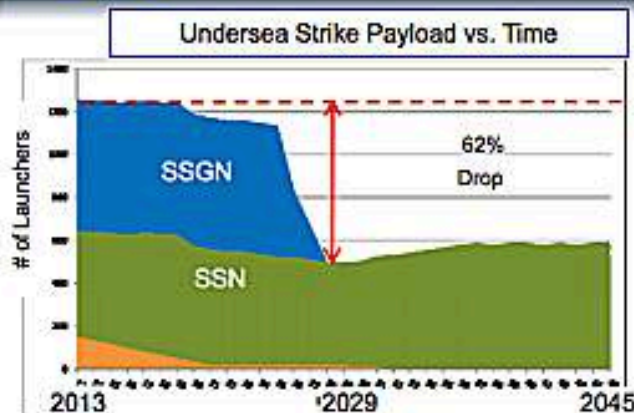
USS Ohio (SSGN-726) with 2 x Dry Deck Shelters for Special Operations Forces. Source, above: <http://defense-update.com>; Source, left: US Navy; Source, below: <https://www.super-hobby.com/>



Some Ohio SSGN & SOF capabilities will be replaced by Virginia Blocks V - VII



Block V: VIRGINIA Payload Module (VPM)

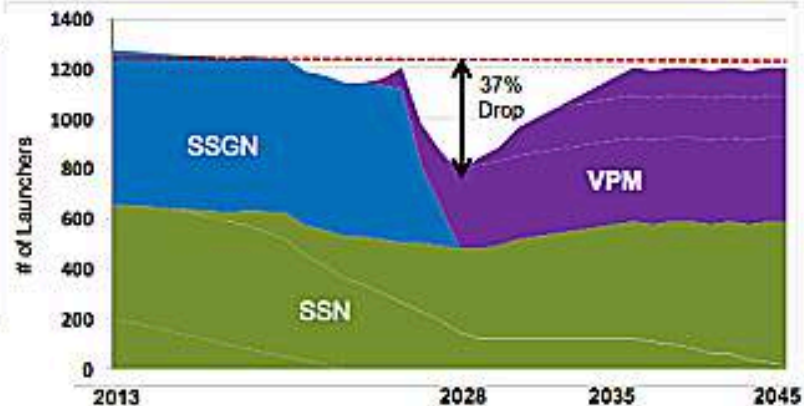


VIRGINIA Payload Module

- Four large tubes in a new hull section
- Uses Multiple All-up Round Canisters (MACs) already employed in SSGN & VIRGINIA Block III Payload Tubes
- Proven VIRGINIA Class construction processes
- Preserves Special Operations Force (SOF) Capacity lost with SSGN retirement



20 VIRGINIAs with VPM close the strike gap



Source: NAVSEA

Future SSGN

- The Navy has developed a Tactical Submarine Evolution Plan (TSEP) that includes examining options for a future SSGN force.
 - The Virginia Block V to VII subs will help mitigate the loss of some SSGN capabilities when the four Ohio-class SSGNs retire by 2028. However, the Virginia-class SSNs won't make up for the full strike capability, or the SOF support, the fleet will lose when the Ohio-class SSGN are retired.
 - TSEP is examining the possibility of using the Columbia-class SSBN design and production line to initiate a future SSGN production line in the mid-2030s.
- The new SSGN could carry a range of new, non-strategic weapons that are not available for the current-generation Ohio-class SSGNs:
 - Long-range anti-ship missiles:
 - In the 1990s, the Navy retired the long-range anti-ship version of the Tomahawk SLCM, UGM-109B, in favor of the shorter-range Harpoon, UGM-84. The Next Generation Land Attack Weapon (NGLAW) with anti-ship capabilities is expected to be the Harpoon replacement. It is being developed for an IOC by 2030.
 - With a more capable anti-ship weapon, the future SSGN can take on the ocean control mission originally envisioned by the Navy in the 1970s for the Advanced Performance High-speed Nuclear Attack Submarine (APHNAS).

Future SSGN

- Nuclear-armed, submarine-launched cruise missile (SLCM):
 - The draft Nuclear Posture Review 2018 stated that restoring the nuclear-armed, submarine-launched cruise missile (SLCM) capability is necessary. That capability was retired by NPR 2010. If this capability is restored, it is likely that the future SSGN would be equipped to carry the new nuclear-armed SLCM.
- Conventional Prompt Global Strike (CPGS) weapons:
 - Navy Strategic Systems Program (SSP) Director Vice Adm. Terry Benedict said on 2 November 2017 that: “I’m very proud to report that at 0300 on Monday night (30 October) SSP flew from Hawaii (Pacific Missile Range Facility)...the first conventional prompt strike missile for the United States Navy in the form factor that...could eventually be utilized...in an Ohio-class tube...that could one day be fielded from guided-missile submarines.”
 - The future SSGN likely would take on the conventional prompt global strike (CPGS) mission, if the Pentagon continues to develop CPGS capabilities.

Cruise missiles and other tactical guided missiles

This section focuses on US land-attack and anti-ship cruise and other tactical missiles that have been or currently are deployed on nuclear-powered submarines and/or surface ships. Not included in this section are several other cruise and tactical missiles that have been or are deployed only on conventionally-powered vessels or aircraft.

Navy roles & responsibilities for cruise & tactical missiles

- **1948:** The “*Key West Agreement*,” approved by President Truman on 21 Apr 1948, defined the aviation roles for the three branches of the military service. The Navy was excluded from the strategic bombardment mission, but maintained its naval aviation arm for tactical missions. The “*Key West Agreement*” did not address missiles.
- **1948:** The “*Newport Agreement*,” signed on 21 Aug 1948, clarified inter-service nuclear roles. The Navy gained access to nuclear weapons and a portion of strategic operations planning while the Air Force gained primary oversight of nuclear weapons development programs.
- **1949:** Secretary of Defense Louis A. Johnson's memorandum, “*Assignment of Responsibility for Guided Missiles*,” dated 7 November 1949, was the first DoD document to delineate responsibilities among the three military branches for guided missile development and use.
 - For surface-to-surface missiles, the Navy was responsible for, “ship-launched guided missiles which supplement, extend the capabilities of, or replace naval aircraft.....”
 - The memo approved continued development of the following Navy nuclear-armed, land-attack cruise missiles: Regulus, Rigel, and Triton.
- **1991:** The GHW Bush Presidential Nuclear Initiative, dated 27 September 1991, ordered all tactical nuclear weapons removed from Navy ships.
 - As of early 2018, all cruise missiles on Navy ships have conventional (non-nuclear) warheads.

US submarine-launched cruise missiles

| Cruise missile | Years in service | Weight | Length | Diam (D) / Span (S) | Speed | Range | Guidance | Warhead |
|--|---|--|------------------|--|---------------------------------------|-------------------------------------|---|---|
| Triton (SSM-N-2) land-attack | Design only 1946 - 1957 | About 13,600 kg (30,000 lb) with booster | 14.3 m (47 ft) | D = 1.5 m (57 in) | Mach 3.5, about 4,520 kph (2,800 mph) | 2,200 - 2,800 km (1,200 - 1,500 mi) | Stellar-inertial + precision terminal homing | Nuclear W27 @ 2 MT |
| Rigel (SSM-N-6) land-attack | Design & flight test only 1946 - 1953 | About 10,800 kg (23,800 lb) with booster | 14.1 m (46.1 ft) | D = 1.1 m (45 in); S = 4.1 m (13.3 ft) | Mach 2.0, about 2,260 kph (1,400 mph) | about 930 km (578 mi) | Modified LORAN with two submarine radio beacons | Nuclear, W5 @ 40 kT |
| Regulus I (SSM-N-8; RGM-6) land-attack | 1955 - 1964 | 6,584 kg (14,515 lb) | 9.8 m (32.17 ft) | S = 6.4 m (21 ft) | Mach 0.9, about 885 kph (550 mph) | 805 km (500 mi) | Radio command | Nuclear, W5 @ 40 kT (from 1955), W27 @ 2 MT (from 1958) |
| Regulus II (SSM-N-9) land-attack | Produced & flight tested 1956, not deployed | 10,433 kg (23,000 lb) | 17.6 m (57.5 ft) | S = 6.1 m (20 ft) | M 2.0 | 1610 km (1,000 mi) | Inertial | Nuclear, W27 @ 2 MT |
| Perseus (UGM-89 / STAM) anti-ship * | Design only, circa 1971 | 3,901 kg (8,600 lb) OA launch | 8.53 m (28 ft) | D = 0.86 m (34 in) | Mach 0.8 | 740.8 km (460 miles) | | Conventional armor piercing 453.6 kg (1,000 lb) |

LORAN: Long Range Navigation; STAM: Submarine-launched Tactical Missile

* See SSN section for details on UGM-89 Perseus / STAM, which began as a shorter-range anti-sub/anti-ship missile and evolved into longer range cruise missiles.

US submarine-launched cruise missiles

| Cruise missile | Years in service | Weight | Length | Diam (D) / Span (S) | Speed | Range | Guidance | Warhead |
|--|--|---|--|--|--------------------------|---------------------|-------------------------------|--|
| Perseus (UGM-89 / STAM) land-attack * | Design only, circa 1971 | 4,132 kg (9,950 lb) OA launch | 8.53 m (28 ft) | D = 86.4 cm (34 in) | Mach 0.8 | 3,334 km (2,071 mi) | Inertial | Nuclear, 117.9 kg (260 lb) |
| Harpoon (UGM-84A, -84L) anti-ship | 1977 - present | 691 kg (1,523 lb) w/ booster | 4.57 m (15 ft) | D = 0.53 m (21 in) S = 0.91 m (3.0 ft) | 864 kph (537 mph) | 130 km (81 mi) | Inertial + radar homing | Conventional, 488 lb |
| Tomahawk TLAM-N (BGM/UGM-109A*) land-attack | 1986 - 1992 | 1,315 kg (2,900 lb); 1,588 kg (3,500 lb) w/ booster | 5.56 m (18.25 ft) ; 6.25 m (20.5 ft) w/booster | D = 0.53 m (21 in) S = 2.67 m (8.75 ft) | 885 kph (550 mph) (est.) | 2,494 km (1,550 mi) | Inertial + TERCOM | Nuclear, W80-0 @ variable 5 – 150 kT |
| Tomahawk TASM (BGM/UGM-109B*) anti-ship | 1980s – early 1990s | 1,361 kg (3,000 lb) w/ booster | 5.56 m (18.25 ft) ; 6.25 m (20.5 ft) w/booster | D = 0.53 m (21 in) S = 2.62 m (8.58 ft) | 885 kph (550 mph) (est.) | 483 km (300 mi) | Inertial + radar homing | Conventional, 454 kg (1,000 lb) HE blast fragmentation |
| Tomahawk TLAM (UGM-109 C, D Block III) land-attack | 1983 - present (retirement in FY2020 expected) | 1,361 kg (3,000 lb) w/ booster | 5.56 m (18.25 ft) ; 6.25 m (20.5 ft) w/booster | D = 0.53 m (21 in) S = 2.62 m (8.58 ft) | 885 kph (550 mph) (est.) | 1,389 km (863 mi) | Various: Inertial, GPS, DSMAC | Conventional, C: 454 kg (1,000 lb) unitary D: bomblets |

TERCOM: Terrain Contour Matching; DSMAC: Digital Scene-Mapping Area Correlator; GPS: Global Positioning System; TLAM: Tomahawk Land Attack Missile; TASM: Tomahawk Anti-Ship Missile

* See SSN section for details on UGM-89 Perseus / STAM, which began as a shorter-range anti-sub/anti-ship missile and evolved into longer range cruise missiles.

** Tomahawk originally designated BGM-109. Changed in 1986 to UGM-109 (underwater launch) and RGM-109 (surface launch)

US submarine-launched cruise missiles

| Cruise missile | Years in service | Weight | Length | Diam (D) / Span (S) | Speed | Range | Guidance | Warhead |
|--|----------------------------|--------------------------------|--|---|--------------------------|-----------------------|---|---|
| Tomahawk TLAM (UGM-109E Block IV) land-attack | 2004 - present | 1,361 kg (3,000 lb) w/ booster | 5.56 m (18.25 ft) ; 6.25 m (20.5 ft) w/booster | D = 0.53 m (21 in) S = 2.62 m (8.58 ft) | 885 kph (550 mph) (est.) | >1,609 km (>1,000 mi) | Various: Inertial, GPS, DSMAC, SATCOM data link | Conventional, 454 kg (1,000 lb) unitary |
| Maritime Strike Tomahawk (UGM-109E Block IV) anti-ship | IOC early 2020s (expected) | 1,361 kg (3,000 lb) w/ booster | 5.56 m (18.25 ft) ; 6.25 m (20.5 ft) w/booster | D = 0.53 m (21 in) S = 2.62 m (8.58 ft) | 885 kph (550 mph) (est.) | >1,609 km (>1,000 mi) | Multi-mode seeker | Conventional anti-ship warhead |
| Next Generation Land Attack Weapon (NGLAW) land-attack & anti-ship | IOC 2030 (expected) | TBD | TBD | TBD | TBD | TBD | TBD | Versions with conventional land-attack warhead or anti-ship warhead |

DSMAC: Digital Scene-Mapping Area Correlator; GPS: Global Positioning System; SATCOM: satellite communications

Triton (SSM-N-2)

Strategic land attack cruise missile

- Submarine or surface ship launched, strategic land attack, ramjet-powered, nuclear-armed, supersonic cruise missile capable of being launched from existing Regulus I handling systems, developed by APL.
- Very high performance:
 - Maximum range: 1,200 – 1,500 miles (2,200 – 2,800 km)
 - Maximum speed: Mach 3.5, about 2,800 mph (4,520 kph), at an altitude of about 80,000 feet (24,384 meters)
 - Guidance system: stellar-inertial with precision terminal homing, such as radar map-matching or thermal infrared. CEP of 1,800 feet (550 meters).
 - Warhead: 1,500 pound (680 kg) W-27 thermonuclear warhead with a yield of 2 MT.
- A production Triton missile would be launched by four solid rocket boosters, and powered in cruise flight a single ramjet engine.
 - Airframe: Length: 47 ft. (14.3 m); diameter: 57 in. (1.5 m)
 - Launch weight about 30,000 pounds (13,600 kg) with booster and warhead.
- Program chronology:
 - 1946: Development started
 - 1947: The designation SSM-2 was allocated and changed in 1948 to SSM-N-2
 - 1954: The Navy planned to have Triton operational in 1965
 - 1955: Entered full-scale development of a version with a launch weight of 27,300 lb. (12,400 kg), including solid rocket boosters and warhead.
 - 1957: Program cancelled

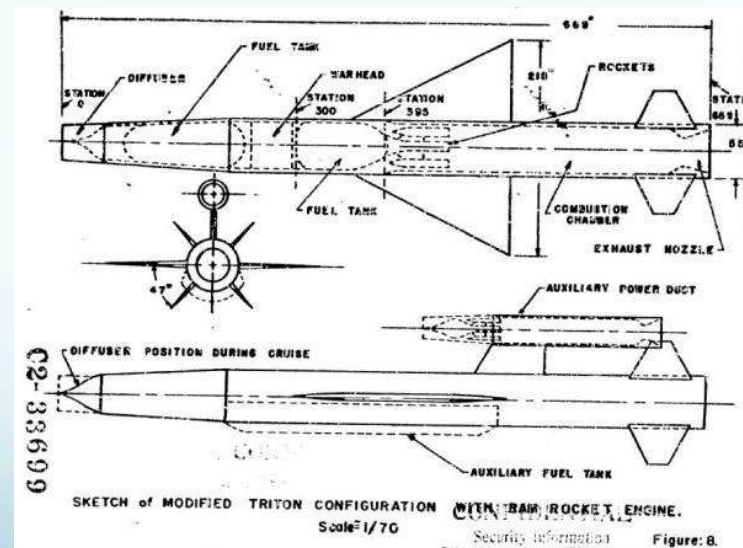
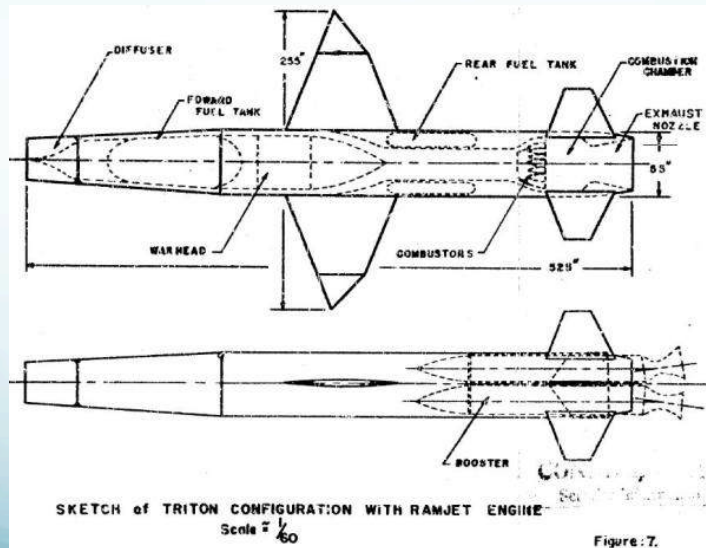
Triton (SSM-N-2)

- With the rapid, successful development of the Polaris submarine-launched ballistic missile (SLBM) program, the operational requirement for the Triton strategic cruise missile was soon eliminated by the more capable SLBMs.



Triton design circa 1951

Source: AIAA / <http://www.designation-systems.net>



Two versions of the Triton cruise missile: early (left), later (right).

Source, two line drawings: US Navy / <https://raigap.livejournal.com/213180.html>

Rigel (SSM-N-6)

Strategic land attack cruise missile

- Submarine or surface ship launched, strategic land attack, ramjet-powered, nuclear-armed, supersonic cruise missile developed by Grumman.
- High performance:
 - Maximum range: about 500 nautical miles (930 km)
 - Maximum speed: Mach 2, 1,400 mph (2,260 kph) at an altitude of 52,500 feet (16,000 meters)
 - Guidance system: modified LORAN requiring two submarines with radio beacons to be deployed along the missile's intended flight path. CEP of 1,800 feet (550 meters).
 - Warhead: 2,990 pound (1,360 kg) W-5 fission warhead with a yield of 40 kT.
- A production Rigel missile would be launched by four solid rocket boosters, and powered in cruise flight by two wingtip-mounted 28 in (71 cm) Marquardt ramjets.
 - Airframe: Length: 46.1 ft. (14.1 m); wingspan: 13.3 ft. (4.1 m); diameter: 45 in. (1.1 m)
 - Launch weight about 23,800 pounds (10,800 kg) with booster and warhead.
- Program chronology:
 - 1946: Development started. Early single ramjet test vehicles were flown in the late 1940s.
 - 1950: Sub-scale (60%) Flight Test Vehicles (FTVs) configured similar to a production missile began in May. The Navy planned to have Rigel operational in 1955
 - 1952: By October, eleven Rigel test flights had failed, while the competing Regulus I program was successful.
 - 1953: In August, the Rigel program was cancelled. Only a mockup of the planned production missile had been completed.

Rigel (SSM-N-6)

Right: Early Rigel ramjet test vehicle, single booster rocket & a single ramjet for cruise flight.

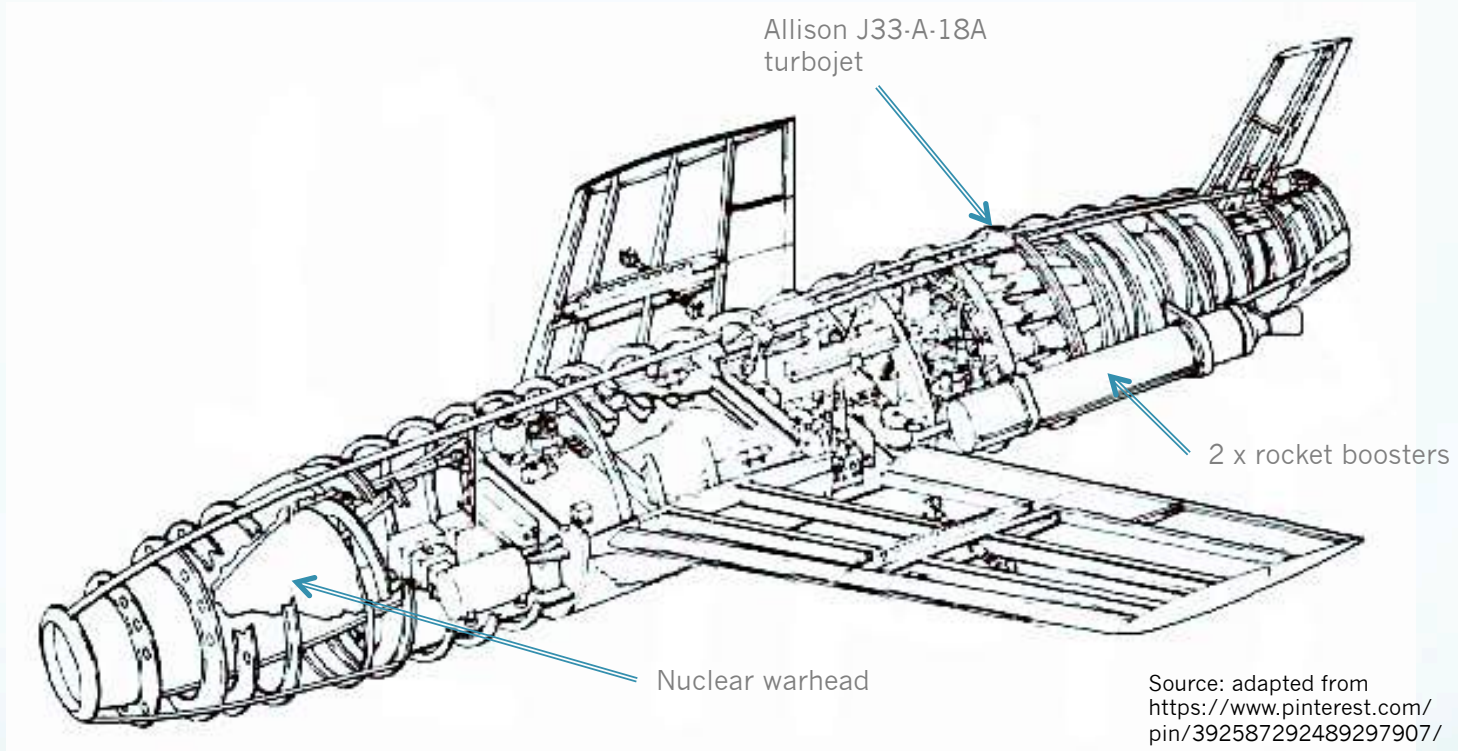
Below: Rigel SSM-N-6, four booster rockets & two wingtip-mounted ramjets for cruise flight.



Source, both diagrams: US Navy / <http://www.designation-systems.net>

Regulus I (SSM-N-8, RGM-6A)

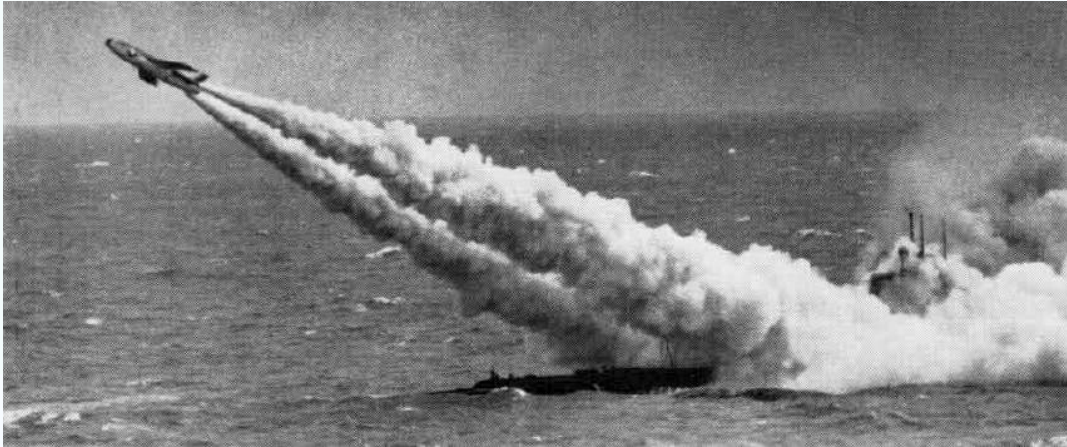
Strategic land attack cruise missile



- The Chance Vought Regulus I was the first strategic, long-range, nuclear-armed guided missile deployed by US Navy
 - Designed to carry a 3,990 lb (1,810 kg) warhead 500 nautical miles at high subsonic speed
 - Warhead: initially a 40 kT W5; 2 MT W27 thermonuclear warhead available from 1958
 - Remotely-controlled by aircraft or ships deployed along the flight-path.
- First flight was in March 1951, first shipboard launch from the aircraft carrier *USS Princeton* in November 1952, and first submarine launch from *USS Tunny* in July 1953.

Regulus I (SSM-N-8, RGM-6A)

Strategic land attack cruise missile



Regulus I launch.
Source: US Navy photo



1st missile mail:
8 June 1959, a Regulus I
launched from *USS
Barbero* (SSG-317)
delivered 3,000 pieces of
mail from Norfolk, VA to
Mayport, FL.



Regulus I being loaded aboard *USS Tunny* (SSG-282).
Source: US Navy photos / <http://fly.historicwings.com/2013/06/missile-mail/>

Regulus II (SSM-N-9, RGM-15A)

Strategic land attack cruise missile



Regulus II aboard *USS Grayback* (SSG-574)

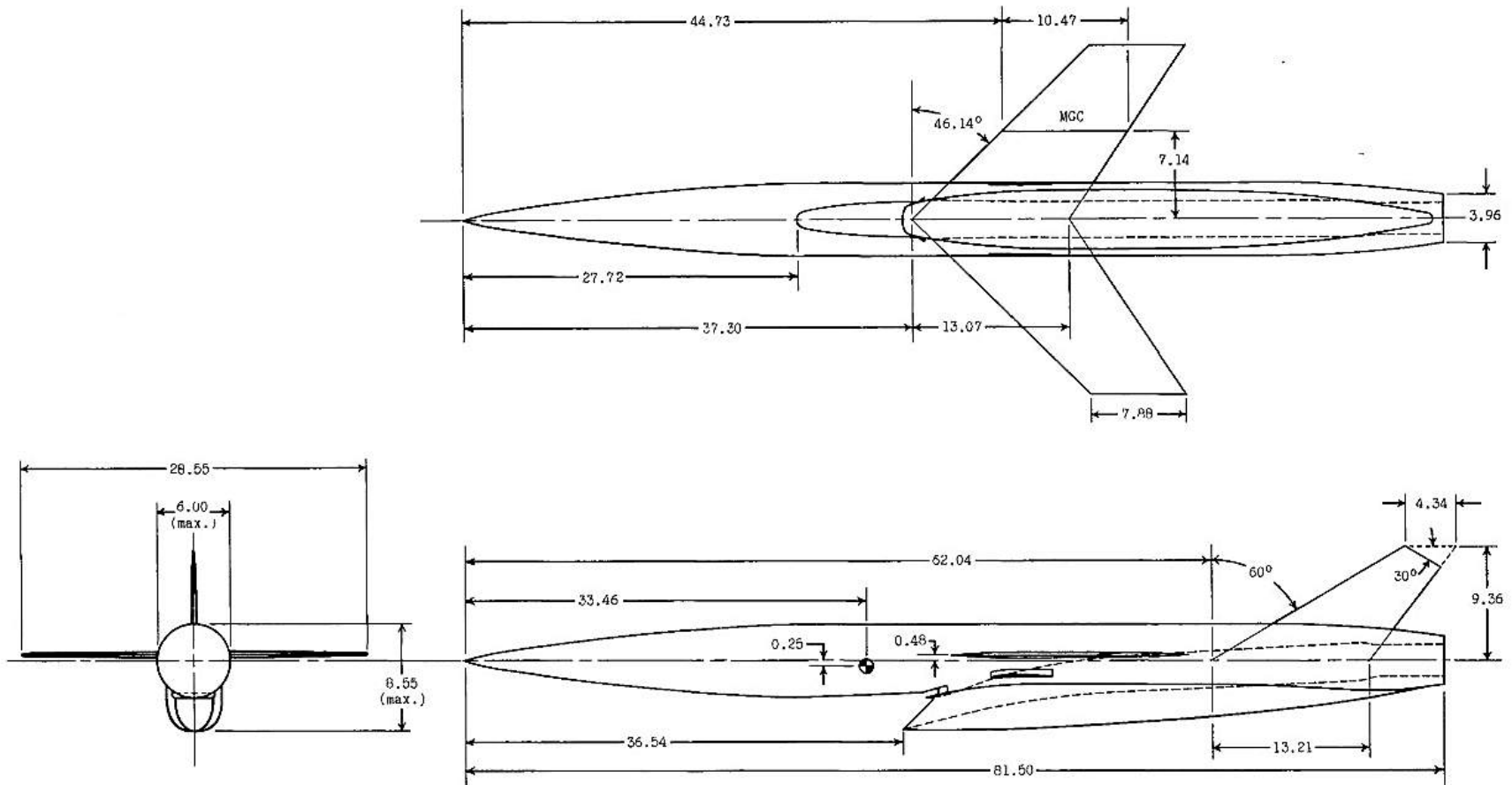
Source: US Navy photo / https://en.wikipedia.org/wiki/SSM-N-9_Regulus_II



Regulus II launch from *USS Grayback* (SSG-574). Source: US Navy photo

- The Chance Vought Regulus II was intended as a replacement for Regulus I.
- Supersonic with greater range, accuracy and an autonomous navigation system.
- Missile had inertial guidance system. Ships equipped with the Regulus II would have been equipped with the Sperry Ship Inertial Navigation System (SINS) to align missile's guidance system prior to launch.
- May 1956: First flight of test version XRSSM-N-9.
- 48 test flights of Regulus II, but only one submarine launch from *USS Grayback* (SSG-574) in Sep 1958.
- Regulus II project was cancelled 18 Dec 58 in favor of Polaris SLBM.

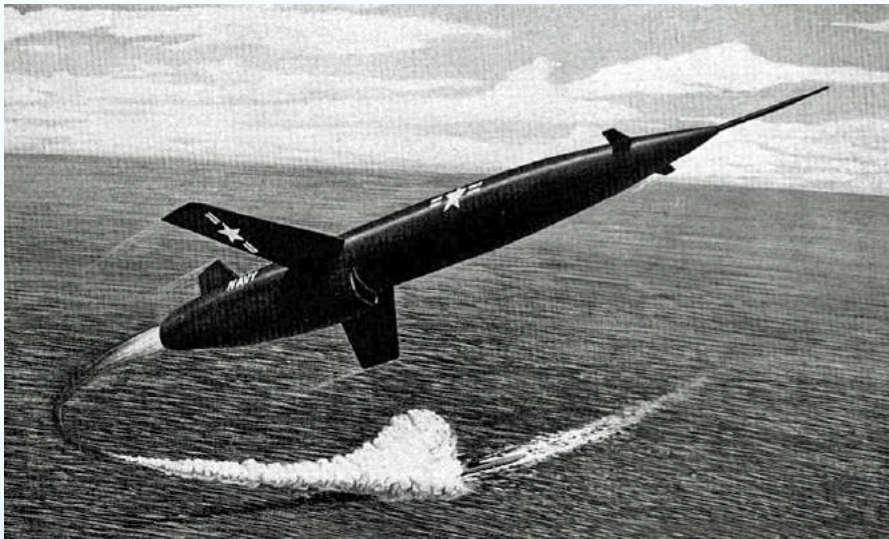
Regulus II (SSM-N-9, RGM-15A)



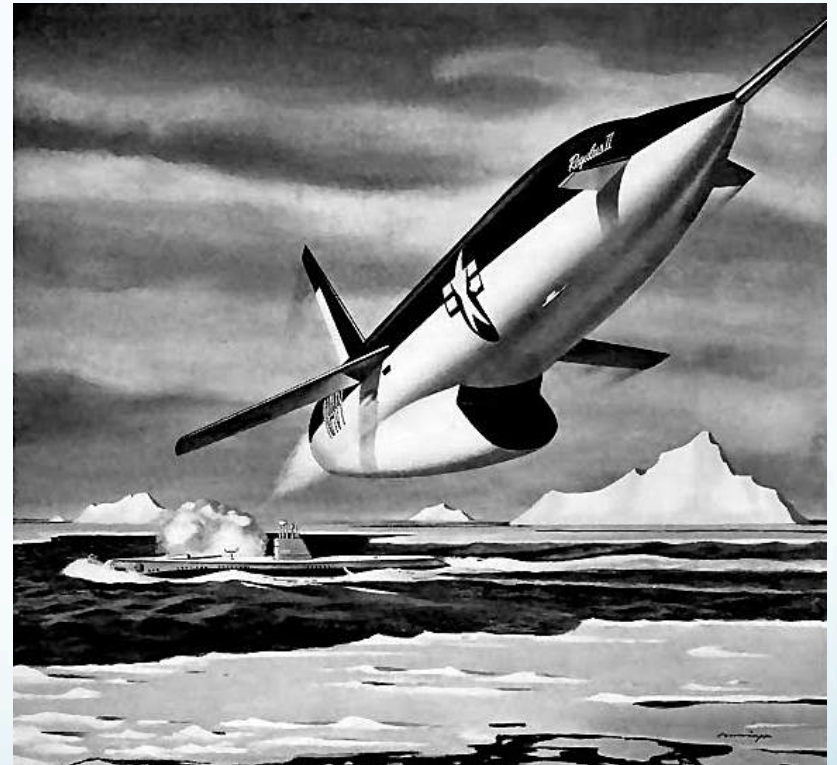
Source: University of North Texas (UNT) Digital Library / NACA report RM SL54H02

Regulus II (SSM-N-9, RGM-15A)

Concept art



Source: All Hands magazine, March 1957, p6

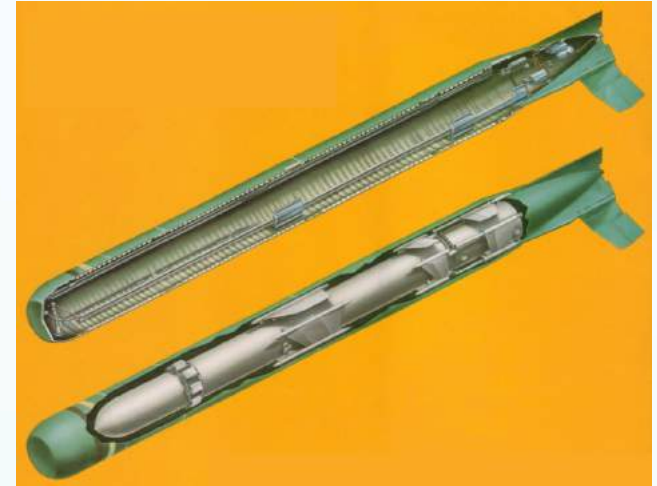


Source: <http://machineagechronicle.com/2011/03/>

Harpoon (UGM-84A, -84L)

Anti-ship cruise missile

- Harpoon missiles are carried by submarines, surface ships and aircraft and can be land-based (i.e., for coastal defense).
- First deployed in the mid-1970s.
- An UGM-84A submarine-launched anti-ship missile is stored as an “all-up-round” in a capsule. The missile is dry launched in the capsule, from which it is released when the capsule reaches the surface and the booster rocket ignites.
- 488 lb (211.3 kg) penetration / high-explosive blast warhead.
- High-subsonic cruise; 81 mile (130 km) range; inertial guidance at sea-skimming altitude to the target area, then active radar homing to the target.



Harpoon capsule

Source: ausairpower.net



Source: ausairpower.net

Harpoon (UGM-84A, -84L)

Anti-ship cruise missile

- UGM-84L Block II Harpoons and backward-compatible Block II upgrade kits provide improved resistance to countermeasures and better discrimination of ship targets from islands and nearby land masses. Service entry was in 2017.
- A Harpoon replacement will not arrive in the fleet until about 2030:
 - The Navy currently is not planning to deploy a submarine-launched version of the Long Range Anti-Ship Missile (LRASM) AGM-158C.
 - The Next Generation Land Attack Weapon (NGLAW) with anti-ship capabilities is expected to be the Harpoon replacement. It is being developed for an IOC by 2030.



Submarine launched Harpoon exiting its capsule. Source: seaforces.org

Tomahawk (UGM-109)

Multi-purpose cruise missile

- Stored as an “all-up-round” in a canister.
- Wet-launched via torpedo tubes or vertical launch system (VLS).
 - Missile is ejected and rocket booster ignites underwater a safe distance from the submarine. Booster falls away when the missile is airborne and the jet engine is started for cruise flight.
 - The missile storage canister remains in the torpedo tube or VLS after launch. The torpedo tube must be cycled to separately eject the canister.
- UGM-109A, Tomahawk Land Attack Missile - Nuclear (TLAM-N):
 - Launched from surface ships or submarines
 - W80-0 thermonuclear warhead, 5–150 kT
 - 350 built
 - 1986: Initial Operating Capability (IOC)
 - 1992: Removed from all warships in accordance with Sep. 1991 GHW Bush “Presidential Nuclear Initiatives.”
 - Nuclear Posture Review (NPR) 1994 allowed the Navy to maintain TLAM-N qualifications for some Los Angeles-class subs. Operational missiles were stored on land, and never made it back to sea.
 - All W80-0 warheads were reported to have been dismantled at the Pantex plant by FY 2012, in accordance with Nuclear Posture Review 2010.



Tomahawk (UGM-109)

Multi-purpose cruise missile

- UGM-109B, submarine-launched anti-ship version:
 - 1st variant to be operationally deployed.
 - Used a radar guidance system very similar to that of the UGM-84 Harpoon
 - 1990s: Retired in favor of the Harpoon anti-ship missile
- UGM-109C & D Block III and UGM-109E Block IV conventional land-attack versions:
 - C & E variants are armed with a 1,000 pound-class unitary warhead.
 - D variant is armed with a sub-munitions dispenser for 166 “bomblets.”
 - Mission planning for the C & D Block III variants is a time-consuming process. These will be retired in FY2020.
 - For the E Block IV variant, mission planning time is reduced to about one hour. The missile has a 2-way UHF SATCOM data link that allows the missile to be re-directed in flight to an alternate pre-programmed target or to a new target, or commanded to loiter in an area. The Block IV also can transmit battle damage imagery and missile health and status messages via the SATCOM data link.



Tomahawk launch. Source: General Dynamics



Source: Smithsonian National Air & Space Museum

Tomahawk (UGM-109)

Multi-purpose cruise missile

- UGM-109 Tomahawk Block IV mid-life recertification:
 - Tomahawk Block IV IOC was in 2006. The Navy plans to keep Block IV Tomahawk missiles in service into the 2040s. Currently the Navy has about 3,000 of these missiles.
 - To reach this goal, a mid-life recertification program is scheduled to start in FY 2019, with the goal of increasing missile service-life by an additional 15-years (total of 30-years), at a recertification rate of 200 to 300 per year. This recertification program includes:
 - Modernizing the navigation and communication systems and Insert new technology that will enable the missiles to operate in areas where GPS satellite navigation signals are jammed or are otherwise inoperative
 - Enhancing warheads
 - Addressing other existing obsolescence issues
 - As part of the recertification program, an unspecified number of existing Tomahawk Block IV missiles will be converted to the Maritime Strike Tomahawk, which will restore the long-range, anti-ship capability that was lost when the UGM-109B was retired in the 1990s.
- UGM-109 Maritime Strike Tomahawk:
 - This version of the recertified Block IV Tomahawk will retain the long range of the Block IV land-attack missile, but will be modified with a new navigation system, multi-mode terminal guidance seeker and a new warhead tailored for the anti-ship mission.
 - The Maritime Strike Tomahawk is expected to have an IOC in FY 2022.
- New Nuclear Strike Tomahawk:
 - The draft Nuclear Posture Review 2018 called for reestablishing the a nuclear strike version of the Tomahawk cruise missile.
 - All W80-0 warheads from the previous UGM-109A TLAM-N were dismantled by FY 2012. No time or cost estimate has been provided for preparing new warheads to arm a new Nuclear Strike Tomahawk.

Next Generation Land Attack Weapon (NGLAW)

- In 2017, the Navy announced plans to develop a surface and submarine launched Next Generation Land Attack Weapon (NGLAW).
 - Despite of its current name, NGLAW will have both a long-range land-attack and maritime strike versions that initially will complement, and later replace, the UGM-109E Tomahawk TLAM and the new Maritime Strike Tomahawk.
 - The mission on the long-range, land-attack version of the NGLAW will be to hit targets too dangerous for manned aircraft or to clear a corridor for those jets, much like the service's current doctrine for the Tomahawk.
- The Navy requested \$9.9 million for the NGLAW in FY 2018 to transition the effort into a formal program of record.
- The Navy estimates that the NGLAW could be operational around 2028 to 2030.
- NGLAW is related to a separate Navy long-range cruise missile program, Offensive Anti-Surface Warfare (OASuW) Increments 1 & 2, which is developing cruise missiles for aircraft and surface ships, but not submarines.

Conventional Prompt Global Strike (CPGS) missile

- This is a system than is intended to deliver a precision conventional warhead to strike any point in the world within 1 hour of launch.
 - To deliver the needed accuracy, the reentry vehicle will be maneuverable and may be configured as a hypersonic glider to expand its targeting flexibility.
 - An adversary needs to be able to distinguish between a CPGS strike and a nuclear SLBM strike, otherwise use of a CPGS weapon could be misinterpreted and a conventional conflict could escalate to a nuclear conflict.
 - DoD concluded that a CPGS warhead should not be developed for an existing nuclear capable missile. Funding for the Navy's Conventional Trident Modification (CTM) proposal was denied.
 - A CPGS warhead will likely fly a different, flatter, trajectory so it is readily distinguishable from a strategic SLBM nuclear warhead flying a ballistic trajectory.
- One candidate for a CPGS weapon is a submarine-launched, intermediate range, global strike missile.
 - The Navy conducted design studies of a submarine launched IRBM for the CPGS role, with various ranges from 1,500 - 3,000 miles (2,414 - 4,818 km) carrying a 2,000 pound (908 kg) conventional warhead with an accuracy of about 5 meters.
 - Two conventional warhead types were examined: a tungsten rod (flechette) warhead intended for area targets and a different warhead for hardened targets.

Conventional Prompt Global Strike (CPGS) missile

- A February 2017 Congressional Research Service report states: “DoD has not decided if it will deploy a PGS system on land or at sea. However, it has left open the option for deploying the system at sea, so that as it develops both the booster and the hypersonic glider technologies, it can pursue technologies that will reduce the cost and risk of the program even if it comes with a reduced range.”
- The Navy is developing CPGS technology into a deployable package. The likely delivery platform will be an Ohio-class SSGN or a Virginia Block V – VII SSN.
- Navy Strategic Systems Program (SSP) Director Vice Adm. Terry Benedict said on 2 November 2017 that: “I’m very proud to report that at 0300 on Monday night (30 October) SSP flew from Hawaii (Pacific Missile Range Facility)...the first conventional prompt strike missile for the United States Navy in the form factor that...could eventually be utilized...in an Ohio-class tube...that could one day be fielded from guided-missile submarines.”

Nuclear-powered special operations submarines

Dr. John Piña Craven

- Dr. Craven served in several important positions in the submarine community:
 - At the David Taylor Model Basin he worked on submarine hull designs
 - He was appointed Project Manager for the Polaris SSBN program
 - He served as Chief Scientist at the Navy's Special Projects Office
- In the latter role, his mission was to devise ways of finding items on the deep ocean bed and then finding ways of salvaging some of them.
 - Determining where to look was his special skill. As a mathematician he used Bayesian search theory to produce probability contour maps that helped localize the search zone.
 - 1965: Dr. Craven had the *Halibut* converted into a secret spy ship equipped with a variety of ocean engineering equipment.
 - 1966: Dr. Craven's work was instrumental in the Navy's search for the missing hydrogen bombs that were lost in the Mediterranean off the Spanish coast following a B-52 refueling accident.
 - 1968: Dr. Craven coordinated *Halibut*'s search for Soviet submarine *K-129*, which sank in the Pacific north of Hawaii.
 - 1974: Dr. Craven's involvement in *Project Azorian*, which attempted to recover *K-129*, has not been disclosed.
- Dr. Craven was responsible for the Navy's Deep Submergence Systems Project that included:
 - Sealab and saturation diving technology development
 - Bathyscaphe *Trieste* development and utilization
- Dr. Craven died on 12 Feb 2015 at the age of 90.
- Suggested reading: *The Silent War: The Cold War Battle Beneath the Sea*, 2001, by Dr. Craven



Source: <http://www.economist.com/news>

US special operations nuclear submarines

| Class | # in Class | Length | Beam | Displacement (tons) | Reactor | Shaft hp | Max speed (kts) | Year originally delivered | Years in spec op service |
|--|------------|--------------------|-----------------|----------------------------------|---------|-----------|----------------------|----------------------------|--------------------------|
| Halibut - SSN-587 (former SSGN-587) | 1 | 106.7 m (350 ft) | 8.8 m (29 ft) | 3,655 (surf), 4,000 (sub) | S3W | 7,300 | 20+ | Jan 1960 (as SSGN) | 1966 – 76 (Note 1) |
| Seawolf - SSN-575 (after hull extension) | 1 | 122.5 m (402 ft) | 8.5 m (28 ft) | >3,250 (surf), > 4,150 (sub) | S2Wa | 13,400 | 19 | Mar 1957 (as SSN) | 1973 – 87 (Note 2) |
| NR-1 | 1 | 45 m (147.7 ft) | 3.8 m (12.5 ft) | 400 | 1 x PWR | Not known | 4.5 (surf) 3.5 (sub) | Oct 1969 | 1969 – 08 |
| Parche - SSN-683 (former Sturgeon-class long-hull) | 1 | 92 m (302 ft) | 9.6 m (31.6 ft) | 4,530 (surf) 5,040 (sub) | S5W | 15,000 | 25 | Aug 1974 (as SSN) | 1978 – 87 (Note 3) |
| Richard B. Russell SSN-687 (former Sturgeon-class long-hull) | 1 | 92 m (302 ft) | 9.6 m (31.6 ft) | 4,042 (surf), 4,339 (sub) | S5W | 15,000 | 25 | Aug 1975 (as SSN) | 1982 – 94 (Note 4) |
| <i>Sam Houston</i> - SSN-609 & <i>John Marshall</i> - SSN-611 (Ethan Allen-class SSBN conversions) | 2 | 125.1 m (410.3 ft) | 10.1 m (33 ft) | 7,070 (surf), 8,010 (sub) | S5W | 15,000 | 20+ | May 62 - Jan 63 (as SSBNs) | 1983 - 92 |
| Parche (SSN-683, after hull extension) | 1 | 122.5 m (402 ft) | 9.6 m (31.6 ft) | 7,000 (surf) (est.), 7,800 (sub) | S5W | 15,000 | < 25 | Aug 1974 (as SSN) | 1991 – 04 (Note 5) |

Notes:

1. Converted for special operations Feb 65 – May 66 at Pearl Harbor Naval Shipyard.
2. Converted for special operations Jan 71 – Jun 73 at Mare Island Naval Shipyard; 15.8 m (52 ft) hull extension installed forward of the sail.
3. Originally converted for special operations Oct 76 – Jul 78 at Mare Island Naval Shipyard.
4. Converted for special operations 1982 at Mare Island Naval Shipyard.
5. Additional conversion at Mare Island Naval Shipyard 1987 – 1991; 30 m (100 ft) hull extension installed forward of the sail.

US special operations nuclear submarines

| Class | # in Class | Length | Beam | Displacement (tons) | Reactor | Shaft hp | Max speed (kts) | Year originally delivered | Years in spec op service |
|--|------------|------------------|------------------|----------------------------|---------|----------|-----------------|-------------------------------|--------------------------|
| <i>Kamehameha</i> - SSN-642 & <i>James K Polk</i> - SSN-645 (Ben Franklin-class SSBN conversions) | 2 | 129.5 m (425 ft) | 10.1 m (33 ft) | 7,250 (surf), 8,250 (sub) | S5W | 15,000 | 20+ | Dec 1965, Apr 1966 (as SSBNs) | 1994 - 02 |
| Jimmy Carter - SSN-23 (Seawolf-class SSN) | 1 | 138 m (453 ft) | 12.9 m (42.3 ft) | 10,069 (surf) 12,157 (sub) | S6W | 52,000 | > 25 | Feb 2005 | 2005 – present (Note 6) |

Notes:

- Originally commissioned in special operations form, with a 30 m (100 ft) hull extension installed aft of the sail.

USS Halibut (SSN-587)

Special operations submarine

- February – September 1965: After serving as an SSGN since 1960, *Halibut* was in Pearl Harbor Naval Shipyard for a major overhaul and was re-designated an SSN in April 1965.
- *Halibut* operated with the Deep Submergence Group, which was involved in deep sea search & recovery.
 - *Halibut* gained the capability to operate a towed underwater search vehicle (the Fish) for deep undersea surveys.
 - With a directional thruster installed on the foredeck, *Halibut* could hover for hours over objects on the sea bed.
- From July – August 1968, *Halibut* supported *Operation Sand Dollar*.



Halibut circa late 1965 with foredeck thruster.
Source, both photos: <https://en.wikipedia.org/>



Halibut circa early 1970s with a DSRV-like saturation diving chamber on the aft deck and foredeck thruster removed.

Operation Sand Dollar

- This operation was initiated under the direction of Dr. John Craven, the Chief Scientist for the US Navy's Special Projects Office, with the goal of locating Soviet submarine K-129, which was the nuclear-armed, diesel-electric Golf II strategic ballistic missile submarine (SSB) that sank on 8 March 1968 in water 16,000 feet (4,877 meters) deep in the northern Pacific Ocean, about 1,560 nautical miles (2,890 km) northwest of Hawaii. The approximate location of the sinking was determined by triangulating data from US SOSUS acoustic monitoring stations.
- 15 July 1968: *Halibut* departed Pearl Harbor with the mission of locating K-129.
- In the assigned search area, *Halibut* lowered a remotely-controlled vehicle (the Fish) three miles to the ocean floor and located the Russian submarine after a three-week search. *Halibut* is reported to have spent the next several weeks doing a detailed photographic survey of the K-129 wreck site.
- Under the later *Project Azorian*, an attempt was made to recover K-129 using the purpose-built *Hughes Glomar Explorer* vessel and a large mechanical claw (the "capture vehicle") manufactured by Lockheed and known as *Clementine* (graphic, below right).

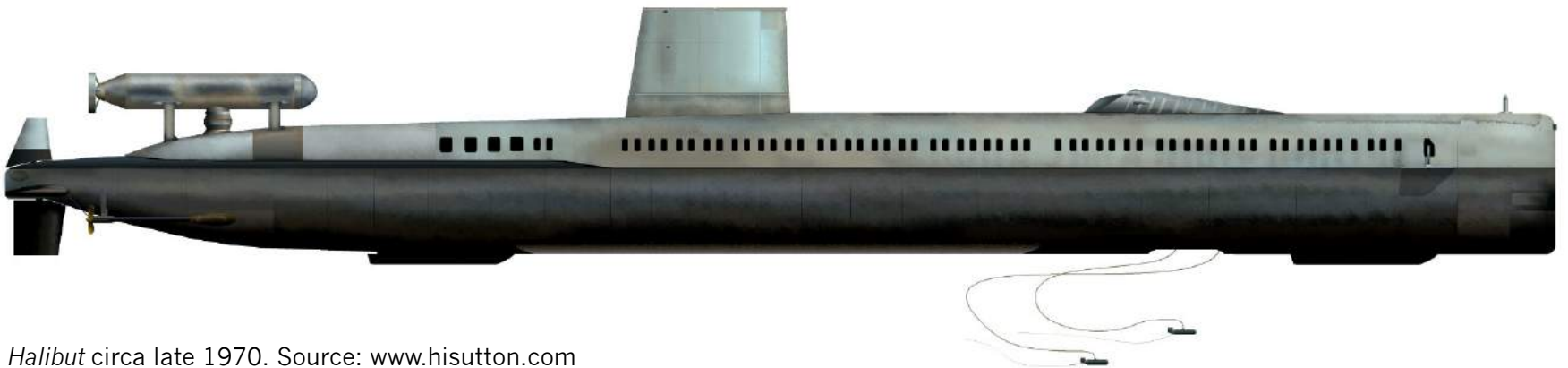


Source, both graphics: <http://adst.org/2016/08/voyage-bottom-sea-cia-mission-raise-soviet-sub/>

USS Halibut (SSN-587)

Special operations submarine

- September 1968 – late 1970: *Halibut* was transferred to Mare Island Naval Shipyard for a refueling overhaul and installation of additional special operations equipment, including:
 - Long- and short-range side-looking sonar
 - Fore and aft side thrusters
 - Port and starboard, fore and aft seabed skids ("sneakers")
 - Anchoring winches with fore and aft mushroom anchors
 - Hangar section sea lock
 - Saturation diving (mixed-gas) habitat on the aft deck (a DSRV look-alike)
- In late 1970, *Halibut* was assigned to Submarine Development Group One, San Diego and engaged in *Operation Ivy Bells* from 1971 – 1976.
- *Halibut* was decommissioned on 30 June 1976 after a service life of 16 years. Its spec op role was taken over by *Seawolf* and later by *Parche*.



Halibut circa late 1970. Source: www.hisutton.com

Operation Ivy Bells

- October 1971: *USS Halibut* embarked to locate and tap an underwater communications cable that ran from the Soviet missile submarine base at Petropavlovsk, on the Kamchatka peninsula, under the Sea of Okhotsk, to Fleet headquarters near Vladivostok.
 - The cable was found at a depth of about 400 feet (122 meters), tapping coils were installed around the cable, and the ability to record messages was demonstrated.

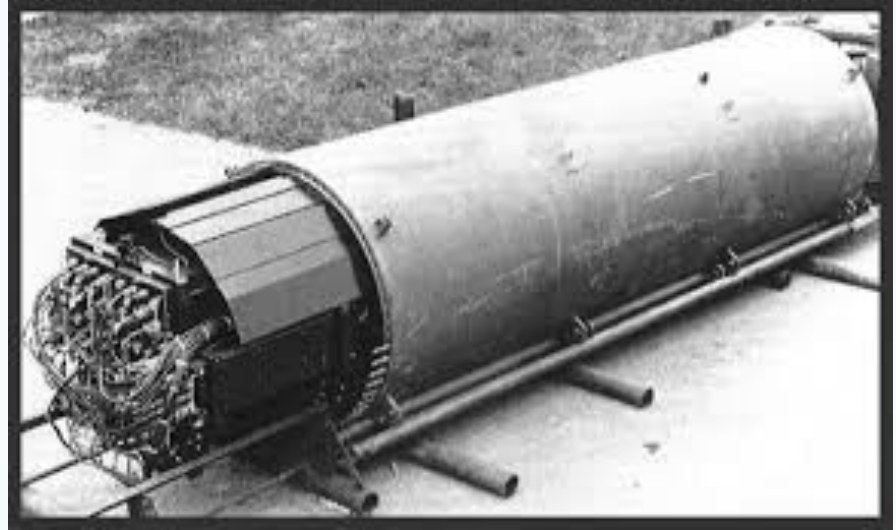


Source: www.hisutton.com

- 1972: *Halibut* returned and attached a high-capacity induction recording pod to the cable.
 - Recording pod was 20 feet (6.1 meters) long and weighed about 6 tons (5,454 kg), and was designed to detach if the cable was raised for repair.
 - The recording technique involved no physical damage to the cable and was unlikely to have been readily detectable.
 - The pods were designed by AT&T.
 - Some or all of the pods were powered by a radioisotope thermoelectric generator (RTG).
- *Halibut* and other special operations subs (*Seawolf* & *Parche*) visited the tap location regularly to exchange recording devices and/or install an improved pod.

Operation Ivy Bells

- In the summer of 1979, *USS Parche* (SSN-683) travelled from San Francisco under the Arctic ice to the Barents Sea, and laid a new cable tap near Murmansk.
- The US continued this operation undetected until 1981, when one day, surveillance satellites showed a number of Soviet warships, including a salvage ship, anchored over the undersea cable in the Sea of Okhotsk.



Induction recording pod. Source: www.usmilitaryforum.com

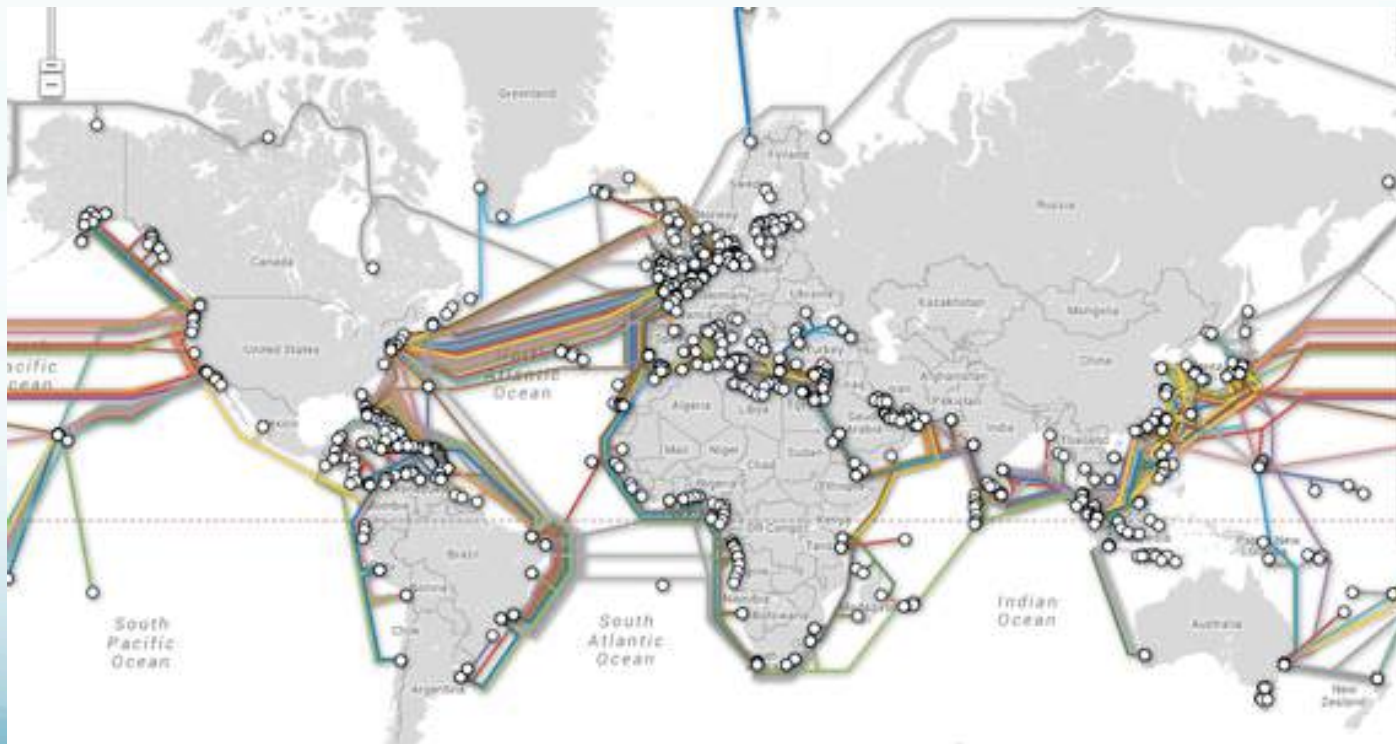
- *USS Parche* was sent to the site to retrieve the pod. *Parche's* divers were unable to find the pod, which apparently had been recovered by the Soviets.
- After a long investigation, it was determined that *Operation Ivy Bells* was revealed to the Soviets in classified information given to them by NSA employee Robert Pelton for payments totaling \$35,000.
- One of the *Ivy Bells* pods is now on display in Moscow at the Museum of the Great Patriotic War.

Operation Ivy Bells

- During 1985, cable-tapping operations were extended into the Mediterranean, to intercept cables linking Europe to West Africa.
- The cable tap in the Barents Sea continued in operation, undetected, until tapping stopped in 1992.
- After the Cold War ended, the *USS Parche* was refitted with an extended hull section forward of the sail to accommodate larger cable tapping equipment and pods. Reportedly, cable taps could be laid by remote control, using drones.

Legacy of *Ivy Bells*

- According to a 2013 article in the *Washington Post*, the US's National Security Agency (NSA) has a modern-day cable-tapping program, known by the names OAKSTAR, STORMBREW, BLARNEY and FAIRVIEW that accesses "communications on fiber cables and infrastructure as data flows past." Apparently the UK and other nations have similar programs.
- TeleGeography, a global research firm, claims that undersea cables carry 99% of all intercontinental data, a category that includes most international phone calls.

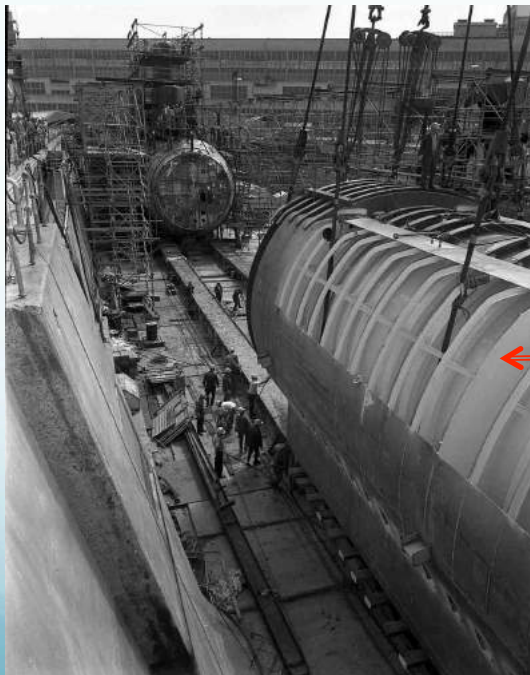


550,000 miles of undersea cables connect the world Source: <https://www.telegeography.com>

USS Seawolf (SSN-575)

Special operations submarine

- After serving as an SSN since 1957, *Seawolf* was in Mare Island Naval Shipyard from early-1971 to mid-1973 for modifications for special operations missions, including installation of:
 - A new 15.8 m (52 ft) “special projects” hull section forward of the sail,
 - Bow and stern thrusters, and
 - Other systems similar to those installed on *Halibut* to support saturation divers and operation of remote underwater vehicles.



Hull insert
being
installed
in drydock



Bow
thrusters

Stern
thrusters

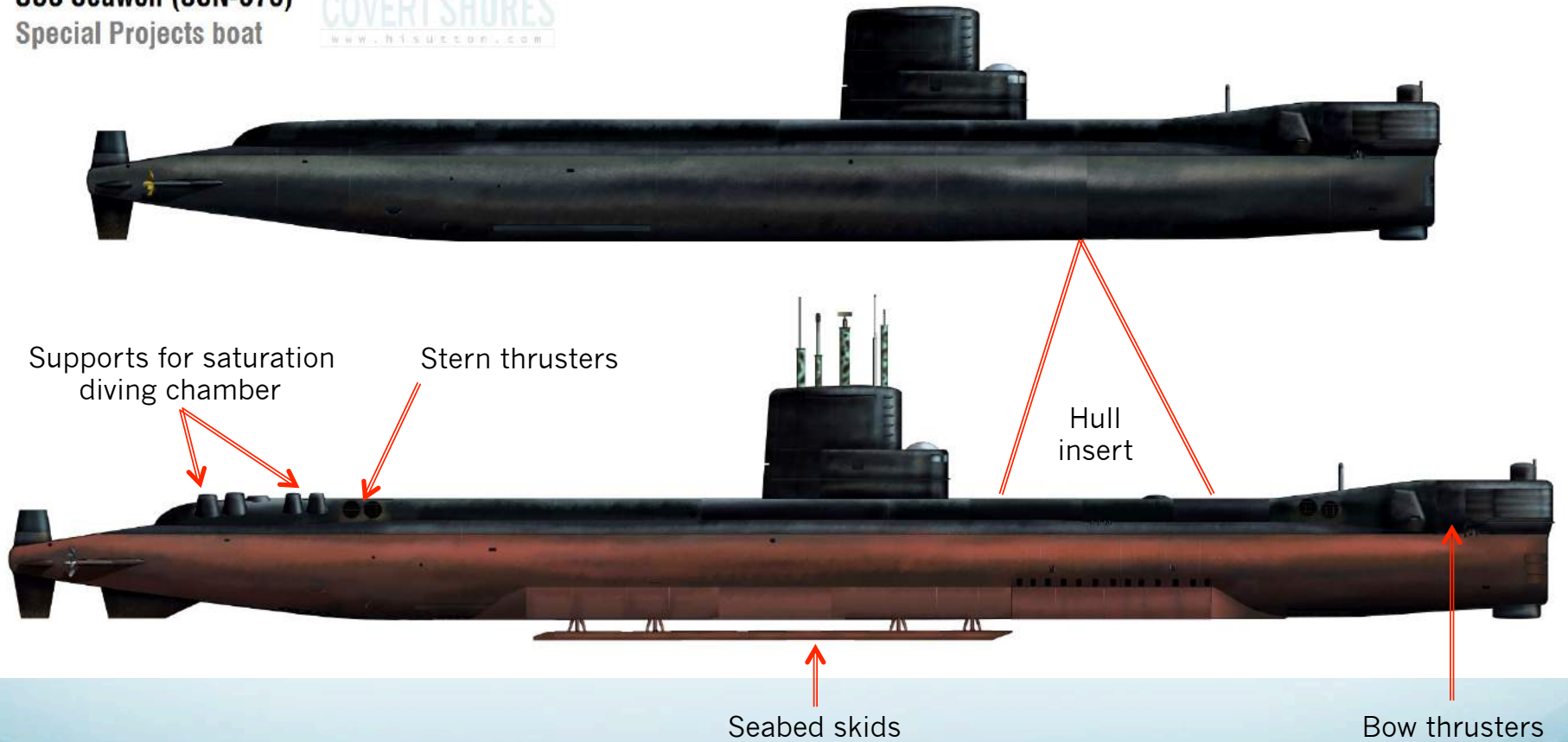
Source, two photos:
<http://navsource.org/archives/08/08575.htm>

USS Seawolf (SSN-575)

Special operations submarine

USS Seawolf (SSN-575)
Special Projects boat

COVERT SHORES
www.hisutton.com



Source: adapted from Covert Shores / www.hisutton.com

USS *Seawolf* (SSN-575)

Special operations submarine

- 1974: *Seawolf* became fully operational and conducted her first Pacific Fleet deployment, which included operating independently for a period of three months.
- Late 1974: *Seawolf*, equipped with special cameras that were lowered to the seabed, examined the site of the failed attempt to raise Soviet submarine K-129.
 - The survey found wreckage scattered over a wide area.
 - A second recovery attempt by *Glomar Explorer* was not made.
- 1975: *Seawolf* came under the exclusive direction of Submarine Development Group One.
- 1975 – 78: *Seawolf* conducted *Operation Ivy Bells* and repeatedly visited the listening devices originally placed in 1972 by *Halibut* on submarine communications cables in the Okhotsk Sea.
 - *Seawolf* exchanged recording devices and brought them back for evaluation.
- 1978: *Seawolf* was refueled.

USS Seawolf (SSN-575)

Special operations submarine

- 1979 – 1982: *Seawolf* continued conducting Operation Ivy Bells.
 - On one mission, the boat returned to the Sea of Okhotsk, installed new recording devices and removed the old units. The boat was damaged during this operation, but returned to port and was brought into dry dock for repairs.
 - In 1982, *Operation Ivy Bells* ended.
- Thereafter, *Seawolf* continued to be used to locate and recover items in the open sea.
 - In 1984, *Seawolf* conducted a 93-day deployment to the western Pacific, then the longest submerged deployment of any submarine.
- June 1986: *Seawolf* returned to Mare Island to prepare for decommissioning.
- March 30, 1987: *Seawolf* was decommissioned.

Naval Reactors 1 (NR-1)

Special operations submarine



Source: <http://navsource.org/archives/>



Source: <http://web.mit.edu/deeparch/>

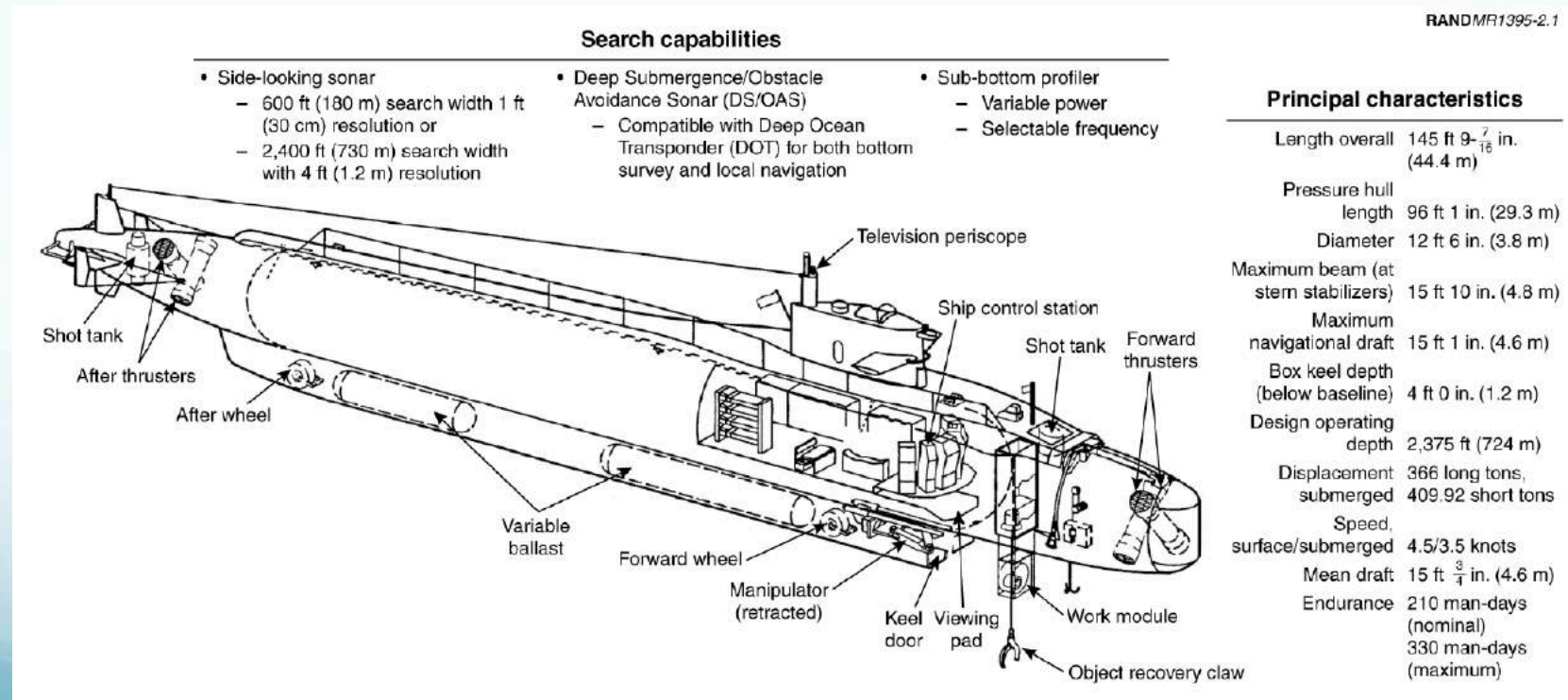
- NR-1 entered service on Oct 1969 as a one-of-a-kind small nuclear submarine capable of operating at great depth and with long endurance (16 – 25 days), even in heavy weather. It conducted military and civilian missions.
- NR-1 generally was towed surfaced or submerged to and from remote mission locations by an accompanying surface tender, which also may have been capable of conducting research in conjunction with the submarine. On one occasion NR-1 was transported across the Atlantic on a wooden cradle in the well deck of a Navy landing ship dock (LSD).
- NR-1 was deactivated in Nov 2008, de-fuelled at Portsmouth Naval Shipyard, and sent to Puget Sound Naval Shipyard (PSNS) to be scrapped. NR-1's sail is on display at the Submarine Force Library & Museum, Groton, CT.
- Suggested reading: Lee Vyborny, *Dark Waters: An Insider's Account of the NR-1, the Cold War's Undercover Nuclear Sub*, New American Library, 2003

Naval Reactors 1 (NR-1)

Special operations submarine

NR-1 is equipped to search for and recover items from the sea floor and to map the sea floor.

- Searches and mapping are facilitated by a sub-bottom profiler and a side-scan sonar system that can produce images of the search area
- A set of deployable wheels allows NR-1 to ride along the contours of the sea bottom

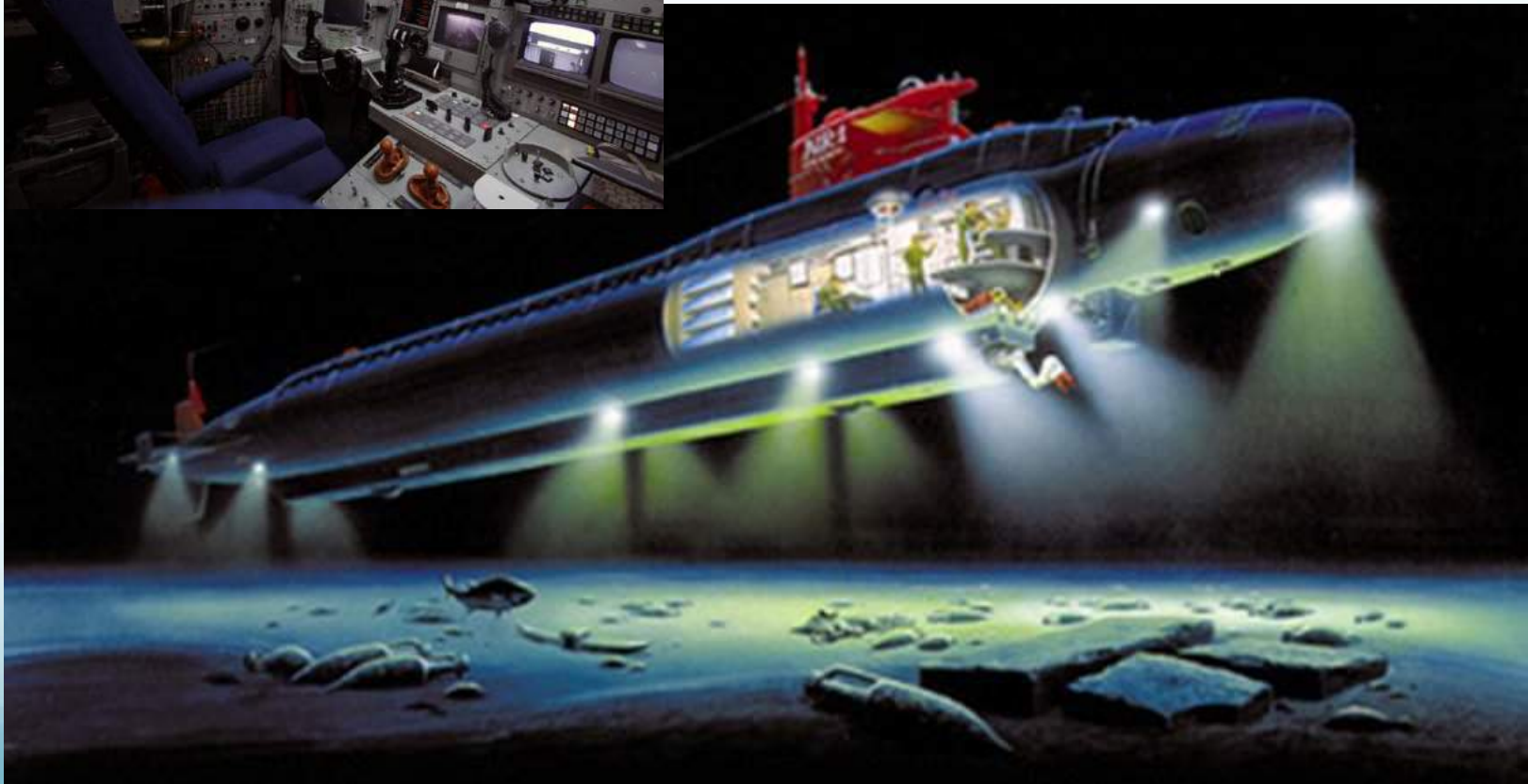


Naval Reactors 1 (NR-1)

Special operations submarine

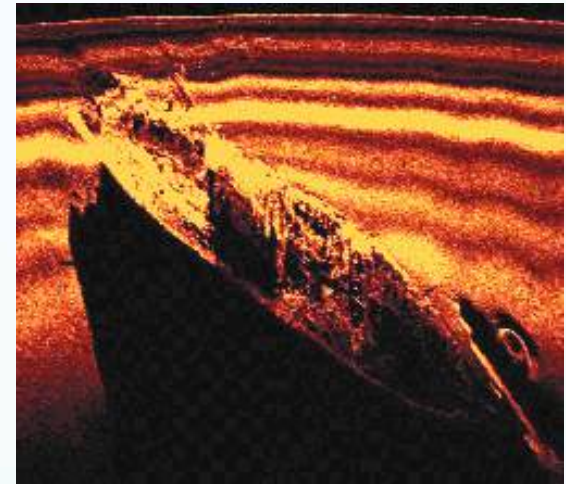


- NR-1 carried a crew 11, all of whom are nuclear-propulsion certified.
- Details on the small PWR powerplant have not been released. It appears that the reactor was refueled once in FY 1989 after 20 years of operation.



NR-1 survey of the *USS Monitor*

- *USS Monitor*, launched on 30 January 1862, served during the Civil War as the Navy's first ironclad warship.
- The Navy has an on-going *Monitor Project* to research and, perhaps ultimately, to recover the vessel.
- Because of strong currents along the bottom, initial efforts to obtain detailed site data had failed. *NR-1*'s exceptional stability and power made it possible for the sub to scan the entire hull with side-looking sonar and help determine the ship's structural integrity with relative ease.
- These images provide an example of the *NR-1*'s unique undersea search and mapping capabilities.



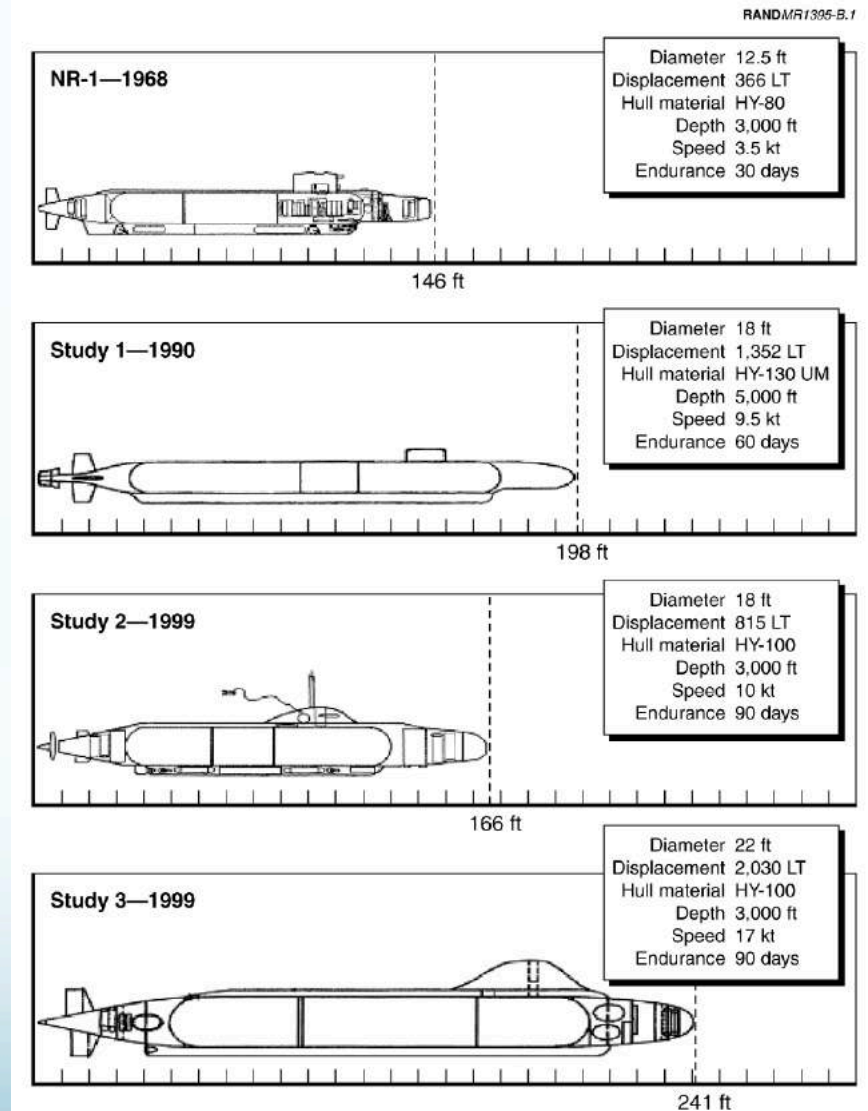
NR-1 sonar images of USS Monitor



Source: http://www.navy.mil/navydata/cno/n87/usw/issue_14/nr1.html

NR-1 replacement studies

- *NR-1* was deactivated in 2008. There are no active plans for building a replacement.
- Results of prior replacement studies in 1990 and 1999 are shown in the accompanying diagram.
- A 2002 Rand study examined the capabilities that an *NR-2* platform might incorporate and the associated mission profiles that could use these capabilities (see Rand report MR1395-2.1).
- The Russians are building advanced, nuclear-powered special operations / deep-ocean exploration subs that are much more capable than *NR-1*.
 - The latest is *Losharik*, which became operational in 2003.



Source: RAND document MR1395-2.1

USS Parche (SSN-683)

Sturgeon-class special operations sub

- Originally a long-hull Sturgeon (637)-class sub, commissioned Aug 1974.
- Oct 1976: *Parche* entered Mare Island Naval Shipyard for various ocean engineering modifications needed for special operations missions.
- Later in the 1970s, *Parche* conducted *Ivy Bells* missions to place wiretaps on Russian underwater communications cables and to periodically retrieve recordings.
- 1987 to 1991: *Parche* underwent an extended refueling overhaul at Mare Island Naval Shipyard during which a 30 m (100 ft) hull extension for “research and development” was added just forward of the sail to provide space for additional crew and special mission equipment:
 - Intelligence gathering
 - Underwater salvage

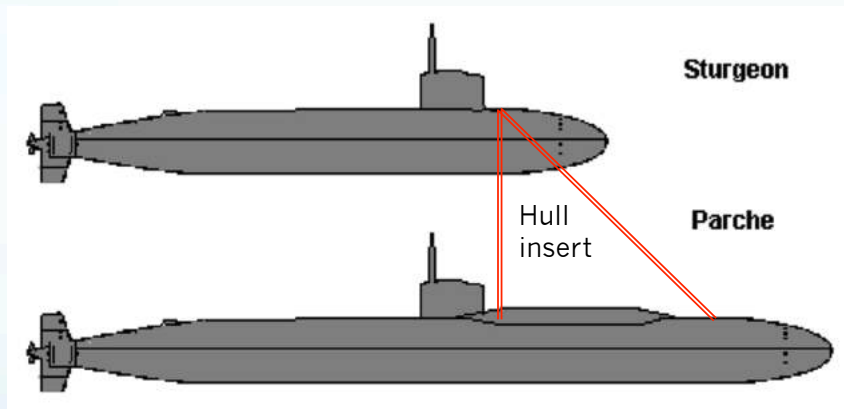


USS Parche circa 1983 (before hull extension). The “DSRV-look-alike” structure on the boat's aft section was a lock in-lockout chamber for saturation divers
Source: www.navsource.org

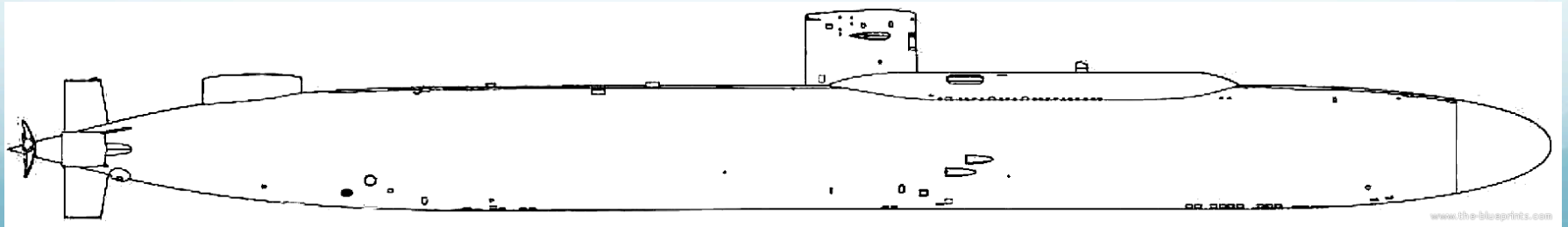
USS *Parche* (SSN-683)

Sturgeon-class special operations sub

- Reportedly, *Parche*'s "ocean engineering" equipment includes remotely-operated underwater vehicles and a remote grapple extended through a hatch in the submarine's keel to locate and salvage relatively small items on the ocean floor (i.e., missiles parts, reentry vehicles).
- Parche* resumed Pacific Fleet operations in 1992.
- Decommissioned in 2004.



Source, above graphic + photo: <https://en.wikipedia.org>



Final USS *Parche* configuraton circa 1992. Source: <https://www.the-blueprints.com/>

USS Parche (SSN-683)

Sturgeon-class special operations sub



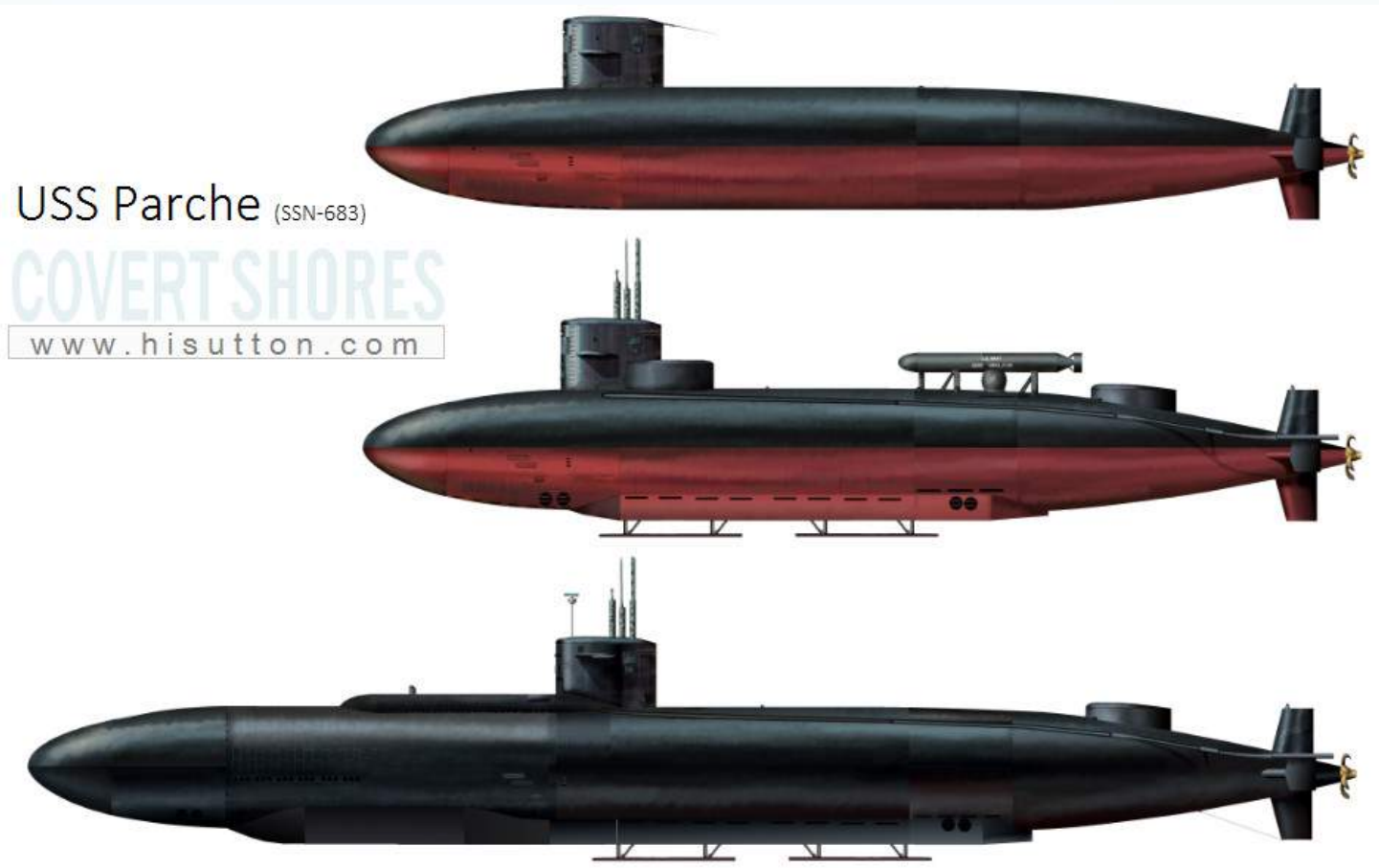
Final *USS Parche* configuraton.

The diagram below depicts the evolution of the *USS Parche* from a long-hull Sturgeon-class SSN through its two iterations of “ocean engineering” modifications.



Source, photo & graphic: www.hisutton.com

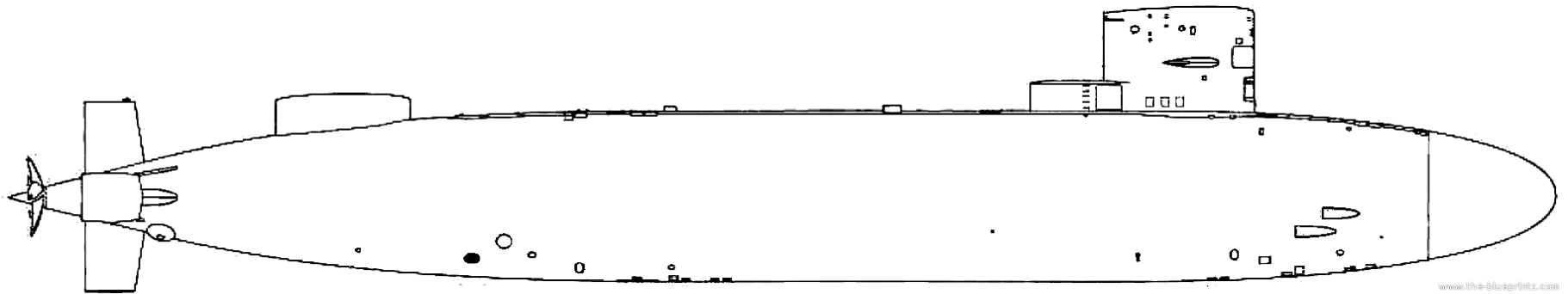
Evolution of *USS Parche* (SSN-683)



Source: adapted from www.hisutton.com

USS *Richard B. Russell* (SSN-687)

Sturgeon-class special operations sub



Source: the-blueprints.com

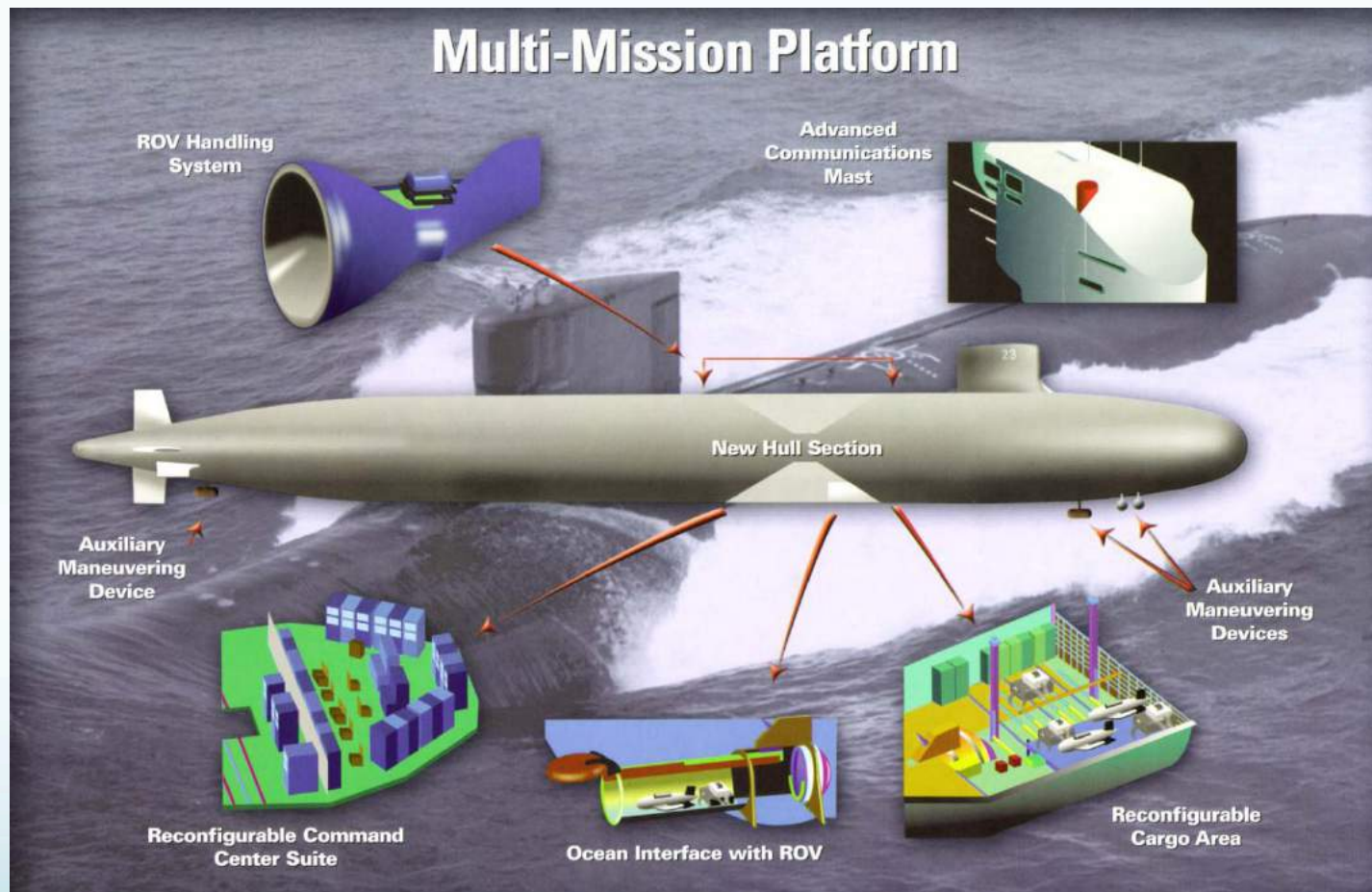


Source: www.navsource.org

- Originally a long-hull Sturgeon (637)-class sub commissioned in Aug 1975. The “bustle” immediately aft of the sail initially housed a tethered communications buoy.
- In 1982, *Russell* entered Mare Island Naval Shipyard for various ocean engineering modifications needed for special operations missions with Submarine Development Group 1. The “bustle” may have been repurposed to house other equipment.
- Decommissioned in 24 June 1994

USS Jimmy Carter (SSN-23)

Seawolf-class special operations sub



Source: <http://www.veteranstoday.com/2011/>

For more information on the SSN-23 Multi-Mission Platform, visit H.I. Sutton's Covert Shores website at: <http://www.hisutton.com/SSN-23.html>

USS Jimmy Carter (SSN-23)

Seawolf-class special operations sub



Source: reuters.com

- Length: 453 feet (138.1 m)
- Displacement:
 - 10,069 t surfaced (est.)
 - 12,157 t submerged
- Can accommodate a Dry Deck Shelter for Special Operations Forces (SOF) on the top deck, behind the sail.
- Retains all the war fighting capabilities of other Seawolf-class SSNs.

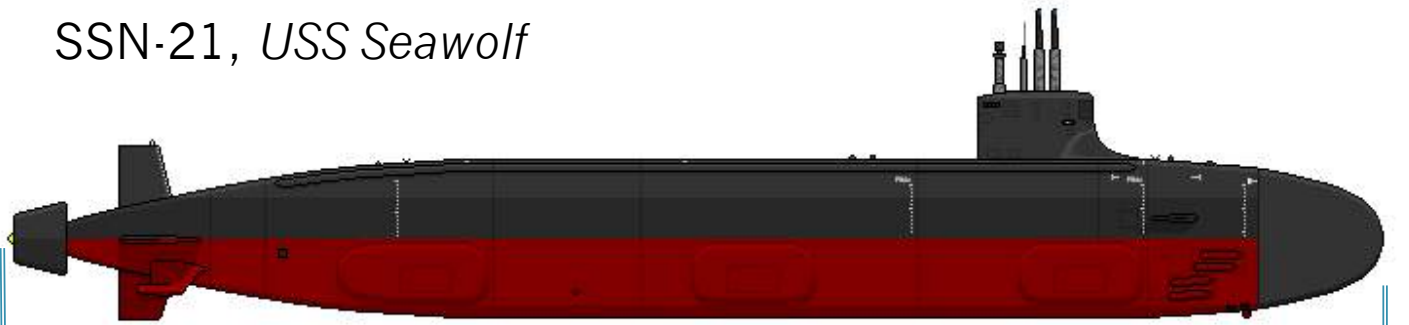
- Electric Boat inserted a 100 ft (30.5 m), 2,500 ton, Multi-Mission Platform (MMP) extension in the middle of *Jimmy Carter's* hull, adding nearly \$1 billion to the baseline \$2 billion price of a Seawolf-class sub.
- The MMP includes an ocean interface to allow divers, remotely-operated vehicles, and other machinery to move between the sub's interior and the ocean. Such capabilities can be used for retrieving objects off the seafloor or deploying monitoring devices and other surveillance equipment.



Source: www.bluebird-electric.net

Comparison of SSN-21 & -23

SSN-21, *USS Seawolf*



107.6 m (353 ft)

138.1 m (453 ft)

SSN-23, *USS Jimmy Carter*



Source: adapted from <http://www.shipbucket.com/images>

US SEAL delivery subs

- Former Ethan Allen-class FBM subs *Sam Houston* (SSBN-609) & *John Marshall* (SSBN-611):
 - 1981: In compliance with the SALT I treaty, these former Polaris missile subs were removed from SSBN service and reclassified as SSN-609 and SSN-611.
 - 1982 – 1983: Both were extensively modified at Puget Sound Naval Shipyard to serve as “motherships” for special operations forces (SOF):
 - Some missile tubes were removed to provide space for berthing up to 67 SOF troops.
 - Other missile tubes were converted into air locks and stowage for SOF equipment.
 - 2 x Dry Deck Shelters (DDS) were installed on the top deck, behind the sail. Each DDS could house a SEAL Swimmer Delivery Vehicle (SDV) and/or other equipment.
 - *Sam Houston* was deactivated March 1991; *John Marshall* was deactivated early 1992.
- Former Ben Franklin-class FBM subs *Kamehameha* (SSBN-642) and *James K Polk* (SSBN-645):
 - 1992 - 1994: The Polaris missile sections on both boats were deactivated and they received SOF modifications to the *Sam Houston* and *John Marshall*, which they soon would replace.
 - 1994: Both boats were reclassified as SSNs and deployed to conduct special warfare operations, replacing.
 - *Polk* was deactivated in 1999; *Kamehameha* was deactivated in 2002. At that time *Kamehameha* was the last original FBM submarine and the oldest sub in the fleet, with 37 years of service.
- SEAL delivery missions continue with the four Ohio-class SSGN subs (former SSBNs), which can carry 2 x DDS, and with SSNs, which can carry 1 x DDS.

Converted SSBN with two DDS

USS Kamehameha (SSN-642)



Sources: Top left www.navy.mil; Top right: usskamehameha.com ; Bottom left: www.americanspecialops.com; Bottom right: www.gettyimages.com

SSNs with one DDS

- A DDS provides specially configured nuclear powered submarines with a greater capability for deploying Special Operations Forces (SOF).
- DDSs can transport, deploy, and recover SOF teams from Combat Rubber Raiding Crafts (CRRCs) or SEAL Delivery Vehicles (SDVs), all while remaining submerged.
- Six long-hull Sturgeon-class SSNs were the first SSNs to be configured to carry a DDS: SSN-678, -679, -680, -682, -684, & -686.
- *USS Dallas* (SSN-700) was the first Los Angeles-class submarine to be configured to carry a DDS mounted aft of the sail.
- Other Los Angeles-class, Seawolf-class & Virginia-class SSNs are equipped to carry a DDS.
- In an era of littoral warfare, this capability substantially enhances the combat flexibility of both the submarine and SOF personnel.



USS Dallas with DDS. Source: www.navy.mil

SEAL Delivery Vehicle (SDV)

Carried by various SSNs & Ohio-class SSGNs

- An SDV is a manned, flooded, battery-powered submersible that can deliver several fully-equipped SEALs to a mission area, be "parked" or loiter in the area, retrieve the SEALs, and return to a designated point. The current version is the Mk 8 Mod 1 SDV.
- The pilot & co-pilot may be part of the fighting team.
- Navigation is by means of Doppler Inertial Navigation System (DINS), forward-looking obstacle avoidance sonar (OAS) & a submarine rendezvous and docking system (RDS) that assists in recovery to the host sub.
- The SDV typically is stored in a Dry Deck Shelter on a submarine, but also can be deployed from amphibious surface ships, large helicopters, or air-dropped from a C-130 transport.



Source: www.sinodefensceforum.com, Jeff Head Oct 13, 2014



Source: www.news.navy.mil



Source: <https://en.wikipedia.org>

Advanced SEAL Delivery System (ASDS) mini-sub

- ASDS-1 was designed to carry 16 SEALs + 2 pilots in 3 compartments: operations, diver lock-out & troop transport.
- Length: 65 ft (19.8 m); beam: 6.75 ft (2.1 m); Displacement: 60 tons
- Propulsion: 67 hp (50 kW) electric motor; max speed 8+ kts; Range: 125+ miles (201 km).



ASDS-1 minisub in 2004. Source: www.navsource.com

688-class submarine *USS Charlotte* (SSN-766) with ASDS-1 in 2002



Source: <https://en.wikipedia.org/>

- The original silver-zinc batteries provided insufficient power for the craft's missions, and more powerful lithium-ion batteries were substituted.
- Nov 2008: battery fire during recharging caused significant damage to ASDS-1.
- The mini-sub was not repaired and the program was cancelled.