Marine Nuclear Power: 1939 - 2018

Part 4: Europe & Canada

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 4: Europe & Canada*. The other parts are:

- *Part 1: Introduction*
- *Part 2A: United States - Submarines*
- *Part 2B: United States - Surface Ships*
- *Part 3A: Russia - Submarines*
- *Part 3B: Russia - Surface Ships & Non-propulsion Marine Nuclear Applications*
- *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 4: Europe & Canada

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Naval nuclear submarines (SSN & SSBN)
& nuclear surface ship and marine reactor concepts

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

United Kingdom

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The beginning of the UK marine nuclear power program

UK marine nuclear timeline

1940s

1950s

1952
1st HEU production at Capenhurst Gaseous Diffusion Plant;
1st UK's A-bomb test
1956
UK Naval Nuclear Propulsion Program (NNPP) formed
1957
1st UK H-bomb test;
Admiralty Reactor Test Establishment (ARTE) established;
Start construction on Dounreay Submarine Prototype 1
1958
US-UK Mutual Defense Agreement (MDA)
12 Jun 1959
Keel laid for 1st UK nuclear sub, *HMS Dreadnought*

1960s

10 Jan 1963
HMS Dreadnought 1st UK underway on nuclear power
Apr 1963
Polaris Sales Agreement
1965
Initial criticality, DSMP 1 (PWR1) prototype
18 Jul 1966
1st Valiant-class SSN commissioned
2 Oct 1967
1st Resolution-class SSBN commissioned
15 Jun 1968
1st UK SSBN deterrent patrol by *HMS Resolution* with Polaris A3T

1970s

15 Jul 1970
1st Churchill-class SSN commissioned
3 Mar 1971
Dreadnought was 1st UK submarine to surface at the North Pole
17 Apr 1973
1st Swiftsure-class SSN commissioned

1980s

1980
Dreadnought SSN retired
Jul 1980
UK Defense white paper
1982
IOC for Polaris / Chevaline
Mar 1982
Trident Sales Agreement
27 May 1983
1st Trafalgar-class SSN commissioned
1984
PWR1 prototype shutdown
1987
Initial criticality, STF (PWR2) prototype

1990s

12 Oct 1991
Last Trafalgar-class SSN commissioned
14 Aug 1993
1st Vanguard-class SSBN commissioned
Dec 94
1st UK Vanguard-class SSBN deterrent patrol with Trident II SLBM
1995
All-nuclear sub fleet.
28 Aug 1996
Last Resolution-class SSBN with Chevaline SLBM decommissioned
1998
UK Strategic Defense Review (SDR)
27 Nov 1999
Last Vanguard-class SSBN commissioned

2000s

2006
UK Defense white paper
2007
300th UK SSBN deterrent patrol
2010
UK Strategic Defense & Security Review (SDSR)

2010s

27 Aug 2010
1st Astute-class SSN commissioned
2015
UK Strategic Defense Review (SDR);
PWR2 prototype shutdown
2016
UK government committed to build Dreadnought-class SSBN;
MoD Submarine Dismantling Project (SDP) started;
Capenhurst selected for ILW storage
2017
SSN flotillas consolidated at Faslane, Scotland

Timeline for the beginning of the UK marine nuclear power program

- **1946:** The US Atomic Energy Act (the McMahon Act) severely limited the transfer of restricted nuclear information and materials from the US to any other nation.
- **1956**: UK Naval Nuclear Propulsion Program (NNPP) formed
- **mid-1950**s: A series of exchange visits defined a framework for renewed nuclear collaboration between the US and the UK.
  - Progress was aided by the UK's first A-bomb test in 1952 and first H-bomb test in 1957.
- **1958**: US-UK Mutual Defense Agreement (MDA)
  - The original MDA included export of one complete Westinghouse S5W submarine nuclear power plant and fuel for the first UK nuclear submarine, *HMS Dreadnought*.
  - The MDA is renewed every 10 years. Use of US enrichment services to enrich UK-supplied uranium was reportedly formalized in a 1984 amendment to the MDA.
- **12 June 1959:** Keel laid for the 1st UK nuclear-powered submarine, the attack submarine *HMS Dreadnought* (S101), with a US-provided S5W reactor.
- **21 January 1962**: Keel was laid for the 1st all-UK designed, nuclear-powered, attack submarine, *HMS Valiant* (S102), with a Rolls-Royce PWR1 "nuclear steam rising plant" (NSRP).
- **10 January 1963**: *HMS Dreadnought* made the 1st UK underway on nuclear power.
- **Mid-1963:** Under the terms of the MDA, cooperation between the US and the UK on naval nuclear propulsion came to an end one year after the UK's S5W plant became operational. NNPP cooperation was terminated as a condition of the transfer in order to ensure future UK operational, design and safety independence.
- **18 July 1966**: *HMS Valiant was* commissioned.

Timeline for the beginning of the UK marine nuclear power program

- **11 December 1962**: Nassau Agreement
  - Under this Agreement between President John F. Kennedy and UK Prime Minister Harold Macmillan, the US agreed to provide the UK with nuclear-capable Polaris missiles, launch tubes, and fire control systems:
    - Equipped with British warheads
    - UK would build five (later four) fleet ballistic missile (FBM) submarines
  - Under a previous Skybolt missile agreement, the UK granted US permission to establish an Advanced Refit Site in Holy Loch, Scotland for US Polaris SSBNs. While the Skybolt missile program was cancelled, US access to the Holy Loch site was confirmed.
  - UK's Polaris missiles were to be part of a ‘Multilateral Force' (MLF) within the North Atlantic Treaty Organization (NATO) and could be used independently only when 'supreme national interests' intervened.
    - Lacking a “dual-key” system, the UK Polaris force was independent.
    - The NATO MLF never was formed.
- **6 April 1963:** Polaris Sales Agreement
  - The Polaris Sales Agreement implemented the Nassau Agreement.
  - Responsibility for the UK’s strategic nuclear deterrent passed from the Royal Air Force to the Royal Navy.
- **8 May 1963:** The Royal Navy ordered four Resolution-class SSBNs.
- **26 February 1964:** Keel laid for the 1^{st} SSBN, *HMS Resolution* (S22).
- **15 June 1968:** *HMS Resolution* started the 1^{st} UK Polaris deterrent patrol from HMNB Clyde Faslane, Scotland.

Timeline for the beginning of the UK marine nuclear power program

- **24 January 1980:** The House of Commons backed the Government's policy to maintain an independent nuclear deterrent force.
- **10 July 1980:** Request to purchase Trident I SLBMs
  - Prime Minister Margaret Thatcher wrote to US President Jimmy Carter requesting the purchase of Trident I (C4) SLBMs on a basis similar to the 1963 Polaris Sales Agreement. This request was modified in 1982, requesting Trident II (D5) SLBMS.
- **March 1982:** Trident Sales Agreement
  - Patterned after the 1963 Polaris Sales Agreement.
  - Agreed by President Ronald Reagan and UK Prime Minister Margaret Thatcher.
  - UK made a 5% research and development contribution to the Trident II program.
  - UK leases 58 Trident II (D-5) missiles from a common pool managed and maintained by the US
- **3 September 1986:** Keel laid for the 1st Vanguard-class SSBN, *HMS Vanguard* (S28), to be armed with Trident II (D5) SLBMs.
- **1994:** *HMS Vanguard* made the 1st UK Trident II deterrent patrol from HMNB Clyde Faslane, Scotland.
- **July 2014:** In the latest update to the US-UK Mutual Defense Agreement (MDA), negotiated and agreed in July 2014, Article III of the agreement was modified to authorize transfer of new reactor technology, spare parts, replacement cores and fuel elements. This will directly benefit the UK's Vanguard-class SSBN replacement, which is 2016 was named the Dreadnought-class SSBN.

UK current nuclear vessel fleet

As of mid-2018

UK's current nuclear vessel fleet

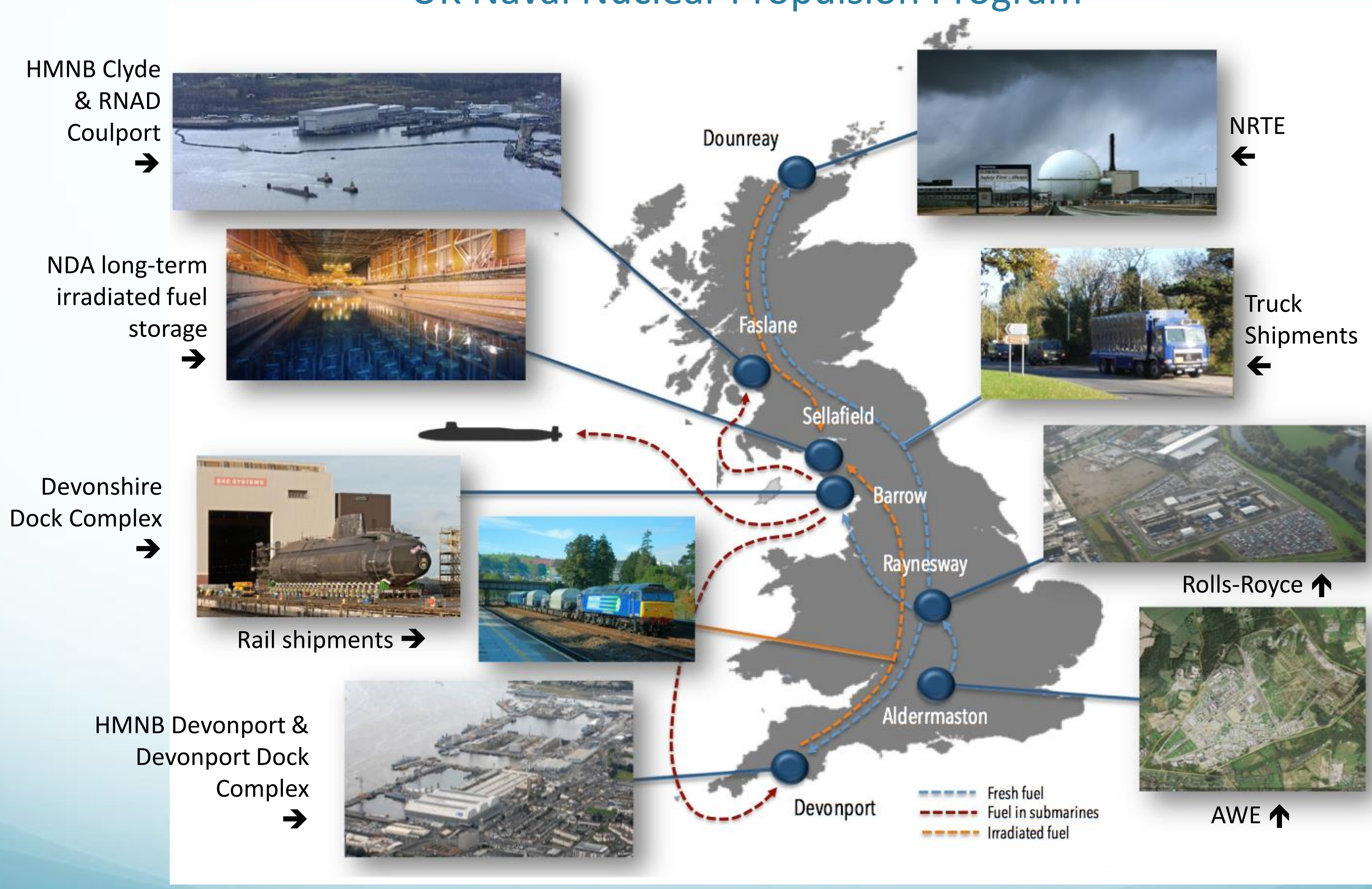
As of mid-2018

- Since 1995, the UK has operated an all-nuclear fleet of submarines.
- Currently, the fleet is comprised of the following six submarines:
  - Three Trafalgar-class SSNs
    - These boats are expected to retire between 2019 – 2022.
  - Three Astute-class SSNs
    - These boats have replaced older Trafalgar-class boats on a 1-for-1 basis.
    - One more Astute-class SSN is expected to join the fleet in 2018.
    - Three more are under construction and are expected to join the fleet between 2020 - 2024.
  - Four Vanguard-class SSBNs
- The UK has not built or operated any nuclear-powered naval or merchant surface vessel.
  - Various UK studies from the late-1950s to the 2000s examined the use of nuclear power in Admiralty vessels (fleet fast tanker, aircraft carrier) and merchant vessels (tanker, dry cargo ship, fast passenger liner).

UK naval nuclear infrastructure

Key facilities

UK Naval Nuclear Propulsion Program



Source: adapted from The UK Naval Nuclear Propulsion Programme and Highly Enriched Uranium, Dr. Nick Ritchie, University of York, UK, February 2015

UK naval nuclear propulsion program infrastructure

- Uranium Enrichment:
  - All UK submarine reactors operate on highly-enriched uranium (HEU) fuel.
  - UK produced its military HEU at the Capenhurst Gaseous Diffusion Plant, in Cheshire, between 1952 and 1962.
  - In addition, the UK received about 13 tons of HEU from the US
  - Uranium enrichment services currently are not needed to support the UK naval nuclear propulsion program.
- Atomic Weapons Establishment (AWE) Aldermaston, Reading
  - Formed in 1987 as the successor to the Atomic Weapons Research Establishment (AWRE).
  - Work at AWE covers the entire life cycle of nuclear warheads; from initial concept, assessment and design, through to manufacture and assembly, in-service support, and decommissioning and disposal
  - Stores and processes HEU for initial fabrication into reactor fuel for the NNPP.
  - AWE required an enriched uranium handling capability in order to be able to guarantee the reliability of existing Trident warheads and produce a successor to the Trident warhead, should this be required. To this end, the New Enriched Uranium Facility (Project Pegasus) at AWE is expected to be operational by 2020; replacing the existing Enriched Uranium Facility built in the 1950s.

UK naval nuclear propulsion program infrastructure

- Rolls-Royce Marine Power Operations, Ltd., Raynesway, Derby
  - Rolls-Royce is the UK Technical Authority for the “Nuclear Steam Raising Plant” (NSRP) and is responsible for managing all aspects of the plant design, safety, manufacture, performance and through-life support.
  - The Raynesway facility includes the Nuclear Fuel Production Plant (NFPP, also known as the Core Design and Manufacturing Site) and the NEPTUNE low-energy reactor used to develop and validate submarine reactor designs.
  - In 2010, the MoD signed the 10-year, £1 B, Flotilla Reactor Plant Support contract with Rolls-Royce to provide through-life support of reactors on the Royal Navy’s nuclear-powered submarines. The contract covers all aspects of support to the PWR1 Nuclear Steam Raising Plants (NSRPs) on Swiftsure- and Trafalgar-class SSNs, and to the PWR2 NSRPs on Astute-class SSNs and Vanguard-class SSBNs.
  - In 2012, MoD awarded a contract to R-R covering the continued operation and maintenance of the reactor core manufacturing facility at Raynesway and the complete modernization of the existing facility.
- Vulcan Naval Reactor Test Establishment (NRTE), Dounreay, Scotland
  - NNPP prototype reactors and related facilities at NTRE are operated by Rolls-Royce on behalf of the Ministry of Defense (MoD).

Vulcan Naval Reactor Test Establishment (NRTE)

Prototype Fast Reactor (PFR)

Electrical substation

Dounreay Submarine Prototype 1 (DSMP1)

Shore Test Facility (STF)

Pump house

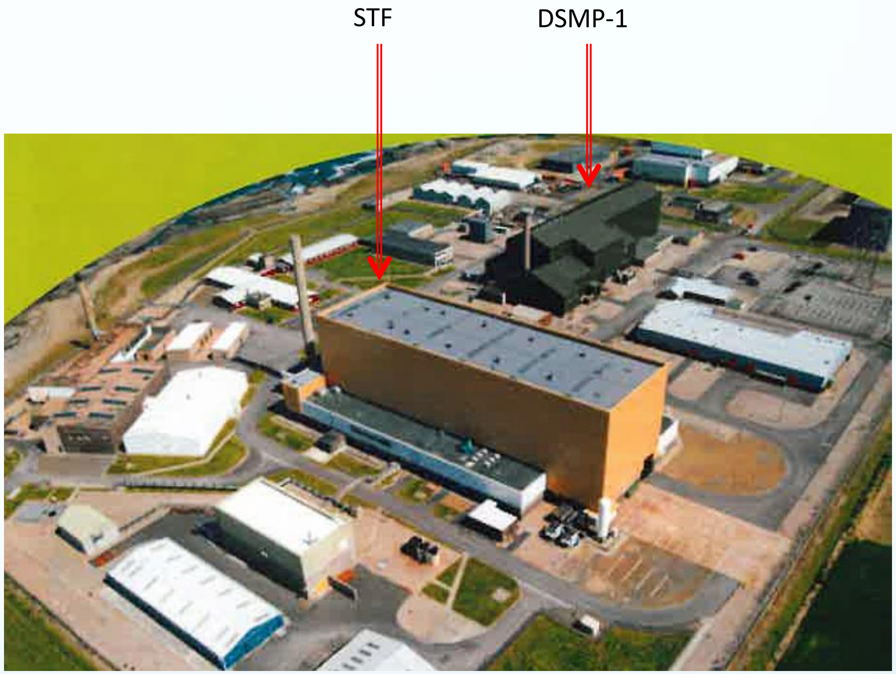
Source: http://wikimapia.org/19494855/HMS-Vulcan#/photo/1836833

Vulcan Naval Reactor Test Establishment (NRTE)

- Admiralty Reactor Test Establishment (ARTE) was established in 1957, adjacent to the United Kingdom Atomic Energy Authority's (UKAEA) Dounreay Nuclear Power Development Establishment on the north coast of Scotland.
  - ARTE was commissioned as HMS Vulcan from 1972 – 81 and thereafter was renamed NRTE.
  - It was also known as the Royal Naval Nuclear Propulsion Test and Training Establishment
- Houses the prototype nuclear reactors of the types operating on Royal Navy submarines.
  - These prototypes have several purposes:
    - Validate the NSSS design before operational employment in the submarine fleet
    - Test new technologies
    - Serve as a testbeds to investigate operational problems encountered in the fleet
    - Provide a realistic environment for training Naval personnel to operate reactor systems (training now accomplished on simulators).
  - The age of the reactor core under test typically has been at least two years in advance of the oldest operational units at sea.
- NRTE is operated by Rolls-Royce on behalf of the MoD.

Vulcan Naval Reactor Test Establishment (NRTE)

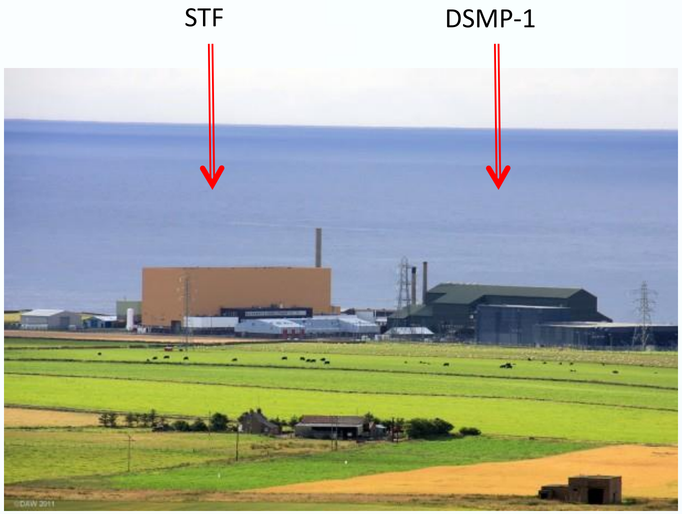
- Dounreay Submarine Prototype 1 (DSMP1) housed the prototype for PWR1.
  - Construction started in 1957. Commissioned and went critical with Core A in 1965.
  - Tested three generations of the Rolls-Royce PWR1 before being shut down in 1984
    - Core A: 1965 – 67
    - Core B: 1968 – 72
    - Core Z: 1974 – 84
  - Re-commissioned in 1987 as a non-nuclear test rig known as the Loss of Coolant Accident Investigation Rig Dounreay (LAIRD).



Source: https://dounreay.com/wp-content/uploads/2017/01/Emergency20Arrangements20for20Residents.pdf

Vulcan Naval Reactor Test Establishment (NRTE)

- Shore Test Facility (STF) housed the prototype for PWR2.
  - Commissioned and went critical with Core G in 1987.
  - Tested two generations of Rolls-Royce PWR2
    - Core G: 1987 – 96
    - Core H (first long-life core): 2002 – July 2015
  - In January 2012, a fuel cladding leak was detected in STF. A similar problem has not been detected in the fleet of submarines operating PWR2 Core H.
  - STF with Core H continued to operate under the Vulcan Trials Operation and Maintenance (VTOM) program until the was closed down in July 2015.



Source: http://www.drookitagain.co.uk/coppermine/displayimage-53-3308.html#top_display_media

- Results from examining the PWR2 Core H removed from STF to determine the cause of the fuel clad leak will have important implications on the Royal Navy's fleet of Astute-class SSNs and Vanguard-class SSBNs, which are operating PWR2 Core H. A second refueling of *HMS Vanguard* started in December 2015. Depending on the outcome of the STF core examination, additional refueling of operating submarines may be required.
- Current plans are for both reactor facilities on NRTE to be decommissioned, including removal of the reactors and their component parts, by 2022. Additional site cleanup work is expected to continue beyond that date.

UK naval nuclear propulsion program infrastructure

- Submarine School and Nuclear Power School:
  - HMS Raleigh in Cornwall
    - The seven schools on site provide a broad spectrum of training, including Submarine School and damage control training
  - HMS Sultan in Gosport
    - The Nuclear Department (ND) provides academic training and education for naval and civilian personnel appointed to posts in support of the Naval Nuclear Propulsion Program. The curriculum integrates submarine systems-related topics with essential academic underpinning knowledge in reactor physics, nuclear engineering, radiation protection and nuclear safety.
    - The ND has a range of training facilities including a Basic Principles Simulator used to illustrate the dynamic response of the plant and a suite of well-equipped laboratories used to provide practical training in radiation science, chemistry, materials and thermal hydraulics.
    - The ND also has access to high-fidelity real-time Maneuvering Room Simulators for each class of in-service submarine.
  - HMNB Clyde in Scotland
    - In 2017, funding for a new nuclear submarine training "hub" at HMNB Clyde was approved. The new schools at HMS Clyde will replace HMS Raleigh and HMS Sultan and will provide academic and technical training for all Royal Naval personnel entering the submarine service from 2022.

UK naval nuclear propulsion program infrastructure

- Devonshire Dock Complex, Barrow-in-Furness, Cumbria
  - This is the only UK shipyard currently capable of building nuclear submarines.
    - All but three UK nuclear submarines have been built at this Barrow-in-Furness shipyard. The three were built at the UK's second nuclear-qualified shipyard, Cammell Laird.
  - Currently owned and operated by BAE Systems Maritime – Submarines
    - In 1955, before the start of UK nuclear submarine construction, the shipyard was known as Vickers Armstrong Shipbuilders, Ltd., changing in 1968 to Vickers Limited Shipbuilding Group.
    - The shipbuilding group was nationalized under the Aircraft and Shipbuilding Industries Act in 1977 and became part of British Shipbuilders.
    - Following re-privatization as Vickers Shipbuilding and Engineering Ltd (VSEL) and consolidation with Cammell Laird in 1986, a series of ownership changes culminated with the shipyard being owned by BAE Systems since 1999.
  - Devonshire Dock Hall (DDH) was built between 1982 and 1986, while the shipyard was nationalized.
    - DDH provides a controlled indoor environment for submarine assembly, and avoids the difficulties caused by building on the slope of traditional slipways.
    - DDH was first used for constructing Vanguard-class SSBNs between 1986 – 1999.
    - DDH has been used for constructing Astute-class SSNs since 2001.

UK naval nuclear propulsion program infrastructure

- Devonshire Dock Complex, Barrow-in-Furness, Cumbria (cont'd)
  - In August 2016, BAE Systems commenced an eight-year shipyard redevelopment effort, starting with the following three projects that are needed for constructing the new Dreadnought-class SSBNs:
    - New Central Yard Complex (CYC)
      - This is where Pressure Hull Units and Submarine Equipment Modules will be integrated, tested and commissioned.
      - The CYC measures 180 m (590 ft) long, 90 m (295 ft) wide and 44 m (144 ft) high; taller but about 2/3 the size of the DDH.
      - Work began in October 2015; it was formally opened in May 2018 at a cost of £130 M.
    - Extension of the Devonshire Dock Hall
      - Extended with two new buildings housing a new state-of-the-art facility for manufacturing submarine Pressure Hull Units.
    - New Off-site Logistics Store for submarine parts and materials.

Devonshire Dock Complex

Source: http://www.blakehenderson.co.uk/history.html

Devonshire Dock Complex shipyard redevelopment

Above: Devonshire Dock Complex redevelopment plan.
Source: http://ukarmedforcescommentary.blogspot.com/

Above: Devonshire Dock Hall (DDH).
Source: https://en.wikipedia.org/

Above: DDH extension (blue). Source: BAE Systems

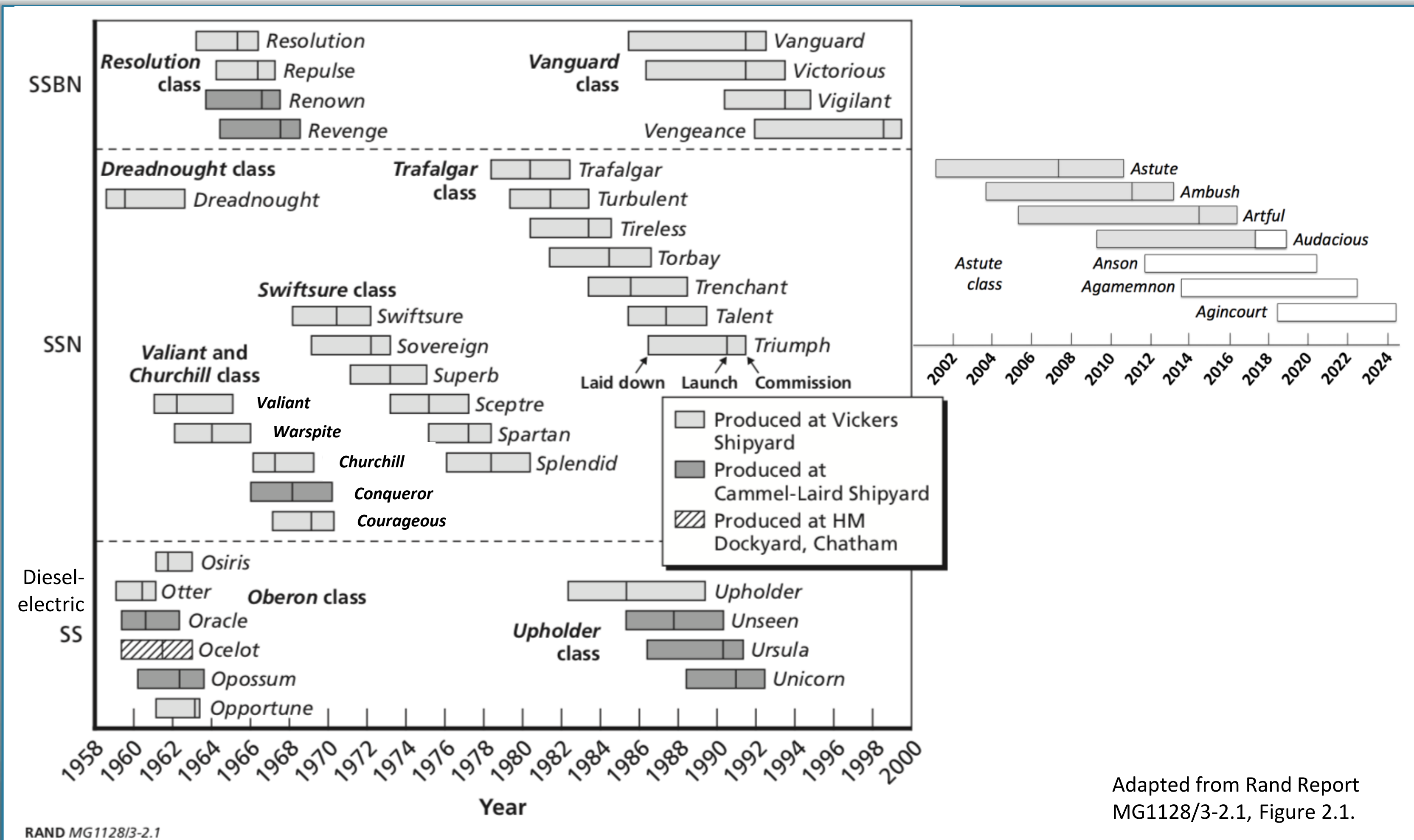
Left: CYC under construction, circa 2017.
Source: BAE Systems

UK naval nuclear propulsion program infrastructure

- Cammell Laird Shipyard, Birkenhead, Merseyside
  - This is the second UK shipyard that has built nuclear submarines.
  - Only three UK nuclear submarines were built at the Cammell Laird shipyard: the Resolution-class SSBNs *HMS Renown* (1964 – 68) and *HMS Revenge* (1965 – 69), and the Churchill-class SSN *HMS Conqueror* (1967 – 71).
  - The shipyard was nationalized along with the rest of the British shipbuilding industry and became part of British Shipbuilders in 1977. In 1986, it returned to the private sector as part of Barrow-in-Furness-based Vickers Shipbuilding and Engineering Ltd (VSEL). At that time, VSEL and Cammell Laird were the only British shipyards capable of building nuclear submarines. After completing the construction of Upholder-class diesel-electric submarines in 1993, the owners of Cammell Laird, VSEL, announced the yard's closure.

UK nuclear submarine shipbuilding history

(1958 to 2018, with projections to 2024)

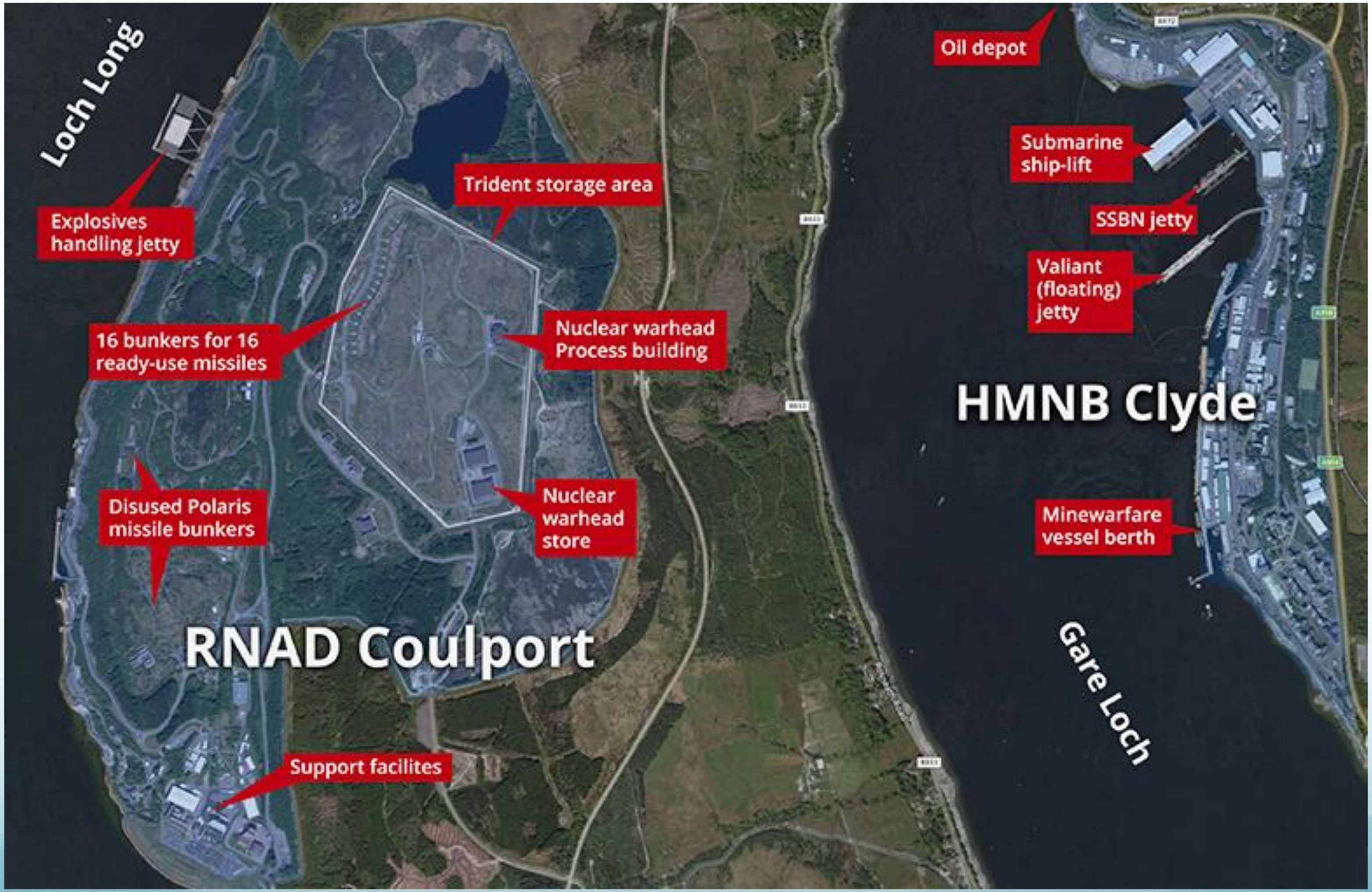


Adapted from Rand Report MG1128/3-2.1, Figure 2.1.

UK naval nuclear propulsion program infrastructure

- HM Naval Base (HMNB) Clyde (Faslane), Gare Loch, Scotland
  - On 10 May 1968, the Clyde Submarine Base officially came into being when HRH The Queen Mother opened the base to serve as the home port for the UK's Resolution-class SSBNs armed with Polaris A3T SLBMs.
    - The Royal Navy Armaments Depot (RNAD), Coulport, which was responsible for servicing the Polaris program (and now the Trident program), can be seen across Faslane Bay and accessed from nearby Loch Long.
  - In the 1990s, the base was significantly expanded to handle the Vanguard-class SSBNs, which were armed with Trident D5 SLBMs.
  - Faslane currently provides facilities for the operation, maintenance, and repair of all classes of UK submarines. By 2020, all UK nuclear submarines have been based here:
    - Vanguard-class SSBNs, since first boat in 1993
    - Astute-class SSNs, since the first boat in 2010
    - The two "youngest" Trafalgar-class SSNs, *Talent* and *Triumph*, will be transferred from HMNB Devonport by 2020.
  - The large, covered shiplift building can raise a fully-loaded Vanguard-class SSBN out of the water for maintenance in a covered hall.
  - There is the dedicated finger jetty for the Vanguard-class SSBNs and the newer 44,000 tonne floating Valiant jetty for use by attack submarines.
  - A squadron of minesweepers also is based at HMNB Clyde.

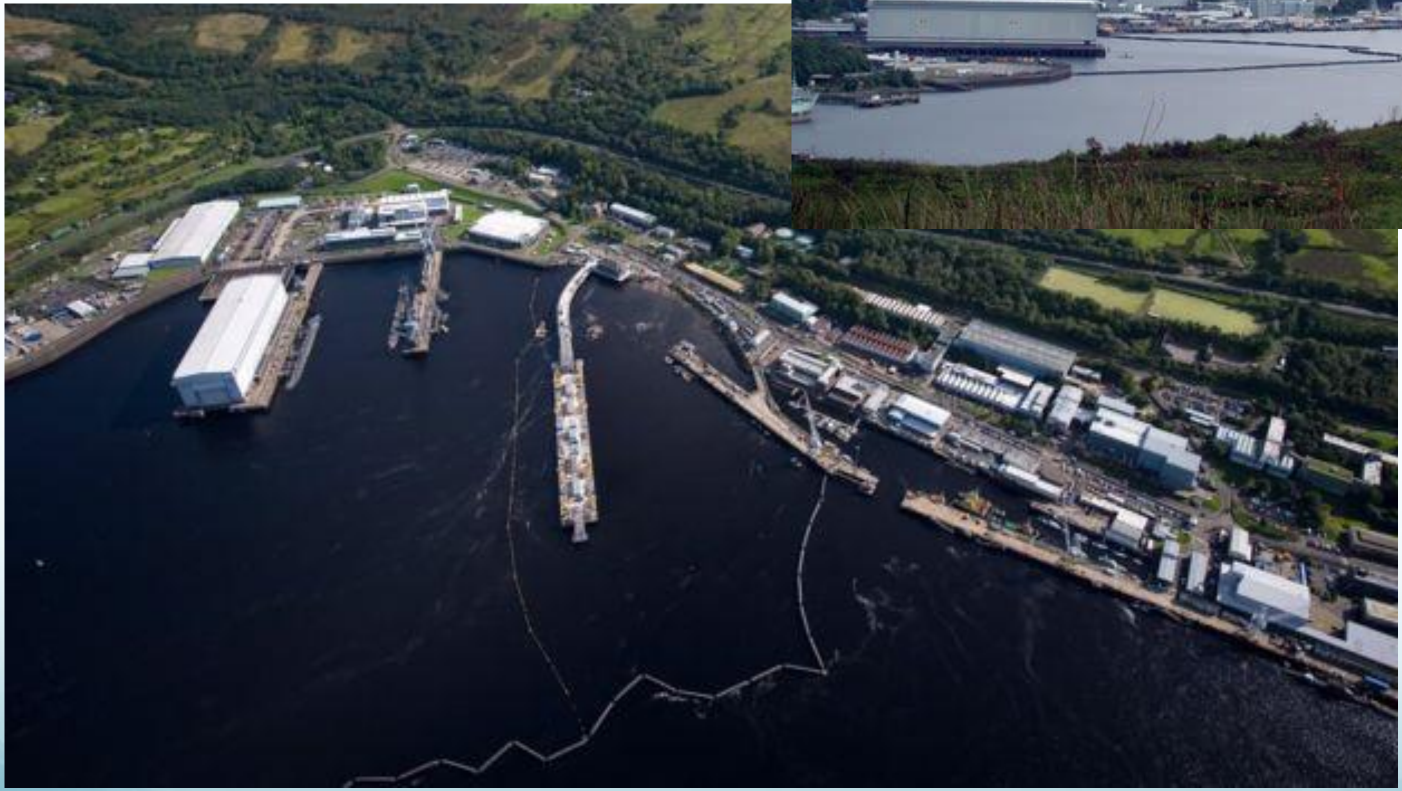
HMNB Clyde (Faslane) and RNAD Coulport



Source: https://www.savetheroyalnavy.org/

HMNB Clyde (Faslane)

In the photo below, the large, white, covered shiplift building is on the left, to its right is the shorter SSBN jetty, and continuing to the right is the longer, curved Valiant floating jetty for SSNs.



Source, above: http://gg.geoview.info/
Source, below: OSMONDC, https://www.bbc.com/news/uk-scotland-43975011

UK naval nuclear propulsion program infrastructure

- Royal Navy Armaments Depot (RNAD), Coulport, Loch Long, Scotland
  - The original network of underground bunkers, roads, support buildings and jetties was constructed to support the UK Polaris missile program between 1963 - 68. The UK's Polaris program was fully serviced at Coulport.
  - Replacing the obsolete Polaris missile with the Trident D5 in the 1990s required major new construction at the site. As an indication of the scale of these facilities, the Trident Works Program at Faslane and Coulport took 13 years and cost around £1.9 billion (at 1994 prices).
  - For the UK's Trident program, Coulport is the storage and loading facility for Trident missiles and warheads. Depot-level maintenance on the missiles is performed in the US at a joint depot at Kings Bay, Georgia.
  - Coulport also used to load and unload other specialist munitions such as cruise missile and, previously, nuclear torpedoes.

Source: Save the Royal Navy article, "Why relocating Trident away from Scotland is virtually impossible," 22 July 2016,

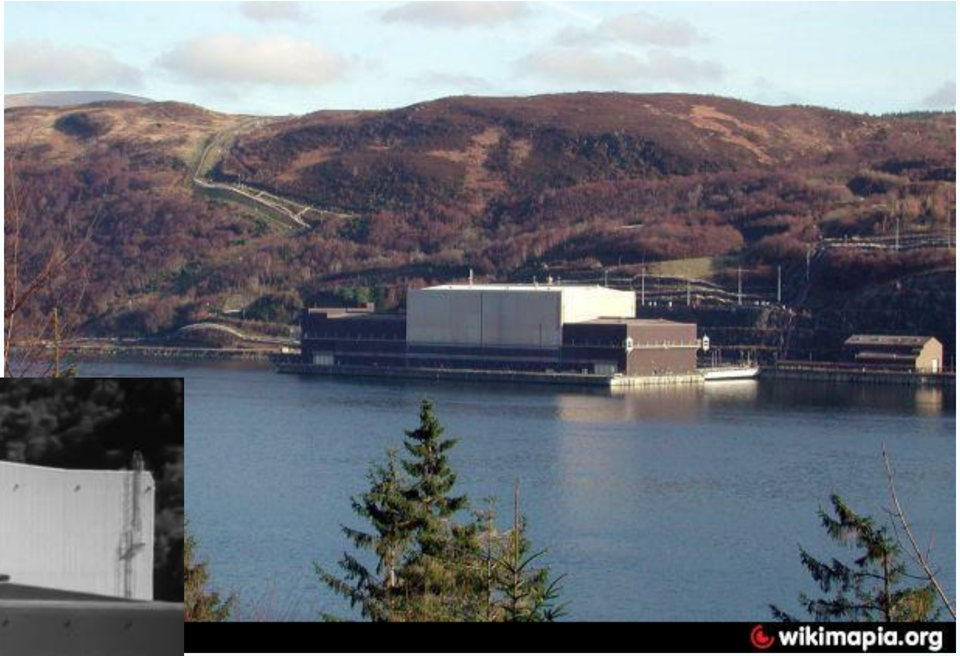
UK naval nuclear propulsion program infrastructure

- Royal Navy Armaments Depot (RNAD), Coulport, Loch Long, Scotland (cont'd)
  - The heart of the Coulport site is the Trident Storage Area which includes 16 large underground bunkers with air-locked doors each able to store a single Trident missile.
  - There are also stores for the British-made nuclear warheads which are manufactured and serviced at the Atomic Weapons Establishment (AWE) in Berkshire and are transported to Coulport in regular road convoys.
  - The warheads are joined with the Trident D5 missiles in the Nuclear Process Building and then taken by lorry to the Explosives Handling Jetty (EHJ). One of the world's largest floating concrete structures, the EHJ is a specially constructed covered floating dock. The submarine enters and the missiles are loaded vertically into the missile tubes by overhead crane.
  - There is also a separate jetty for loading torpedoes, which also are stored on the Coulport site.

Source: Save the Royal Navy article, "Why relocating Trident away from Scotland is virtually impossible," 22 July 2016,

Royal Navy Armaments Depot (RNAD), Coulport, Scotland

Explosives Handling Jetty with the covered floating submarine loading dock at RNAD Coulport



Vanguard-class SSBN with the covered Explosives Handling Jetty in the background at RNAD Coulport

Source: http://ardentinny.org/category/rnad-coulport/

UK naval nuclear propulsion program infrastructure

- Devonport Royal Dockyard and Her Majesty's Naval Base (HMNB) Devonport, Plymouth
  - The Devonport Royal Dockyard, operated by Babcock International, is co-located with HMNB Devonport to form the largest naval support site in Western Europe.
  - Babcock International's facilities at Devonport Royal Dockyard include the UK's sole licensed site for refitting and refueling/defueling nuclear-powered submarines.
    - This is where Trafalgar-class SSNs and Vanguard-class SSBNs undergo major overhauls and upgrades. Astute-class SSNs also will be overhauled here.
    - Thirteen (13) decommissioned nuclear submarines are in "afloat storage" in the Devonport dockyard.
  - HMNB Devonport currently is the home port for Submarine Flotilla (SUBFLOT) South, which operates Trafalgar-class SSNs.
    - Four of these SSNs have been decommissioned and are in afloat storage at Devonport Royal Dockyard with the reactors still fuelled.
    - *HMS Trenchant* will be decommissioned in 2019 in Devonport.
    - *HMS Talent* and *HMS Triumph* will relocate to HMNB Clyde (Faslane), Scotland by 2020 where they will serve until their decommissioning dates in 2021 – 22.

UK naval nuclear propulsion program infrastructure

- Devonport Royal Dockyard and Her Majesty's Naval Base (HMNB) Devonport, Plymouth (cont'd)
  - Attack submarines currently are defueled / refueled at the dockyard's Submarine Refit Complex (SRC). The SRC, located in the northwest corner of Basin 5, is comprised of Docks 14 and 15, the Nuclear Support Facility (NSF) building, and the Nuclear Utilities Building (NUB).
  - Ballistic missile submarines are defueled /refueled in Dock 9 in Basin 5.

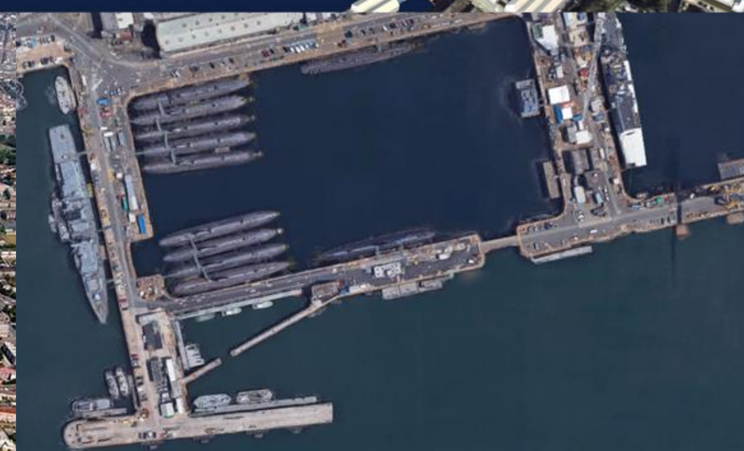
Devonport Royal Dockyard & HMNB Devonport

Source, right two photos: https://www.thecartogroup.com/babcock-international-hms-devonport-3d-gis/

Decommissioned submarine afloat storage, Basin 3

Submarine Refit Complex, Basin 5

Source, above: https://www.royalnavy.mod.uk/devonport



Above: Submarine afloat storage in Basin 3

Devonport Royal Dockyard

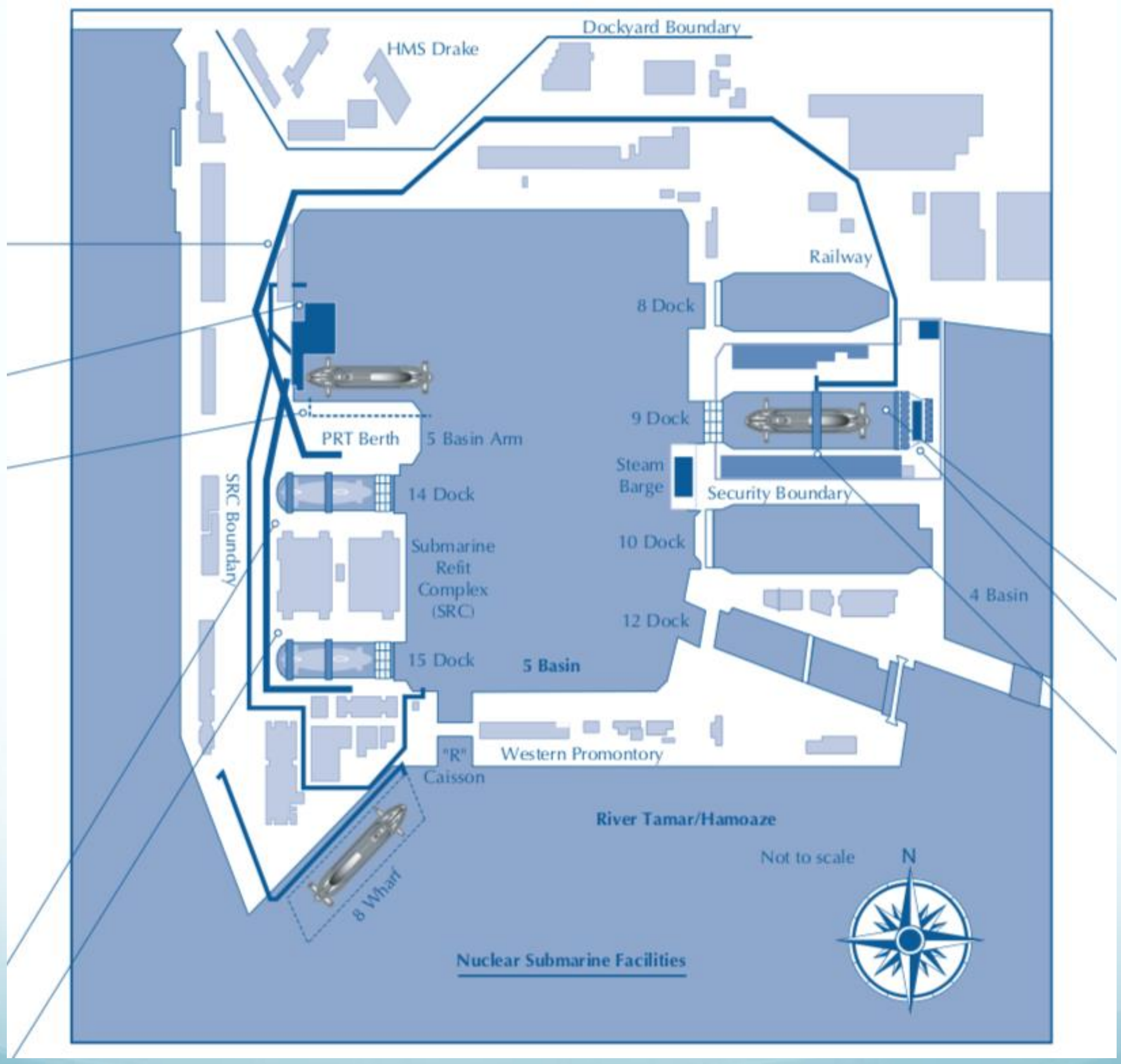
Submarine Refit Complex, Basin 5

Shared facilities

Nuclear transfer route

Low-level refueling facility (temporary storage of spent fuel)

Power range testing berth (used for tests at end of refit)



SSBN facilities

Seismically-qualified Dock 9

Primary circuit decontamination facility

Reactor access house On Dock 9

SSN facilities

Seismically-qualified Docks 14 & 15 (Dock 14 for Astute)

Low-level waste facilities For Docks 14 & 15

Source: adapted from https://www.nao.org.uk/wp-content/uploads/2002/12/020390.pdf

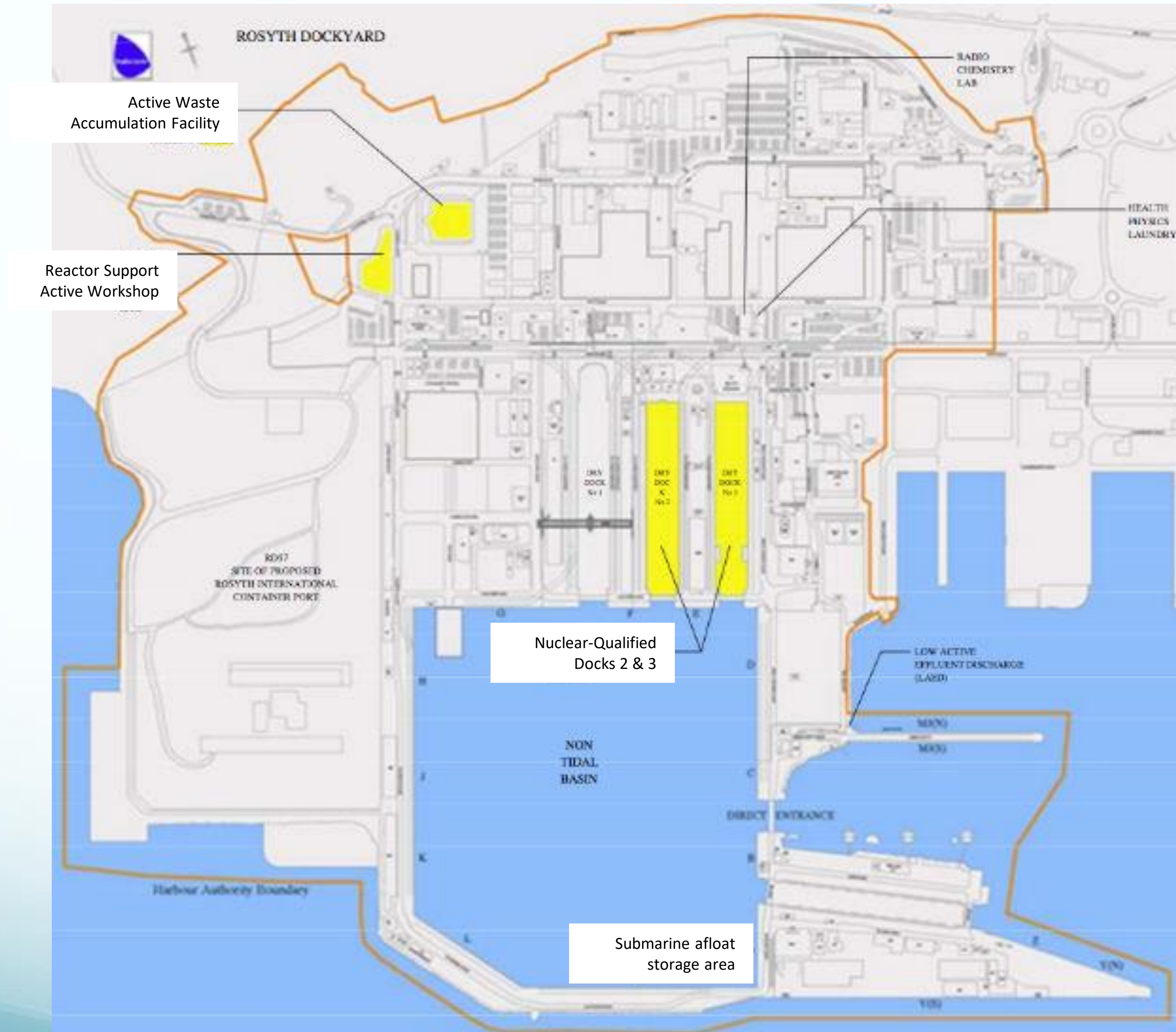
UK naval nuclear propulsion program infrastructure

- Royal Naval Dockyard Rosyth and HMNB Rosyth, near Edinburgh, Scotland
  - Rosyth has a long history of refitting UK nuclear submarines. The UK's first nuclear-powered submarine, *HMS Dreadnought*, began her service at Rosyth in 1963 and the third Polaris-armed SSBN, *HMS Renown,* was refitted in 1971-73.
  - In 1984, Rosyth was chosen as the sole location for refitting the Royal Navy's nuclear submarine fleet, and in 1986 extensive rebuilding commenced to facilitate this new role.
    - In 1993, the government switched the refitting role to Devonport Royal Dockyard in Plymouth. Nearby HMNB Rosyth (HMS Caledonia) naval base closed in 1995.
    - The last nuclear submarine refitting program at Rosyth ended in 2003.
  - In 1997 the Rosyth Dockyard became the first former naval dockyard to be privatized. The new owner was Babcock International.
  - Seven decommissioned nuclear submarines are in "afloat storage" at Rosyth. All have been defueled. The nuclear fuel was transferred to Sellafield in Cumbria and none remains at the dockyard.
  - Modules of the Royal Navy's two Queen Elizabeth-class aircraft carriers are being constructed across six UK shipyards, with final assembly at Rosyth.

Rosyth Dockyard, Scotland

Rosyth Dockyard on the Fife River. Nuclear submarines in afloat storage can be seen in the main basin, right side.
Source: https://ukdefencejournal.org.uk/rusting-nuclear-submarines-rosyth-finally-dismantled/

Rosyth Dockyard, Scotland



Rosyth nuclear licensed facilities are highlighted in yellow. Source: http://www.neimagazine.com/

UK naval nuclear propulsion program infrastructure

- The Office for Nuclear Regulation (ONR)
  - Nuclear safety oversight for licensed activities.
- Interim "afloat storage" sites for decommissioned nuclear submarines
  - Devonport Royal Dockyard, Plymouth
  - Rosyth Dockyard, Scotland
- Nuclear Decommissioning Authority (NDA) Sellafield site, Cumbria
  - Operated by Sellafield, Ltd. but owned by the NDA.
  - Provides for long-term irradiated naval fuel storage. Spent naval reactor fuel is placed in dedicated MoD storage ponds.
  - Ultimately, the spent fuel must either be reprocessed to recover unused U-235 or sent for permanent disposal, most likely in a future UK Geologic Disposal Facility (GDF)
- URENCO Nuclear Stewardship [formerly Capenhurst Nuclear Services (CNS)], near Chester
  - Selected in July 2016 as the preferred supplier for storing reactor pressure vessels from decommissioned Royal Navy submarines that have been processed through the MoD's Submarine Dismantling Program (SDP), which started in 2016.
- UK Geologic Disposal Facility (GDF)
  - Provides for the final disposition of radioactive items and waste from submarine decommissioning.
  - GDF is being developed by the UK Department of Energy and Climate Change. The GDF is not expected to be available until after 2040.

UK naval nuclear reactors

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

- All UK submarine reactors use HEU fuel.
- The 1998 UK Strategic Defense Review (SDR) reported the following inventory of HEU available for use in submarine reactors:
  - The defense stocks of fissile material included 21.9 tonnes of HEU.
  - All stocks of HEU will be retained outside safeguards, since material no longer needed for nuclear weapons will be used for the naval nuclear propulsion program.
- The International Panel on Fissile Materials (IPFM) reported the following UK HEU inventory data:
  - According to the official HEU balance released in 2006, the total audited stock of military HEU was reported to be 21.86 tonnes as of 31 March 2002. The average enrichment of the material was not given.
  - Since the 2002 audit, an estimated 2.1 tonnes of HEU were removed from the stockpile, so the military HEU stock as of the end of 2016 is estimated to be 19.8 tonnes.
- The Royal Navy has established a more than 55 year track record of safe naval reactor operation with HEU-fueled reactors.

UK naval submarine reactors

As of mid-2018

<table>
<tr><td>PWR</td><td colspan="24">ROLLS-ROYCE PWR 1 REACTOR PLANT</td><td colspan="12">ROLLS-ROYCE PWR2 REACTOR PLANT</td></tr>
<tr><td>STATUS</td><td colspan="21">DECOMMISSIONED</td><td colspan="3">IN SERVICE</td><td></td><td colspan="8">IN SERVICE</td><td colspan="3">IN BUILD</td></tr>
<tr><td>CLASS</td><td></td><td></td><td colspan="2">VALIANT</td><td colspan="4">RESOLUTION</td><td colspan="3">CHURCHILL</td><td colspan="6">SWIFTSURE</td><td colspan="7">TRAFALGER</td><td></td><td colspan="4">VANGUARD</td><td colspan="7">ASTUTE</td></tr>
<tr><td>REACTOR CORE</td><td>HMS DREADNOUGHT</td><td>DS / MP1 PROTOTYPE @ VULCAN</td><td>HMS VALIANT</td><td>HMS WARSPITE</td><td>HMS RESOLUTION</td><td>HMS RENOWN</td><td>HMS REPULSE</td><td>HMS REVENGE</td><td>HMS CHURCHILL</td><td>HMS CONQUEROR</td><td>HMS COURAGEOUS</td><td>HMS SWIFTSURE</td><td>HMS SOVEREIGN</td><td>HMS SUPERB</td><td>HMS SCEPTRE</td><td>HMS SPARTAN</td><td>HMS SPLENDID</td><td>HMS TRAFALGER</td><td>HMS TURBULENT</td><td>HMS TIRELESS</td><td>HMS TORBAY</td><td>HMS TRENCHANT</td><td>HMS TALENT</td><td>HMS TRIUMPH</td><td>SFT PROTOTYPE @ VULCAN</td><td>HMS VANGUARD</td><td>HMS VICTORIOUS</td><td>HMS VIGILANT</td><td>HMS VENGANCE</td><td>HMS ASTUTE</td><td>HMS AMBUSH</td><td>HMS ARTFUL</td><td>HMS AUDACIOUS *</td><td>HMS ANSON</td><td>HMS AGAMEMNON</td><td>HMS AGINCOURT</td></tr>
<tr><td>S5W</td><td>O/F</td><td colspan="35"></td></tr>
<tr><td>CORE A</td><td>RF</td><td colspan="10">ORIGINAL FIT</td><td colspan="25"></td></tr>
<tr><td>CORE B</td><td></td><td colspan="10">REFUEL</td><td colspan="6">ORIGINAL FIT</td><td colspan="19"></td></tr>
<tr><td>CORE Z</td><td></td><td>RF</td><td colspan="9"></td><td colspan="6">REFUEL</td><td colspan="7">ORIGINAL FIT & REFUEL</td><td colspan="12"></td></tr>
<tr><td>CORE G</td><td colspan="24"></td><td colspan="5">ORIGINAL FIT</td><td colspan="7"></td></tr>
<tr><td>CORE H</td><td colspan="24"></td><td colspan="5">REFUEL</td><td colspan="7">ORIGINAL FIT</td></tr>
</table>

O/F = Original fit; RF = Refuel
Anticipates *HMS Audacious* commissioning later in 2018.

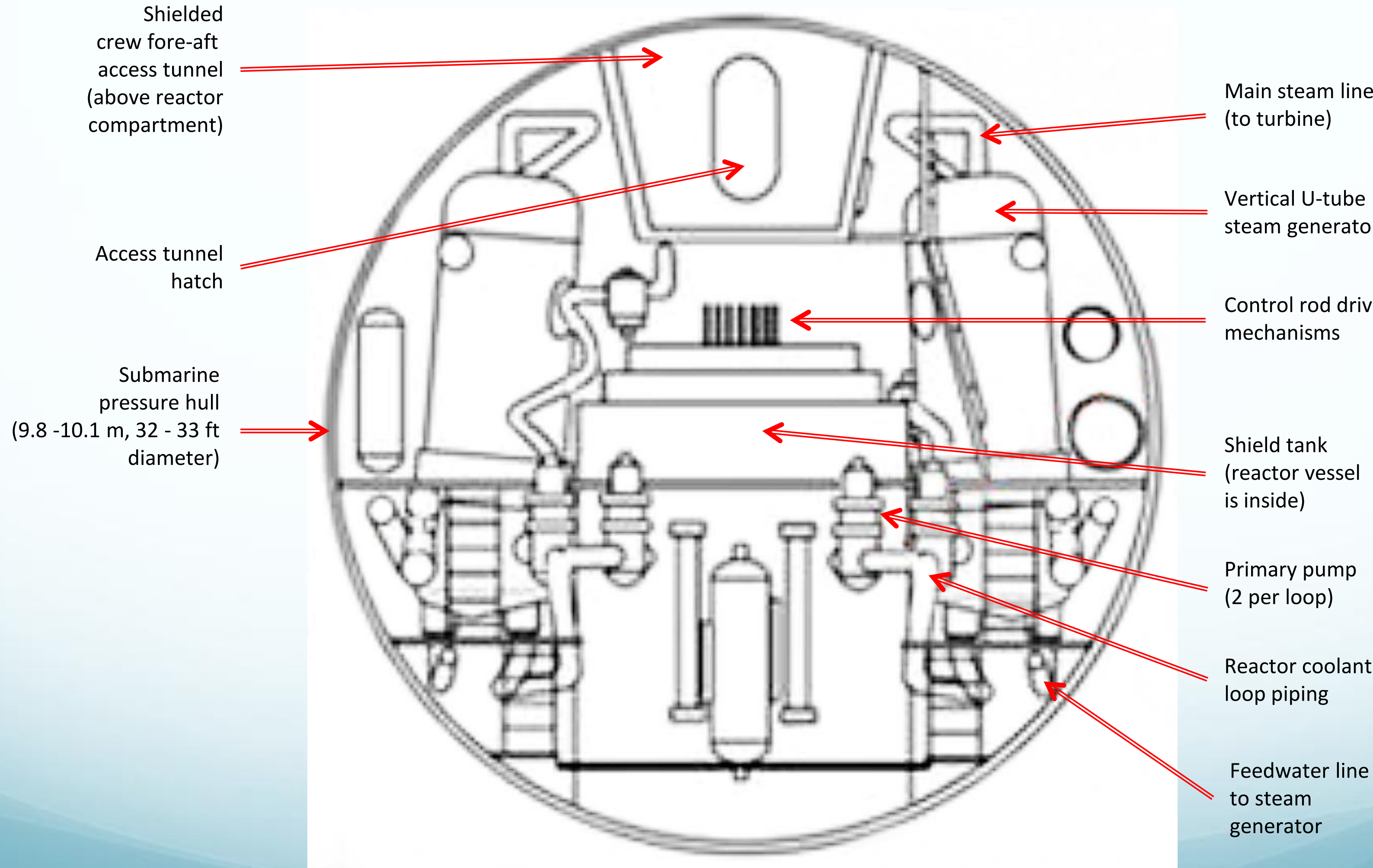
Source: adapted from Rolls-Royce; Chris Palmer, 'Management of Key Technologies in the UK Naval Nuclear Propulsion Programme', presentation at the CSIS Project on Nuclear Issues (PONI) Capstone Conference 2011, US Strategic Command, 6 December 2011

PWR1

- PWR1 was the first nuclear propulsion plant designed and manufactured by Rolls-Royce Marine Power Operations, Ltd. (formerly Rolls-Royce and Associates) for the UK nuclear submarine program.
- The PWR1 is a two-loop Nuclear Steam Rising Plant (NSRP) based on the Westinghouse S5W pressurized water reactor and Nuclear Steam Supply System (NSSS). The original PWR1 delivered comparable output: about 15,000 shaft horsepower (11 MW), implying a reactor power of about 78 MWt.
- PWR1 reactor evolution spanned three core designs:
  - Core 1 (A), which was based on the the Westinghouse S5W core design, was the original core on Valiant and Churchill-class SSNs and Resolution-class SSBNs. It also replaced the original Westinghouse-manufactured S5W core on *Dreadnought*.
  - Core 2 (B) was the original core on Swiftsure-class SSNs and the replacement core on Valiant- and Churchill-class SSNs and Resolution-class SSBNs.
  - Core 3 (Z) was the original core on Trafalgar-class SSNs. It also was the replacement core on Swiftsure- and Trafalgar-class SSNs. This was the ultimate development of the PWR1.

PWR1

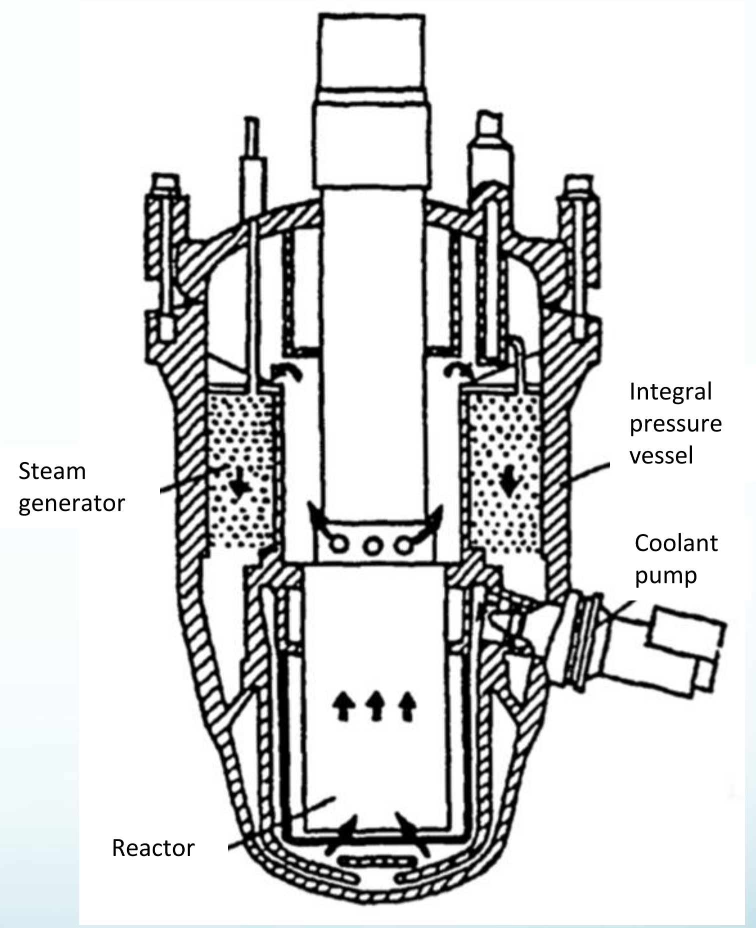
Reactor compartment cross-section



Source: adapted from https://www.express.co.uk/news/uk/766212/

Saturated water reactor (SWR)

- In the early 1970s, the UK considered an SWR as a follow-on to the PWR1.
- The SWR featured an integral primary system with partial boiling of the coolant in the core.
- The advantages expected from the integral primary system did not materialize as the SWR design progressed. Work on SWR was abandoned and Rolls-Royce returned to a two-loop PWR primary system for the PWR2.



SWR integral primary system.
Source: "Design and properties of marine reactors and associated R&D," Studsvik/ES-96/29, 1996

PWR2

- Development of the PWR2 began in 1976 to meet the operational requirements of the Vanguard-class ballistic missile submarines.
  - The goals included increased power, lower acoustic noise output, increased safety margins, and lower manufacturing and through-life costs than PWR1 Core Z.
  - PWR2 was described in the UK Defense Board (09)62 assessment of propulsion alternatives for the "Successor" (Vanguard replacement) SSBN as follows: "The PWR2-based family incorporates variants of the current PWR2 propulsion system (at sea in Vanguard and Astute), which has been developed incrementally through successive classes of submarines since the original exchange of data between the UK and the US in the 1960s."
  - PWR2 is an incrementally-developed, two-loop PWR, with a general resemblance to the US S5W and UK PWR1 naval reactors.
- For the Vanguard-class SSBN, the PWR2 NSRP delivers steam to two main turbines with a combined rating of about 27,500 shaft horsepower (20.5 MW), implying a reactor power of about 130 - 145 MWt.
- For the Astute-class SSN, the PWR2 NSRP was "re-packaged" to fit in the smaller diameter Astute hull (11.3 m / 37.1 ft. vs. 12.8 m / 42 ft. diameter for a Vanguard hull).

PWR2

- PWR2 Core G
  - This was the original core at the STF prototype at NTRE.
    - Zero-power criticality tests were conducted in 1985 before Core G was loaded into STF.
    - Initial criticality at STF occurred on 25 July 1987.
  - This also was the original core for the Vanguard-class SSBNs.
    - Initial operations occurred in 1992 after the launch of *HMS Vanguard*.
    - A mid-life refueling was needed.
- PWR2 Core H
  - Rolls-Royce claims a ten-fold improvement in core life over the first US S5W and UK PWR1 cores used on UK submarines, which has been reported to be about 5,500 equivalent full power hours on *Dreadnought's* Westinghouse S5W core.
  - PWR2 Core H began shore-based testing in the STF prototype in 2002. PWR2 Core H operations were concluded and STF was permanently shutdown in 2012.
  - This is the replacement core for the Vanguard-class SSBNs, replacing Core G.
    - Initial fleet operations with Core H occurred after the mid-life Long Overhaul Period and Refueling [LOP(R)] for *HMS Vanguard*, which ended in June 2004. By December 2015, the last Vanguard-class SSBN had been refueled with Core H.
  - This also the original core on Astute-class SSNs and is expected to be a life-of-the-boat core for the boat's planned 25 - 30 year service life.
    - Initial operations on *HMS Astute* occurred after launch in 2007. As of mid-2018, three Astute-class SSNs are operating with Core H and one more is expected to be launched in 2018.

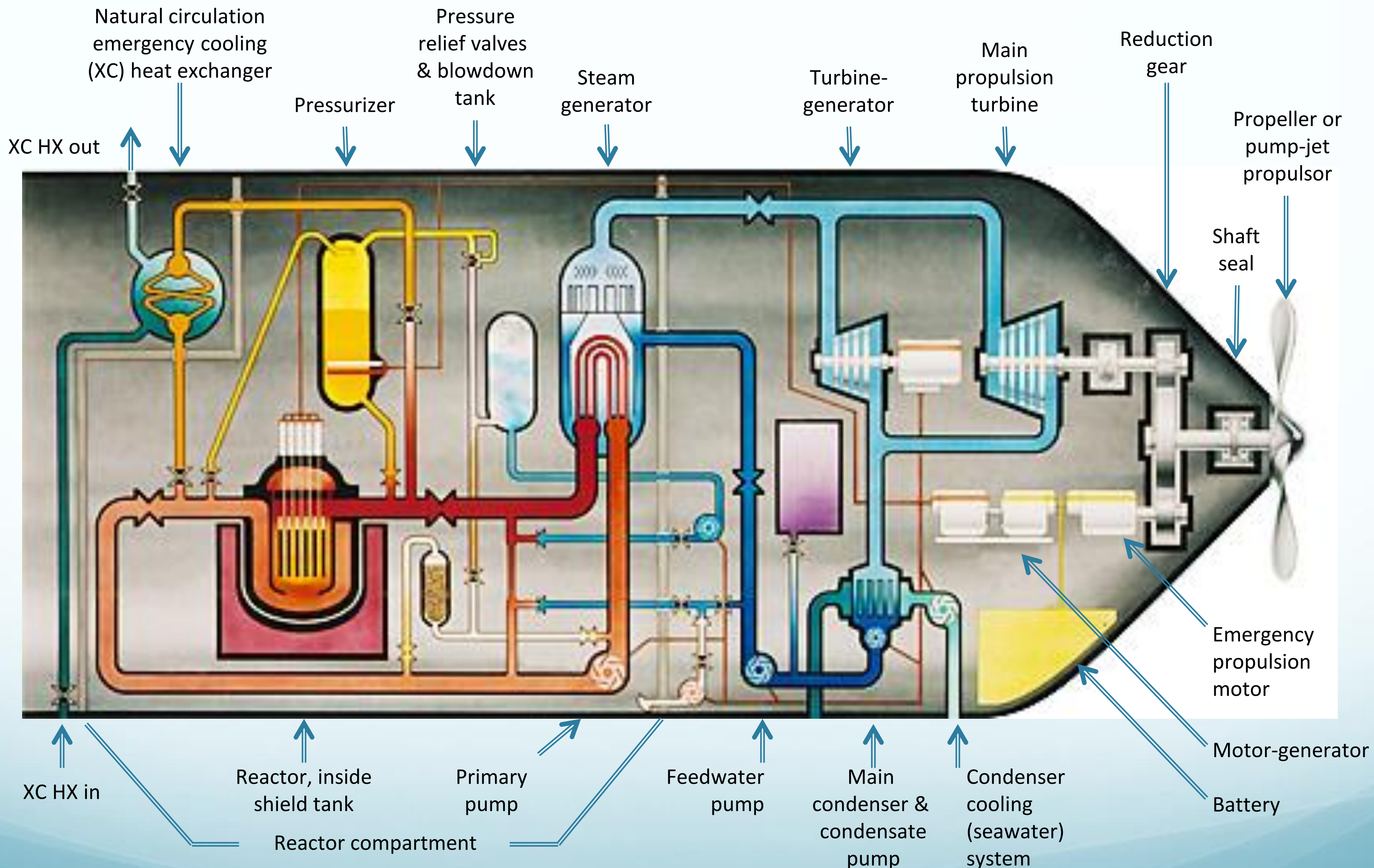
PWR2

- PWR2 Core H (cont'd)
  - In January 2012, a fuel cladding leak was detected in the PWR2 Core H operating in the STF prototype at NTRE, Dounreay. A similar problem has not been detected in the Astute- and Vanguard-class submarines operating PWR2 Core H. However, this problem has had the following implications for the Royal Navy's submarine fleet: *
    - A decision was made to refuel *HMS Vanguard* during its next "deep-maintenance" period, which started in December 2015 and will last about 3.5 years. This additional refueling will add £120 M to the cost of the scheduled "deep-maintenance."
    - A decision on whether to refuel the next oldest Vanguard-class SSBN, *HMS Victorious*, when she enters her next planned deep maintenance period, does not need to be made until 2018.
    - The implications for the Astute-class SSNs will be the subject of further analysis, particularly once there is an opportunity to examine the PWR2 Core H from Dounreay. However, as the Astute SSNs are only now entering service and thus their cores have seen far less operation, a decision on whether or not to refuel any of them will not be needed for many years to come.
- PWR2 and a derivative known as PWR2b were considered as candidates for the Dreadnought-class SSBN. PWR3 was selected for this SSBN.

* Speech by Philip Hammond, Secretary of State for Defense, to Parliament, 6 March 2014. https://www.gov.uk/government/speeches/nuclear-submarines

Rolls-Royce submarine PWR

Simplified process diagram



Source: https://www.rolls-royce.com/products-and-services/marine/

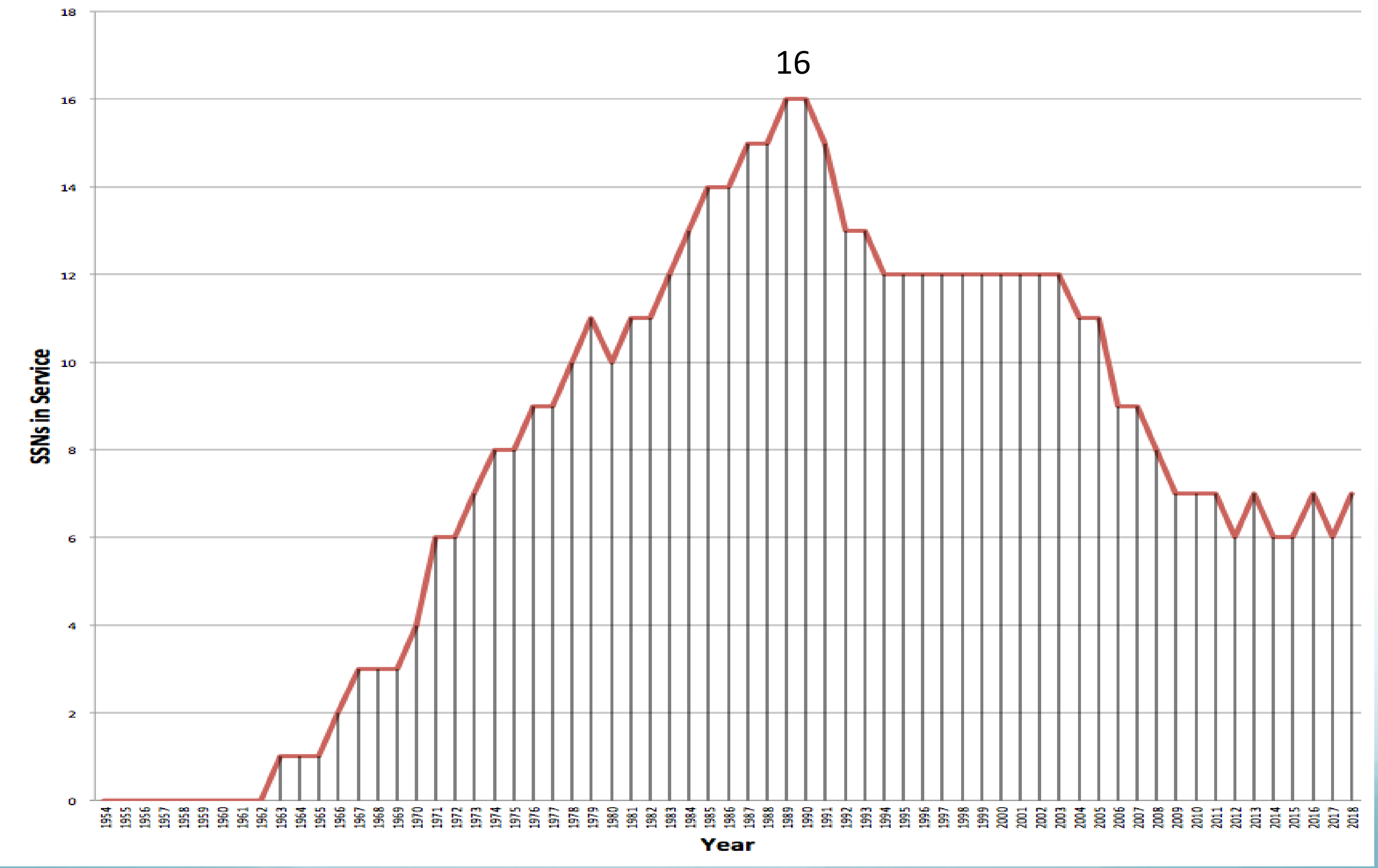
PWR3

- PWR3 was selected over a PWR2 derivative design based on demonstration of safety improvement and total life cycle cost reduction.
- This reactor design is being developed as part of the Dreadnought-class SSBN program which will start replacing the existing Vanguard-class SSBNs in about 2030.
  - The PWR3 (aka Core J in one source) plant will deliver improvements in terms of safety, integrity and availability, while at the same time reducing life-cycle costs.
- In May 2011, the UK MoD Defense Board said the PWR3 would be ‘based on a modern US plant’ and noted that US support provided ‘independent peer review of the UK’s NNPP capability and helped to optimize its PWR3 concept design.’
  - A likely candidate is the S9G reactor used on US Virginia-class SSNs.

UK Royal Navy nuclear-powered submarines

Source: https://www.royalnavy.mod.uk/

Historical size of the UK SSN fleet 1963 - 2018



Source: Author

Nuclear-powered fast attack submarines (SSN)

UK fast attack subs (SSNs)

Class	# in Class	Length	Beam	Displacement (tons)	Reactor	Shaft hp	Max speed (kts)	Years delivered	Years in service
Dreadnought (S101)	1	81 m (265.7 ft)	9.5 m (31.2 ft)	3,500 (surf), 4,000 (sub)	S5W	15,000 (est.)	28	Apr 1963	Apr 1963 - 1980
Valiant	2	86.8 m (285 ft)	10.1 m (33.3 ft)	4,400 (surf), 4,900 (sub)	PWR1 Core A/B	15,000 (est.)	29	Jul 1966 – Apr 1967	Jul 1966 – Aug 1994
Churchill	3	86.8 m (285 ft)	10.1 m (33.3 ft)	4,400 (surf), 4,900 (sub)	PWR1 Core A/B	15,000 (est.)	29	Jul 1970 – Nov 1971	Jul 1970 – Apr 1992
Swiftsure	6	82.9 m (272 ft)	9.8 m (32 ft)	4,400 (surf), 4,900 (sub)	PWR1 Core B/Z	15,000 (est.)	>28	Apr 1973 – Mar 1981	Apr 1973 – Dec 2010
Trafalgar	7	85.3 m (280 ft)	9.8 m (32 ft)	4,800 (surf), 5,300 (sub)	PWR1 Core Z	15,000 (est.)	>28	May 1983 – Oct 1991	May 1983 - present
Astute	4 built + 3	96.9 m (318 ft)	11.3 m (37 ft)	7,000 (surf), 7,400 (sub)	PWR2 Core H	27,500 (est.)	29	Aug 2010 - present	Aug-2010 - present
Maritime Underwater Future Capability (MUFC)	TBD	TBD	TBD	TBD	Likely PWR3	TBD	TBD	Expected mid-to-late 2030s	

HMS Dreadnought (S101)

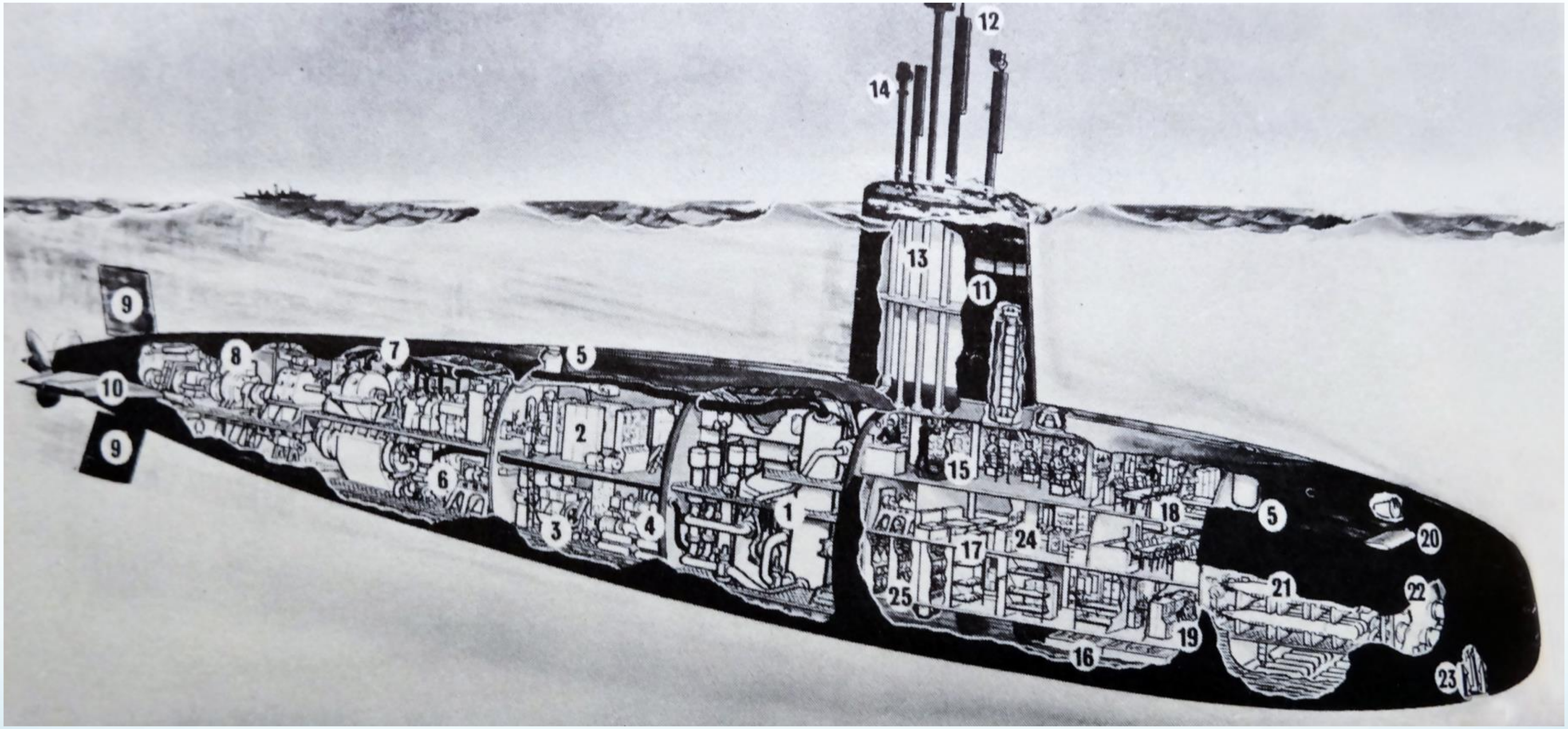
UK's 1st nuclear-powered submarine

Source: http://www.rnsubs.co.uk

- The hull and combat systems of *Dreadnought* were of British design and construction. The propulsion plant was provided by the US
  - Built by Vickers Ltd, Shipbuilding Group, Barrow-in-Furness, Cumbria
  - Keel laid on 12 June 1959; launched on 21 October 1960; and accepted into service in April 1963.
- Propulsion: 1 x Westinghouse S5W PWR rated @ 78 MWt
  - 2 x main steam turbines with a combined rating of 15,000 shp (11MW); driving a single propeller.
  - Reactor operating life for the initial Westinghouse core was about 5,500 equivalent full-power hours (EFPH).
  - Refueled with Rolls-Royce PWR1 Core 1 (A)

HMS Dreadnought (S101)

UK's 1st nuclear-powered submarine



Source: Royal Navy / via N. Polmar, "Atomic Submarines," 1963

Legend:
1 – reactor compartment; 2 – reactor control compartment; 3 – auxiliary machinery; 4 – diesel engine; 5 – escape hatch; 6 – main condenser; 7 – main steam turbines; 8 – electric propulsion motor; 9 – rudders; 10 – stern planes; 11 – surface navigating bridge; 12 – periscope; 13 – radar and radio aerials; 14 – snorkel; 15 – control room; 16 – electric batteries; 17 – crew's quarters; 18 – officer's quarters; 19 – electrical equipment; 20 – bow planes; 21 – torpedo room; 22 – torpedo tubes; 23 – stowed anchor; 25 – store room and refrigeration space.

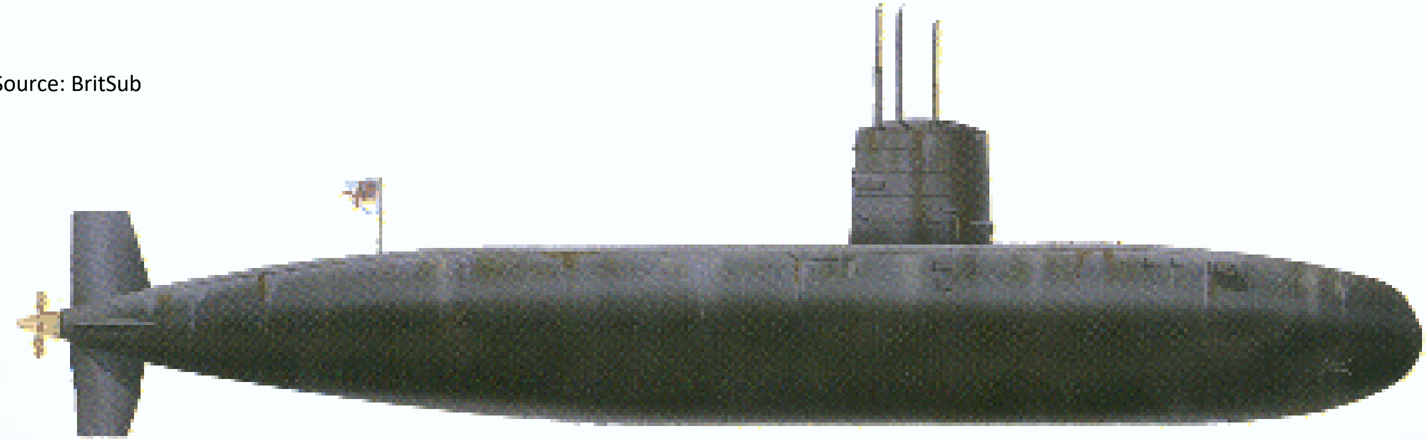
HMS Dreadnought (S101)

UK's 1st nuclear-powered submarine

- Armament: 6 x 533 mm (21 inch) torpedo tubes; stowage for up to 24 torpedoes; also mines.
- Operational matters:
  - 10 Jan 1963: *HMS Dreadnought* made the 1st UK underway on nuclear power.
  - *Dreadnought* participated in many fleet exercises and worldwide deployments to demonstrate the capabilities of a nuclear-powered submarine.
  - On 3 March 1971, *Dreadnought* became the 1st UK submarine to surface at the North Pole.
  - In November 1977, *Dreadnought*, two frigates and two support vessels took part in *Operation Journeyman*, the UK naval deployment to the Falkland Islands in the South Atlantic to prevent an invasion by Argentina.
  - *Dreadnought* was withdrawn from service in 1980 after a service life of 17 years. It has been defueled and currently is laid up in "afloat storage" at Rosyth Dockyard, Scotland, pending final disposition.
  - There is interest in converting *Dreadnought* to a museum ship and returning it to Barrow-in-Furness.

Valiant-class SSN

Source: BritSub



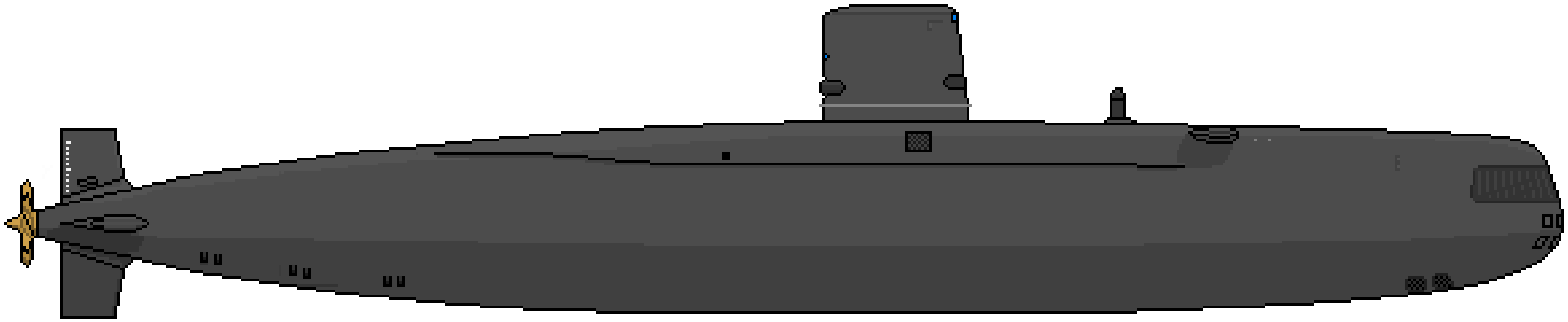
- The two boats in this class were the 1st all-British designed nuclear-powered subs.
  - Built by Vickers Ltd, Shipbuilding Group, Barrow-in-Furness
  - Introduced "rafting" to isolate large, rotating machinery from the hull (a WW II German idea) and thereby provide better sound quieting than in contemporary US nuclear subs. The US Navy subsequently adopted rafting in its Permit-class SSNs.
  - 1st ship in class, *Valiant*, was accepted into service in July 1966.
- Propulsion: 1 x Rolls-Royce PWR1, Core 1 (A), rated @ about 78 MWt
  - 2 x main steam turbines with a combined rating of about 15,000 shp (11MW); driving a single propeller
  - Refueled with Rolls-Royce PWR1 Core 2 (B)
- Armament: 6 x 533 mm (21 in) torpedo tubes; storage for 26 weapons
  - Mark 8 or Tigerfish torpedoes; mines
  - Retrofitted with UGM-84 Harpoon anti-ship cruise missiles

Valiant-class SSN

- Operational issues:
  - In October 1968, *Warspite* collided with a Russian sub (possibly an Echo II). *Warspite* was able to return to port.
  - In 1967 Valiant set a Royal Navy record for sailing 12,000 miles (19,312 km) submerged in 28 days, from Singapore to the UK.
  - *Valiant* served in the 1982 Falklands War.
  - These subs were decommissioned by 1991 (*Warspite*) and 1994 (*Valiant*) after cracks were discovered in the primary coolant system. Average service life was 26 years.
  - They have been defueled and are laid up in "afloat storage" in Devonport Docks pending final disposition.

Source: http://nuclear.artscatalyst.org/

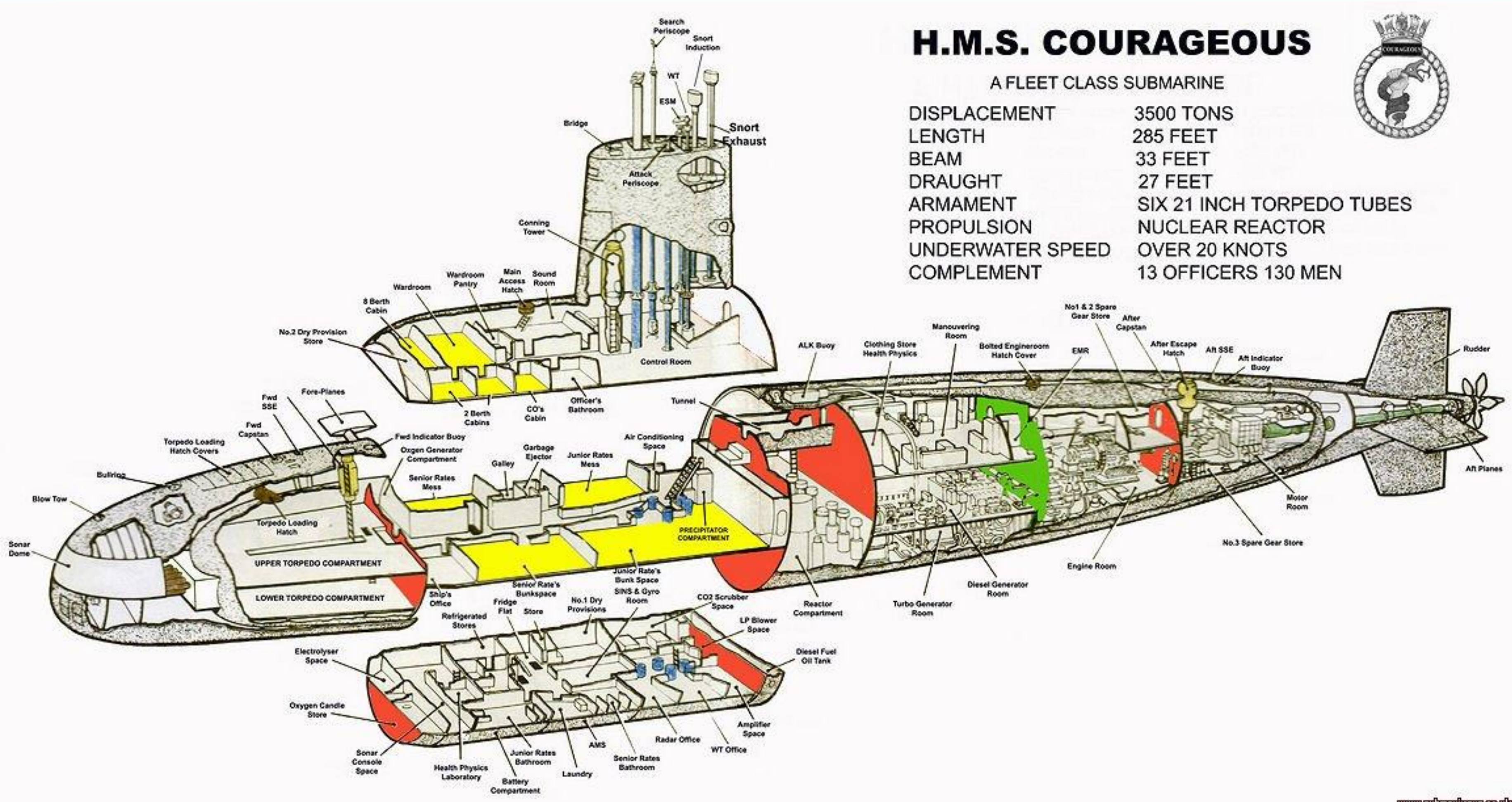
Churchill-class SSN



Source: BritSub

- Three boats in the class; essentially an improved Valiant class.
  - *Churchill* & *Courageous* were built by Vickers Ltd, Shipbuilding Group, Barrow-in-Furness.
  - *Conqueror* was built by Cammell Laird in Birkenhead.
  - All were commissioned between 1970 – 71.
- Propulsion: 1 x Rolls-Royce PWR1, Core 1 (A) rated @ about 78 MWt
  - 2 x English Electric main steam turbines with a combined rating of about 15,000 shp (11MW); driving a single propeller
  - Refueled with Rolls-Royce PWR1 Core 2 (B)
- Armament: 6 x 533 mm (21 in) torpedo tubes; stowage for 26 weapons
  - Mark 8 or Tigerfish torpedoes; mines
  - Retrofitted with UGM-84 Harpoon anti-ship cruise missiles

Churchill-class SSN



Source: submariners.co.uk

Churchill-class SSN

- Operational issues:
  - Operated with a crew of 103.
  - *Churchill* conducted trials on the 1st full-size submarine pump-jet propulsor.
  - In the late 1970s, Churchill-class SSNs received a sonar system update that included a towed array sonar.
  - In 1981, *HMS Courageous* became the first UK SSN to deploy with the Harpoon anti-ship cruise missile.
  - *HMS Conqueror* is the only nuclear-powered submarine known to have engaged and sunk an enemy ship with torpedoes, sinking the Argentine cruiser *General Belgrano* on 2 May 1982 during the Falklands War.
  - All Churchill-class SSNs have been decommissioned and defueled.
    - *Churchill* and *Conqueror* are laid up in “afloat storage” at the Devonport Dockyard pending final disposition. They have been defueled.
    - *Courageous* is a museum ship at the at the Devonport Naval Heritage Center in the Devonport Dockyard.

HMS Conqueror (S48)

Conqueror passing Golden Gate Bridge

Conqueror is the only nuclear-powered submarine known to have engaged and sunk an enemy ship with torpedoes.

Source, Above photo: http://www.rnsubs.co.uk/Boats/BoatDB2/
Below photo: Twitter, AncientSubHunter
Ship's crest: https://picclick.co.uk/HMS-CONQUEROR

HMS Courageous (S50)

Museum ship at the Devonport Naval Heritage Center

Control room, ship control station

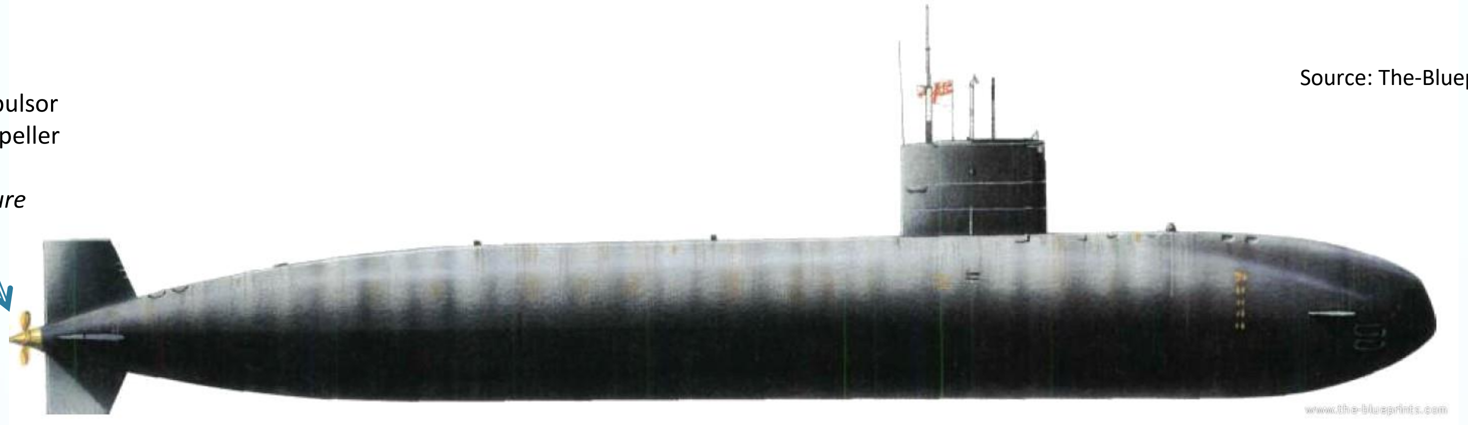
Torpedo room,
6 bow torpedo tubes

Source, two photos: https://devonportnhc.wordpress.com/warshiptours/
Ship's crest: https://www.pinterest.com/pettitdavis/ship-crests/

Swiftsure-class SSN

Source: The-Blueprints.com

Pump-jet propulsor instead of propeller on all in class except *Swiftsure*



- Six boats in the class, all built by Vickers Ltd, Shipbuilding Group, Barrow-in-Furness between 1973 – 1981.
  - Based on Valiant-class with various improvements, including flank sonar arrays & towed sonar array, improved sound isolation of pipeworks for rafted machinery.
  - Hull maintained its diameter for a greater length than in previous UK classes, similar to contemporary US Permit-class subs.
- Propulsion: 1 x Rolls-Royce PWR1, Core 2 (B) rated @ about 78 MWt
  - 2 x main steam turbines at a combined rating of about 15,000 shp (11MW); driving a single shrouded pump-jet propulsor (except *Swiftsure,* which was fitted with a propeller).
  - All pipework connections to equipment on the main machinery raft had expansion/flexible coupling connections, which helped reduced noise. The US Navy licensed the main shaft flexible coupling arrangement for use in US-built submarines.
  - Refueled with Rolls-Royce PWR1 Core 3 (Z).

Swiftsure-class SSN

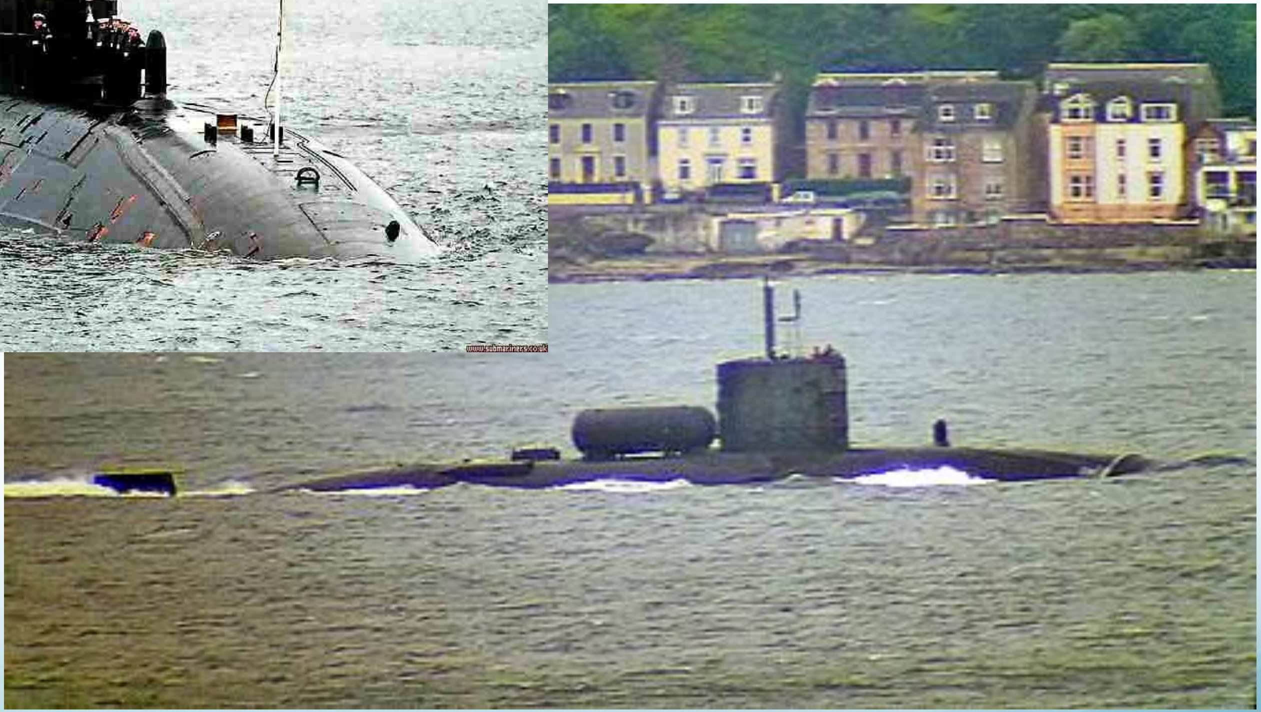
- Armament: 5 x 533 mm (21 in) torpedo tubes; storage for 24 weapons
  - Tigerfish, and later, Spearfish torpedoes
  - UGM-84 Harpoon anti-ship cruise missiles (until 2004)
  - UGM-109 Tomahawk land-attack cruise missiles on two boats (since 1998)
- Operational matters:
  - These SSNs were designed primarily for use in the ASW screening role for task forces and in independent anti-ship and ASW roles. Their sonar suite was similar to that of the Valiant-class SSNs.
  - *Splendid* became the 1st UK ship armed with the Tomahawk land-attack cruise missiles and employed them during the Kosovo War.
  - In 1981, *Sceptre* collided with a Soviet submarine, thought to be a Delta III SSBN.
  - The *Spartan* and *Splendid* served in the 1982 Falklands War.
  - In 2000, thermal fatigue cracks in the primary coolant system resulted in small leaks that required remediation for all Swiftsure-class and Trafalgar-class SSNs.
  - The last Swiftsure-class SSN was decommissioned in 2010, with the class having an average service life of about 27 years (19 – 32 year range). The 2006 UK Defense white paper noted that the availability of the longer serving boats was significantly reduces in their later years.
  - Five boats are laid up in "afloat storage" in Devonport Dockyards with the reactors still fuelled. One boat, the *Swiftsure,* is in Rosyth, where it is the first boat to enter the MoD's Submarine Dismantling Program (SDP).

Swiftsure-class SSN

Top left: http://users.skynet.be/RonSubCovers/
Top right: http://www.military-today.com/navy/swiftsure_class.htm
Bottom: Royal Navy photo via http://www.seaforces.org/marint/Royal-Navy/Submarine/Swiftsure-class.htm

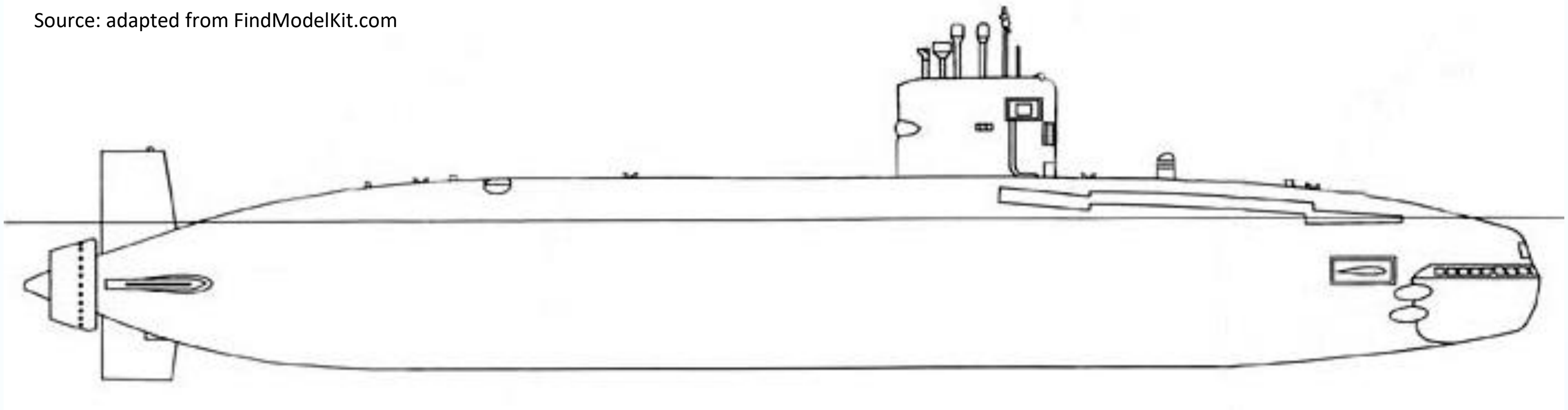
HMS Spartan (S105)

Swiftsure-class SSN with Dry Deck Shelter



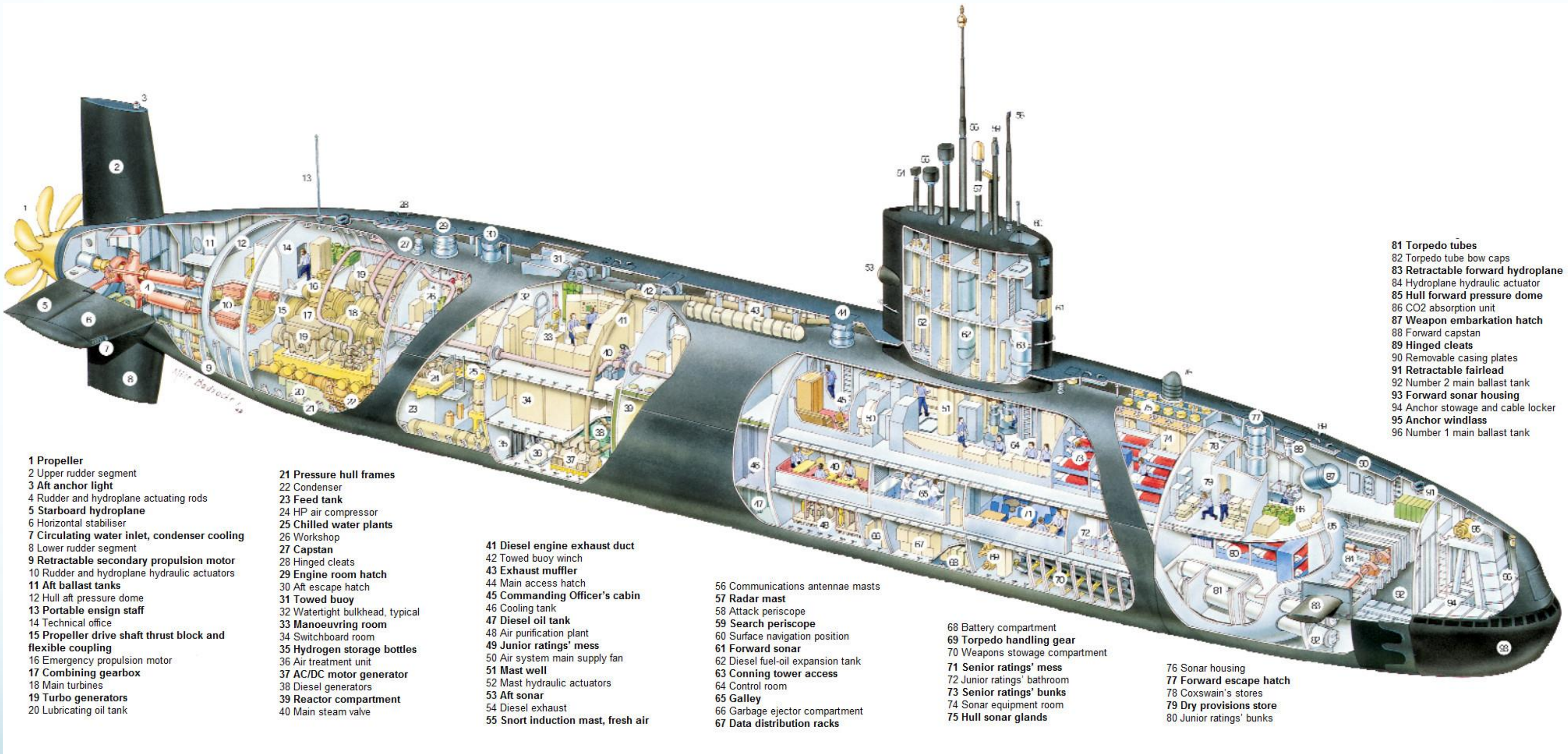
Source, Above: Paul Thailon – Ships, Wildlife, Scenery
Top left: Source: http://www.rnsubs.co.uk/Boats/BoatDB2/

Trafalgar-class SSN


Source: adapted from FindModelKit.com

- There are seven boats in the class; all built by Vickers Ltd., Shipbuilding Group, Barrow-in-Furness. All were commissioned between 1983 – 1991 with an original service life of 20 years.
  - Based on the Swiftsure-class with various improvements, including newer sonar, reduced radiated noise, anechoic tiles on the hull and pumpjet propulsor.
- Propulsion: 1 x Rolls-Royce PWR1, Core 3 (Z) rated @ about 78 MWt
  - 2 x GEC steam turbines delivering about 15,000 shp (11MW); driving a single pump-jet propulsor (except *Trafalgar, which* was fitted with a 7-bladed propeller).
- Armament: 5 x 533 mm (21 in) torpedo tubes; stowage for up to 30 weapons:
  - Spearfish torpedoes
  - UGM-109 Tomahawk land-attack cruise missiles

Trafalgar-class SSN



Note: The above diagram shows a conventional propeller, which is only found on *HMS Trafalgar.*
All other boats in this class have a shrouded pump-jet propulsor in place of the propeller.

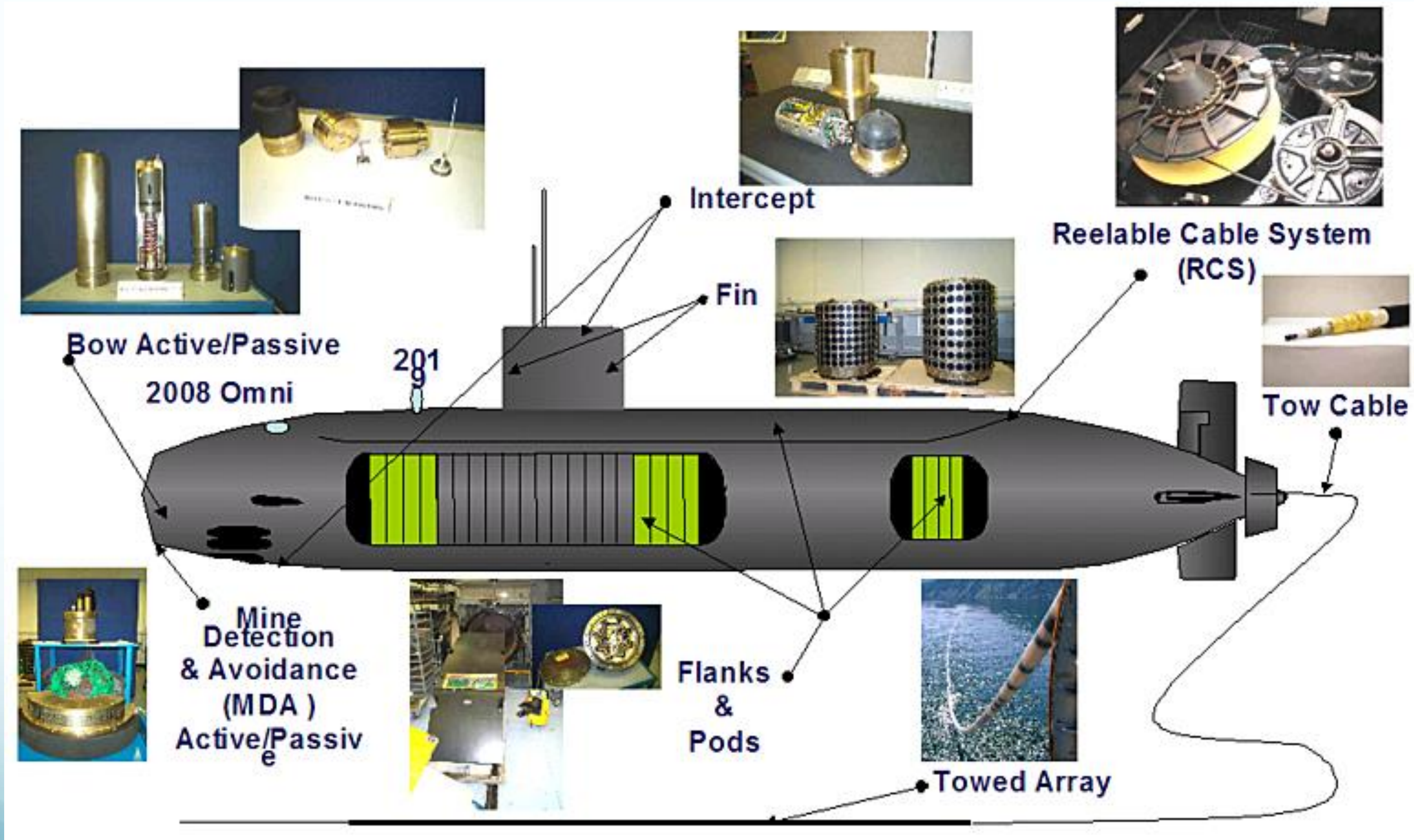
Source: Navy News via https://imgur.com/r/submarines/IDz4gZt

Trafalgar-class SSN

- Operational matters:
  - These SSNs operate with a crew of 130.
  - In the longest solo deployment for any British sub, in 1993 *Triumph* covering a distance of 41,000 miles (66,000 km) while submerged, operating from the UK to Australia.
  - In 2000, thermal fatigue cracks in the primary coolant system resulted in small leaks that required remediation for all Trafalgar-class and Swiftsure-class subs.
  - The operating life of the Trafalgar-class SSNs was extended 10 years due to delays in deploying their replacement, the Astute-class SSN.
  - The four "youngest" Trafalgar-class SSNs, *Torbay, Trenchant, Talant,* and *Triumph*, received a major sonar system update during their mid-life refit. They received the Thales Sonar 2076, which is a fully integrated passive/active search-and-attack sonar suite that also is installed as original equipment on Astute-class SSNs.

Trafalgar-class SSN

Thales Sonar 2076 Installation

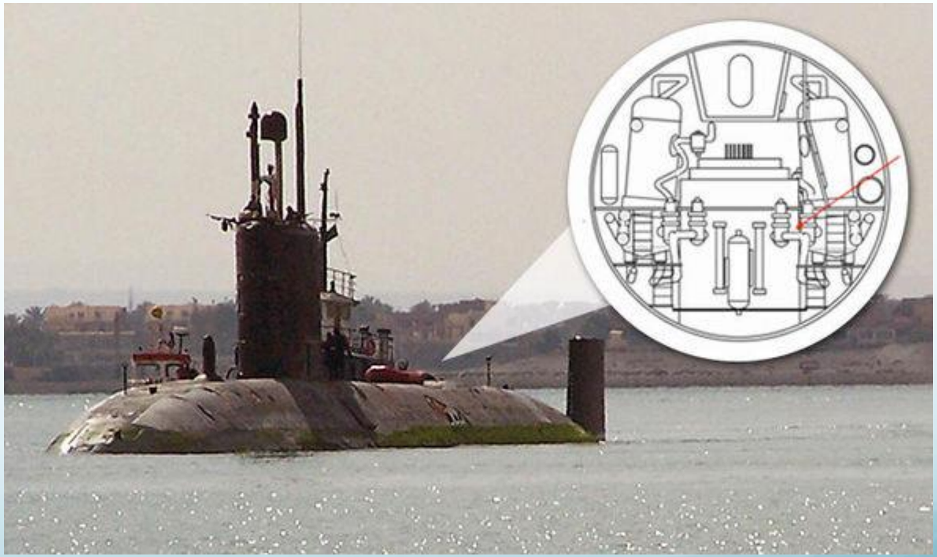


Source: adapted from Thales via http://aviationweek.typepad.com/ares/2007/05/critical_review.html

Trafalgar-class SSN

- Operational matters (cont'd):
  - In February 2017, the four operational Trafalgar-class SSNs were temporarily taken out of service for inspections related to the discovery on *Trenchant* of a fracture on a metal weld connecting a main coolant pipe to the reactor vessel.
    - The affected weld location was inside the water-filled shield tank surrounding the reactor vessel. Access for examination and repair was acknowledged to be difficult. All four Traflagar-class subs were inspected to determine if this was a generic safety issue.
    - The resolution must have been satisfactory because these SSNs returned to service and *Trenchant* participated in ICEX 2018 in the Arctic. *Torbay* retired in 2017.

  - By mid-2018, four Trafalgar-class SSNs were decommissioned and laid up with the reactors still fuelled in "afloat storage" in the Devonport Dockyard.
  - *Trenchant is* scheduled to be decommissioned in 2019.
  - *Triumph,* and *Talent* will relocate to HMNB Clyde by 2020. Then all of the UK nuclear subs will be homeported at the same base.



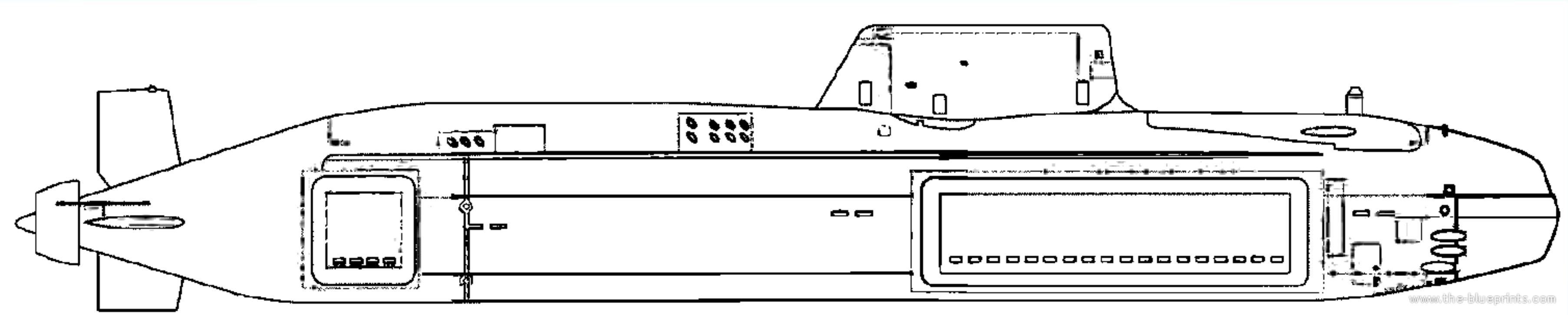
Location of weld fracture.
Source: https://www.express.co.uk/news/uk/766212/

HMS Tireless (S88)

Trafalgar-class SSN in the Arctic

Top left and right: *Tireless* at US Navy's Applied Physics Laboratory Ice Station (APLIS) during ICEX 2007.
Source: both from http://www.defenceimagery.mod.uk/
Bottom left: Tireless at the North Pole in 2004. Source: https://en.wikipedia.org/
Ship's crest source: https://www.elite-designs.co.uk/

Astute-class SSN



Source: adapted from wwww.The-Blueprints.com

- The Astute-class SSN initially was referred to as the Batch 2 Trafalgar Class (B2TC). The starting point was the detailed design of the sixth boat in the class, *HMS Talent*, but with the larger PWR2 reactor plant developed for the Vanguard-class SSBNs.
- The result was a longer and beamier boat than the existing Trafalgar hull, with internal compartments redesigned to accommodate the PWR2 reactor plant, along with the command and sensor suite for the Submarine Command System (SMCS), and the fully-integrated Thales Type 2076 sonar suite, which was installed during mid-life refits on the "youngest" four Trafalgar-class SSNs.

Astute-class SSN

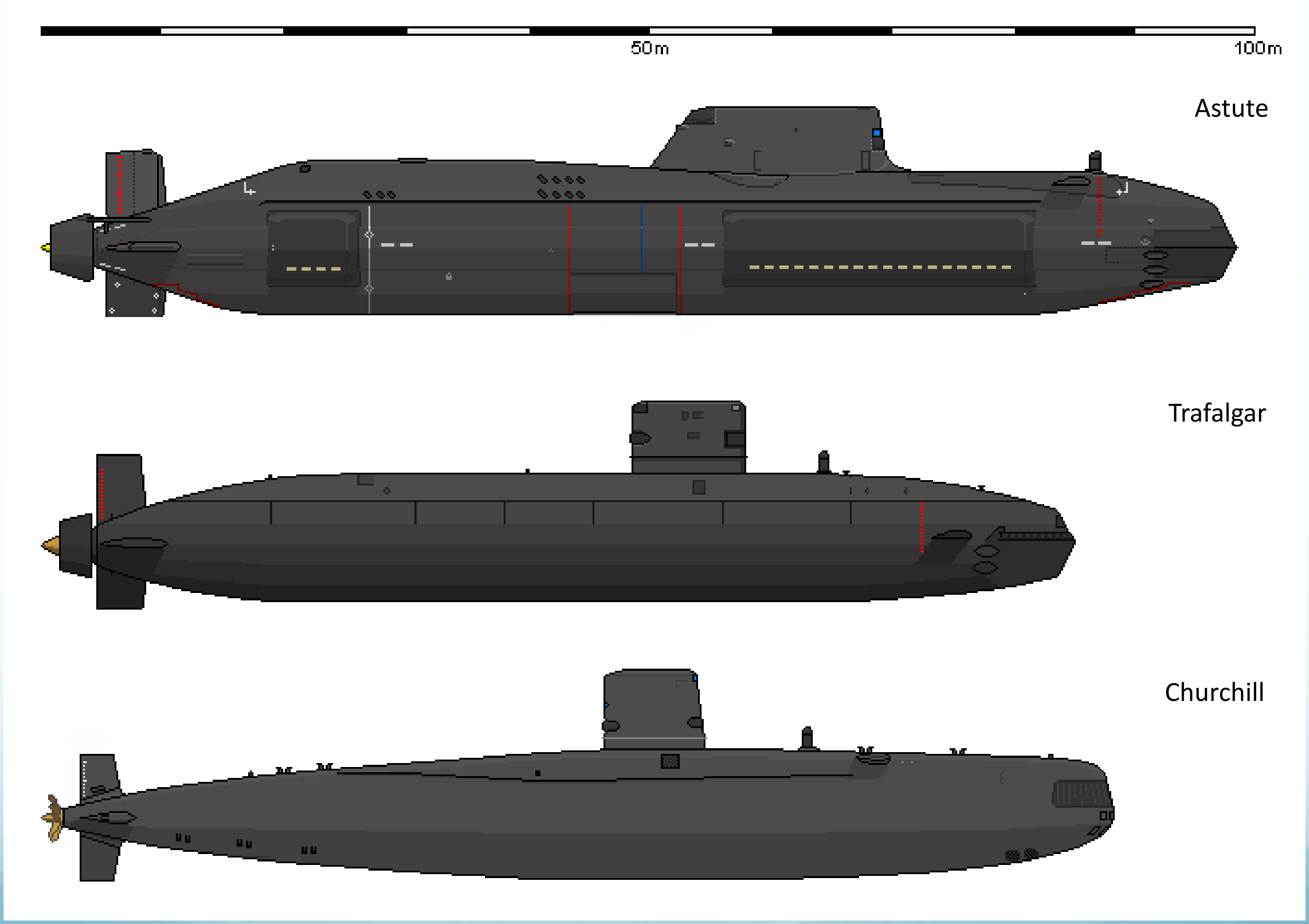
- Planned to be a class of seven boats; built by BAE Systems Maritime – Submarines (formerly Vickers Ltd, Shipbuilding Group), Barrow-in-Furness. .
  - As of mid-2018, three boats have been delivered: *Astute, Ambush and Artful*.
  - One boat, *Audacious*, is scheduled for delivery later it 2018. It successfully completed its dockside trim & dive test in January 2018. This test is used to accurately determine the submarine's weight and center of gravity.
  - The remaining three boats, *Anson, Agamemnon*, and *Agincourt* are expected to be delivered between 2020 - 2024.
- Propulsion: 1 x Rolls-Royce PWR2 Core H rated @ about 130 - 145 MWt
  - Secondary steam plant with two Alsthom propulsion steam turbines delivering about 27,500 shp (20.5 MW), driving a single Rolls-Royce pump-jet.
  - Two emergency diesel generators, one emergency drive motor on the main propulsion shaft, and one retractable electric motor.
  - PWR2 Core H is a life-of-the-boat reactor.
  - The PWR2 for the Vanguard-class SSBN was "re-packaged" to fit the smaller diameter Astute-class SSN hull (11.3 m / 37.1 ft. vs. 12.8 m / 42 ft. diameter for a Vanguard hull).
- Armament: 6 x 533 mm torpedo tubes; stowage for up to 36 weapons
  - Spearfish heavyweight torpedoes
  - Tomahawk Block IV land-attack cruise missiles
  - Can be fitted with a "dry deck shelter" aft of the sail for special operations forces and their equipment

Astute-class SSN

- Operational matters:
  - Astute operates with a crew of 98.
    - Astute is the second Royal Navy submarine class, after the Vanguard class SSBNs, to have a bunk for each member of the ship's company, ending the practice of 'hot bunking',
  - In 2012, *Astute* demonstrated its ability to compete effectively in exercises against a US Virginia-class SSN, aided by its quietness of operation and capabilities of the Thales Sonar 2076 integrated sonar suite.
    - This is the same sonar system retrofitted to four Trafalgar-class SSNs, with the only significant difference being in the reel system for the towed array sonar.
  - The Astute-class has a design top speed in the 29 – 30 knot range. In January 2015, the UK National Audit Office confirmed that this speed target had been met, quelling rumors of slower performance.
  - The last Astute-class SSN, *HMS Agincourt*, was funded in 2018 at a price of £1.5 B. Construction started in May 2018.

Comparison of UK SSN classes

Astute, Trafalgar & Churchill classes



Source: wwww.The-Blueprints.com

Building Astute-class SSNs

Forward hull and bow during construction

Sub on right: Empty space in bow is where the Thales Sonar 2076 main active/passive conformal array will be installed. Source: MoD 45147399, http://www.defenceimagery.mod.uk/

Sub on left: Bow pressure hull closure dome with penetrations for six torpedo tubes.
Source: http://www.naval-technology.com/

Building Astute-class SSNs

Aft hull and stern during construction

Below: Stern pressure hull segment. Note the propulsion shaft penetration in the center of the closure dome. Source: http://www.naval-technology.com/

Above: Stern cone aligned with stern pressure hull closure dome.
Source: MoD 45147400, http://www.defenceimagery.mod.uk/

Building Astute-class SSNs

Ambush under construction in Devonshire Dock Hall

Source: Daily Mail

Building Astute-class SSNs

HMS Audacious in the Devonshire Dock Hall

Source: http://wired.co.uk

Building Astute-class SSNs

Three boats under construction in the Devonshire Dock Hall

Source: http://www.telegraph.co.uk/business/

HMS Astute

Source: http://www.telegraph.co.uk/

HMS Astute

Source: screenshot from https://www.youtube.com/watch?v=DOYDyC3wnsI

HMS Astute with dry deck shelter

Codenamed '*Project Chalfont*', this dry deck shelter pod is intended as a wet/dry lockout chamber for Special Boat Service commandos. Another version of the pod is reported to house a mini-sub that can be deployed submerged. The pod has been tested since 2012, and used operationally on *Astute* for the first time in 2014.

Source, top: http://gentleseas.blogspot.com/2015/06/
Source, bottom: Getty Images via Daily Mail, http://www.dailymail.co.uk/news/article-2587116/

Maritime Underwater Future Capability (MUFC)

- In the late 1990s, the Astute follow-on was called the Future Attack Submarine (FASM) program. This program was cancelled in 2001 due to cost overruns, delays, budget cuts and a decreasing projection for the number of SSNs required by the Royal Navy.
- Today, the Maritime Underwater Future Capability (MUFC) program is intended to define the follow-on to the Astute-class SSN.
  - The MUFC could result in an entirely new submarine design, but, for cost reasons, more likely will be a multi-mission submarine development of the Astute-class SSN.
  - It is likely that an MUFC SSN will be powered by the new PWR3 selected for the Dreadnought-class SSBN.
- 2005 RAND report MG-326/2-MOD notes that design of the replacement submarine would have to begin about 10 years in advance of delivery of the first of class.
  - With a projected 25 year service life for Astute-class SSNs, the MUFC design effort would need to start by about 2024 to produce the first MUFC boat by about 2034, when the first Astute-class SSN should be retiring. A life-extension program for the Astute-class boats would delay this date.
- A key challenge for MUFC will be timing the program start to be consistent with the availability of UK resources for design and manufacturing.
  - The demands for progressing the new Dreadnought-class SSBN program compete for many of the same resources needed to start up a new SSN program.

Submarine-launched tactical weapons

Torpedoes,
Tactical missiles

Mk 24 Tigerfish torpedo

Source: https://upload.wikimedia.org/wikipedia/commons/5/5f/Tigerfish_torpedo.jpg

- This was the UK's previous generation of 533 mm (21 inch) submarine-launched, wire-guided / homing torpedo, intended for use against surface and submarine targets.
  - The final Mod. 2 version was manufactured by Marconi Underwater Systems, Ltd.
- Guided by wire to the point of passive sonar acquisition, then passive sonar terminal homing.
- Basic design parameters:
  - Weight: 1,550 kg (3,417 lb)
  - Length: 6.5 m (21 ft)
  - Propulsion: Electrically-powered, chloride silver-zinc oxide battery, driving a propeller
  - Maximum speed: 65 kph (40 mph, 35 knots)
  - Maximum range: 39 km (21 naut. miles) at slow speed; 13 km (7 naut. miles) at high speed
  - Warhead: 134 to 340 kg (295 to 750 lb) Torpex high-explosive.
- The Tigerfish torpedo was withdrawn from service in 2004. It was replaced by the Spearfish torpedo.

Spearfish torpedo

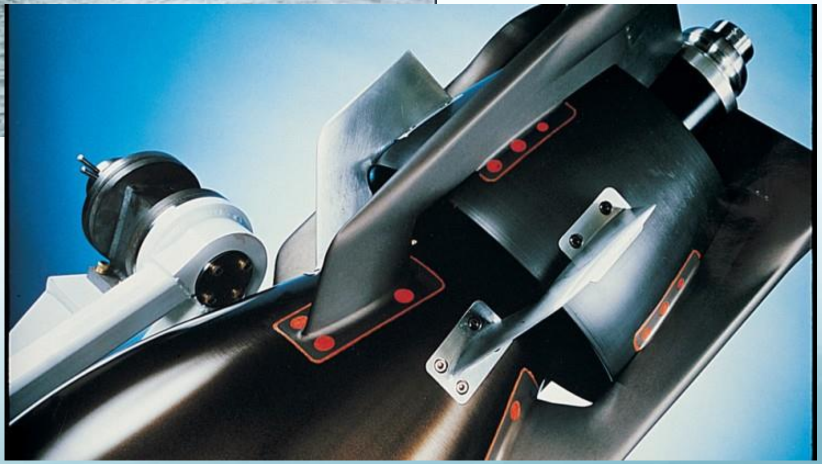
- This is the UK's current generation of 533 mm (21 inch) high-speed, heavyweight, submarine-launched torpedo.
  - Manufactured by BAE Systems – Underwater Systems from 1988 – 2003.
  - In service from 1992 to the present, replacing the Tigerfish torpedo.
- Guided by wire or by autonomous active or passive sonar, for use against surface and submarine targets in oceanic and coastal waters.
- Basic design parameters:
  - Weight: 1,850 kg (4,080 lb)
  - Length: 7 m (23 ft)
  - Propulsion: Otto fuel + oxidizer for a gas turbine driving a pump jet propulsor
  - Maximum speed: 113 kph (70 mph, 61 knots)
  - Maximum range: 54 km (33.6 miles)
  - Warhead: 300 kg (660 lb) high-explosive, detonated by contact or proximity fuse.
- On December 2014, the UK Ministry of Defense awarded BAE Systems a £270 million contract to upgrade the Spearfish torpedo inventory and deliver the upgraded Mod. 1 torpedoes to the fleet between 2020 and 2024. Upgrades include:
  - New insensitive-munition warhead
  - A change to the fuel system to improve safety
  - Full digitization of the weapon and a new fiber-optic guidance link to improve performance

Spearfish torpedo

Source: BAE Systems

Spearfish torpedo

Loading a Spearfish on a Trafalgar-class SSN. Source: https://www.telegraph.co.uk/



The Spearfish pumpjet propulsor. Source: https://www.thinkdefence.co.uk/2014/11/spearfish-torpedo-upgrade/

Harpoon (UGM-84A)

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 from 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

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

- UK IOC in 1981 on Churchill-class SSN *HMS Courageous*. Retrofitted on Valiant-, Churchill-, and Swiftsure-class SSNs.

Tomahawk (UGM-109E Block IV)

Land attack cruise missile

- Stored as an “all-up-round” in a canister.
- Wet-launched via torpedo tubes. Missile is ejected and the 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.
- UGM-109E Block IV is armed with a 1,000 pound (454 kg)-class unitary warhead.
- Mission planning time 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.
- Carried on Swiftsure-, Trafalgar- and Astute-class SSNs.

Tomahawk launch. Source: General Dynamics

Source: Smithsonian National Air & Space Museum

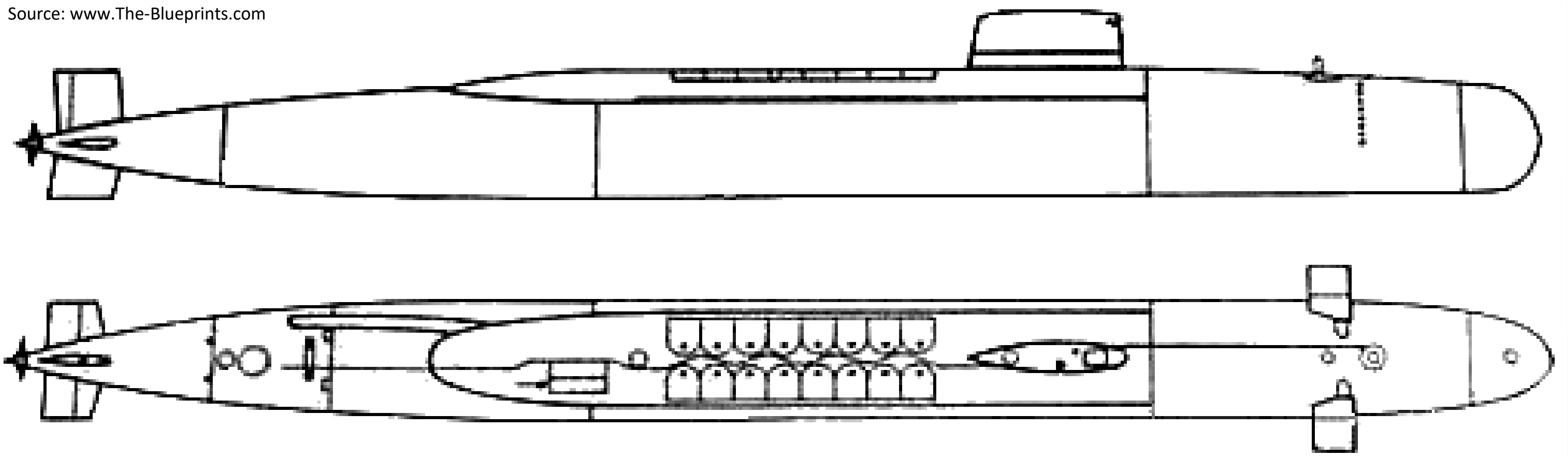
Nuclear-powered strategic ballistic missile submarines (SSBN)

UK strategic missile subs (SSBNs)

Class	# in Class	Length	Beam	Displacement (tons)	Reactor	Shaft hp	Max speed (kts)	Years delivered	Years in service
Resolution	4	129.5 m (425 ft)	10.1 m (33 ft)	7,500 (surf), 8,400 (sub)	PWR1 Core 1 / 2	15,000 (est.)	25 kts	Oct 67 – Dec 69	Oct 67 – May 92
Vanguard	4	149.9 m (491.8 ft)	12.8 m (42 ft)	14,900 (surf) (est.), 15,900 (sub)	PWR2 Core G / H	27,500	25 kts	Aug 93 – Nov 99	Aug 93 - present
Dreadnought	4	152.9 m (501 ft)	12.8 m (42 ft)	17,200	PWR3	TBD	TBD	Earliest - 2028	Early 2030s

Resolution-class SSBN

Source: www.The-Blueprints.com



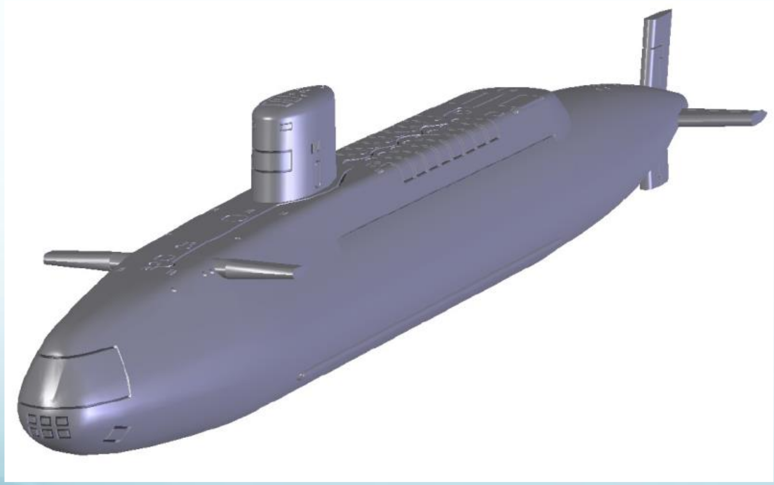
- Four boats in this class; *Resolution & Repulse* were built by Vickers Ltd, Shipbuilding Group, Barrow-in-Furness; *Renown & Revenge* were built by Cammell Laird, Birkenhead.
  - All were commissioned between October 1967 and December 1969, with an original design service life of 20 years.
- Propulsion: 1 x Rolls-Royce PWR1, Core 1 (A), rated @ about 78 MWt; 2 x main steam turbines with a combined rating of about 15,000 shp (11 MW); driving a single propeller.
  - Refueled with PWR1 Core 2 (B)
- Armament:
  - Initially, 16 x Polaris A3T SLBMs; upgraded in 1980s to the Polaris/Chevaline A3TK.
  - 4 x 533 mm (21 in) torpedo tubes; Tigerfish heavyweight torpedoes.

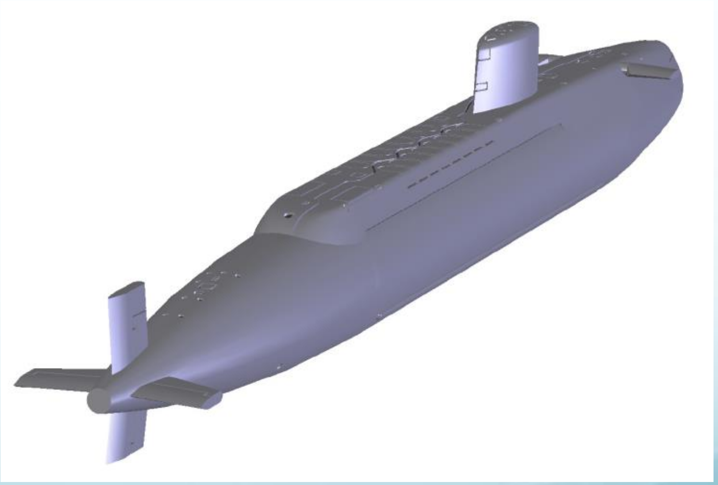
Resolution-class SSBN

- Operational matters:
  - Resolution-class SSBNs incorporated "rafting" to isolate large, rotating machinery from the hull and thereby provide better sound quieting. Rafting was first introduced in nuclear submarines on the UK Valiant-class SSNs. Other features included:
    - A machinery loading hatch provided a means for loading / unloading large items
    - Test depth was 275 meters (902 feet).
  - In February 1968, the lead boat, *Resolution*, fired Britain's first Polaris missile during an exercise off Cape Kennedy (now Cape Canaveral), Florida.
  - *Resolution* started the first UK Polaris deterrent patrol on 15 June 1968.
  - *Repulse* was the last of the UK Polaris SSBNs, continuing to operate with the Polaris/Chevaline A3TK until being decommissioned on 28 Aug 1996.
    - By then, two Vanguard-class SSBNs armed with Trident II SLBMs were operational and a third boat was set to join the UK SSBN fleet later in 1996.
    - The last US Polaris A-3 deterrent patrol was made in 1981. By then, the remainder of the original US Polaris SSBN fleet had transitioned to Poseidon C3 and Trident I C4 SLBMs. The UK never adopted the Poseidon C3 or Trident I C4 SLBMs.
  - UK Polaris/Chevaline deterrent patrols were conducted for 28 years. The average service life for the Resolution-class SSBNs was about 26 years (22 to 28 year range).
  - The 2006 UK Defense white paper reported there was a significant loss of availability and an increase in support costs towards the end of the SSBN's service lives.

Resolution-class SSBN

HMS Resolution. Source, photo above: http://www.hmsresolution.org.uk

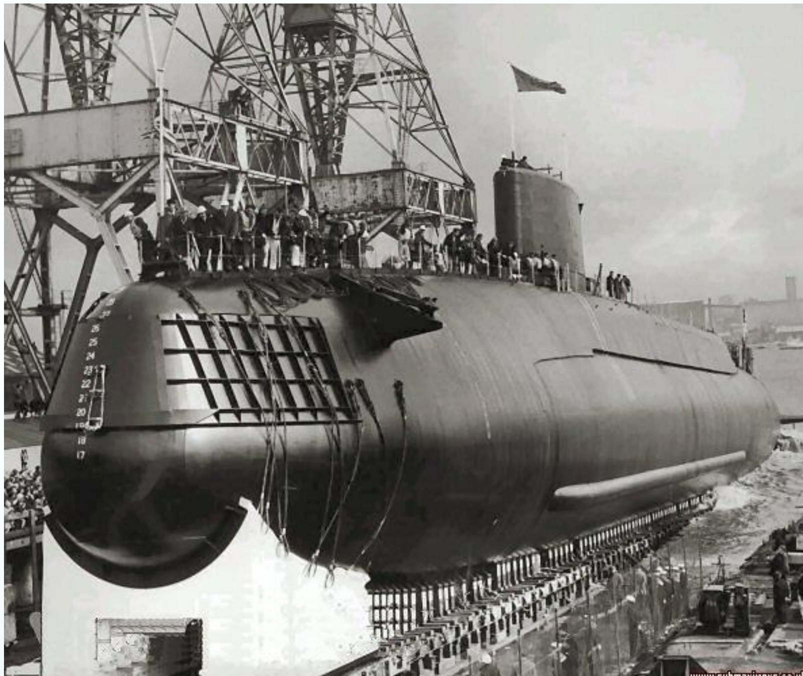


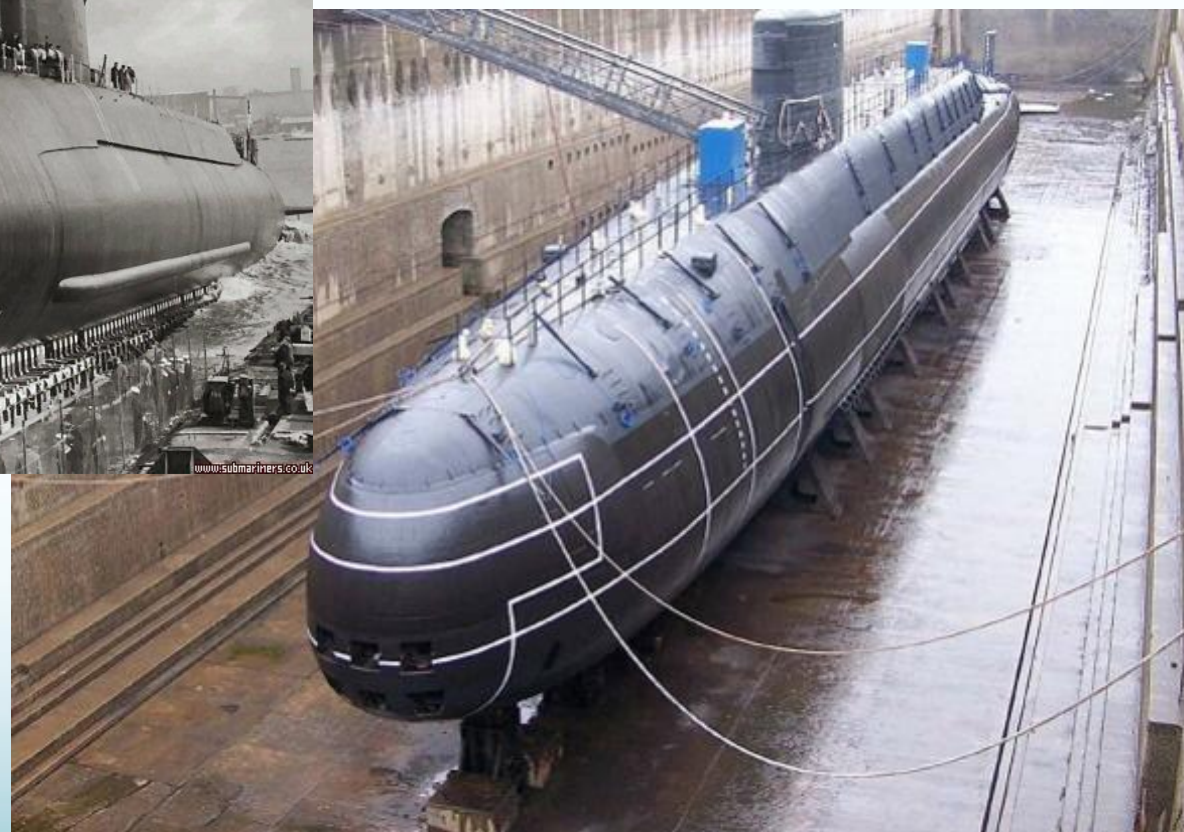


Source, two graphics: http://www.okbgrigorov.com/Projects_im/Resolution/

Resolution-class SSBN

HMS Revenge





Source, both photos: http://forum.sub-driver.com/forum/

1980 UK Defense white paper

"The future United Kingdom nuclear deterrent force"

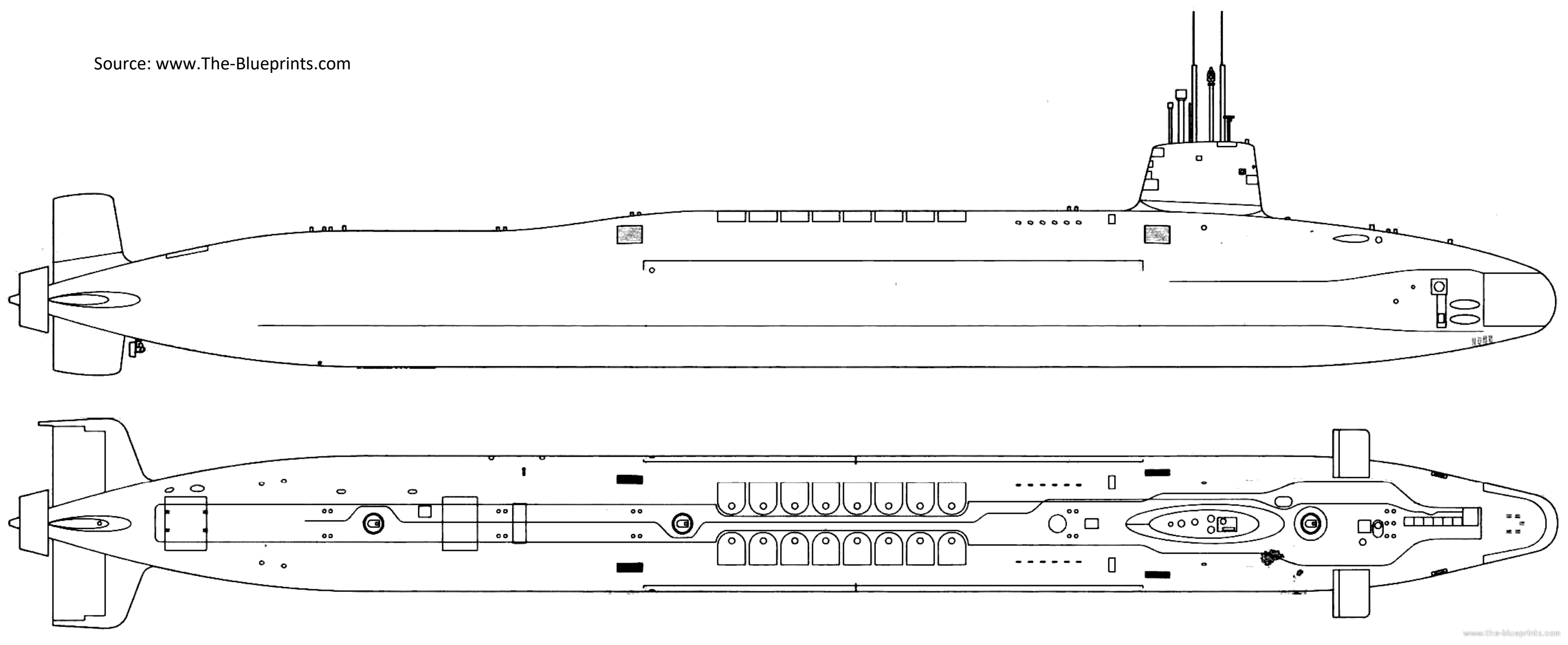
- This July 1980 white paper was presented to Parliament to define the program to replace the Resolution-class SSBNs.
- Key issue raised included:
  - Explained why submarines were clearly the best platforms for the UK's future strategic nuclear force.
  - Summarized the UK's letter from PM Margaret Thatcher to President Jimmy Carter requesting the sale of Trident I SLBMs and associated systems for use on a new class of UK SSBNs, under terms similar to the 1963 Polaris Sales Agreement (Nassau Agreement).
  - Resolution-class SSBN fleet status:
    - In the early 1960s, special efforts made it possible to deploy the first UK SSBN less than six years after the Nassau Agreement was signed. The greater complexity for modern systems will result in longer lead-times for the next-generation SSBN.
    - Since 1969, the Resolution-class SSBNs have maintained a continuous, at-sea deterrence, with at least one SSBN on patrol.
    - Original SSBN service life was 20 years; which has been extended to 28 years.
    - Propulsion machinery and missile support systems are aging and pose a heavier maintenance load, with a growing risk that refit periods will be prolonged or an unexpected defect will challenge the ability of the SSBN fleet to meet the continuous patrol objective.
    - The Polaris SSBN force requires only 2,500 servicemen, less than 1% of UK military manpower.

1980 UK Defense white paper

“The future United Kingdom nuclear deterrent force”

- Chevaline SLBM replacement
  - The US Trident I SLBM is operational and represents a low-risk path for the next-generation UK SLBM.
  - Acknowledges that the US is developing the more advanced and powerful Trident II SLBM, but there is greater risk if the UK were to choose this SLBM now.
- Size of the replacement SSBN fleet
  - Four of five replacement SSBNs will be required. The specific number can be determined later.
- Cost of the replacement SSBN fleet
  - Total acquisition cost for the Trident system will be about £4.5 – 5.0 B over 15 years, including submarines, missiles, warheads, support equipment and facilities, including construction required at the Coulport armament depot and the Faslane SSBN operating base.

Vanguard-class SSBN



- On 24 January 1980, the UK House of Commons backed the government defense policy to retain an independent nuclear deterrent focused on a next-generation SSBN, as described in the UK Defense white paper 1980.
- Vanguard-class SSBNs were the replacement for the Resolution-class SSBNs. All were commissioned between 1993 – 99, with an original design life of 25 years, which has been significantly extended.
- The four boats were built by Vickers Ltd, Shipbuilding Group, Barrow-in-Furness

Vanguard-class SSBN

- Propulsion: 1 x Rolls-Royce PWR2, originally Core G, rated @ about 145 MWt.
  - 2 X GEC steam turbines delivering about 27,500 shp (20.5 MWt), driving a single pump-jet propulsor.
  - 2 x retractable auxiliary propulsion motors.
  - The Vanguard-class SSBNs were the first class of UK nuclear submarines to use PWR2.
  - The reactor was refueled with the long-life PWR2 Core H that likely would permit Vanguard SSBNs to operate for a total of 40 years if permitted by other life-limiting factors.
- Armament:
  - 16 missile tubes, but no more than 8 Trident II (D5) SLBMs with a total of 40 warheads per boat
    - The original UK-designed warhead is thought to be similar to a 100 kT US W76.
    - In about 2011, the UK adopted the US-designed W76-1 nuclear warhead. The UK government also confirmed that the UK also was adopting the US-designed Mk-4A reentry vehicle. This is the same combination of warhead and RV used on US Trident II SLBMs.
  - 4 x 533 mm (21 in) torpedo tubes; Spearfish heavyweight torpedoes.

Vanguard-class SSBN

- Operational matters:
  - Vanguard-class SSBNs operate with two crews of 135.
    - Vanguard is the first Royal Navy submarine class to have a bunk for each member of the ship's company, ending the practice of "hot bunking."
  - All four boats are based at HM Naval Base Clyde (*HMS Neptune* aka Faslane).
  - 1994: *Vanguard* made its 1st Trident II deterrent patrol. It took about 14 years from the UK's 1980 request to purchase Trident SLBMs from the US to the initial operating capability (IOC) for the UK's Trident system.
  - The four Vanguard-class subs are deployed as follows:
    - One is on patrol
    - Two are in port undergoing routine servicing and training
    - One is in maintenance / overhaul
  - 4 Feb 2009: *Vanguard* collided with French SSBN *Le Triomphant* in the Atlantic. *Vanguard* returned under its own power to Faslane for repairs.
  - In January 2012, a fuel cladding leak was detected in the PWR2 Core H operating at the Shore Test Facility (STF) prototype at Vulcan NTRE. A similar problem has not been detected in the Astute- and Vanguard-class submarines operating PWR2 Core H. However, a decision was made to refuel *HMS Vanguard* during its next 3.5 year "deep-maintenance" period, which started in December 2015. This additional, and originally unplanned, refueling will add £120 M to the cost of the scheduled 'deep-maintenance."

Vanguard-class SSBN

- Operational matters:
  - A summary of the Vanguard-class mid-life Long Overhaul Period and Refueling [LOP(R)] and additional refueling overhauls is in the table below. A decision on a second refueling during a scheduled "deep maintenance" period for other Vanguard-class SSBNs will be based on the outcome of examinations of the PWR2 Core H from the STF prototype. A decision on a second refueling for *HMS Victorious* may be made in 2018.
  - 26 July 2013: *HMS Victorious* completed the 100th Trident II deterrent patrol by Vanguard-class SSBNs.
  - Vanguard-class SSBNs will start retiring in about 2030, after a service life of about 37 years. They will be replaced by Dreadnought-class SSBNs on a 1-for-1 basis.

SSBN	Start refueling overhaul	End refueling overhaul	Approx. cost
Vanguard [mid-life LOP(R)]	Feb 2002	Jun 2004	Not known
Victorious [mid-life LOP(R)]	Jan 2005	Jul 2008	£270 M
Vigilant [mid-life LOP(R)]	Oct 2008	Mar 2012	£333 M
Vengeance [mid-life LOP(R)]	Mar 2012	Dec 2015	£350 M
Vanguard [2nd LOP(R)]	Dec 2015	mid-2019	LOP + £120 M for the additional refueling

Vanguard-class SSBN

Source: Ian Jack "The Long Read, Trident: The British Question," The Guardian, 11 Feb 2016

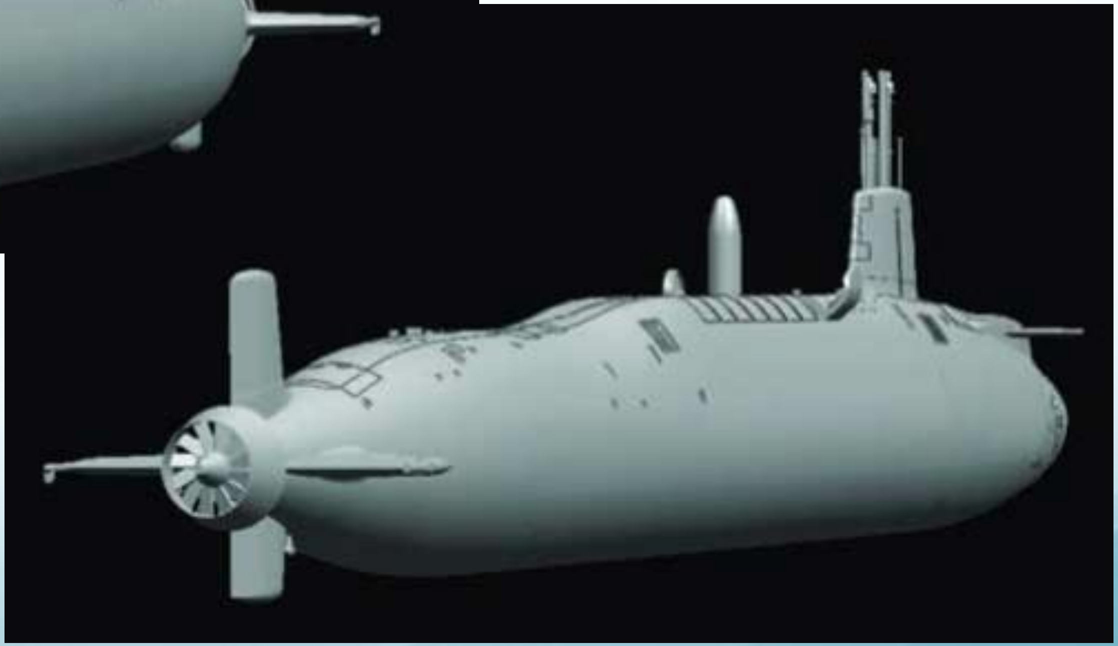
Vanguard-class SSBN

Source: Above: http://www.jeffhead.com/modelbuilds/vanguard-03.jpg
Below: Ian Jack "The Long Read, Trident: The British Question," The Guardian, 11 Feb 2016

Vanguard-class SSBN

HMS Vengeance. Source: MoD via http://www.seaforces.org/marint/Royal-Navy/Submarine/Vanguard-class.htm

Vanguard-class SSBN



Source, two model photos:
https://www.scalehobbyist.com/manufacturers/

1998 UK Strategic Defense Review (SDR)

- This SDR, published in July 1998, presented a updated, post-Cold War view of UK strategic defense and security requirements.
- SSBN fleet:
  - The fleet of four Vanguard-class SSBNs will enable the UK to maintain continuous deterrent patrols over the lifetime of the Trident force.
  - Only one SSBN will be on patrol at a time, carrying a reduced load of 48 warheads. This is one-half of the maximum of 96 warheads announced previously.
  - The continuous at-sea deterrent patrols are maintained, not least to avoid a misunderstanding or escalation if a Trident SSBN were to sail during a crisis period.
  - SLBMs will not be targeted and normally will require several days 'notice to fire'.
- Nuclear weapons:
  - With the withdrawal of the last Royal Air Force WE177 free-fall bombs in March 1998, the Trident SLBM is the UK's only nuclear weapon.
  - Trident will cover both strategic and sub-strategic requirements. The potential explosive power deployed on a Trident SSBN is one-third less than a Polaris SSBN armed with the Chevaline SLBM.
  - A stockpile of less than 200 operationally available warheads is needed. This is a reduction of one-third from the maximum of 300 announced previously.
  - The 58 Trident D5 missile bodies already purchased from the U.S are sufficient to maintain a credible deterrent.

1998 UK Strategic Defense Review (SDR)

- UK fissile material inventory:
  - The UK's current defense stocks of fissile material are:
    - 7.6 tonnes of plutonium,
    - 21.9 tonnes of highly enriched uranium and
    - 15,000 tonnes of other forms of uranium.
  - All stocks of highly enriched uranium will be retained outside safeguards, since material no longer needed for nuclear weapons will be used for the naval nuclear propulsion program.
- Trident system cost:
  - The estimated total cost of acquiring the Trident system, including the Vanguard-class SSBNs and infrastructure improvements, was about £12.5 B. That was about three times the original estimate of £4.5 – 5 B presented in the UK Defense white paper 1980.
  - The annual cost of the Trident submarine force will average about £280 M per year over its life time.
  - The current annual cost of the UK warhead and fissile material program is about £400 M per year. About one-third is directly related to Trident.
  - The annual cost (including the continuing costs from earlier programs) is little more than 3% of the annual defense budget.

1998 UK Strategic Defense Review (SDR)

- SSN fleet:
  - Forecasts a continuing post-Cold War decline in the likelihood of an open-ocean anti-submarine or anti-surface threat.
    - Reduces the SSN fleet from 12 to 10 boats over a period of several years.
    - Maintains the purchase order for the first three Astute-class SSNs and affirms the intention to purchase two more after 2000.
    - States and intent to reduce the peacetime tasking required for the SSN fleet. However, the SDR acknowledges a growing requirement for deployment and exercise of Tomahawk capable submarines.
  - Provides for continued modernization of the nuclear-powered attack submarines:
    - All SSNs will equipped to fire Tomahawk land attack missiles to increase their utility in force projection operations.
    - All seven Trafalgar-class boats will be retrofitted for Tomahawk missiles.
  - One SSN is assigned to first echelon forces 'Spearhead Forces’ that are maintained at very high readiness for deployment as needed.

2006 UK Defense white paper

“The future of the United Kingdom’s nuclear deterrent”

- This December 2006 white paper was presented to Parliament to explain the urgency for approving and funding the “Successor” SSBN program to replace the Vanguard-class SSBNs.
- Key issue raised included:
  - The Trident SLBM is the UK’s only nuclear weapon.
  - It will take about 17 years from decision to operation of a replacement SSBN.
  - Vanguard-class SSBN retirement:
    - Even with a modest service life extension from the original 25 years to 30 years, Vanguard-class SSBNs will start retiring in 2022.
    - Limiting components include the steam generators, other elements of the nuclear propulsion system and some non-nuclear support systems.
    - Any further extension of the life of the submarines would mean that the limiting components would need to be replaced or refurbished, and this would require a major refit of the submarines. This would not significantly extend the lives of the submarines and would not be cost effective.
    - A substantial life extension, as the US did with their Ohio-class SSBNs, cannot be accomplished on the Vanguard-class SSBNs because of substantial design differences.

2006 UK Defense white paper

“The future of the United Kingdom’s nuclear deterrent”

- Existing UK nuclear warheads:
  - The existing warhead design can remain operational into the 2020s. It remains to be determined if the warheads can be refurbished to extend their lives, or if it will be necessary to develop a replacement warhead.
  - The stockpile of operationally available warheads can be reduced to less than 160. This will represent a 20% reduction from the 200 warheads called for in the 1998 Strategic Defense Review.
- Existing Trident D5 SLBMs:
  - Unless the UK participates in the Trident D5 life extension program, it will not be possible to maintain the existing Trident D5 SLBMs in service much beyond 2020, except at much greater cost and technical risk. The decision to participate or not is required by 2007.
  - The Vanguard-class submarines can operate without the Global Positioning Satellite (GPS) system and the Trident D5 missile does not use GPS at all. There is nothing in the planned Trident D5 life extension program that will change this position.

2010 UK Strategic Defense and Security Review (SDSR)

"Securing Britain in an Age of Uncertainty"

- This SDSR, published in October 2010, included updated guidance for submarine force structure in 2020, replacement SSBN program cost savings, and the Royal Navy's SLBM and warhead limits.
- Future Force 2020: Naval submarine force level
  - 4 x Trident II (D5) SSBNs
  - 7 x Astute SSNs to protect the nuclear deterrent force and maritime Task Groups, provide global strategic intelligence, and provide a Tomahawk Land Attack Missile strike capability.
- SSBN cost reductions:
  - Extend the life of the current Vanguard-class SSBNs to the late 2020s into the early 2030s.
  - Defer delivery of the first new Dreadnought-class SSBN from 2024 until 2028.
  - Defer decisions on a replacement for the current Trident II nuclear warhead. A replacement warhead is not required until at least the late 2030s.
  - Reduce the cost of the Dreadnought-class SSBN missile compartment by collaborating with the US on a common design.
- SLBM policy limits:
  - Reduce the number of warheads onboard each submarine from 48 to 40.
  - Reduce the number of operational missiles on each submarine to 8.
  - Reduce the operationally available warheads from fewer than 160 to no more than 120.
  - Reduce our overall nuclear weapon stockpile to no more than 180.

2015 UK Strategic Defense and Security Review (SDSR)

- This SDSR, published in November 2015, included a commitment to the Dreadnought SSBN program, retirement of the Royal Air Force's strategic nuclear weapons, and a further clarification on the Royal Navy's SLBM and warhead limits.
- Trident II warhead inventory:
  - In 1993 the UK decided retire and not to replace the Royal Air Force's WE177 free-fall bomb, leaving the Royal Navy's Trident II warheads as their only nuclear weapons.
  - The UK retains an stockpile of about 225 warheads and is working towards reducing to a total stockpile of 180 by the mid-2020s.
  - The 160 operationally available warheads are set to be reduced to 120 in the same period.
  - The current Trident warheads are expected to remain operational into the late 2030s.
- SLBM policy limits:
  - Each Vanguard-class SSBN was designed to carry up to 16 Trident II (D-5) missiles. Each Trident II missile is capable of carrying up to 12 warheads.
  - Under the March 1982 Trident Sales Agreement, the UK leases at total of 58 Trident II missiles from the US
  - By UK policy, each Vanguard SSBN is limited to carrying no more than 8 missiles with a total of 40 warheads.

2015 UK Strategic Defense and Security Review (SDSR)

- SSBN fleet:
  - Affirms UK commitment to an independent nuclear deterrent under *Operation Relentless*, which was initiated in 1969.
  - Commits to the 4 x SSBN deterrent fleet with at least one SSBN on Continuous at Sea Deterrent patrol at all times.
  - SSBNs will continue to carry 40 warheads and not more than 8 operational SLBMs.
  - Commits to a 20 year acquisition program to replace Vanguard-class SSBNs with new "Successor"-class SSBNs (now named Dreadnought-class), with an initial service date in the early 2030s.
- Trident SLBM nuclear warheads:
  - Retains no more than 120 operationally available warheads.
  - By the mid-2020s, reduces the overall nuclear weapons stockpile to no more than 180 warheads, meeting the commitment made in SDSR 2010.
  - A replacement nuclear warhead is not required until at least the late 2030s, possibly later. However, given the long lead time, SDSR 2015 acknowledges that a government commitment to replacing the current strategic nuclear warhead is needed soon. The Atomic Weapons Establishment (AWE) will be responsible for developing the new warhead.
- SSN fleet:
  - Commits to a 7 x SSN fleet

Dreadnought-class SSBN

Notional drawing of Dreadnought-class SSBN. Source: BAE Systems Maritime

- Timeline:
  - The concept phase for the "Successor" SSBN started in September 2007.
  - The final decision to commit to the Dreadnought SSBN program was made by the UK government in July 2016. Four Dreadnought SSBNs will be built to replace Vanguard-class SSBNs on a one-for-one basis.
  - Construction of the lead ship, *HMS Dreadnought* (10th UK ship to bear that name), started in mid-2016 at the BAE Systems Maritime shipyard at Barrow-in-Furness.
  - Delivery of the lead ship is expected to occur in 2028, with a first deterrent patrol in the early 2030s.

Dreadnought-class SSBN

- Program Cost:
  - In December 2006, the Defense white paper, "The Future of the United Kingdom's Nuclear Deterrent," it was estimated that the Dreadnought submarines and their infrastructure would cost around £15 - 20 billion (at 2006/2007 prices), broken down as follows:
    - £11 - 14 billion for a class of four new submarines.
    - £0.25 billion to participate in the Trident D5 missile life extension program.
    - £2 – 3 billion for possible refurbishing of the warheads.
    - £2 – 3 billion for infrastructure spent over the life of the submarines (30 years).
  - By 2017, the program total budget had grown to £31 billion with £10 billion contingency fund.
- Propulsion:
  - Initially there were three alternatives: a PWR2 as used on the Vanguard-class SSBNs, an updated PWR2b derivative adapted from the current Astute SSN propulsion plant, and a new PWR3 based on a modern US submarine propulsion plant.
  - In May 2011, the UK MoD Defense Board selected the PWR3 reactor, which would be 'based on a modern US plant' and US support would be provided for an 'independent peer review of the UK's NNPP capability and help to optimize its PWR3 concept design.'
    - The US Virginia-class S9G reactor plant is a likely candidate.

Dreadnought-class SSBN

Notional drawing of Dreadnought-class SSBN. Source: UK Ministry of Defense

Dreadnought-class SSBN

- Armament
  - Twelve missile tubes behind the sail.
    - Dreadnought-class and the new US Columbia-class SSBNs will share a common missile compartment (CMC) design, the basic building block of which is a “quad-pack” of four (2 x 2) modular missile tubes.
    - Each missile tube measures 86” (2.18 m) in diameter and 36’ (10.97 m) in length. These large, versatile tubes could potentially carry a variety of payloads:
      - Trident D5 or next-generation submarine-launched ballistic missile (SLBM),
      - Multiple All-up Round Canisters (MACs), each accommodating 7 x Tomahawk cruise missiles or other weapons / devices per tube,
      - Special forces equipment and vehicles,
      - Unmanned underwater vehicles (UUVs), deployable decoys and sensors and encapsulated unmanned air vehicles (UAVs).
    - Current plans are to carry Trident II (D5) SLBMs in eight missile tubes. The remaining four tubes will be used for other purposes.
  - Torpedo tubes, likely 4 x 533 mm (21 in)
  - Also may carry tactical weapons or other devices external to the pressure hull.
  - This flexible design could yield more than one version in the same basic hull: a dedicated strategic SSBN, and a multi-purpose SSN / SSGN like a US Virginia Block V or a Russian Yasen-M.

Dreadnought-class SSBN

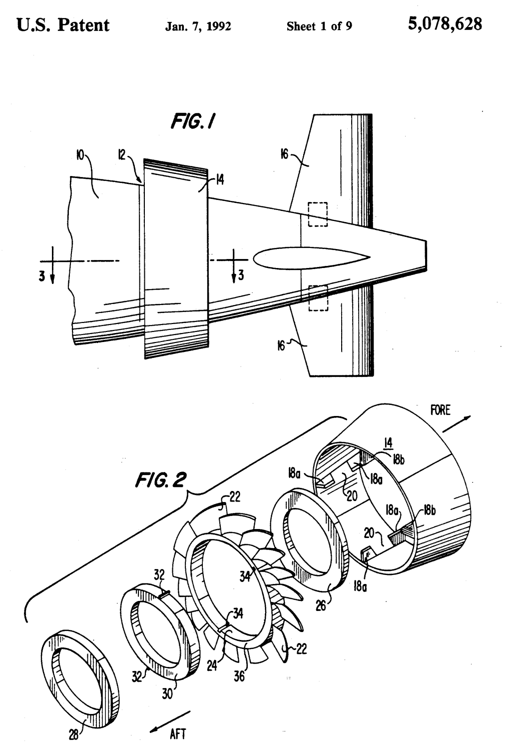
- Design features:
  - The Dreadnought-class draws heavily from proven Astute-class design innovations and technologies.
    - Unorthodox external “advanced hull form” that is designed for low-cost fabrication using largely flat or single curvature surfaces.
  - Greater level of automation
  - Common Missile Compartment (CMC)
  - Electrical instead of hydraulic actuators for control surfaces.

CMC “quad-pack” Source: General Dynamics

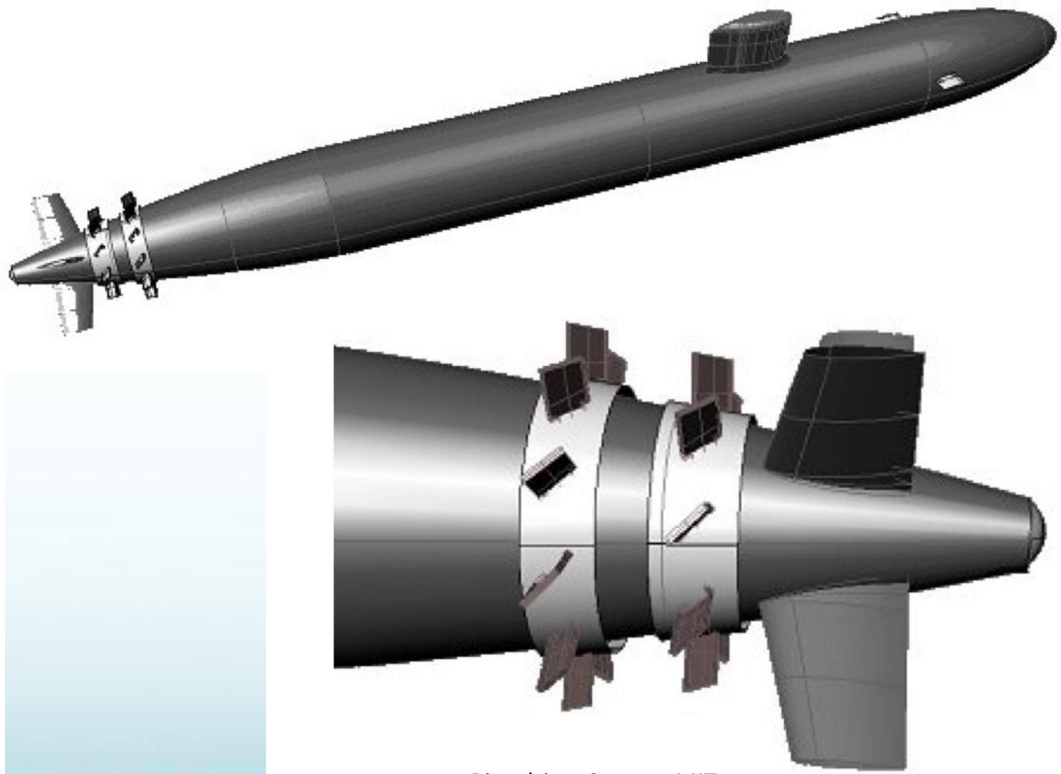
  - The UK’s Next-generation Naval Propulsion Plant is expected to include electric propulsion and possibly a Submarine Shaftless Drive (SSD): a watertight electric motor outside the pressure hull that drives a pump-jet propulsor or other type of propulsor.
    - The US Navy has reviewed the UK SDD plans.

Submarine shaftless drive (SSD) concepts

- The particular SSD configuration being considered for the Dreadnought-class SSBN is not known. In addition to a pump-jet, here are other possible SSD configurations.



Source: Newport News Shipbuilding & Drydock



Rim-drive, Source: MIT

Submarine-launched ballistic missiles (SLBMs)

UK submarine-launched ballistic missiles (SLBMs)

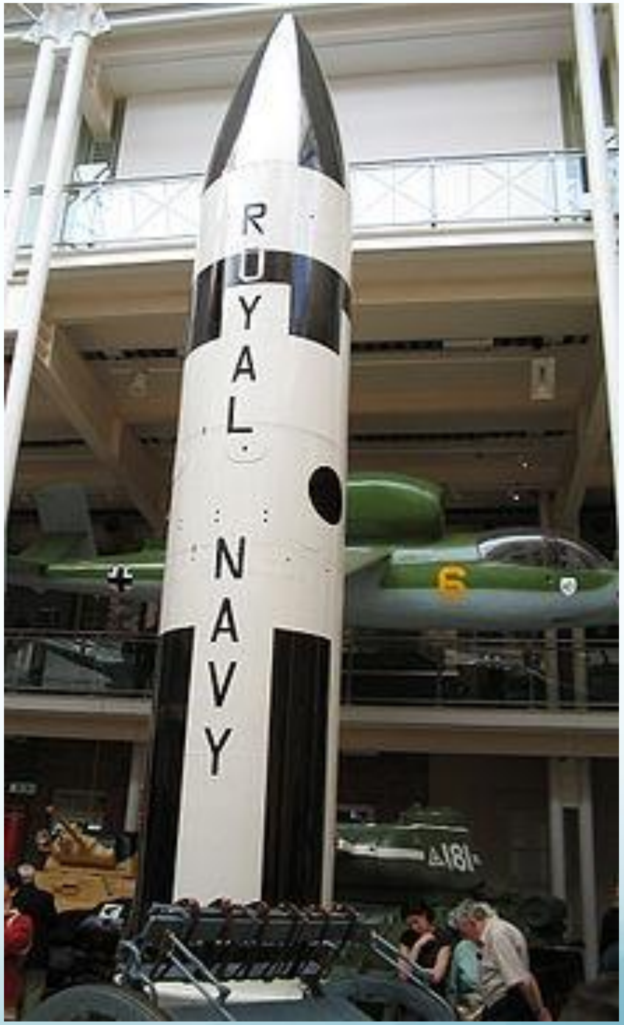
SLBM	Years in service	Weight	Length	Diameter	# of stages	Range (mi) / Guidance	Warhead
Polaris A3T	Jun 1968 - 1982	16,193 kg (35,700 lb)	9.45 m (31.0 ft)	1.37 m (54 in)	2 (solid)	4,023 km (2,500 mi.) /inertial	Mk 2 RV cluster, 3 x UK-designed ET.317 @ 200 kT
Polaris A3TK (Chevaline)	1982 - 1996	> 16,193 kg (> 35,700 lb)	9.45 m (31.0 ft)	1.37 m (54 in)	2 (solid)	3,138 km (1,950 mi.) / inertial	UK RV cluster, 2 x UK-designed improved ET.317 @ 225 kT + penetration aids
Trident II D5 (UGM-133)	1996 - present	58,967 kg (130,000 lb)	13.6 m (44.6 ft)	2.11 m (83 in)	3 (solid)	> 6,437 km (> 4,000 mi.) / stellar inertial	The original UK-designed warhead is thought to be similar to a 100 kT US W76 In about 2011, UK adopted the US-designed W76-1 nuclear warhead and later adopted the Mk-4A reentry vehicle.
Trident II D5LE (Life extension version)	2017 - present	Same as above	Same as above	Same as above	Same as above	Same as above	US-designed W76-1 nuclear warhead and Mk-4A reentry vehicle

Polaris A3T and A3TK (Chevaline)

- Polaris A3T missiles were deployed aboard the four UK Resolution-class SSBNs starting in 1968.
  - This was the final production model Polaris SLBM, incorporating hardened missile electronics to resist ABM attack in the boost phase, but not a hardened warhead.
  - Each missile carried three UK-designed E.317 200 kT thermonuclear warheads in US-designed Mark 2 re-entry vehicles.
  - The multiple warheads were aimed at one target, but could be set to impact up to 70 km from each other.
- In the early 1980s, UK implemented a life extension program called “Chevaline”.
  - Reduced the number of E.317 warheads from three to two, increased warhead yield to 225 kT, employed UK-designed hardened re-entry vehicles to protect the warhead, and added a Penetration Aids Carrier (PAC) that dispensed 27 re-entry decoys.
  - This UK-designed re-entry vehicle was the 1st to use 3-Dimensional Quartz Phenolic (3DQP) as the heat shield + neutron radiation shield material.
    - AVCO subsequently was licensed to produce 3DQP for US warheads.
  - Penetration aids increased the likelihood of defeating the Soviet anti-ballistic missile system.

Polaris A3T and A3TK (Chevaline)

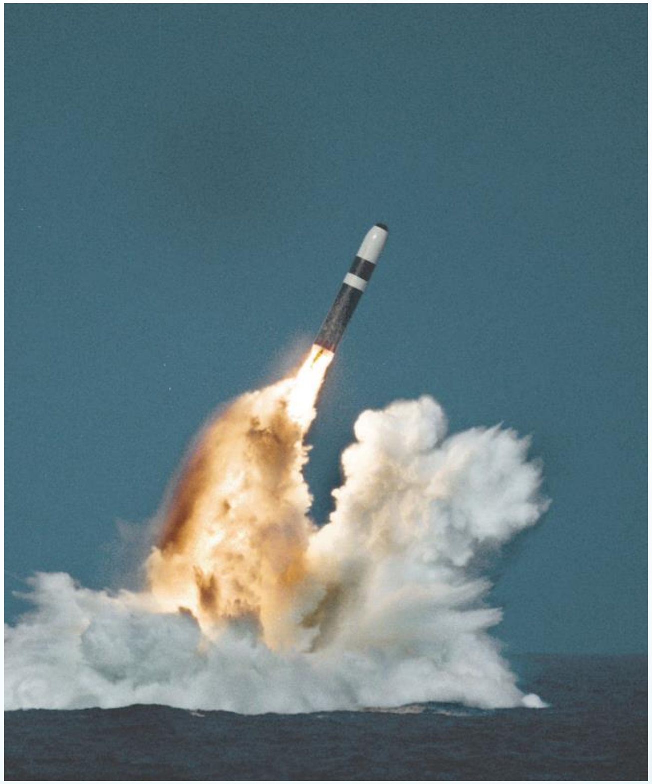
- Life extension enabled the UK to delay commitment to Trident SLBM program.
- The upgraded Polaris A3TK, with the Chevaline MRV warheads, were in service from 1982 – 1996 on Resolution-class SSBNs.
  - The last US Polaris A3 SLBMs were retired in 1982, 14 years before the retirement of the UK's Polaris A3TK.
  - The US Polaris SSBNs transitioned to Poseidon and Trident I SLBMs. The UK SSBN fleet never transitioned to either of these SLBMs.
  - The UK's Resolution-class SSBNs were replaced by Vanguard-class SSBNs, which was designed for the Trident II (D5) SLBM. *HMS Vanguard* made its 1st deterrent patrol with Trident II missiles in 1994.



Chevaline. Source: https://www.flickr.com/photos/indieflickr/109835335/

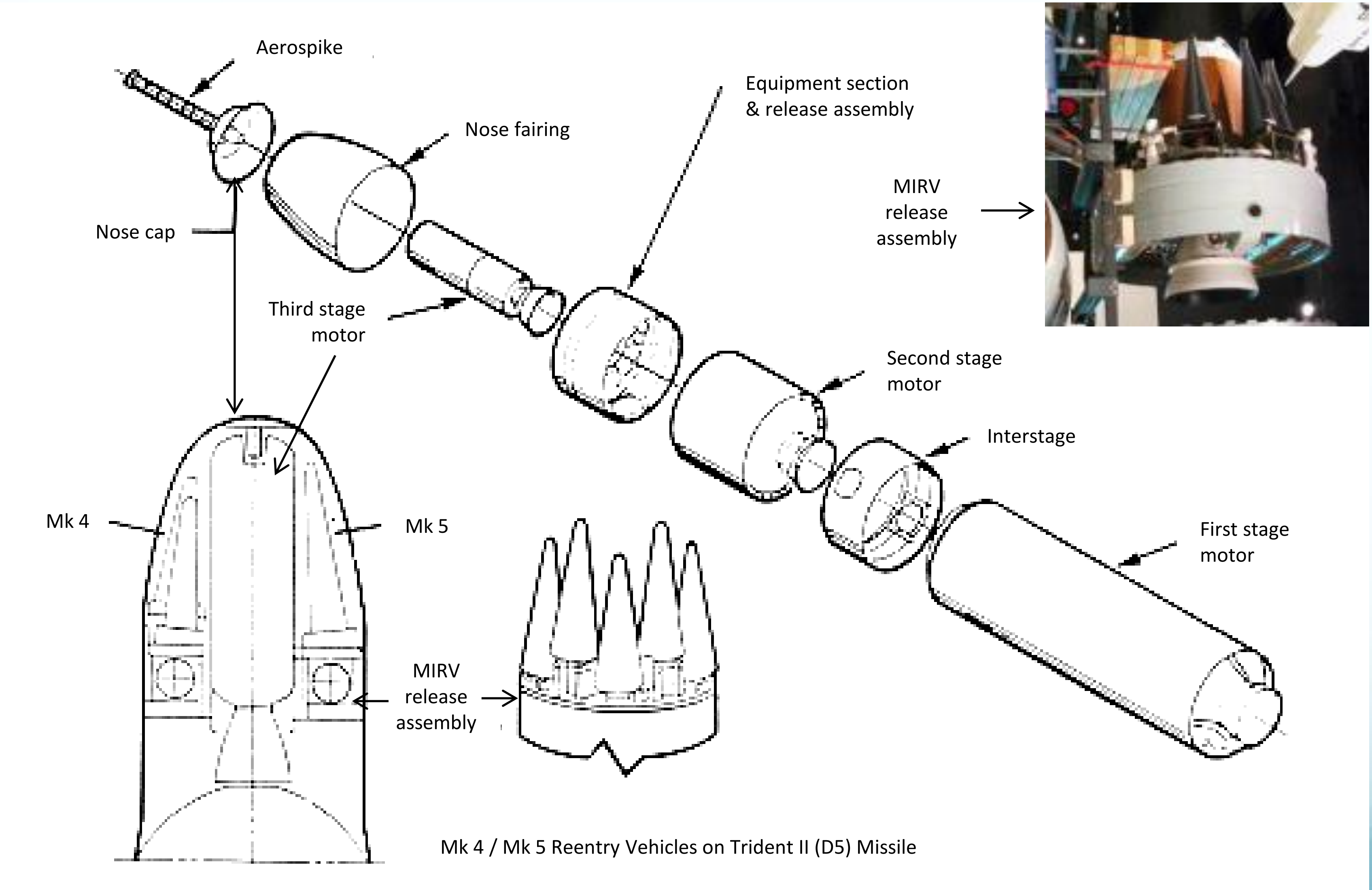
Trident II D5 (UGM-133)

- Under the March 1982 Trident Sales Agreement, the UK leases a total of 58 Trident II missiles from the US
- Deployed on UK Vanguard-class and US Ohio-class SSBNs.
- Range: > 6,500 naut. mi (> 12,000 km).
- Mk 6 Mod 1 astro-inertial guidance system, which is capable of Global Positioning System (GPS) updates; CEP about 100 m (328 ft).
- UK IOC on Vanguard-class SSBNs was in 1994.
  - UK SSBNs deploy with a maximum of 8 Trident II (D5) SLBMs with a total of 40 warheads per boat (an average of five warheads per missile).
  - In about 2011, UK adopted the US-designed W76-1 nuclear warhead and later adopted the Mk-4A reentry vehicle.
- The Trident II currently make up 100% of the UK strategic nuclear deterrent.
- Trident II D5 Life Extension Program will extend the life of the missile to 2042. Life-extended Trident II D5 missiles (D5LE) were introduced to the SSBN fleet in March 2017.



Trident II (D5) launch.
Source: https://en.wikipedia.org/wiki/UGM-133_Trident_II#/

Trident II D5 details



MIRV
release
assembly →

Mk 4 / Mk 5 Reentry Vehicles on Trident II (D5) Missile

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

UK disposition of decommissioned nuclear submarines

Inventory of decommissioned submarines

Submarine	Location	OSD	Hull age	Status
Dreadnought	Rosyth	1980	58	Defuelled
Conqueror	Devonport	1990	50	Defuelled
Warspite	Devonport	1991	54	Defuelled
Churchill	Rosyth	1991	50	Defuelled
Swiftsure	Rosyth	1991	48	Being dismantled
Courageous	Devonport	1992	49	Defuelled (museum)
Revenge	Rosyth	1992	52	Defuelled
Valiant	Devonport	1994	55	Defuelled
Resolution	Rosyth	1994	53	Defuelled
Repulse	Rosyth	1996	52	Defuelled
Renown	Rosyth	1996	53	Defuelled
Splendid	Devonport	2003	40	Fuelled
Sovereign	Devonport	2006	48	Fuelled
Spartan	Devonport	2006	41	Fuelled
Superb	Devonport	2008	45	Fuelled
Trafalgar	Devonport	2009	38	Fuelled
Sceptre	Devonport	2010	43	Fuelled
Turbulent	Devonport	2012	37	Fuelled
Tireless	Devonport	2014	36	Fuelled
Torbay	Devonport	2017	35	Fuelled
Trenchant	Devonport	2019	32	Active
Talent	Devonport	2021	31	Active
Triumph	Devonport	2023	30	Active

- Plans for the safe and timely disposal of nuclear submarines have been discussed for decades but successive UK governments have avoided difficult decisions and handed the problem on to their successors.
- There currently are 20 former Royal Navy nuclear submarines awaiting disposal; 7 are in Rosyth, Scotland and 13 are in Devonport, Plymouth.

Status of UK submarine disposal in mid-2018.
“OSD” = Out of Service Date. “Hull age” = years since hull laid down.

Source: https://www.savetheroyalnavy.org/the-painfully-slow-process-of-dismantling-ex-royal-navy-nuclear-submarines/

Submarine afloat storage

- After decommissioning, retired nuclear submarines are placed in "afloat storage" in non-tidal basins in the Rosyth Dockyard in Scotland and the Devonport dockyard in Plymouth. Both locations are nuclear licensed sites operated by Babcock International for the MoD.
  - Classified equipment, stores and flammable materials are removed along with with rudders, hydroplanes and propellers while the hull is given treatments to help preserve its during afloat storage.
- Defueling nuclear submarines prior to or during afloat storage ended in 2002, when the UK Office of Nuclear Regulation (ONR) determined that defueling facilities at the dockyards were out of date.
- The subs in afloat storage do not represent a great hazard but maintaining them safely while they await dismantling is a growing cost for the UK Ministry of Defense (MoD).
- In 2017, it was reported that a total of £16m was spent in a five-year period on the 19 laid-up submarines at Roysth and Devonport (the 20th sub, Torbay, joined the 19 other decommissioned subs in "afloat storage" in July 2017).

Submarine afloat storage

Devonport Dockyard

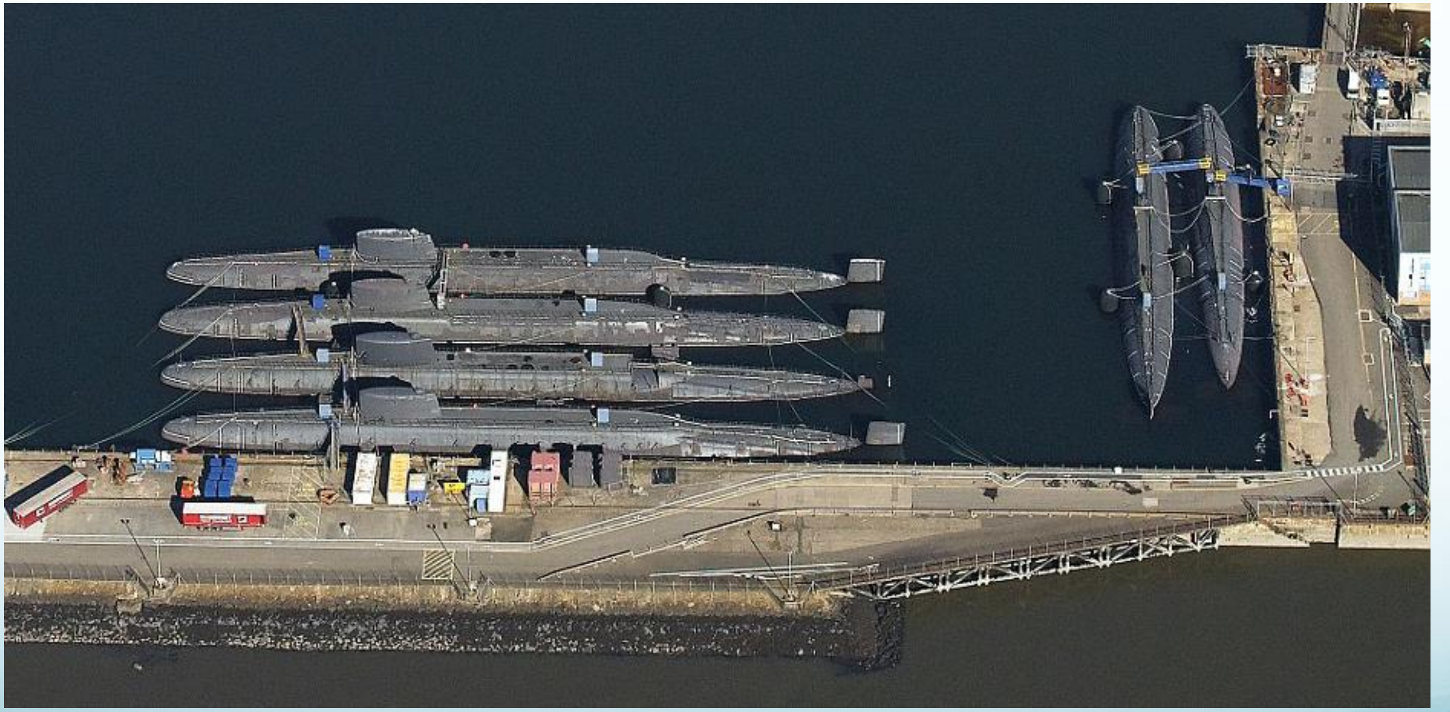
- In mid-2018, there were 13 decommissioned SSNs laid up in Devonport Dockyard Number 3 Basin, more than entire active UK submarine fleet (10).
- The flotilla of decommissioned submarines at Devonport Dockyard will continue to grow. Three more Trafalgar-class SSNs will decommission and join them before 2023, with 4 larger Vanguard-class SSBNs to follow between 2028 - 34.

Source: https://www.savetheroyalnavy.org/the-painfully-slow-process-of-dismantling-ex-royal-navy-nuclear-submarines/

Submarine afloat storage

Rosyth Dockyard

- In mid 2018, seven decommissioned Royal Navy nuclear submarines were in "afloat storage" at Rosyth Dockyard as they await dismantling. All have been defueled.
- They include the former SSBNs *HMS Resolution, HMS Repulse, HMS Renown* and *HMS Revenge*, pictured in the foreground below. Also included are the SSNs *HMS Churchill* and *HMS Swiftsure*, pictured right. *HMS Swiftsure* is the lead ship for demonstrating the processes to be used in the MoD's Submarine Dismantling Project.



Source: Ken Whitcombe Aerial Photography Solutions via The Daily Mail, adapted from http://www.dailymail.co.uk/news/article-4095364/Where-Cold-War-workhorses-die-Dismantling-work-set-begin-seven-decommissioned-Royal-Navy-nuclear-submarines-Rosyth-dockyards.html

Submarine dismantling project

- MoD's Submarine Dismantling Project (SDP) began in 2016 when the former *HMS Swiftsure* was selected to be the first submarine to enter the SDP process developed by the MoD and Babcock International.
- *HMS Swiftsure* will be dismantled entirely and the process studied and refined before contracting is agreed for dismantling the remaining decommissioned submarines. SDP activities will extend over several decades, with the initial *Swiftsure* demonstration / validation phase taking at least 15 years.
- The following waste streams will be generated by SDP:
  - Only about 1% of each submarine will be characterized as intermediate-level radioactive waste (ILW); mainly the reactor pressure vessel (RPV).
  - About 4 % will be low-level radioactive waste (LLW), including most of the Nuclear Steam Rising Plant (NSRP) components (steam generators, primary pumps, the reactor pressure vessel head).
  - About 5% will be non-radioactive hazardous waste.
  - The remaining 90% is mostly high-grade steel that can be sold for recycling (3,500 - 4,800 tons from SSNs, about 6,700 tons from Resolution-class SSBNs).

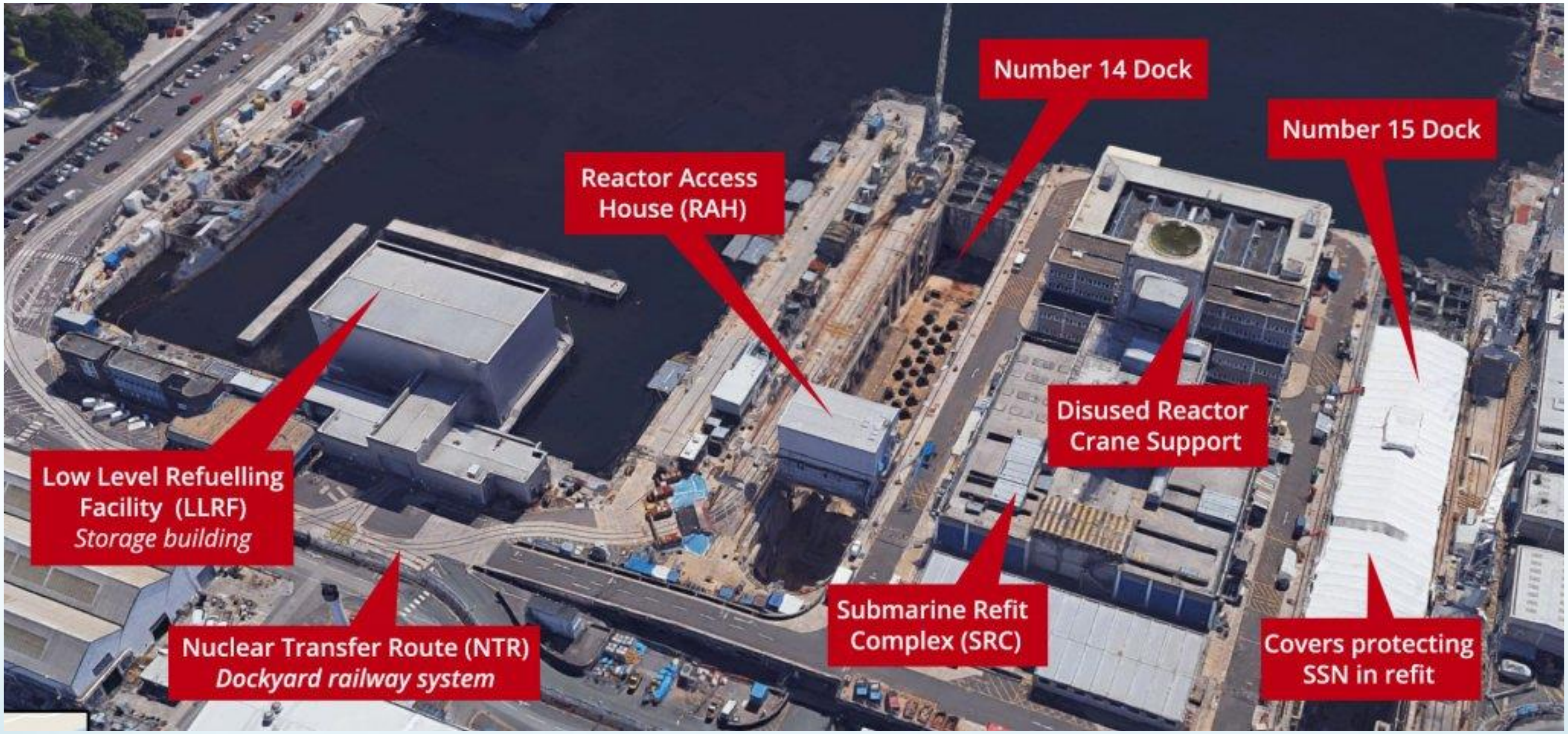
Submarine dismantling project

Process overview

- The process consists of the following four major stages:
  - Stage I: Remove all LLW from the submarine,
  - Stage II: Remove all ILW, including the reactor pressure vessel (RPV).
    - In July 2016, Capenhurst Nuclear Services (CNS), near Chester was selected as the preferred supplier for storing reactor pressure vessels from retired Royal Navy submarines. In July 2017, CNS was re-branded as URENCO Nuclear Stewardship.
    - This facility will be designed to safely and securely store the RPVs for up to 100 years.
  - After removing all remaining non-radioactive hazardous waste, the remaining non-radioactive material will be recycled for re-use by conventional ship-breaking techniques. This work will take place in the UK to maintain the security of UK nuclear submarine technology.
  - Final disposition of radioactive items and waste from submarine decommissioning will be in the UK Geologic Disposal Facility (GDF) being developed by the UK Department of Energy and Climate Change. The GDF is not expected to be available until after 2040.

Submarine dismantling project

Stage I & II dismantling facilities at Devonport



The upgraded nuclear facilities at Devonport that will be used for the submarine de-fuelling and dismantling process.

Source: https://www.savetheroyalnavy.org/the-painfully-slow-process-of-dismantling-ex-royal-navy-nuclear-submarines/

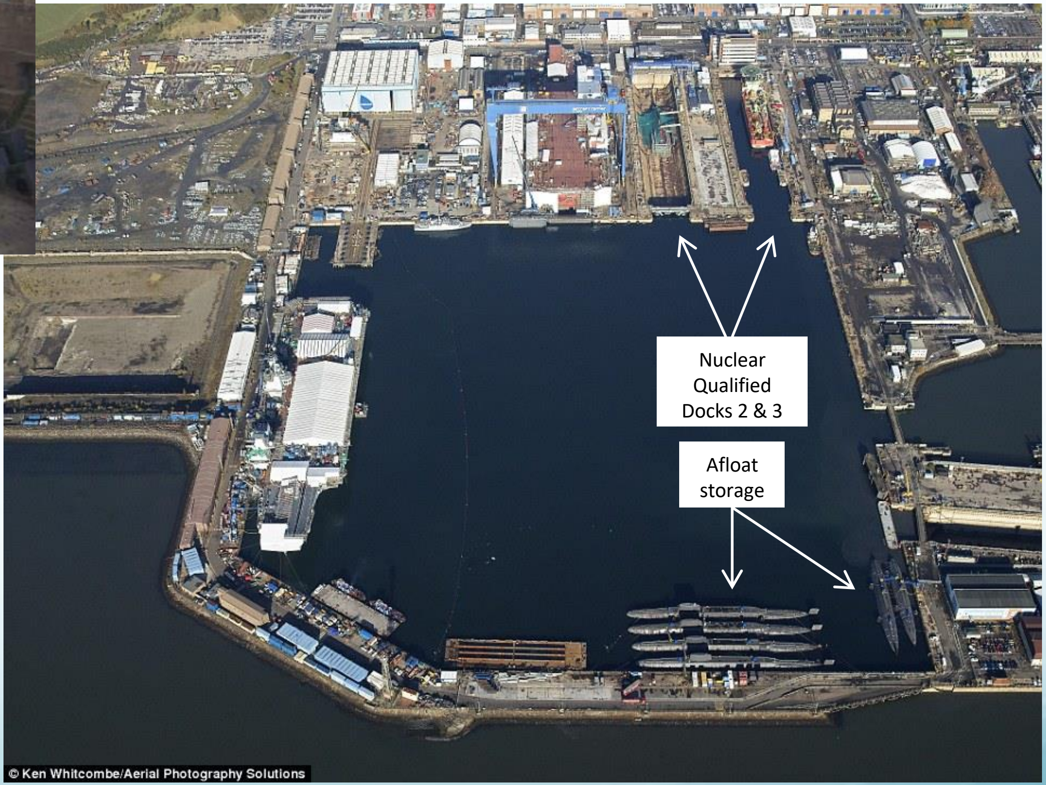
Submarine dismantling project

Stage I & II dismantling facilities at Rosyth

SSN in Rosyth dock.
Source: http://www.neimagazine.com/

- In December 2014, The Office for Nuclear Regulation (ONR) granted consent for the project to dismantle the seven nuclear submarines at Rosyth.

- The MoD's Submarine Dismantling Program (SDP) will demonstrate its dismantling processes at Rosyth on the *HMS Swiftsure,* which is one of the seven boats that have been in afloat storage in the Dockyard.



Source: Ken Whitcombe Aerial Photography Solutions via The Daily Mail, http://www.dailymail.co.uk/

Submarine dismantling project

Stage I process details

- Stage I low-level waste (LLW) removal:
  - A special crane has been built at Rosyth for removing LLW from *Swiftsure.*
  - A covered accessway has been built between a purpose-built dockside facility and the submarine to ensure the whole LLW removal operation is completely contained and safely controlled.
  - A hole cut in the top of the submarine hull will be used for access to the reactor compartment and associated areas, and will be used to safely remove all of the radioactive and contaminated LLW.
  - The waste will then be packaged for transport and disposal using existing LLW management processes.
  - Removal of LLW from *Swiftsure* is planned to be completed in 2018.

Source: http://www.nwemail.co.uk/Blueprint-for-breaking-up-Britains-nuclear-subs-unveiled-a655a30f-fb14-46db-97fd-febf67472418-ds

Submarine dismantling project

Stage II process details

- Stage II intermediate-level waste (ILW) removal:
  - This stage focuses on removing the Nuclear Steam Rising Plant (NSRP aka NSSS, Nuclear Steam Supply System).
    - The Reactor Pressure Vessels (RPV) is classed as Intermediate Level Waste (ILW).
    - Other NSRP components, including the RPV head, are classified as LLW.
  - The first main task will be to remove the two steam generators through holes cut in the top of the pressure hull and place them into containers suspended from the Reactor Access House (RAH).
  - Then the primary circuit pipework, pressurizer and coolant pumps can be removed.
  - The RPV head is removed and a temporary head closure is put in place.
  - The primary shield tank (PST) surrounding the RPV will be drained of hazardous chemicals
  - The RPV is then attached to a lifting cradle in the RAH. The RPV is then lifted out of the submarine and placed in a special container ready on the dock bottom

Source: http://www.nwemail.co.uk/Blueprint-for-breaking-up-Britains-nuclear-subs-unveiled-a655a30f-fb14-46db-97fd-febf67472418-ds

Submarine dismantling project

Stage II process details

- Stage II intermediate-level waste (ILW) removal (cont'd):
  - Once the RPV is sealed in the container, it is lifted onto a transporter and taken by road to Capenhurst where it will be stored in purpose-built above ground buildings until at least 2040.
  - The remaining parts of the PST are also removed and cut up into manageable sizes.
  - All liquids and materials removed during the process have to be sorted, segregated, size-reduced if necessary and packed into appropriate containers ready to be stored, reprocessed or recycled.

Source: http://www.nwemail.co.uk/Blueprint-for-breaking-up-Britains-nuclear-subs-unveiled-a655a30f-fb14-46db-97fd-febf67472418-ds

UK nuclear surface ship and marine reactor concepts

UK Maritime Commission merchant ship studies

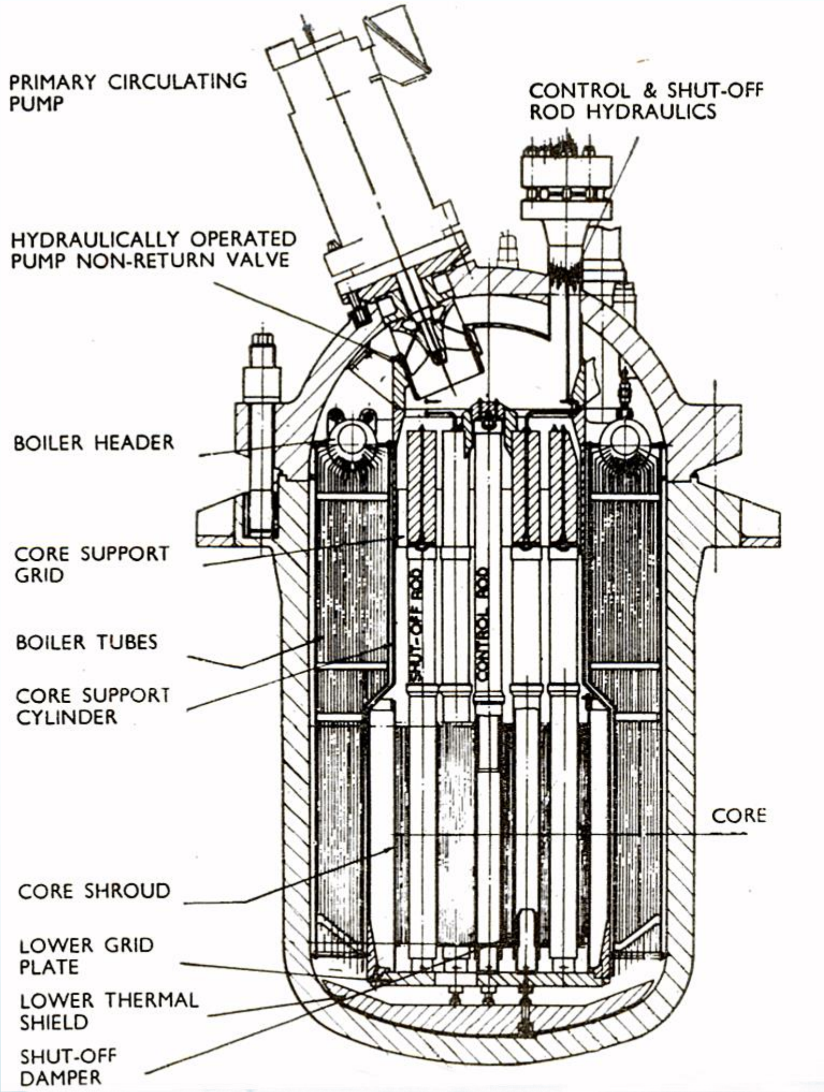
- In 1955, initial UK interest in marine reactors for merchant ships focused on reactors moderated by organic liquid.
- In 1960 the Ministry of Transport requested feasibility studies for a nuclear powered 65,000 ton deadweight commercial tanker designated Y127.
  - Industry participants for the nuclear propulsion plant studies were English Electric, Hawker Siddley, Babcock and Wilcox, Mitchell Engineering and the Nuclear Power Group.
  - The nuclear propulsion plant concept for the Y127 commercial tanker used either an indirect cycle boiling water reactor or an organic moderated reactor, delivering 20,000 shp to a single screw. The industry team was asked to consider this propulsion plant for use in the Y501 Fast Admiralty Replenishment Tanker.
  - The conceptual Y127 commercial tanker measured 775 ft. in length, 112.5 ft. beam, and a maximum loaded draught of 43.5 ft.

UK Maritime Commission merchant ship studies

- By 1963, the UK Maritime Commission was focused on a smaller nuclear powered tanker: 27,000 ton, 20,000 shp.
- Two marine reactor concepts were selected for use in UK commercial marine vessels:
  - Vulcain integral pressurized water reactor
  - Integral Boiling Reactor (IBR)
- Both reactors were designed to be removed from the ship as a unit and replaced by another complete unit.
  - Onboard refueling was avoided.
- There were no plans for a land-based prototype reactor.

Vulcain integral PWR

- Vulcain was a compact, integral PWR proposed to the UKAEA in 1961 by Babcock and Wilcox (USA) and Belgo-Nucleaire.
- Reactor, steam generator and primary circulating pump volute were inside the reactor vessel; steam drums and circulating pump motor were outside the reactor vessel.
- Vulcain was a "spectral shift" PWR with a variable moderator that was a mix of light and heavy water. During the reactor lifetime, the ratio of light water-to-heavy water was increased to compensate for the loss of reactivity from fuel burnup.



Source: New Scientist (No. 327) Feb 1963

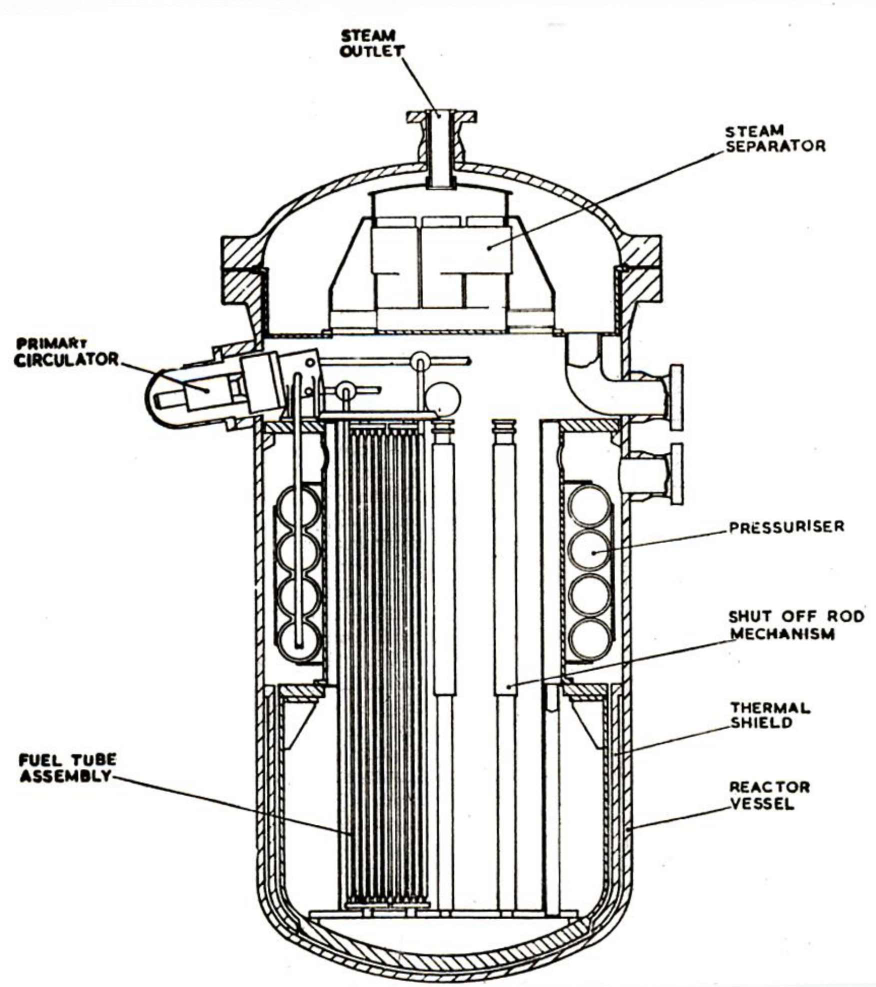
Integral Boiling Reactor (IBR)

Indirect cycle

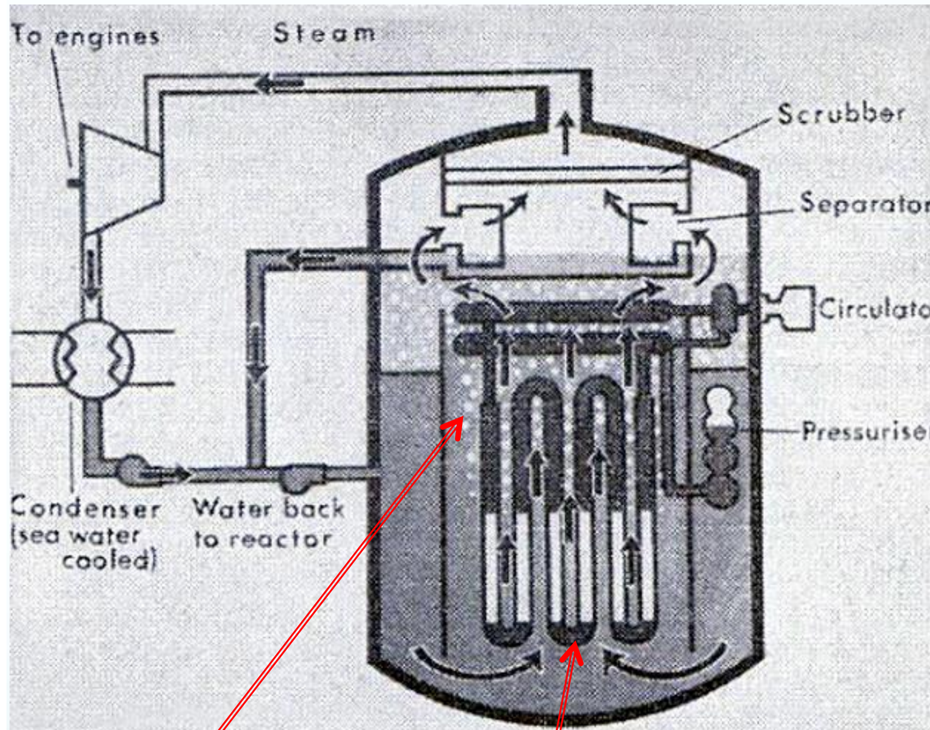
- IBR was a compact, integral, “packaged” reactor designed by UKAEA. The reactor core, heat exchanger, primary circulating pumps, and a pressurizer all were contained within the reactor vessel.
  - In the indirect cycle core, the fuel rods are enclosed in pressure tubes that are joined to form a closed, sub-cooled (not boiling) primary cooling circuit with a circulating pump and pressurizer.
  - Heat from this primary cooling circuit is transferred across the tube walls into the secondary coolant, which boils in the core region and generates steam for driving a propulsion turbine. The turbine exhaust steam is condensed and returned back to the reactor.
- Distributed nuclear “poison” in fuel elements compensate for reactivity from high fuel loading early in life. Then poison and fuel burnup at comparable rates throughout the life of the core, simplifying the operational control of core reactivity with control rods.

Integral Boiling Reactor (IBR)

Indirect cycle



Source: New Scientist (No. 327) Feb 1963



Source: New Scientist (No. 330) Mar 1963

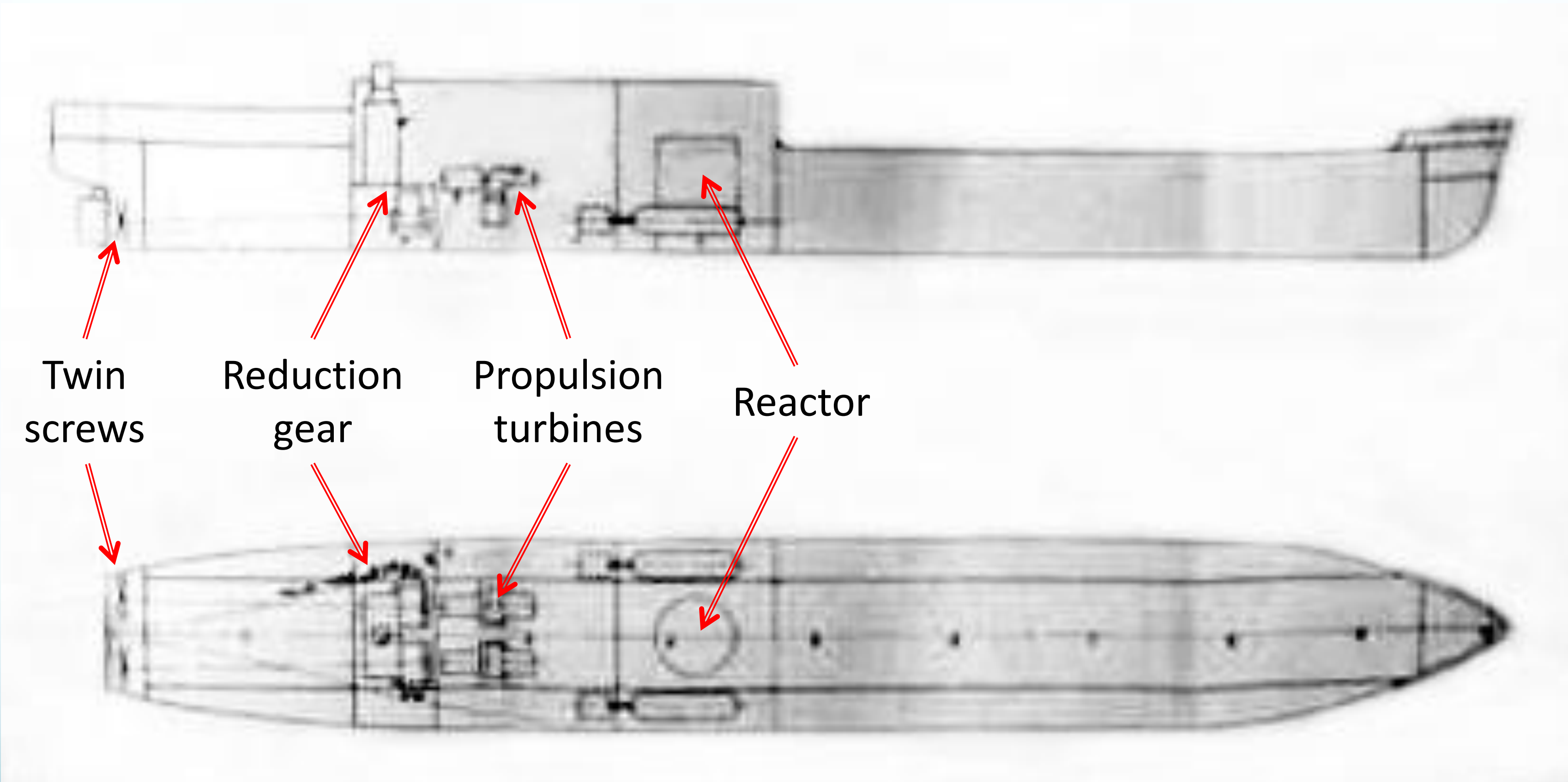
Secondary coolant boils in core region & generates steam for the turbine

Small volume, sub-cooled, closed primary coolant tube circuit with circulator & pressurizer

Admiralty tanker studies

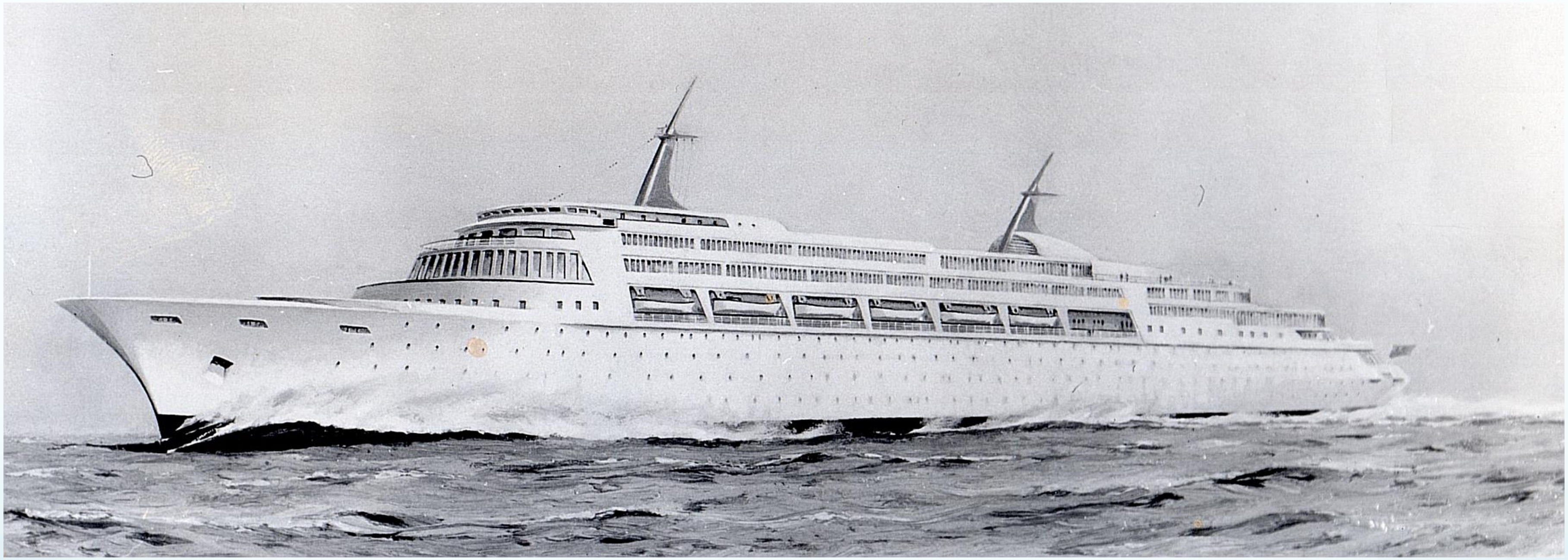
- Admiralty interest in surface ship nuclear propulsion began in 1958 with a 140 – 170 MWt gas-cooled reactor design concept for a 50,000 shp fleet tanker.
- In following years, other reactor concepts were proposed for the fleet tanker, including pressurized water reactor, boiling water reactor, organic moderated reactor, and steam cooled heavy water reactor.
- In 1960, the Admiralty developed a requirement for a 35,000 ton Fast Admiralty Replenishment Tanker designated Y501, with a commercial counterpart designated Y502.
- The nuclear propulsion plant being studied by the Ministry of Transportation for the Y127 commercial tanker also was considered for the Y501 / Y501 design; either an indirect cycle boiling water reactor or an organic moderated reactor.
- The Y501 / Y502 designs were abandoned in November 1961 because they was not cost effective.

Fast Admiralty Replenishment Tanker Y501 concept



Source: Adapted from Royal Fleet Auxiliary Historical Society

United Kingdom fast nuclear powered ocean liner concept



Source: http://ansnuclearcafe.org/2018/01/25/

UK marine nuclear power current trends

UK current trends

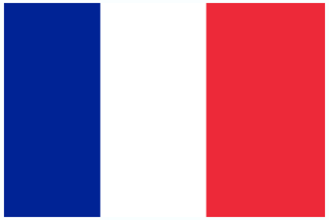
- **Operations**
  - UK plans to maintain a fleet of 7 SSNs and 4 SSBNs
  - The new Astute-class SSNs are proving to be very capable boats.
  - By 2020, all of the Royal Navy's submarines will be homeported at HMNB Clyde in Faslane Scotland. Other submarine support activities also are moving to Faslane. The new nuclear power and submarine schools in Faslane are expected to be in operation by 2022.
  - A fuel clad leak was detected in 2012 during operation of the PWR2 Core H in the STF prototype at NTRE Dounreay. That reactor was permanently shutdown in 2015. Results from examining the PWR2 Core H removed from STF to determine the cause of the fuel clad leak will have important implications for the Royal Navy's fleet of Astute-class SSNs and Vanguard-class SSBNs, which are operating PWR2 Core H. A second refueling of *HMS Vanguard* started in December 2015. Depending on the outcome of the STF core examination, additional (and originally unplanned) refueling of operating submarines may be required.
- **New build**
  - Astute-class SSN new-build is continuing. Construction of the seventh (and last) Astute-class boat, *HMS Agincourt*, began in May 2018, with an expected completion date in 2024.
  - The Dreadnought-class SSBN new-build program started in mid-2016, with delivery of the lead ship, *HMS Dreadnought,* as early as 2028.
  - Astute-class and Dreadnought-class subs are being built by BAE Systems Maritime, at the Devonshire Dockyard Complex in Barrow-in-Furness, which is being significantly updated.

UK current trends

- **Phase-out / replacement**
  - The seven Trafalgar-class SSNs are being replaced on a 1-for-1 basis by Astute-class SSNs. Four have retired. The last three Trafalgar-class boats scheduled to retire in 2019, 2021 and 2022.
  - Vanguard-class SSBNs will start retiring in about 2030. They will be replaced by Dreadnought-class SSBNs on a 1-for-1 basis.
- **New submarine development**
  - The Dreadnought-class SSBN has moved from design and development to long-lead procurement and construction.
  - The Maritime Underwater Future Capability (MUFC) program is intended to define the replacement for Astute-class SSNs, which will not be required until the mid-to-late 2030s.
- **New marine reactor development**
  - The US-UK Mutual Defense Agreement (MDA), Article III, was modified in July 2014 to authorize the transfer from the US to the UK of new reactor technology, spare parts, replacement cores and fuel elements. While this arrangement will speed the development, and likely reduce the cost, of the PWR3 being developed for the Dreadnought-class SSBN, it will make the UK more dependent on US naval reactor technology.
  - The MoD has announced that the Rolls-Royce PWR3 will be ‘based on a modern US plant’. A likely candidate is the S9G reactor used on US Virginia-class SSNs.
  - The Shore Test Facility (STF) PWR2 prototype reactor at NTRE Dounreay was permanently shutdown in 2015. There are no plans for a new UK prototype submarine reactor.

UK current trends

- **Final disposition of retired nuclear submarines**
  - 20 decommissioned submarines are in “afloat storage” at Devonport and Rosyth dockyards. Nine of these submarines have not yet been defueled. The number of decommissioned submarines awaiting defueling will increase as three more Trafalgar-class SSNs are retired by 2022. Vanguard-class SSBNs will start retiring in about 2030.
  - Ex-*HMS Swiftsure* is the first retired Royal Navy nuclear submarine to enter the Submarine Dismantling Program (SDP) and is being used to validate the SDP process. SDP started in 2016.
  - The Nuclear Decommissioning Authority’s (NDA) Sellafield site in Cumbria will continue to provide long-term storage for irradiated (spent) fuel removed from decommissioned nuclear submarines.
  - The UK Ministry of Defense (MoD) announced in July 2016 the selection of Capenhurst Nuclear Services (now known as URENCO Nuclear Stewardship) as the site for interim storage of reactor pressure vessels (RPVs) removed from decommissioning nuclear submarines by the SDP. The RPVs are classified as intermediate-level radioactive waste.
  - Final disposition of radioactive items and waste from the SDP will be in the UK Geologic Disposal Facility (GDF) being developed by the UK Department of Energy and Climate Change. The GDF is not expected to be available until after 2040.



France

- Submarines (SSN / SNA and SSBN / SNLE)
- Aircraft carrier
- Non-propulsion marine nuclear applications

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

France

Table of Contents

The beginning of the French marine nuclear power program

France marine nuclear timeline

October 1945
Commissariat à l'énergie atomique (CEA) established

1954
French Admiralty secured funding for a nuclear sub
2 Jul 1955
Construction began on 1st nuclear sub, Q-244, with natural U PHWR
5 Oct 1956
Navy instructed to develop a nuclear missile delivery capability
1958
Q-244 construction stopped; Launched defense HEU production program
7 May 1959
US provided France with enriched U for research purposes, but not sub reactor design information
1959
Q-244 program abandoned; Nuclear Propulsion Group established in CEA; Cadarache established as site for land-based prototypes

1960
Start construction on Pierrelatte U enrichment plant
13 Feb 1960
1st French nuclear test
18 Mar 1960
PAT prototype approved
6 Dec 1960
10-yr shipbuilding plan approved: 4 SSBNs + 1 SSN
14 Aug 1964
PAT prototype initial criticality
1966
Gymnôte 2 SLBM test sub completed
1968
1st M-1 SLBM launched
24 Aug 1968
1st French thermonuclear test

1 Dec 1971
1st French sub, *Le Redoutable* SSBN, commissioned
28 Jan 1972
Le Redoutable SSBN 1st deterrent patrol, Initial Operating Capability (IOC) with M-1 SLBM
1974
IOC M-2 SLBM
1975
CAP prototype operational at Cadarache
1977
IOC M-20 SLBM

1982
Améthyste program initiated to develop improved Rubis-class SSN
23 Feb 1983
1st French SSN, *Rubis,* commissioned
1985
IOC M-4A SLBM, CAP conversion to RNG started
1986 – 1988
Rubis derivative proposed to Canada
14 May 1988
Improved SSN, *Améthyste,* launched
1989
1st Rubis-class SSN starts *Améthyste* upgrade, RNG prototype operational at Cadarache

1992
PAT prototype retired
7 Jul 1993
Last Rubis / Amethyst-class SSN, *Perle,* commissioned
26 Mar 1994
Lead 2nd-gen SSBN, *Le Triomphant,* launched
1995
Last of Rubis-class SSNs completed *Améthyste* upgrade
1996
IOC M-45 SLBM
27 Jan 1996
Last French thermonuclear test
1997
Le Triomphant SSBN 1st deterrent patrol

2001
Nuclear aircraft carrier *Charles de Gaulle* commissioned
2002
Le Redoutable converted to museum ship
2008
Last 1st gen SSBN, *Le Inflexible,* decommissioned
2008
French govt agreed to support Brazil's nuclear submarine program

2010
IOC M-51.1 SLBM
2015
IOC M-51.2 SLBM
2018 - 2019
1st Barracuda-class SSN expected to be launched
2018 - 2020
RES prototype expected to begin operation at Cadarache

1940s	1950s	1960s	1970s	1980s	1990s	2000s	2010s

Timeline for the beginning of the French marine nuclear power program

- **October 1945**: ***Commissariat à l'énergie atomique*** (CEA, French Atomic Energy Commission) was established
  - Responsible for all scientific, commercial, and military uses of nuclear energy
- **Late 1953**: A Marine-CEA Liaison Committee was created to advance the use of nuclear propulsion by the French Navy (Marine National).
  - At the time France did not have enriched uranium.
- **1954**: The French Admiralty secured funding for a nuclear-powered submarine, which was to be powered by a natural uranium fueled, pressurized heavy water-cooled and moderated reactor (PHWR). There was no funding for a land-based prototype.
- **2 Jul 1955**: Construction began in Cherbourg on France's 1st nuclear-powered submarine, to be designated the Q-244.
- **5 Oct 1956**: A French Ministry of Defense directive instructed the Navy to be able to, "contribute (to the strike capability) by delivering missiles from vessels, in particular nuclear-propelled submarines, and possible on-board aircraft", and to reconsider the conditions for aircraft carriers to survive in the nuclear environment.
- **Oct 1957**: President Eisenhower proposed at a NATO conference that the US would be willing to cooperate with NATO member states interested in developing a nuclear-powered submarine.

Timeline for the beginning of the French marine nuclear power program

- **1958**: Construction on Q-244 was stopped when it was determined that the planned heavy water reactor would be too large for the submarine. Other reactor technical issues and material supply chain issues (zirconium and heavy water) contributed to the decision.
- **1958**: Under the Atoms for Peace program, the US provided France with design details for the Shippingport commerical PWR, which was developed by Naval Reactors and became the first US commercial nuclear power plant.
  - This provided French engineers with a detailed introduction to PWR technology.
- **8 January 1959**: Charles de Gaulle was inaugurated as French President.
  - Shortly thereafter, France committed to develop an independent source of enriched uranium production and an independent nuclear deterrent force.
- **7 May 1959**: Under the Franco-American Defense Agreement of 1959, the US agreed to sell France 440 kg (970 lb) of highly-enriched uranium (HEU) for a land-based installation purposes.
  - This uranium could not be used for the Q-244 reactor, but it was used later in France's first land-based reactor prototype.
  - US Congress refused to grant France access to classified submarine reactor design information or to supply a complete naval nuclear propulsion plant as the US had agreed to do for the UK in 1958.

Timeline for the beginning of the French marine nuclear power program

- **1959**: The Q-244 project was finally abandoned.
- Following the experience with Q-244, the following steps were taken in 1959 to build an independent national naval nuclear program:
  - The Commissariat à l'Energie Atomique (CEA) established the Nuclear Propulsion Group (GPN) (later named Nuclear Propulsion Department).
  - 11 September 1959: The French Navy sends to GPN the characteristics required for a nuclear propulsion installation.
  - The Centre for Nuclear Studies at Cadarache was selected as the site for French land-based naval prototype reactors.
  - Development began on France's first uranium enrichment plant at Pierrelatte (Tricastin).
- **6 Dec 1960**: The long-term (1959 and 1969) naval shipbuilding plan was approved. It included the following naval nuclear vessels:
  - 1959 – 1964: one SSBN (SNLE)
  - 1964 – 1969: three SSBNs (SNLEs) + 1 fast attack sub (SNA)
- **1 March 1972:** The Strategic Ocean Force (French: Force océanique stratégique, FOST) was created.

French current nuclear vessel fleet

As of mid-2018

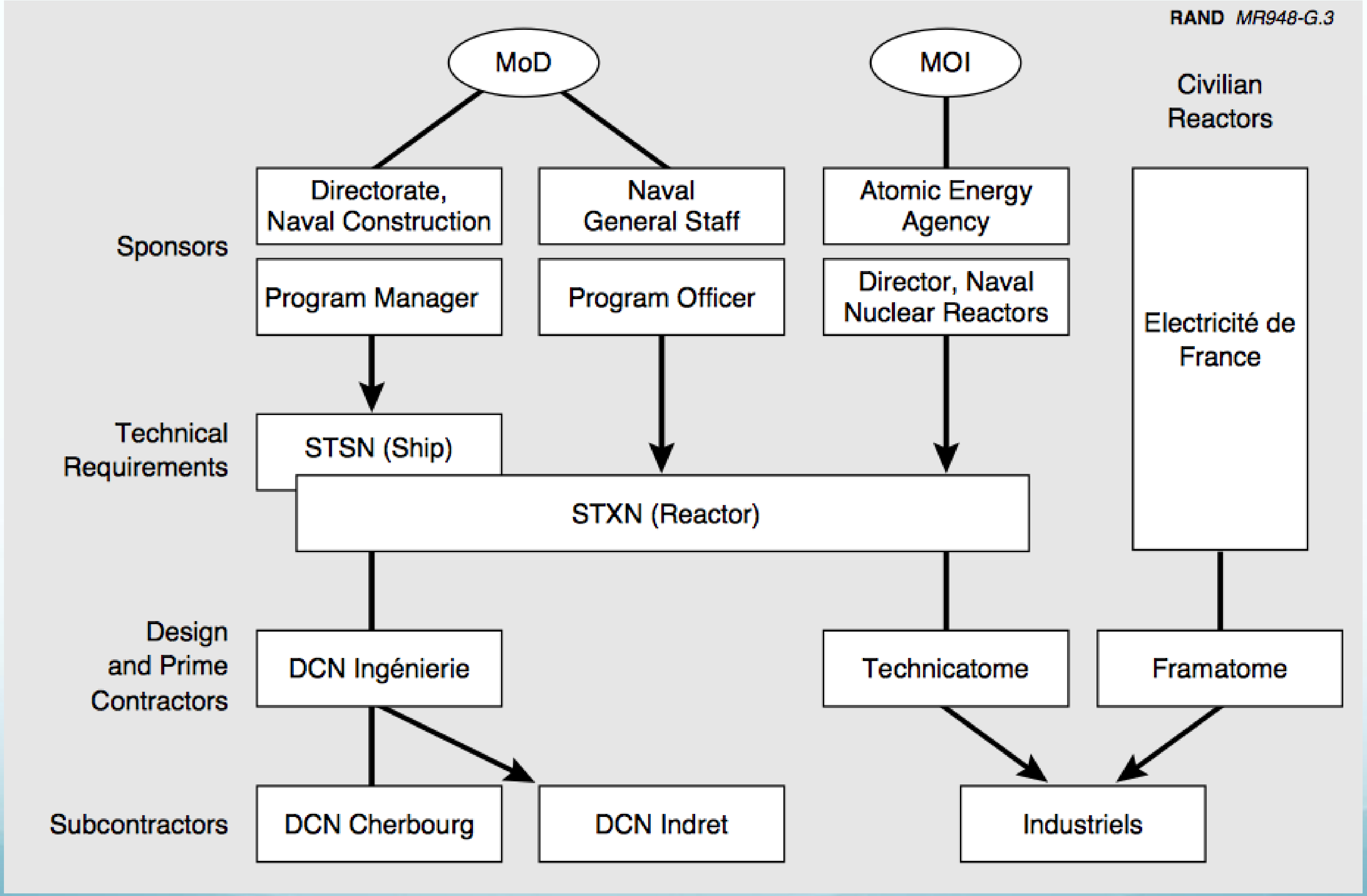
France's current nuclear vessel fleet

As of mid-2018

- The submarine force (***Forces sous-marines***) of France operates an all-nuclear fleet of submarines comprised of the following two classes:
  - Six Rubis / Améthyste-class SSNs based in Toulon, on the Mediterranean, form an attack submarine squadron (Escadrille des Sous-Marins Nucléaires d'Attaque, ESNA).
  - Four Le Triomphant-class SSBNs based at Île Longue, on the Atlantic, form the strategic oceanic force (Force océanique stratégique, FOST).
- France requires at least two SSBNs to be continuously available, with at least one on patrol.
  - The other two SSBNs in the fleet may be in a periodic maintenance or overhaul cycle.
- The French Navy also operates one nuclear-powered aircraft carrier, *Charles de Gaulle*, based in Toulon.
- France does not operate any merchant nuclear-powered vessels.
- The last French diesel-electric submarine, *Ouessant* (S623), was decommissioned in 2001.

French naval nuclear infrastructure

French naval nuclear propulsion program infrastructure



Source: RAND Report MR948-G.3

French naval nuclear propulsion program infrastructure

Function	Responsible organization
Nuclear safety authority	Directeur pour la sûrete nucléaire de Défense (DSND)
Naval reactor design and manufacturing	Areva TA (formerly Technicatome)
Naval reactor fuel manufacturing	Areva TA (formerly Technicatome)
Naval reactor prototypes and nuclear crew training	• Cadarache Nuclear Research Center, operated by Areva TA (formerly Technicatome) for the Commissariat à l'Energie Atomique (CEA) • School of the Military Applications of Atomic Energy of Cherbourg
Nuclear ship design bureau	DCN (Direction des Constructions Navales) Ingenierie
Nuclear ship dismantling and deconstruction:	DCNS Cherbourg for both functions
Long-term nuclear waste management	ANDRA (French National Agency for Radioactive Waste Management)

French naval nuclear propulsion program infrastructure

- Uranium enrichment:
  - mid-1950s: France had no source of enriched uranium.
  - 1957: Two pilot-scale, gaseous diffusion uranium enrichment process lines were tested at the Saclay Nuclear Research Center.
  - 1958: The project was launched to build France's first uranium enrichment plant at the Pierrelatte (Tricastin) site.
  - 1960 to 1967: The Pierrelatte gaseous diffusion plant was built with four enrichment units (low, medium, high, very high).
    - The low-enrichment unit was commissioned in 1964.
    - Production of HEU to support military applications using the high and very high units started in 1966.
    - The entire plant was operational by the beginning of 1967.
  - Enrichment operations at Pierrelatte ended in June 1996 when France decided to stop producing HEU for nuclear weapons purposes. The plant is being decommissioned and dismantled.
  - Only PWR/SNLE reactors for 1st-generation SSBNs required HEU fuel.
    - The first PWR/SNLE-powered SSBN entered service in 1971; the last retired in 2008.
    - All later French naval reactors operate with low-enrichment fuel (LEU ≤ 20% enrichment).

French naval nuclear propulsion program infrastructure

- Shipyards:
  - DCNS Cherbourg shipyard has built all French nuclear submarines.
  - DCNS Brest (The Arsenal at Brest) shipyard built the nuclear-powered aircraft carrier *Charles de Gaulle* and the Q-244 submarine, which was not completed.
    - Major overhauls of ballistic missile submarines take place in Basin 10. Missiles and nuclear fuel are stored at the SSBN base at Île Longue during overhauls.

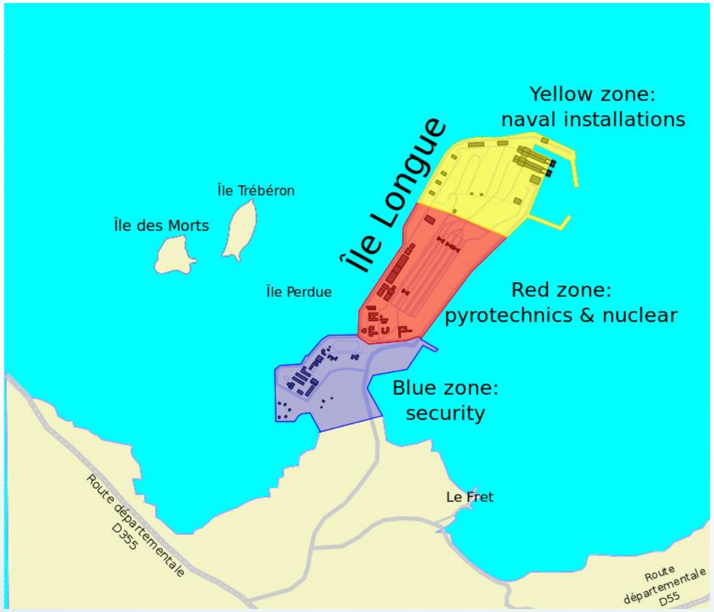
DCNS Cherbourg. Source: DCNS

French naval nuclear propulsion program infrastructure

- Naval bases
  - French nuclear-powered vessels operate from two home ports, the Île Longue (Long Island) Submarine Base, located south of the harbor of Brest, on the Atlantic coast in Brittany, and the Military port of Toulon on the Mediterranean.
  - Île Longue (Long Island) Submarine Base
    - 1965: President Charles de Gaulle selected Île Longue as home base for the nuclear ballistic missile submarines. Work on the base began in 1967.
    - 28 January 1972: *Le Redoubtable* departed on the first French SSBN deterrent patrol.
    - All four Le Triomphant-class SSBNs, which constitute France's Strategic Oceanic Force (Force océanique stratégique, FOST), are based here.
    - Île Longue submarine base provides support, logistical supply and reconditioning material for nuclear ballistic missile submarines. The base undertakes loading and unloading of strategic missiles as well as loading and unloading of fuel components for nuclear steam supply.
    - The port-based French nuclear submarine ballistic missiles undergo maintenance at the base. Each submarine undergoes a maintenance period of forty days at Île Longue after returning from patrol.
    - SSBN missiles and nuclear fuel are removed at Île Longue before undergoing major overhaul at the DCNS shipyard in Brest.

Source: https://www.naval-technology.com/projects/lilelonguesubmarineb/

Île Longue (Long Island) submarine base, Brest



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

Source: http://lepeuplebreton.bzh/2017/03/06/presidentielle-nucleaire-militaire/

Source: http://www.zone-interdite.net/

Île Longue (Long Island) submarine base, Brest

SSBN at Île Longue (Long Island) Submarine Base, Brest, France. Source: https://alchetron.com/Brest-Arsenal

French naval nuclear propulsion program infrastructure

- Naval bases (cont’d)
  - Military port of Toulon (arsenal de Toulon)
    - Home port of the French Navy Mediterranean fleet.
      - A squadron consisting of all six Rubis / Améthyste SSNs (Escadrille des Sous-Marins Nucléaires d'Attaque, ESNA) is based in Toulon along with the nuclear-powered aircraft carrier *Charles de Gaulle (R91)*.
      - In the future, all of the new Barracuda SSNs will be based in Toulon.
    - DCNS operates and maintains the Toulon naval port facilities. It is responsible for the maintenance of the attack submarines, *Charles de Gaulle* aircraft carrier and conventional surface vessels. Services include:
      - Major technical overhauls and refits of the Rubis / Améthyste-class SSNs
      - Major technical overhaul and refits of the future Barracuda-class SSNs
    - The port has 11 drydocks and quays dedicated for ship repair and maintenance services.
      - Missiessy and Malbousquet quays are used by the nuclear attack submarines. These quays have a range of drydocks and are equipped with mobile roofs to accommodate the submarines during the refitting of nuclear equipment.
      - The Milhaud quays are the main mooring points for frigates, aircraft carriers, fleet tankers and landing ships.

Source: https://www.naval-technology.com/projects/toulonnavalbase/

Military port of Toulon

Toulon harbor and naval base. Nuclear-powered aircraft carrier *Charles de Gaulle* in foreground, above.
Source, both photos: http://www.skyscrapercity.com/

French naval nuclear propulsion program infrastructure

- Cadarache Nuclear Research Center
  - Cadarache, established in 1959 near Aix in Provence, includes a secret, licensed nuclear site dedicated to naval nuclear propulsion.
  - The Commissariat à l'Energie Atomique (CEA) manages Cadarach, and with contractor Areva TA (formerly Technicatome), operates the experimental facilities and reactor prototypes that are necessary for the French naval propulsion program to:
    - Sustain the evolutionary development of French naval reactors
    - Test new fuels & new core architectures, validate computational models & simulations, and qualify new concepts
    - Provide technical support for nuclear propulsion operations
    - Train the French Navy operators

Overview of Cadarache site; the ITER (fusion test facility) construction can be seen in the foreground . Source: Shutterstock.com - 1076049362

Source: https://fr.wikipedia.org/wiki/Centre_de_Cadarache#/

Cadarache Nuclear Research Center

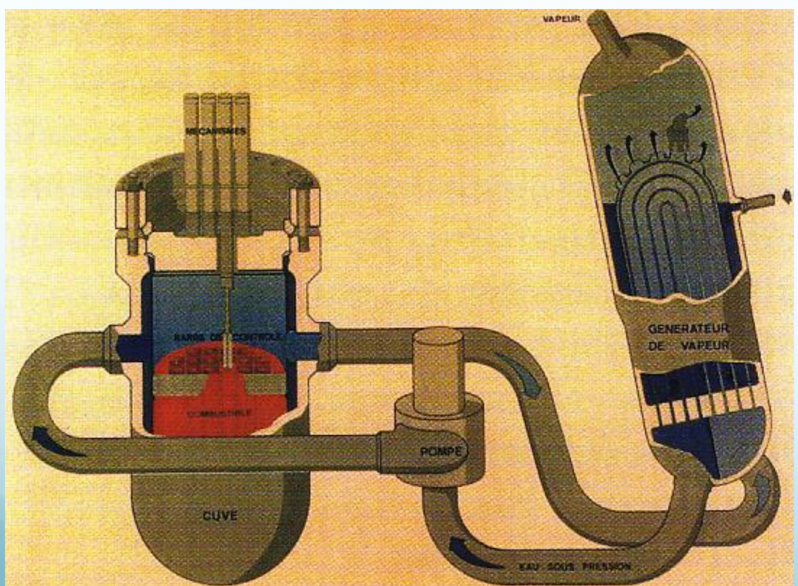
Naval reactor prototypes

Prototype	Years of operation	Comments	Vessels supported by the reactor
PAT [*Pilote A Terre (land-based nuclear unit)*]	1964 to 1992	Resulting fleet reactor: PWR/SNLE	1st-generation (Le Redoutable-class) ballistic missile subs (SNLE/M4)
CAP [*Chaufferie Avancée Prototype (advanced NSSS prototype)*]	1975 to 1985	Resulting fleet reactor: PWR/SNA-72 (aka CAS-48 and K48) Renovated from 1985 to 1989 to become the RNG.	1st-generation (Rubis / Améthyste-class) attack subs (SNA)
RNG [*Réacteur de Nouvelle Génération (new generation reactor)*]	1989 to 2005	Resulting fleet reactor: K15	2nd-generation (Le Triomphant-class) ballistic missile subs (SNLE-NG) and the *Charles de Gaulle* aircraft carrier
RES [*Réacteur d'Essais (Testing Reactor) or Réacteur d'Expérimentations scitnifiques (Scientific Experiment Reactor)*]	Originally intended to replace RNG in about 2009. Not yet operational in 2018.	Resulting fleet reactor: improved K15	2nd-generation (Barracuda-class) attack subs (SNA), also earlier-generation K15 reactors on Le Triomphant-class SNLEs and the *Charles de Gaulle* aircraft carrier

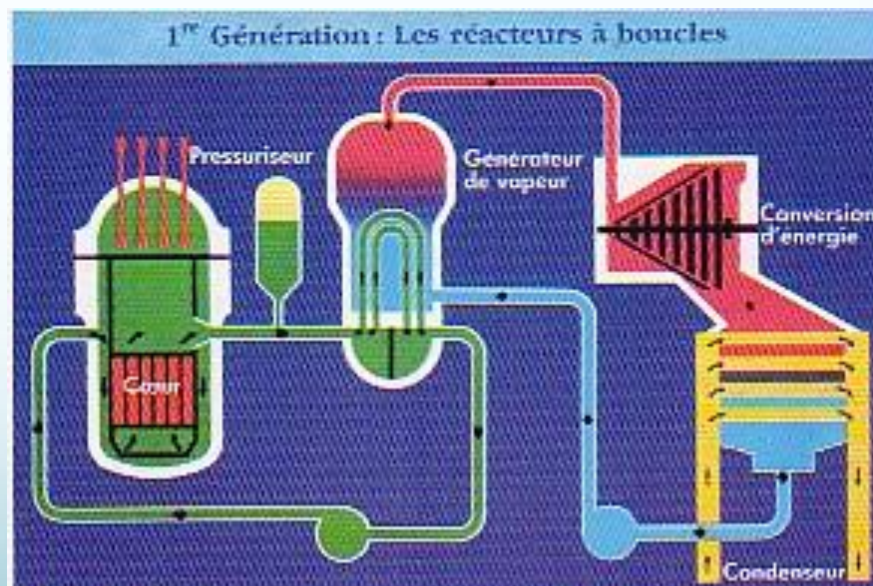
PAT prototype

- The PAT (*Pilote A Terre)* prototype reactor was the first French naval prototype reactor. It was a two-loop PWR, similar to the PWR/SNLE installed later on Le Redoutable-class strategic ballistic missile submarines (SNLEs).
- 17 November 1959: In response to French Navy specifications, CEA's Nuclear Propulsion Group (GPN) submitted a preliminary draft for design and construction of the prototype reactor; estimated cost was 180 million francs (about USD $36.5 million in 1959).

One of two PAT primary loops showing
the reactor (left), U-tube steam generator (right) &
one of two primary coolant pumps per loop (middle)



Primary & secondary system
simplified process flow diagram for PAT and PWR / SNLE

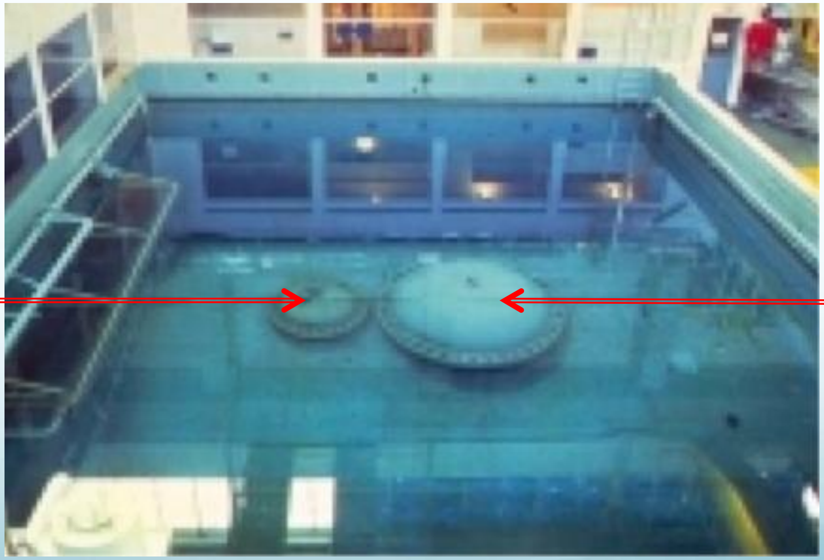


Source, both diagrams: Jean-Luc Delaeter, "La génèse de la propulsion nucléaire en France," 2005

PAT prototype

- 18 Mar 1960: Construction of the PAT [Pilote A Terre] prototype was approved.
- The HEU for the first core was provided by the US Plate-type metallic alloy fuel was selected for the initial core at PAT.
- Reactivity measurements on a PAT core mockup were made at the Azur critical facility (co-located at the PAT). Initial criticality was achieved on 9 April 1962.
- The PAT reactor facility was comprised of two modules: the Pool Module and the Reactor Module, which is installed in the pool.
- In February 1963, the reactor vessel, steam generators, pressurizer and other components were installed in the PAT reactor module.

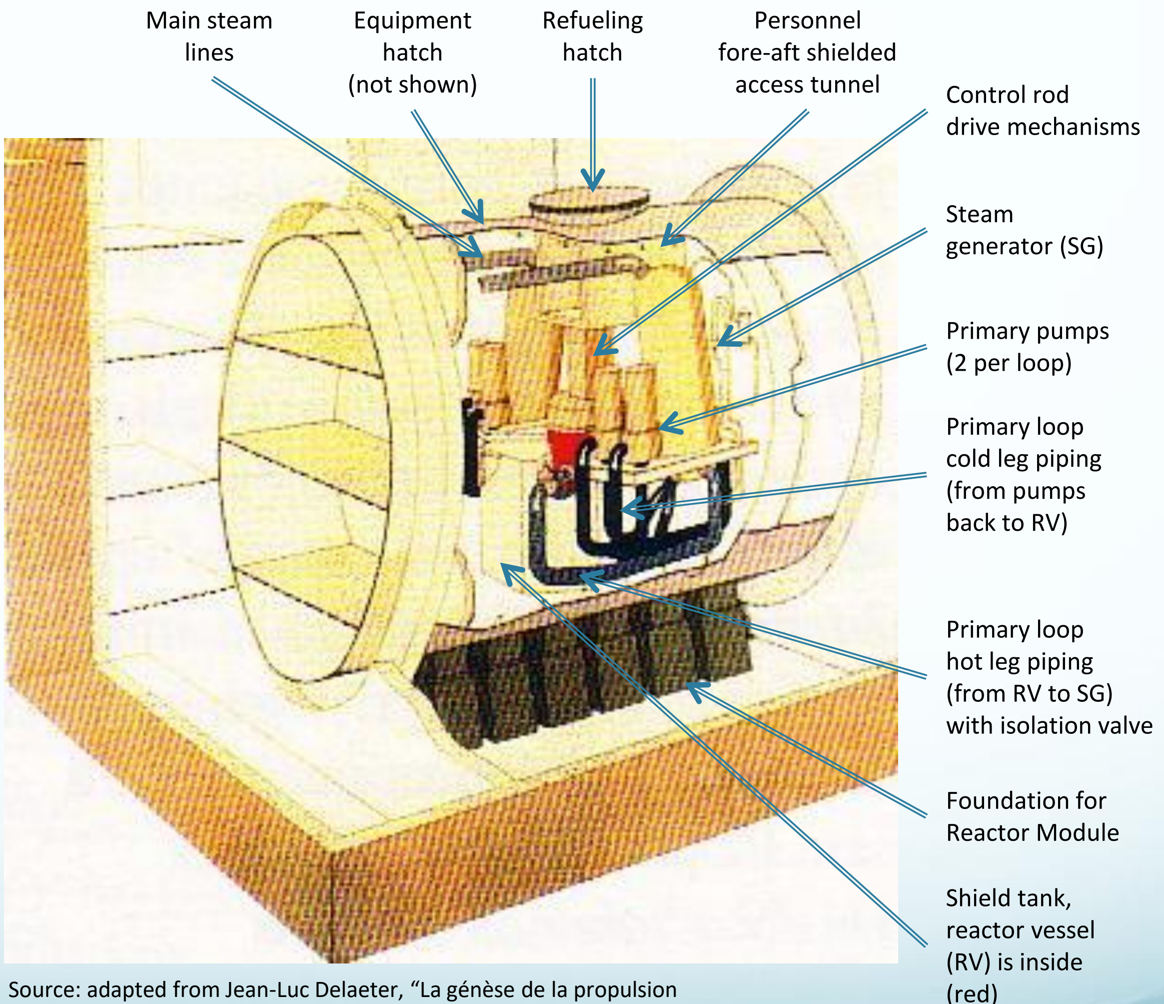
Pool Module with the Reactor Module visible at the bottom of the pool



Source: cadarache.cea.fr

PAT prototype

- The Reactor Module sits on a foundation in the Pool Module.
- Note the fore-aft shielded personnel access tunnel across the top of the reactor compartment (under the refueling hatch).
- The pressurizer & pressure relief tank are located against the back wall and are not visible.
- Main feedwater lines, which return secondary water to the SGs, are not shown.

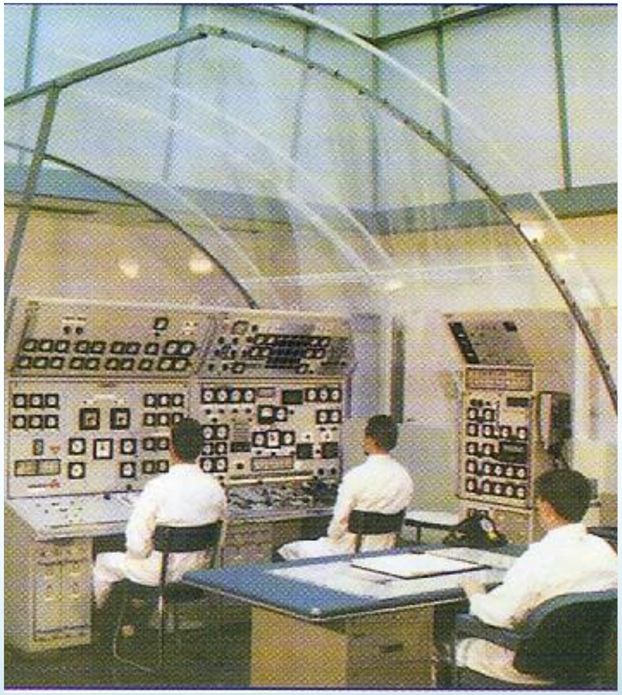


Source: adapted from Jean-Luc Delaeter, “La génèse de la propulsion nucléaire en France,” 2005

PAT prototype

- On 14 August 1964, initial criticality was achieved at PAT. It reached full power 10 days later; less than five years after the start of construction.
- From 19 October to 18 December 1964, the PAT conducted a virtual cruise, equivalent to a world tour.
- PAT was employed in the following capacities:
  - Improving knowledge of plant behavior and response to incidents that could be encountered during a submarine patrol
  - Improving operating procedures
  - Training naval nuclear operators
  - Training maintenance teams in a representative environment
  - Qualifying several generations of nuclear fuel
  - Characterizing the effects of aging on the integral NSSS

PAT control room:
Steam system operator (left panel), Reactor operator (right panel), Electrical system control panel is on the right side. The submarine hull is visualized with the plexiglas panels.



Source: Jean-Luc Delaeter, "La génèse de la propulsion nucléaire en France," 2005

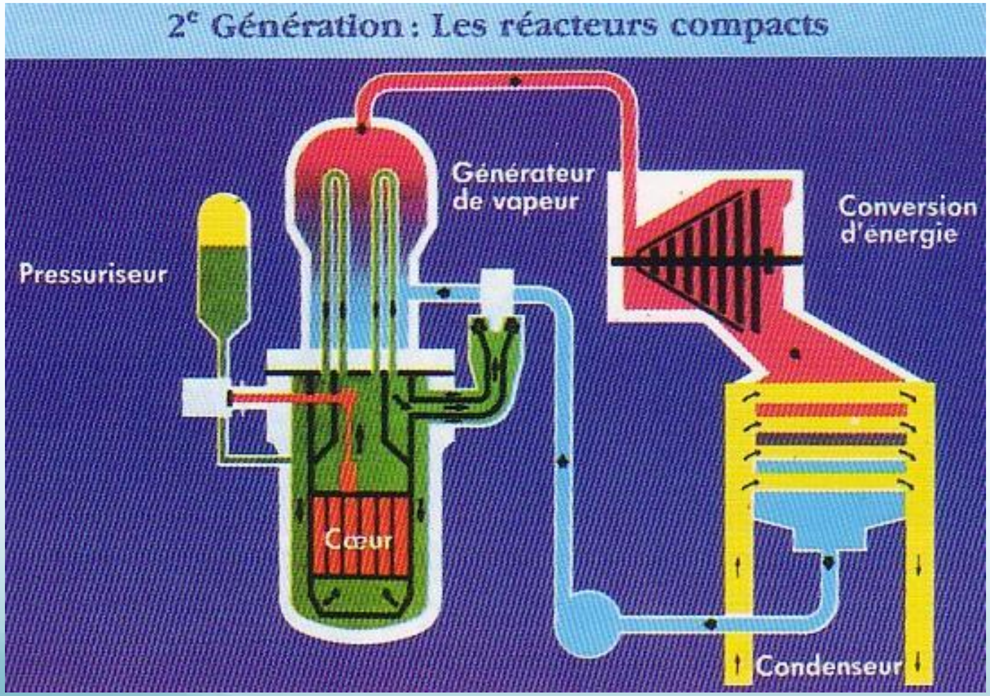
PAT prototype

- Experience from PAT helped refine the design of the PWR/SNLE:
  - Improve radiation shielding:
    - Initial operation at PAT led to early identification and remediation of a neutron streaming problem in the annular space between the reactor vessel and the shield tank (similar to a problem encountered on Japan’s nuclear-powered surface ship Mutsu). It also enabled reducing the gamma ray shielding in areas that were over-protected.
  - Improved reactor core design:
    - The first core used HEU plate-type fuel with burnable poison.
    - Subsequent "long-life" cores used moderately enriched UO_2 fuel, developed four to five times more energy, and could power a submarine for more than half of its service life.
  - PAT allowed extensive experimentation with in-depth measurements that would be impossible on board an operational submarine, as well as interventions for modification or maintenance not constrained by the submarine’s deployment schedule.
- During its 28 years of operation at PAT, from August 1964 to October 1992, more than 3,500 reactor startups were conducted and more than 2,800 sailors were trained.
- PAT was permanently shutdown in October 1992.
- In 1994, Technicatome was contracted by CEA to dismantle PAT. In 2002, PAT's nuclear fuel was completely discharged and the water circuits were drained.

CAP prototype

- CAP [*Chaufferie Avancée Prototype (advanced NSSS prototype)*] was the second French naval reactor prototype. It was a small integral PWR, which became the technical basis for the CAS-48 (K48) reactor installed later on Rubis / Améthyste-class SNAs (attack submarines).
- The integral NSSS design yielded the following improvements:

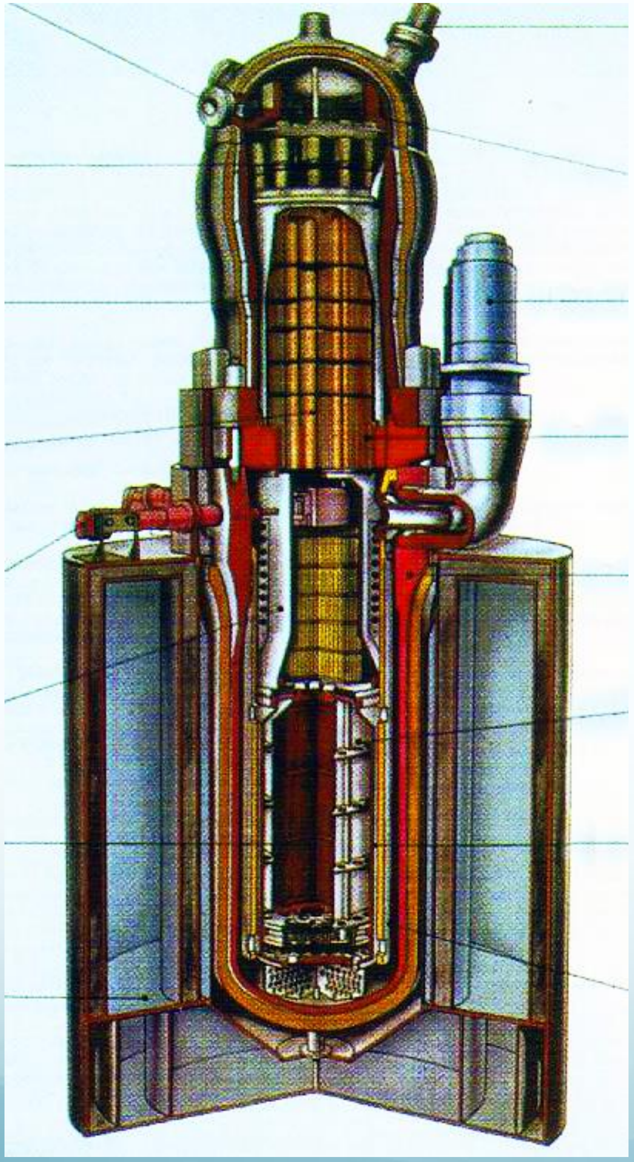
Primary & secondary system simplified process flow diagram for CAP and CAS-48



Source: Jean-Luc Delaeter, "La génèse de la propulsion nucléaire en France," 2005

- Quieter operation
  - Natural circulation provides core cooling at "cruising" speed.
  - Smaller primary pumps are used at higher speed.
  - Large integral vessel mass filters internal noise transmission.
- Reduced overall NSSS equipment and shielding mass.
- Good shock resistance; the integral vessel is supported near its center of gravity.
- Faster assembly on board, with no large-diameter piping welds made in the shipyard.

CAP prototype



- The CAP reactor is a small integral PWR, with the reactor in the lower part of the vessel, surrounded by a shield water tank for radiation shielding.
- The once-through steam generator is in the upper part of the vessel, with the main steam and feedwater lines connecting at the top.
- The primary pump connects to the vessel just above the shield tank, as do the control rod drive mechanisms.
- Primary system pressure is maintained by an external pressurizer, which is not shown in this diagram.

Source: Adapted from Jean-Luc Delaeter, “La génèse de la propulsion nucléaire en France,” 2005

CAP prototype

- CAP was built from 1970 to 1975 in an extension of the PAT building.
  - Initial criticality was achieved in November 1974.
  - CAP was put in service in 1975.
- CAP was essential for validating the new concepts of the small integral PWR.
- CAP also was used for CEA tests of MOX fuel assemblies (mixed-oxide, with a mixture of uranium and plutonium).
- CAP was taken out of service in 1985 for the start of a four-year renovation period that would convert CAP into the RNG prototype.

RNG prototype

- The RNG [*Réacteur de Nouvelle Génération (new generation reactor)]* prototype is the product of a major renovation of the CAP prototype conducted from 1985 to 1989.
- The renovated prototype reactor, now re-named RNG, was intended to qualify many innovations and design improvements planned for the K15 large integral reactor that would be installed on the Le Triomphant-class SNLE (SSBN) and the *Charles de Gaulle* aircraft carrier.
  - RNG initial operations occurred in 1989.
  - The first K15-powered submarine, *Le Triomphant*, was launched in July 1993 and entered service in 1997.
- The RNG improvements included:
  - Significant gains in acoustic quieting of the NSSS, which was a major objective to support the new program SNLE. These improvements included revised support of the boiler (NSSS) block, reduced coolant flow velocity, improved rotating machinery with DC (direct current) motors, flexible equipment mounts,
  - Fully-digitized control and protection system.
- RNG was retired in 2005.

RES prototype

- The RES [*Réacteur d'Essais (Testing Reactor*) *or Réacteur d'Expérimentations scitnifiques (Scientific Experiment Reactor*)] program was launched in 1995 by the Nuclear Propulsion Directorate in CEA's Military Applications Division as a replacement for the RNG prototype.
- The RES facility consists of two major parts:
  - A test reactor for developing nuclear steam supply systems (NSSS) for naval nuclear propulsion;
  - A fuel storage and examination pool designed to house irradiated fuels from the French Navy's vessels, CEA's research reactors and, in the future, the RES itself.
- The RES test reactor is an upgraded version of the K15 nuclear steam supply system (NSSS) that currently is operating on four Le Triomphant-class SSBNs and the aircraft carrier *Charles de Gaulle*. The upgraded K15 will be the NSSS for the new Barracuda-class SSNs.
- RES missions:
  - **Support the currently operating nuclear fleet** : The reactor will reproduce the operation of the nuclear steam supply system (NSSS), test equipment under more extreme conditions than those experienced in an operating plant. It will contribute to improving operational availability and demonstrating safety margins.
  - **Qualify the fuel and cores of current and future NSSS:** The thermo-mechanical qualification of fuels and the validation of codes used to simulate core behavior under irradiation are essential for optimizing and improving NSSS performance while ensuring safe operation.
  - **Develop and qualify innovative technology for the Barracuda-class SSN*:*** The RES is the platform on which *Barracuda* required performances are to be demonstrated, and its innovations are to be qualified, for example: core performances (burn-up, lifetime...); architecture of the NSSS unit (supporting structures, radiation protection), instrumentation and controls, and human-machine interfaces.

RES prototype

- Key milestones:
  - 2003: Construction started.
  - 2005: Work on the pool module was completed.
  - 2007: The reactor vessel was installed.
  - 2010: The integral steam generator was installed.
  - 2010: Cooling towers were completed. These will be used during operation to reject core heat to the atmosphere.
  - As of mid-2018: No report yet of initial criticality.
- RES includes comprehensive in-core and in-pool instrumentation.
  - In-core instrumentation makes it possible to develop a map of neutron flux in real time.
  - The experimentation on the first core of the RES, called the "Hippocampus experiment", will allow the qualification of the core design codes, the validation in full size of the core of the Barracuda program, the qualification of the nuclear fuel used from this core, as well as than the qualification of new materials for the future.

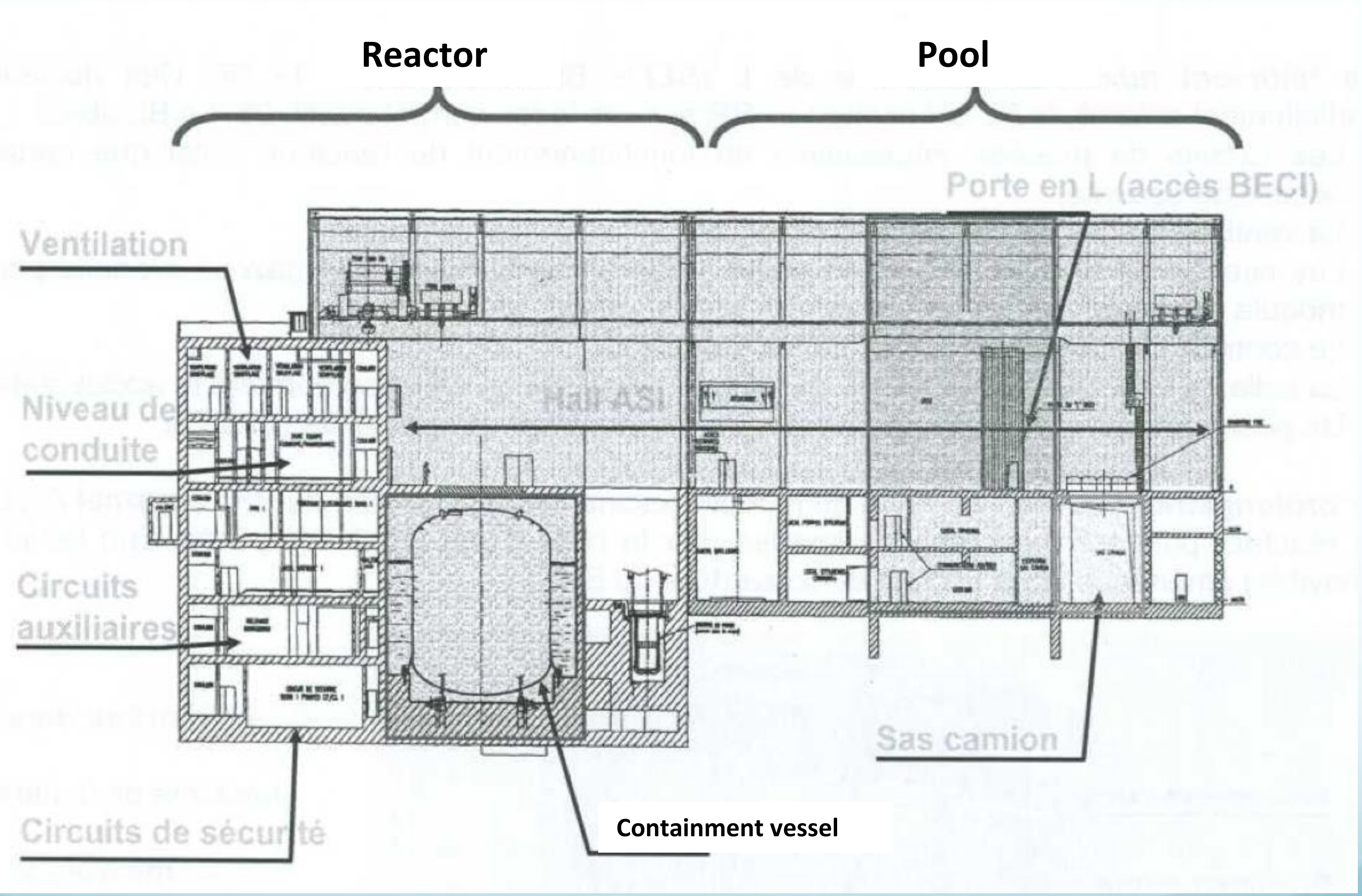
RES prototype

RES Pool Module.
Source: cadarache.cea.fr

RES main buildings.
Source: CEA

RES prototype

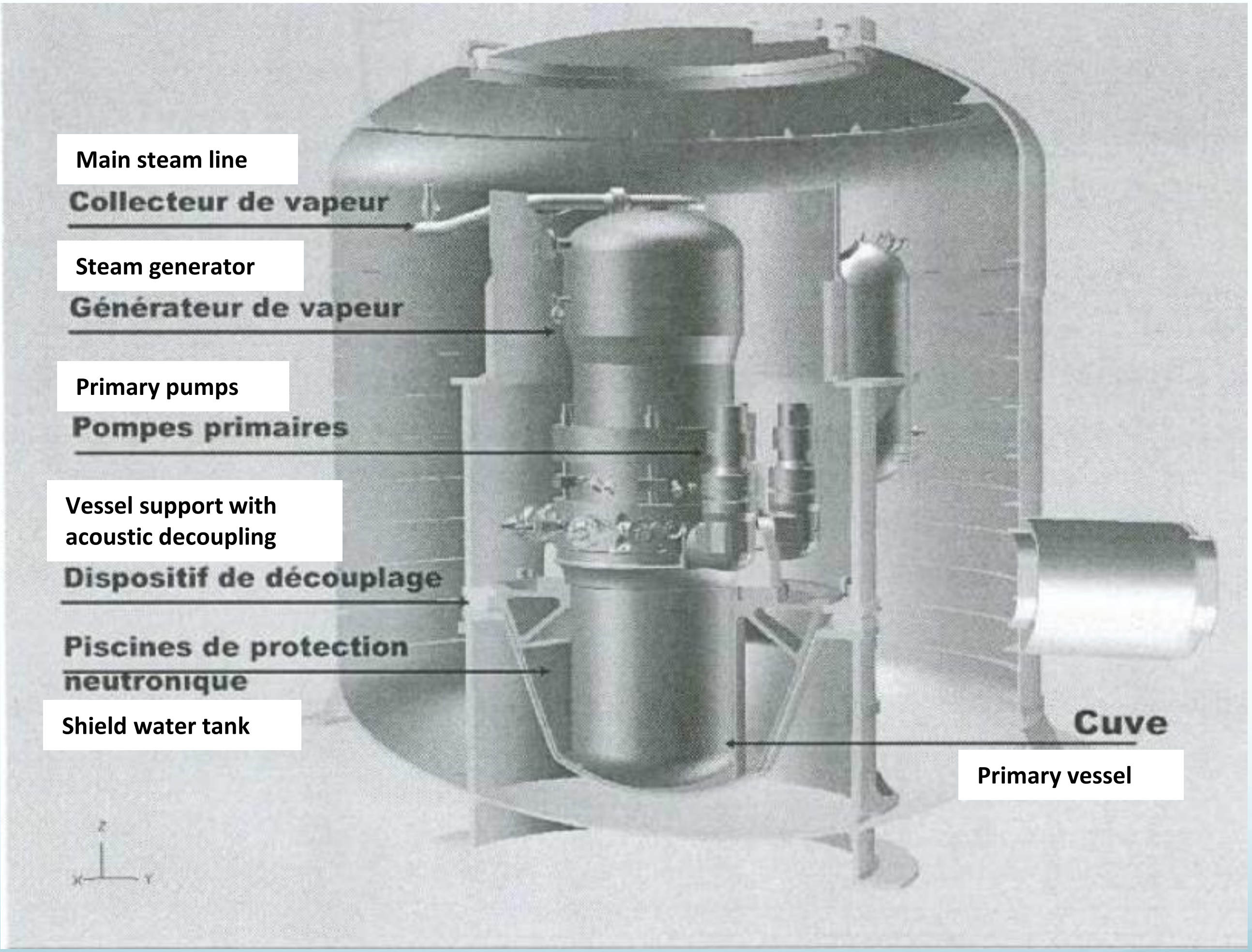
East-west building cross-section



Source: S. Pivet & J-L Minguet, "Le Réacteur d'essais RES - Réacteur d'essais de la propulsion navale," http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/37/118/37118538.pdf?r=1

RES prototype

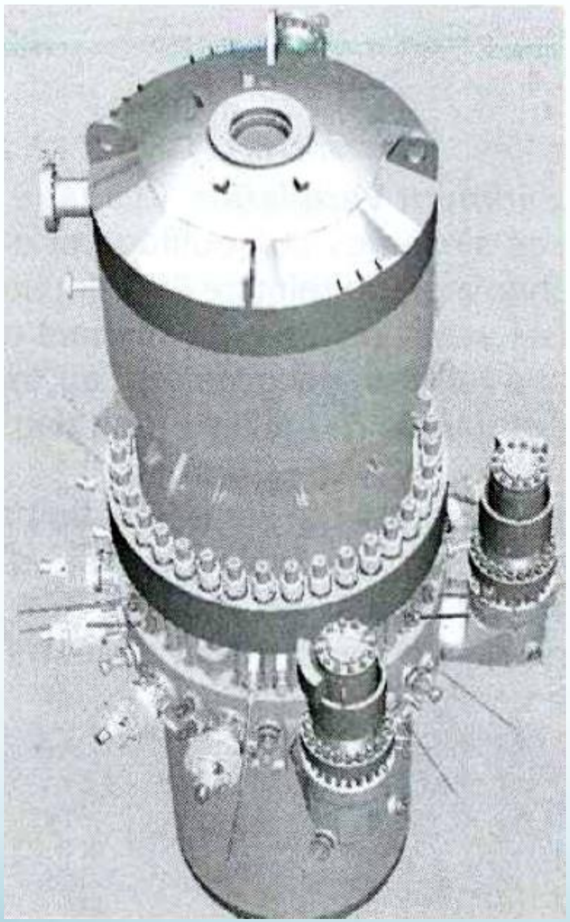
General arrangement inside the containment vessel

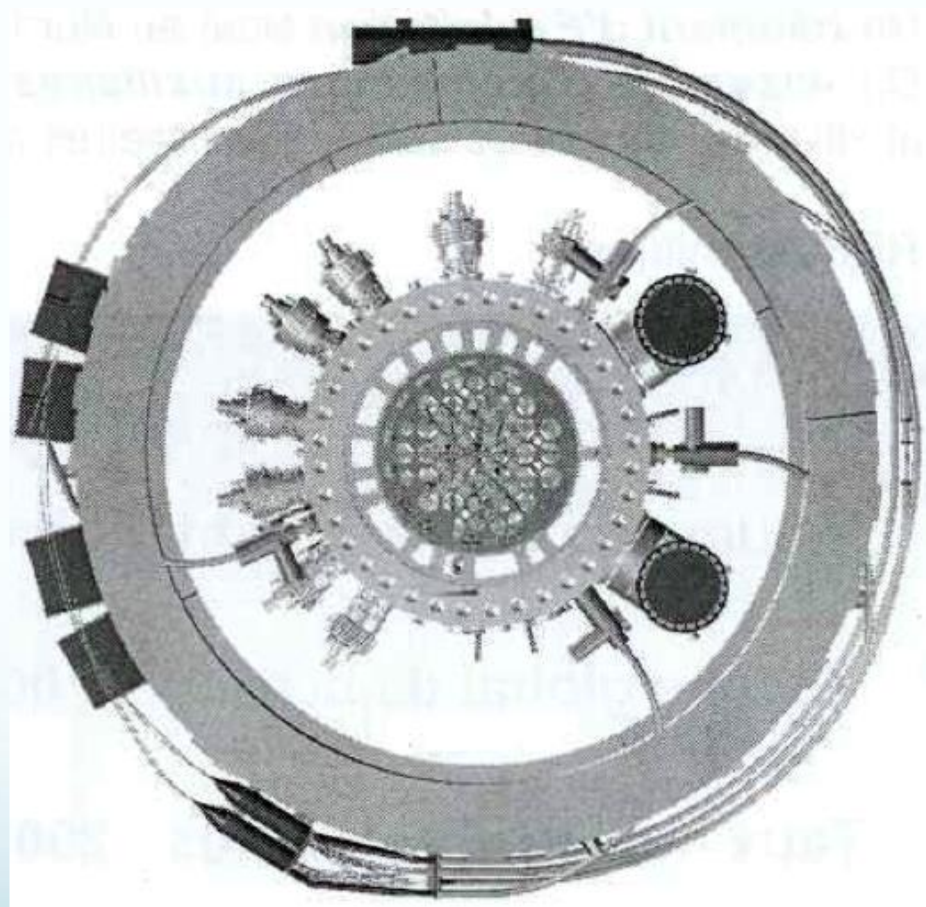


Source: S. Pivet & J-L Minguet, “Le Réacteur d'essais RES - Réacteur d'essais de la propulsion navale,” http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/37/118/37118538.pdf?r=1

RES prototype

NSSS and its arrangement inside the containment





Source: S. Pivet & J-L Minguet, “Le Réacteur d'essais RES - Réacteur d'essais de la propulsion navale,” http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/37/118/37118538.pdf?r=1

French naval nuclear reactors

French highly-enriched uranium (HEU) inventory

- Some French naval reactors use HEU fuel.
- The International Panel on Fissile Materials (IPFM) reported the following French HEU inventory data as of December 2016:
  - France produced HEU at a dedicated enrichment complex near Pierrelatte at the Tricastin site. HEU production at Pierrelatte ended in late June 1996. The plant was shut down and is being dismantled.
  - The current stock of military-related weapon-grade HEU is therefore estimated to be 26 ± 6 tonnes.
  - France also has declared a stock of 4,806 kg of civilian HEU, including 3,264 kg of fresh HEU.
  - Some of the civilian material may have been produced domestically, but a significant fraction is probably of US and Russian origin for use in research-reactor fuel. With this uranium taken into account, the total HEU stock is 31 ± 6 tonnes.

French naval nuclear reactors

- All naval reactors are PWRs designed & built by Technicatome (now Areva TA).
- There are four generations of French naval marine reactors:
  - PWR/SNLE loop-type PWR for the *Le Redoutable*-class SSBNs, using HEU fuel.
  - CAS-48 (aka PWR/SNA-72 and K48) integral PWR for the Rubis / Améthyste-class SSNs, using LEU fuel.
  - K15 integral PWR for the Le Triomphant-class SSBNs & *Charles de Gaulle* aircraft carrier, using fuel with a much higher enrichment than in the CAS-48, likely HEU.
  - Improved K15 integral PWR for the Barracuda-class SSNs, expected to use LEU fuel.
- Unique French nuclear safety rules have resulted in naval reactor operating cycles that are substantially different than in US and UK naval plants. *
  - Following nuclear safety practices established by the French civilian nuclear safety authority ASN (*Autorité de sûreté nucléaire*), the defense nuclear safety authority DSND (*Directeur pour la sûrete nucléaire de Défense)* requires that all reactor pressure vessels be inspected from the inside every 10 years using a dedicated inspection machine and requires the withdrawal of fuel assemblies and all the internal components of the reactor pressure vessel. These pressure vessel inspections are performed during each major overhaul (an IPER) of the nuclear-powered ship, which typically occurs at 8 – 10 year intervals.
  - After the inspection is complete the Navy may reload the same core if it is capable of operating until the next IPER, or a new core may be loaded.

* Source: Alain Tournyol du Clos, "France's Choice for Naval Nuclear Propulsion – Why Low-Enriched Uranium Was Chosen," Federation of American Scientists, December 2016

French naval nuclear reactors

- To accommodate the need for loading and unloading the reactor core and vessel internals several times during the service life of a submarine and for replacing large equipment, removable rectangular hatches, called brèches, are built into the top of the submarine hull.*
  - Brèches can be described as removable portions of the pressure hull that will fit in such a manner that the external pressure will seal them in the correct position. Inside the hull, safety bolts ensure that even in severe shocks the brèches will stay in place.
  - One brèche is located directly above the reactor vessel.
  - It has been reported that the SSBN *Le Redoutable* executed a core unloading and loading in the short maintenance period (typically 40 days) between patrols. This would have occurred at Île Longue submarine base.

Large equipment being handled through a brèche on SSN *Améthyste*, with a protective combing over the seating surface. *

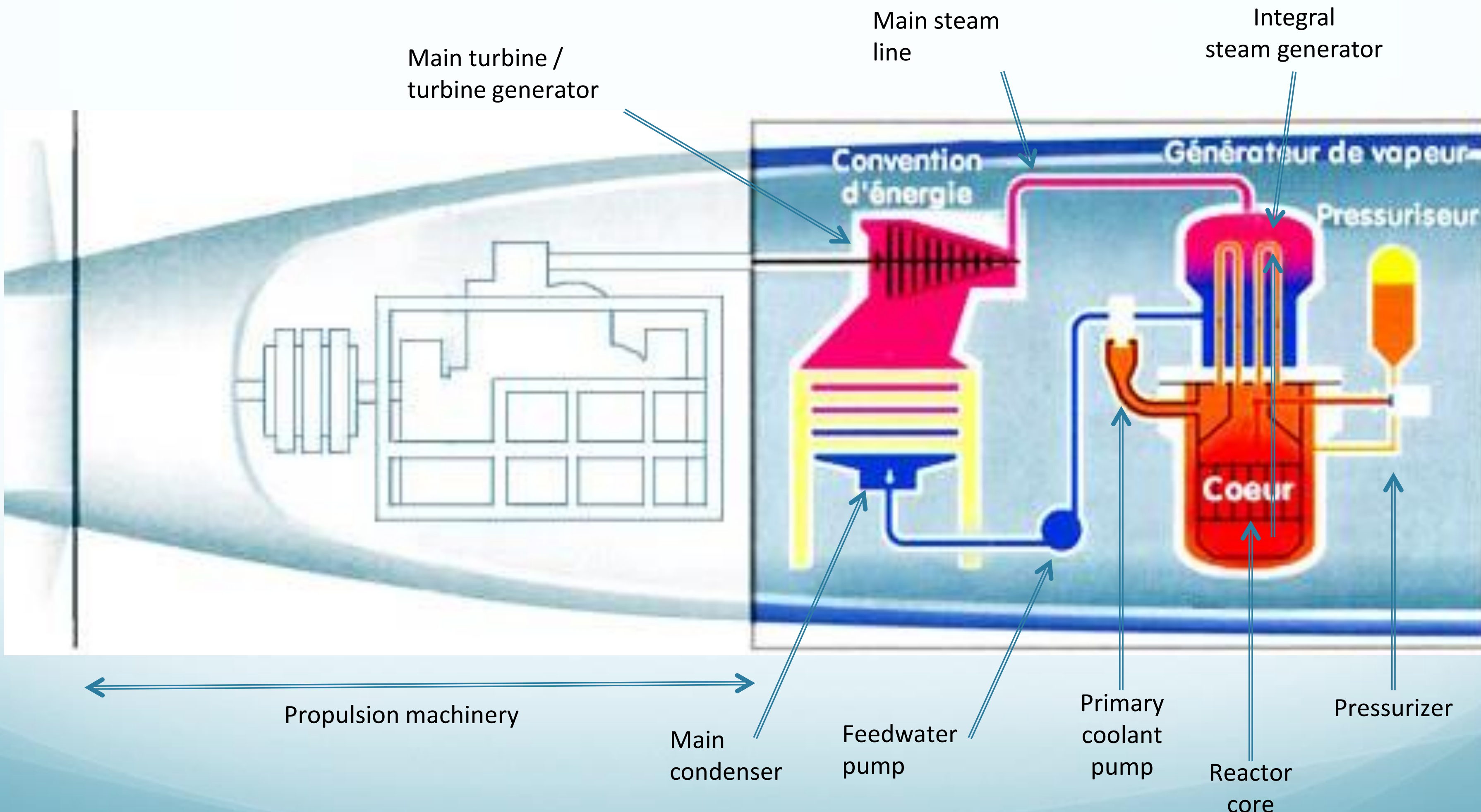
* Source: Alain Tournyol du Clos, "France's Choice for Naval Nuclear Propulsion – Why Low-Enriched Uranium Was Chosen," Federation of American Scientists, December 2016

French naval nuclear reactors

- Considering that unloading the core is compulsory at each overhaul to fulfill nuclear safety regulations and that it can be done as often as necessary without affecting the diving performances of the submarine hull, the need to develop a lifetime core is not of paramount importance for the French Navy. *

* Source: Alain Tournyol du Clos, "France's Choice for Naval Nuclear Propulsion – Why Low-Enriched Uranium Was Chosen," Federation of American Scientists, December 2016

French submarine integral PWR propulsion plant process flow diagram



Representative of CAS-48 and K15 reactors. Source: adapted from http://www.world-nuclear.org

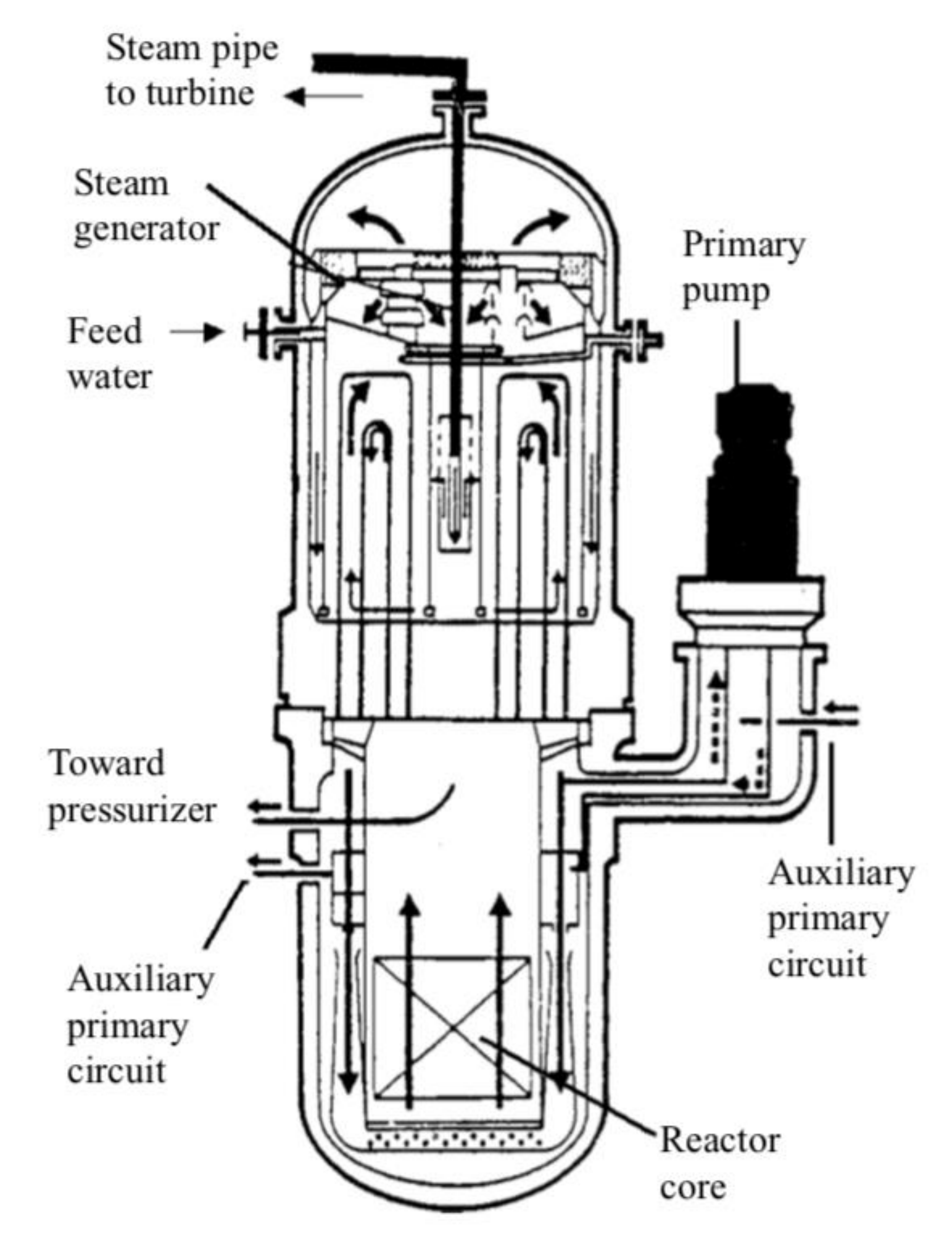
PWR/SNLE

- Loop-type PWR rated at 83 MWt (est.)
  - Two primary coolant loops, with a loop configuration similar to the PAT prototype at Cadarache, but with changes enabled by the slightly larger submarine hull diameter than anticipated in the design of PAT.
  - This basic configuration is generally similar to the US S5W and UK PWR1 naval nuclear plants.
- Fuel: uranium enrichment up to 90%, metal alloy plate-type fuel
- Installed on Le Redoutable-class SSBN
  - Entered operational service in 1971.
  - Last ship in class was decommissioned in 2008.

CAS-48 integral PWR

(aka PWR/SNA-72 & K48)

- Integral PWR rated at 48 MWt; similar to the CAP prototype at Cadarache.
- Fuel: uranium enrichment 7%, UO_2 “Caramel” fuel.
  - Reactor life for SSN operating cycle is about 7 years
- Single-pass primary coolant system capable of operating on natural circulation at lower (cruising) power and with forced circulation at higher power.
- The once-through integral steam generator is located above the reactor.
- Timeline:
  - Development started in the early 1970s
  - Installed on French Rubis / Améthyste-class SSNs; entered operational service in 1983.
- In 1987 – 89, Canada considered a French offer to supply an Améthyste-derivative SSNs with the CAS-48 propulsion plant.



CAS-48

Integral primary system

This is a cross-section of the integrated reactor and steam generator as used in France's Rubis / Améthyste-class SSNs.

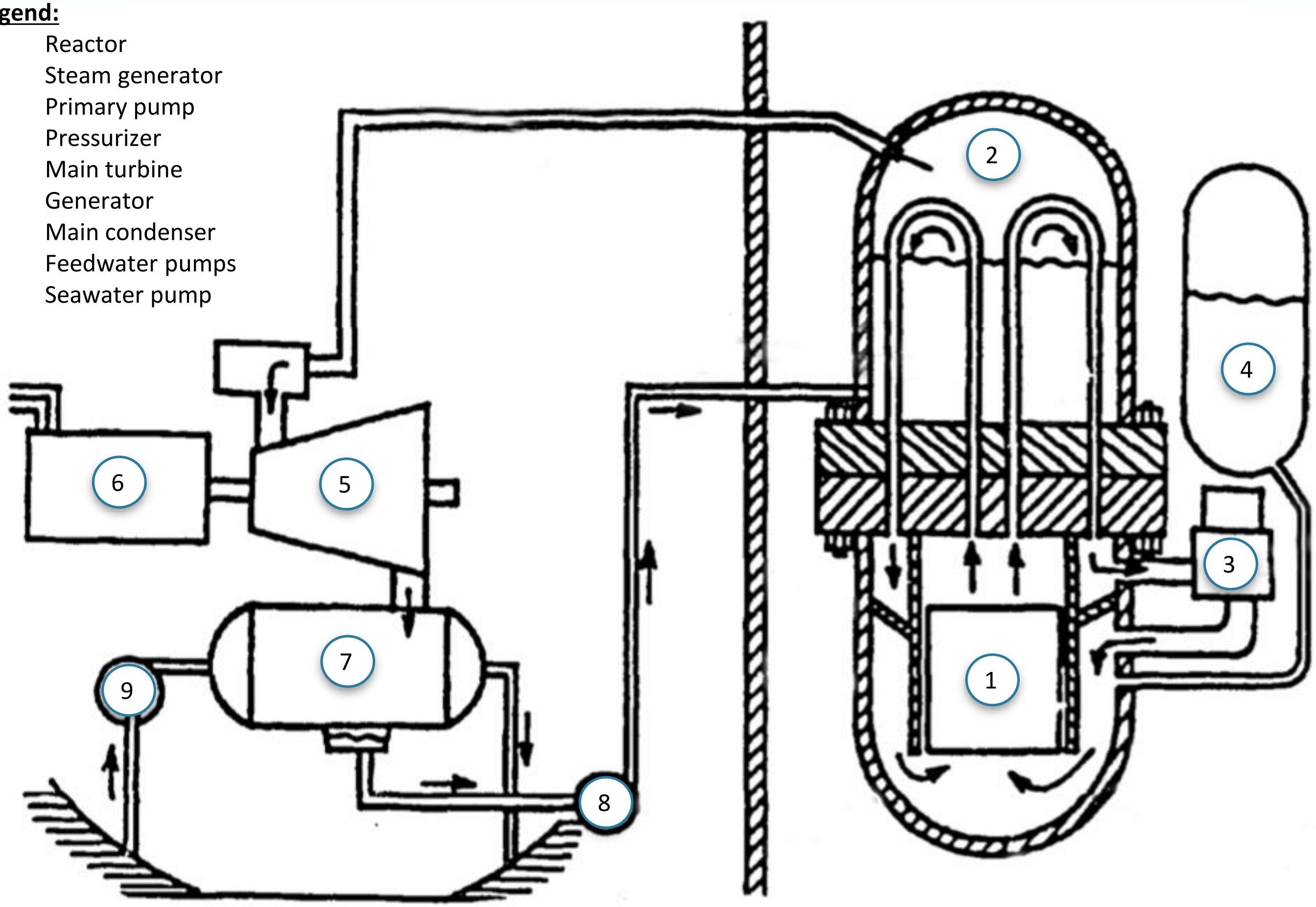
Source: Thomas Lynch, "Canadian Acquisition Program (CASAP), Nuclear Propulsion," Wings Magazine (April 1988), p. 64-68
via
Chunyan Ma & Frank Von Hippel, "Ending the Production of Highly Enriched Uranium for Naval Reactors"
http://fissilematerials.org/library/ma01.pdf

CAS-48

Reactor and power conversion system

Legend:

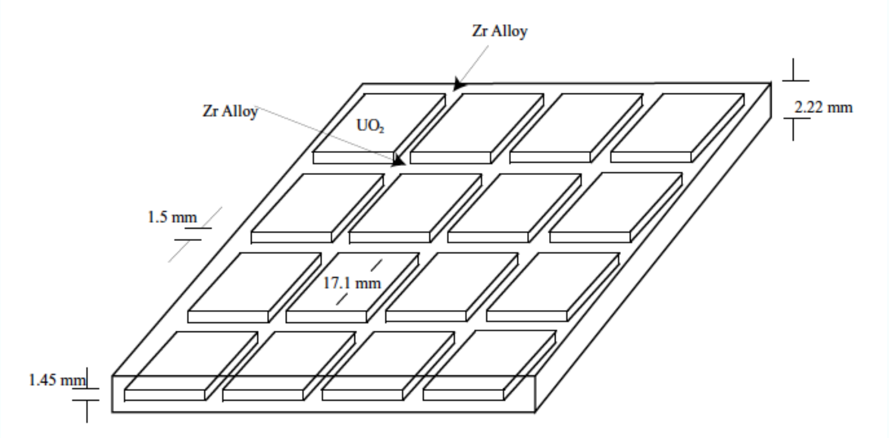
1 Reactor
2 Steam generator
3 Primary pump
4 Pressurizer
5 Main turbine
6 Generator
7 Main condenser
8 Feedwater pumps
9 Seawater pump



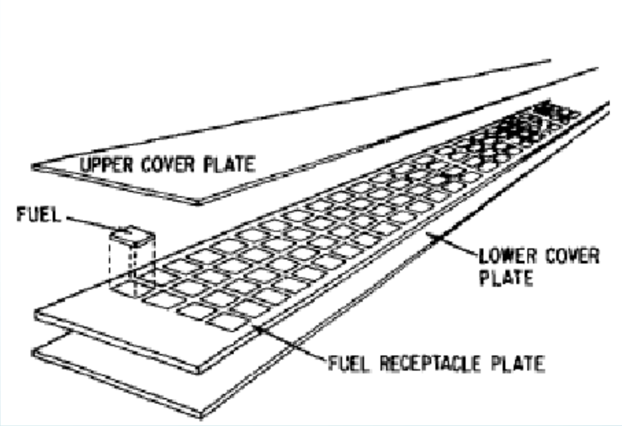
Source: http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/27/073/27073072.pdf

LEU Caramel fuel

- "Caramel" fuel used in the CAS-48 reactors on Rubis / Améthyste-class SSNs is a plate-type fuel with platelets of LEU UO_2 embedded in a zirconium alloy grid that is enclosed between two cladding layers of zirconium alloy to form a fuel plate. Individual fuel plates are assembled to form a fuel assembly.
- The Caramel design addresses the issue of poor UO_2 thermal conductivity while enabling the use of LEU fuel enriched to significantly less than 20% to deliver high specific power with low fuel temperature.
- CEA's investigation of Caramel fuel started in 1977. The core of the CEA's high-performance OSIRIS test reactor, at Saclay, was converted to Caramel fuel and operated successfully since December 1979.
- The first French submarine using Caramel fuel, with an enrichment of 7%, was *Rubis,* which was launched in 1979 and commissioned in 1983.



Closeup view of Caramel fuel configuration.
Source: Chunyan Ma & Frank Von Hippel, "Ending the Production of Highly Enriched Uranium for Naval Fuel," The Nonproliferation Review, Spring 2001



Caramel fuel plate configuration on OSIRIS.
Source: Humberto Soares, et al., "Loss of Coolant Accident Analysis on OSIRIS Research Reactor Using the RELAP5 Code," January 2011

K15 integral PWR

(Originally SNLE-NG)

- Development began in 1985.
- Integral PWR rated at 150 MWt.
  - Design is similar to an enlarged CAS-48 with improved layout of the piping and heat exchanger. Design improvements were demonstrated on the RNG prototype at Cadarache.
  - Improved coolant flow through the larger integral pressure vessel, with reduced hydraulic resistance, provides adequate natural circulation core cooling up to about 40 - 49 % reactor power.
- Fuel:
  - Much higher uranium enrichment than in the CAS-48 reactor (which is 7% enrichment). Some sources claim K15 uses HEU fuel at > 90% enrichment.
- Installed on Le Triomphant-class SSBNs (1 x K15 reactor) & *Charles de Gaulle* aircraft carrier (2 x K15 reactors); entered operational service in 1997 on *Le Triomphant*.
  - Reactor life for an SSBN operating cycle is believed to 20 - 25 years (one mid-life refueling required);
  - Reactor life for an aircraft carrier operating cycle was claimed to be about 5 years running at 25 knots (a little less than full power). In practice, *Charles de Gaulle* has been refueled twice since initial criticality in 1998, at approximately nine year intervals.

K15 integral PWR

- Photos below show the bottom ½ of a K15 integrated PWR vessel for the Le Triomphant-class SSBN. The photo, right, clearly shows the L-shaped mountings for the two primary pumps. The top ½ of the vessel containing the steam generator is installed separately.
- The complete K15 vessel is about 10 m (32.8 ft.) tall and 4 m (13.1 ft.) in diameter. Le Triomphant-class SSBN hull outer diameter is 12.5 m (41 ft.).

Source: https://pk.all.biz/nuclear-propulsion-systems-g69930

Source: CEA

Improved K15 integral PWR

- The design is based on the K15 integral PWR nuclear steam supply system (NSSS). This reactor was expected to be tested in the RES prototype facility at Cadarache. However, significant delays have been encountered in the completion of RES, and, as of mid-2018, initial criticality of the reactor prototype has not yet occurred.
- Objectives for the improved K15 include:
  - Reduce the physical size of the NSSS so it can fit on a Barracuda-class SSNs, which has an outer hull diameter of 8.8 m (28.9 ft). The complete K15 vessel is about 10 m (32.8 ft.) tall.
  - Improve the NSSS natural circulation performance and quietness of operation.
  - Operate with LEU fuel and deliver thermal power comparable to the K15.
  - Achieve 10 years of operational activity between refueling.
  - Reduced the time needed for refueling (target 3 months vs. 5 months currently).
  - Improve the human-machine interfaces with the instrumentation, control and protection systems.
  - Reduce life-cycle costs (construction + operation).
  - Improve safety.
  - Improve availability.
- The first Barracuda-class SSN is expected be launched in the 2018 – 2019 timeframe.

French naval nuclear vessels

Q-244,
Strategic ballistic missile submarines (SSBN / SNLE),
Fast attack submarines (SSN / SNA),
and Aircraft carrier

Nuclear-powered strategic ballistic missile submarines (SSBN / SNLE)

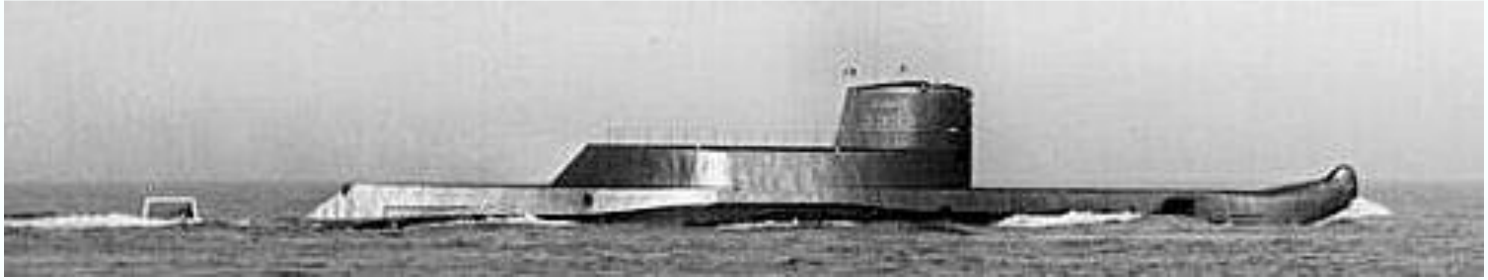
Strategic ballistic missile submarines (SSBN/SNLE)

Class	# in Class	Length	Beam	Displacement (tons)	Reactor	Shaft hp	Max speed (kts)	Years delivered	Years in service
Gymnôte 2 SLBM test platform	1	84 m (275.6 ft)	10.6 m (34.8 ft)	3,000 (surf), 3,250 (sub)	Diesel-electric	Not known	10	1966	1966 - 1987
Le Redoutable	6	148 m (485.6 ft)	10.6 m (34.8 ft)	8,045 (surf), 8,940 (sub)	1 x PWR/SNLE 83 MWt	16,000	> 20	1971 - 85	1971 - 2008
Le Triomphant	4	138 m (452.8 ft)	12.5 m (41 ft)	13,930 (surf), 15,800 (sub)	1 x PWR/K15 150 MWt	30,000 (est)	26	1997 - 2010	1997 - present
3rd-generation (3G) SSBN								Late 2030s	

The French name for a ballistic missile nuclear submarine is SNLE, for "Sous-marin Nucleaire Lanceur d'Engine" ("Nuclear-powered, Device-launching Submarine")

Q-251 / S655, *Gymnôte 2*

SLBM test platform

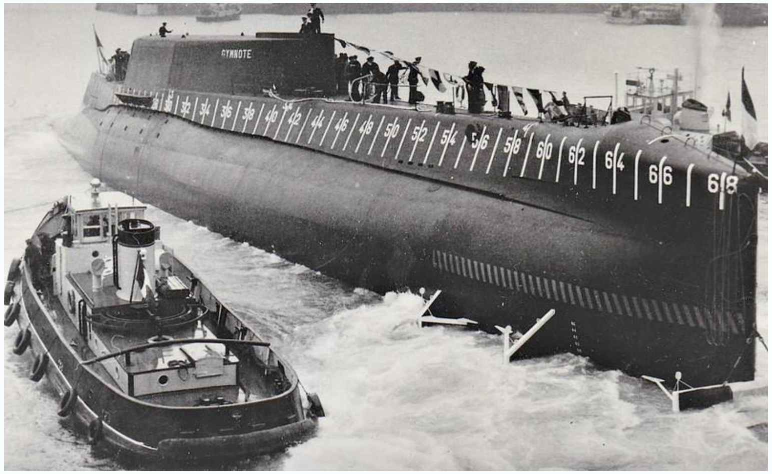


Source: adapted from http://www.netmarine.net/bat/smarins/gymnote/

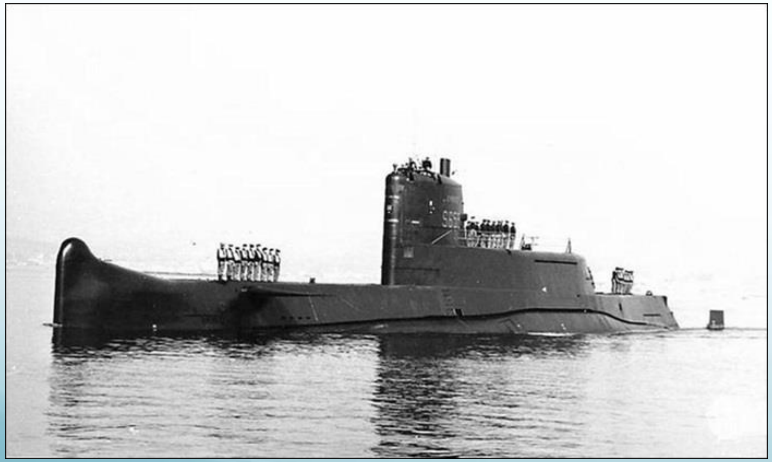
- Following the decision to develop an independent French sea-based deterrent force, it was decided to complete the Q-244 hull (now designated Q-251) as a diesel-electric powered experimental submarine for testing the new French submarine-launched ballistic missiles (SLBMs) and associated ship systems.
  - The prominent casing abaft the sail housed four (2 x 2) vertical missile launch tubes.
  - *Gymnôte 2* was also fitted with the prototype guidance and inertial navigation system intended for France's 1st strategic missile submarine (SSBN), *Le Redoutable*.
  - *Gymnôte 2* was completed in 1966 and conducted more than 100 test launches of the M-1, M-2, M-20 and M-4 SLBMs
    - 1st M-1 launched in 1968
    - Extensively rebuilt in 1977 – 79 to support M-4 missile testing
    - Development tests of the M-4 were carried out from 1980 – 1984
- *Gymnôte 2* was re-designated S655 in the 1980s and was decommissioned in 1987.

Q-251 / S655, *Gymnôte 2*

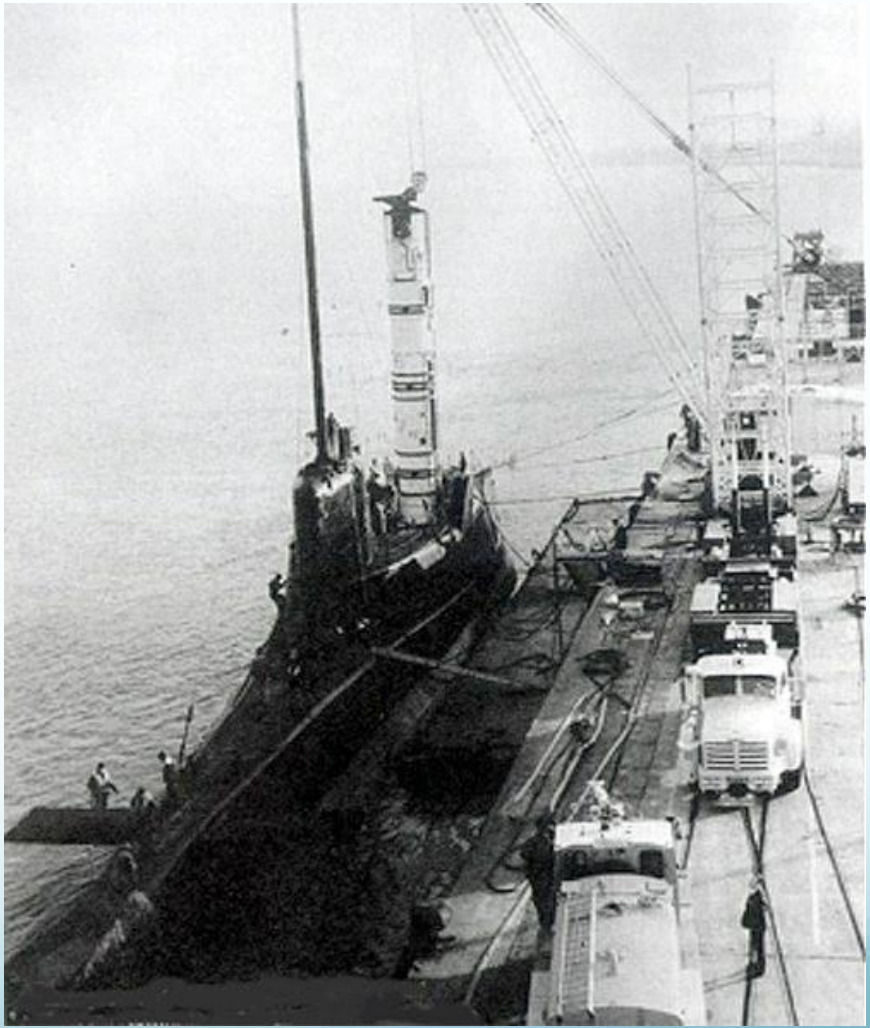
SLBM test platform



Above: *Gymnote 2* launch at Cherbourg in 1964.
Source: https://www.celebritypix.us/celebrities/submarine-gymnote-celebrities-28ac0.html



Source: http://worldmilitary.net/1-Warships/France/10-SS/1966%20-%20Gymnote/



Gymnôte 2 loading a test SLBM.
Source: https://imgur.com/a/Vf2UQ

Q-251 / S655, *Gymnôte 2*

SLBM test platform

Gymnôte 2 bow view.
Source, both photos: https://imgur.com/a/Vf2UQ

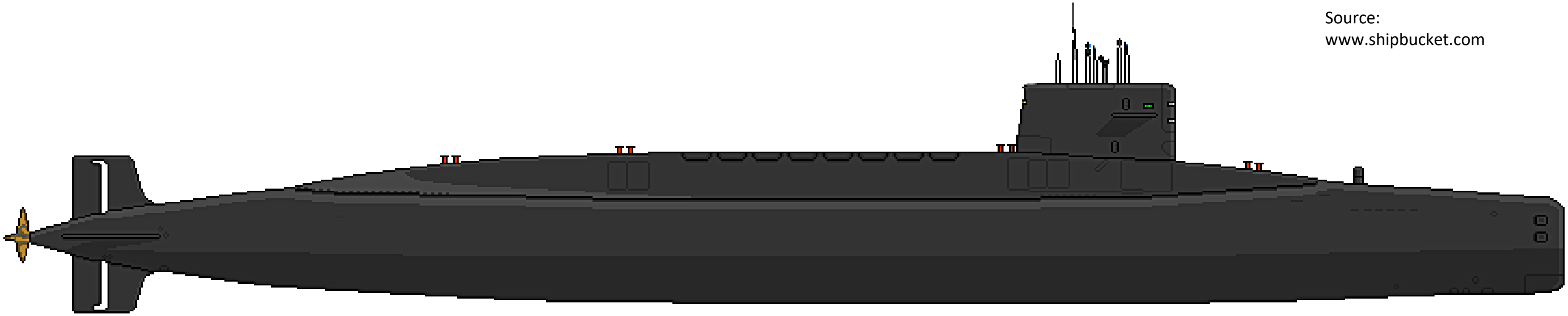
Gymnôte 2 stern view

Q-251 / S655, *Gymnôte 2*

SLBM test platform

Gymnôte 2 with telemetry mast for underwater launch test.
Source: http://worldmilitary.net/1-Warships/France/10-SS/1966%20-%20Gymnote/

Le Redoutable-class SSBN



Source:
www.shipbucket.com

- The December 1960 long-range shipbuilding plan established French's commitment to built the Redoutable-class SNLE. The lead ship of this six boat class, *Le Redoutable* (S611), was the 1st French nuclear-powered vessel; commissioned on 1 December 1971.
- Propulsion: 1 x loop-type PWR/SNLE rated @ 83 MWt (est) with HEU fuel.
  - 2 x steam turbines with a combined rating of 16,000 shp (12 MW); driving a single propeller.
- Armament: 16 SLBMs and 4 x 533 mm (21 in) torpedo tubes for F-17 & L-5 torpedoes.
  - The first two boats, *Le Redoutable* and *Le Terrible* originally were armed with M-1 SLBMs.
  - The third boat, *Le Foudroyant* originally was equipped with the M-2 SLBM. The first two boats were retrofitted with the M-2 system during their normal overhauls.

Le Redoutable-class SSBN

- Armament (cont'd)
  - The fourth and fifth boats, *L'Indomptable* and *Le Tonnant*, originally were equipped with the M-20 SLBM. The three earlier boats were retrofitted with the M-20 system during their normal overhauls.
  - The last boat, *Le Inflexible,* was completed in 1982 and was equipped originally with the M-4 SLBM, the Exocet SM-39 anti-ship cruise missiles and many other system upgrades.
  - Under a program named "Refonte M4," all earlier boats except *Le Redoutable* were upgraded with the M-4 SLBMs and other improvements incorporated in *Le Inflexible.*
- Operational matters:
  - Operated by two crews, Bleu (blue) and Ambre (amber)
  - *Le Redoubtable* started France's 1st deterrent patrol on 28 January 1972, armed with M-1 missiles.
  - The capabilities to handle newer SLBMs and other weapon systems were incorporated during construction of later boats in this class.
    - M-2 SLBM was introduced in 1974 on boat three
    - M-20 SLBM was introduced in 1976 on boat four
    - M-4 SLBM, SM-39 Exocet anti-ship missile, improved sonar, navigation and tactical information systems were introduced in 1985 on boat six, *Le Inflexible*

Le Redoutable-class SSBN

- Operational matters (cont'd):
  - Five earlier boats (all except *Le Redoubtable*) were heavily upgraded from 1985 to the M-4 SLBM and other weapons and system standards of *Le Inflexible*. These modernized boats were re-commissioned from 1987 to 1993.
  - December 1991: *Le Redoubtable* was decommissioned.
    - During her 20 years of service, *Le Redoutable* made 51 deterrent patrols, operated for 90,000 hours under water and covered a distance of nearly 800,000 miles (32 times around the world).
    - Thereafter, the remaining five SSBNs were referred to as "L'Inflexible-class SNLE M4."
  - 2002: *Le Redoutable* was converted to a museum ship for the Cité de la Mer naval museum in Cherbourg.
  - January 2008: The last ship in this class, *Le Inflexible,* was decommissioned after a 23 year service life.

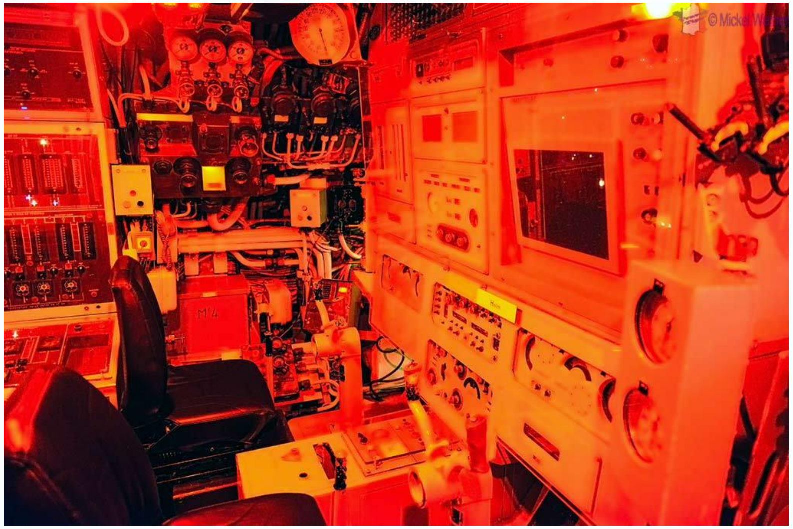
Le Redoutable-class SSBN

Le Redoutable underway. Source: Military-Today.com

Source: http://www.studiomilou.sg

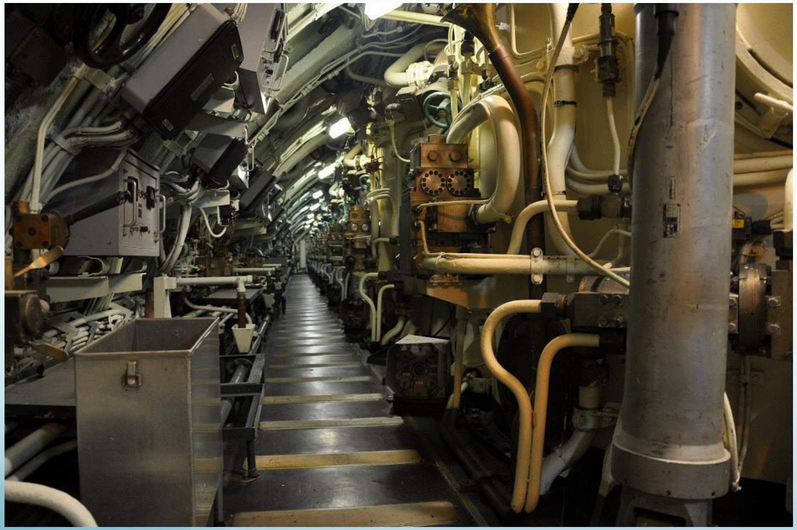
SNLEs at Cherbourg. Source: http://www.defense.gouv.fr/dga/

Le Redoutable museum ship



Le Redoutable helm & diving stations

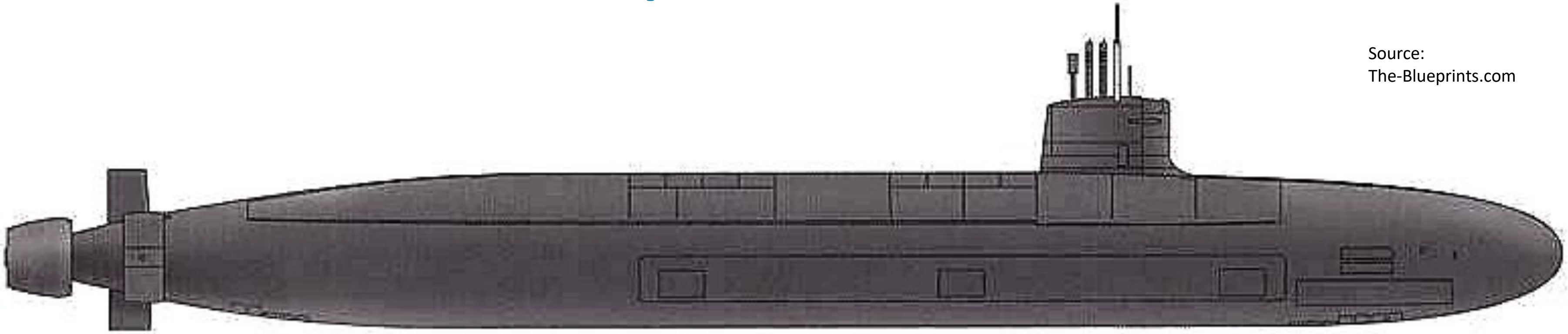
Le Redoutable combat stations



Le Redoutable missile compartment.
Source, four photos: https://travelfrance.tips/cherbourg-cite-de-la-mer/

Le Redoutable torpedo room

Le Triomphant-class SSBN



Source:
The-Blueprints.com

- This four boat class of SSBNs (reduced from initial plans for six) replaced the six *Le Redoutable*-class SSBNs. They all were built at the DCNS Cherbourg shipyard at a total cost of more than €9 billion. They were commissioned between 1997 – 2010.
- Propulsion: 1 x K15 integral PWR rated @ 150 MWt using LEU fuel.
  - Secondary "turboreductor" system believed to consist of 2 x steam turbine-alternators; 1 main propulsion DC electric motor; driving a single pump-jet propulsor.
  - Overhaul / refueling is carried out about every 9 years on this class of submarine.
  - Reactor power is comparable to an S6G/D1G core 2 nuclear plant on a US Los Angeles Flight 1-class SSN, which delivers 30,000 shp propulsion power.
- Armament: 16 SLBMs and 4 x 533 mm (21 in) torpedo tubes.
  - The first three boats originally were armed with M45 SLBMs and L5 active/passive homing torpedoes.
  - The last boat, *Le Terrible*, was the first boat armed with the M-51.1 SLBM and the F17 anti-ship torpedoes & Exocet SM-39 anti-ship cruise missiles.
  - Armaments on all boats were upgraded to the *Le Terrible* standard by 2018.

Le Triomphant-class SSBN

- Operational matters:
  - Typical crew size is 15 officers and 96 sailors. Each SSBN has two crews.
  - Diving depth is 500 m (1,640 ft).
  - Lead ship, *Le Triomphant* (S616), was launched on 26 March 1994; then conducted three years of testing before being commissioned on 21 March 1997 and conducting its 1st deterrent patrol later that year armed with M45 SLBMs.
  - Apr 2002 – Oct 2004: *Le Triomphant's* 1st refueling overhaul (30 months).
  - Feb 2009: *Le Triomphant* collided with UK SSBN *Vanguard* in the Atlantic. Both ships returned to port for repairs.
  - Sep 2010: Last boat in class, *Le Terrible* (S619), was commissioned.
    - It is the first French submarine entirely designed through the use of computer-assisted design (CAD).
    - *Le Terrible* was the first French SSBN armed with the M51 SLBM and fitted with the SYCOBS combat system (SYstem de COmbat Barracuda-SSBN) and SGN-3E navigation system that will be installed on the new Barracuda-class SSNs.
    - France's national audit court, the Cour des Comptes, estimated that the unit production cost of *Le Terrible* was € 3,096 million (in 2009 Euros, about $4.3 B).

Le Triomphant-class SSBN

- Operational matters (cont'd):
  - 2010 – 2013: *Le Vigilant* (S618) was at the DCNS Brest shipyard for its mid-life overhaul and refueling. This overhaul is part of the "IA M51 program" (regular overhaul / adaptation for the M51 missile), which will bring the three earlier Le Triomphant-class SSBNs up to the standard of the *Le Terrible*.
    - Adapted to deploy the M51 new-generation SLBM, the F21 new-generation heavyweight torpedo for self-defense, and the Exocet SM39 anti-ship missile.
    - Fitted with the SYCOBS tactical combat system and SGN-3E navigation system, which also will be fitted on the Barracuda class SSN.
  - 2013 – 2015: *Le Triomphant* (S616) receives its IA M51 overhaul & refueling; price about $113 M.
  - 2015: TNO (Tête nucléaire océanique, oceanic nuclear warhead) warhead was expected to start replacing TN 75 warheads on the M51 SLBMs.
  - Dec 2016 – June 2018 (planned): *Le Téméraire* (S617) receives its IA M51 overhaul & refueling. Now all Le Triomphant-class SSBNs are operational with the M51 SLBM.

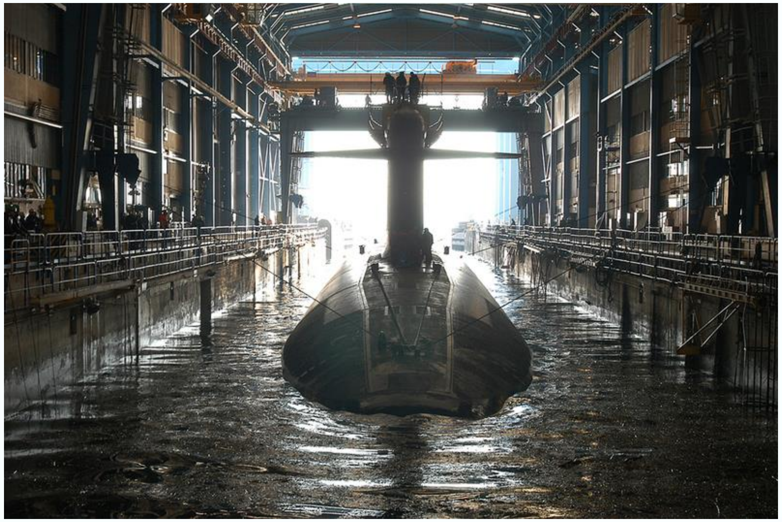
Le Terrible (S619) SSBN

Source: Military-Today.com

Le Triomphant (S616) control room

Source: DCNS / http://www.deagel.com/library/

Le Triomphant (S616) mid-life refit



Source, three photos: https://www.ouest-france.fr

- 19-month "*IA M51 Program*" (Regular overhaul / adaptation for the M51 missile) mid-life refit and refueling was conducted by DCNS from April 2002 – October 2004 at the naval shipyard in Brest.
- The SSBN was modernized to handle the M-51 SLBM & F21 torpedo; also fitted with the SYCOBS tactical combat system and SGN-3E navigation system that also is employed on the new Barracuda-class SSN.
- Cost estimate: $133 M

"3G" Future SSBN

- Initial work on the future SSBN began in 2012, or perhaps earlier.
  - Director Generale de l'Armement (DGA) said that research and development expenditure on French strategic systems would increase to $132 million per year from 2012. Much of this funding will be used to develop the new 3G (third generation) class of SSBNs to replace the Le Triomphant-class.
- 3G-class SSBN work is expected to accelerate in the late 2020s, with construction work on the lead replacement SSBN starting in the late 2030s.
  - By then, the lead 2nd-generation SSBN, *Le Triomphant*, will be approaching a service life of 40 years, which is almost twice the service life of 1st-generation Le Redoutable-class SSBNs.

Submarine-launched ballistic missiles (MSBS*)

* MSBS (*Mer-Sol-Balistique-Stratégique*, "sea-ground ballistic strategic")

French submarine-launched ballistic missiles (MSBS*)

SLBM	Years in service	Weight	Length	Diameter	# of stages	Range / Guidance	Warhead
M-1	1971 - 1974	18,000 kg (39,683 lb.)	10.36 m (34.0 ft.)	1.5 m (4.29 ft.)	2	2,414 km (1,500 mi.) / Inertial	1 x 500 kT MR41
M-2	1974 - 1977	20,000 kg (44,092 lb.)	10.36 m (34.0 ft.)	1.5 m (4.29 ft.)	2	3,058 km (1,900 mi.) / inertial	1 x 500 kT MR41
M-20	1977 - 1991	20,000 kg (44,092 lb.)	10.4 m (34.1 ft.)	1.5 m (4.29 ft.)	2	3,000 km (1,864 mi.) / Inertial	1 x 1.0 – 1.2 MT TN60, superseded by TN61 in late 1977
M-4A --- M-4B	1985 - 2008	36,000 kg (79,366 lb.)	11.05 m (36.3 ft.)	1.93 m (6.3 ft.)	3	4,000 km (5,000 km) / inertial ---- 2,485 mi. (3,106 mi.)/ inertial	Up to 6 x 150 kT TN70 MIRV, superseded by TN71 MIRV in 1987
M-45	1996 – 2016	35,000 kg (77,160 lb.)	11.05 m (36.3 ft.)	1.93 m (6.3 ft.)	3	6,000 km (3,728 mi.) / inertial	Up to 6 x 107 kT TN75 MIRV

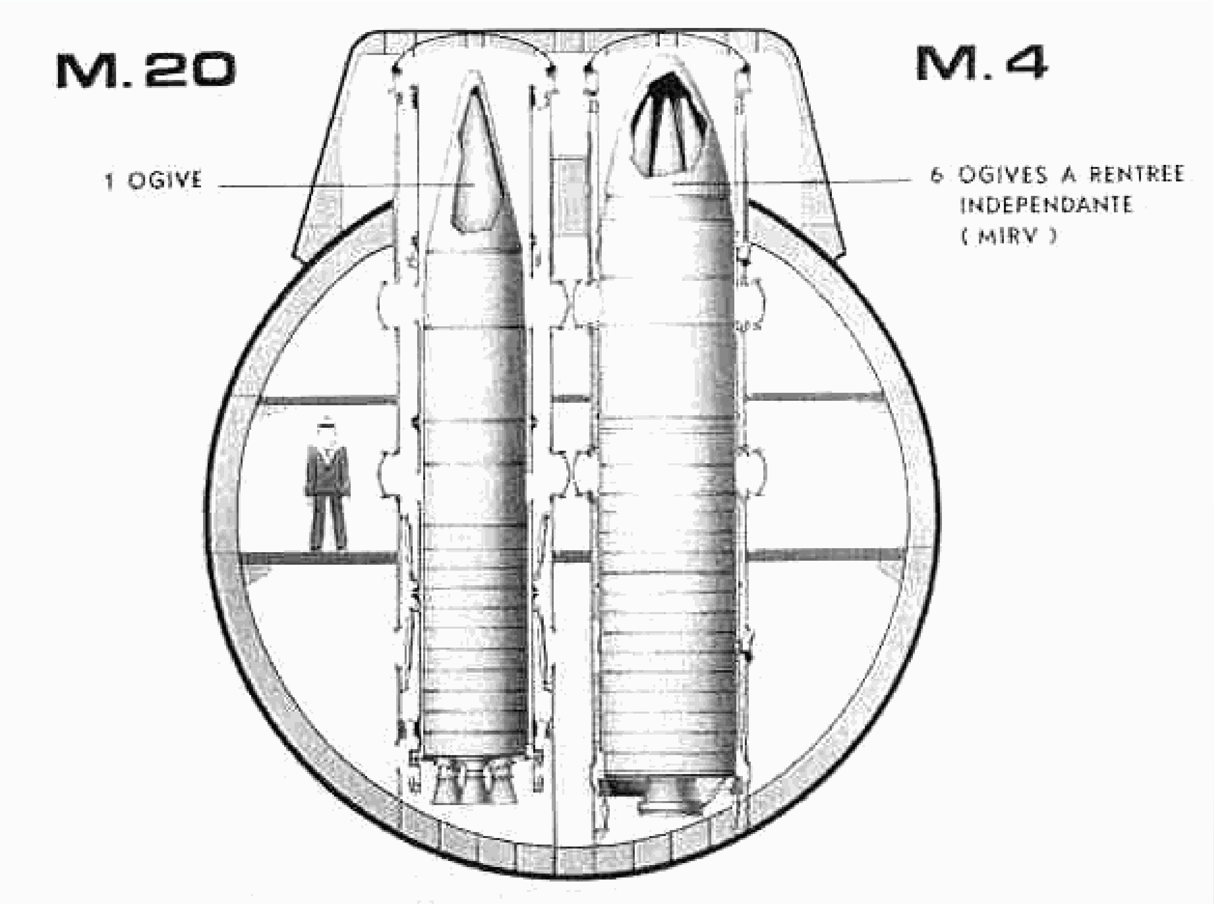
* MSBS (*Mer-Sol-Balistique-Stratégique*, "sea-ground ballistic strategic")

French submarine-launched ballistic missiles (MSBS*)

SLBM	Years in service	Weight	Length	Diameter	# of stages	Range / Guidance	Warhead
M-51.1	2010 - present	52,000 kg (114,640 lb)	12.0 (39.4 ft.)	2.3 m (7.5 ft.)	3	8,000 – 10,000 km (4,971-6,214 mi.) / Inertial	Up to 6 x 107 kT TN75 MIRV
M-51.2	2015 - present	52,000 kg (114,640 lb) (est)	12.0 (39.4 ft.)	2.3 (7.5 ft.)	3	8,000 – 10,000 km (4,971 - 6,214 mi.) / stellar inertial	Up to 10 x 150 kT TNO maneuverable warheads
M-51.3	2025 (planned)	Weight TBD	12.0 (39.4 ft.) (est)	2.3 (7.5 ft.) (est)	3	Range TBD / stellar inertial	TNO maneuverable warheads

* MSBS (*Mer-Sol-Balistique-Stratégique*, "sea-ground ballistic strategic")

Comparison of French submarine-launched ballistic missiles (MSBS)



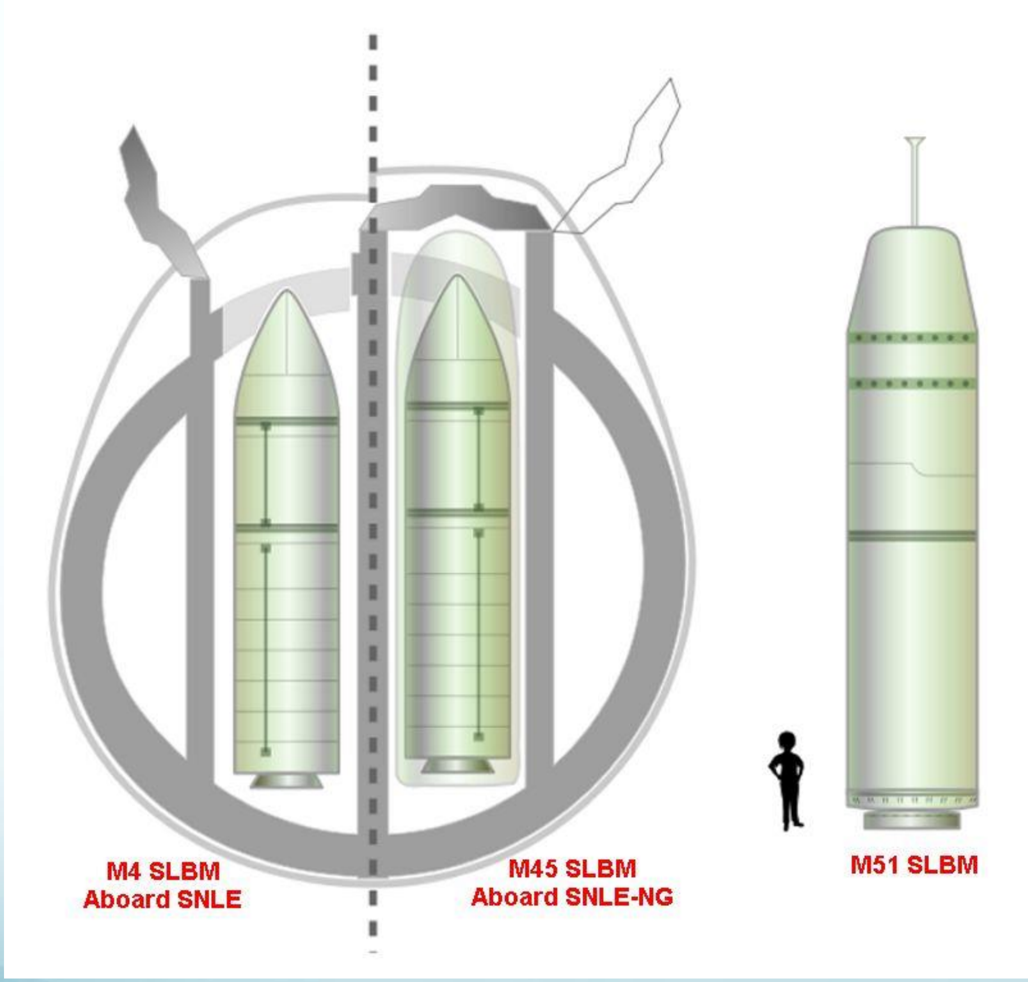
Left hull & missile profile: SNLE Le Redoutable-class with single warhead M-20 SLBM.
Right hull & missile profile: SNLE Le Redoutable-class with MIRV warhead M-4 SLBM.
Source: https://fas.org/nuke/guide/france/slbm/m-4.htm

The M-20 weighed about the same as the M-2 it replaced, and fit in the same missile tube.

The M-4 was considerably larger than the M-20. The M-4 weighed 80% more than the M-20 (36,000 vs. 20,000 kg), was almost one-half meter longer and larger in diameter.

Four SNLE boats were substantially modified to accommodate the M-4 SLBM. *Le Inflexible* was designed originally for the M-4.

Comparison of French submarine-launched ballistic missiles (MSBS)



Left hull & missile profile: SNLE Le Redoutable-class with M-4 SLBM.
Right hull & missile profile: SNLE-NG Le Triomphant-class with M-45 SLBM.
Right missile profile: M-51 missile, with aerospike extended, for Le Triomphant-class.
Source: Wikimedia Commons

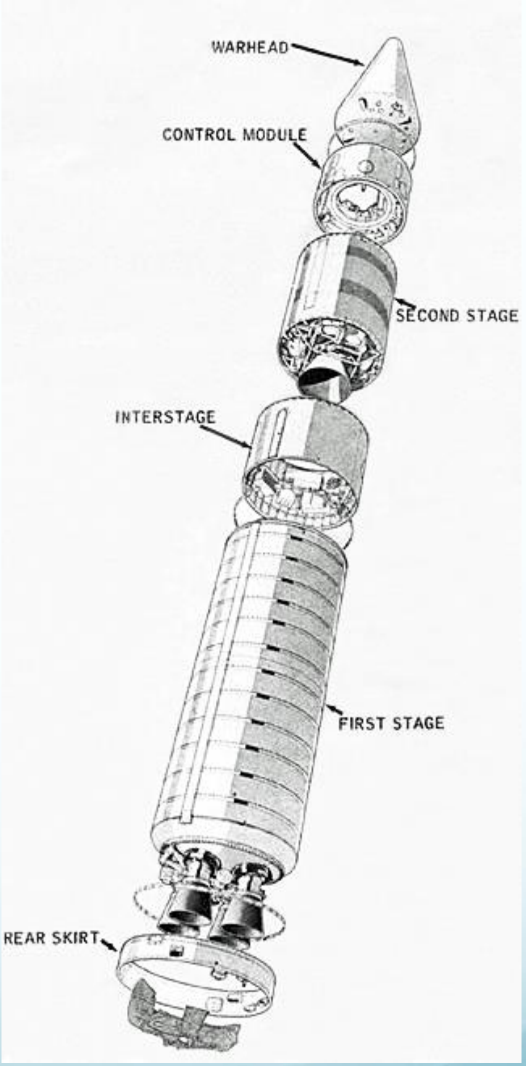
The M-45 is based on the M-4 and both are similar in weight and size. The M-4 was only used on SNLE boats, and the M-45 was used only on the SNLE-NG boats.

At a weight of 52,000 kg (114,640 lb.), the M-51 is 40% heavier than the M-45, about one meter longer and larger in diameter.

Three SNLE-NG boats were substantially modified to accommodate the M-51 SLBM. *Le Terrible* was designed originally for the M-51.

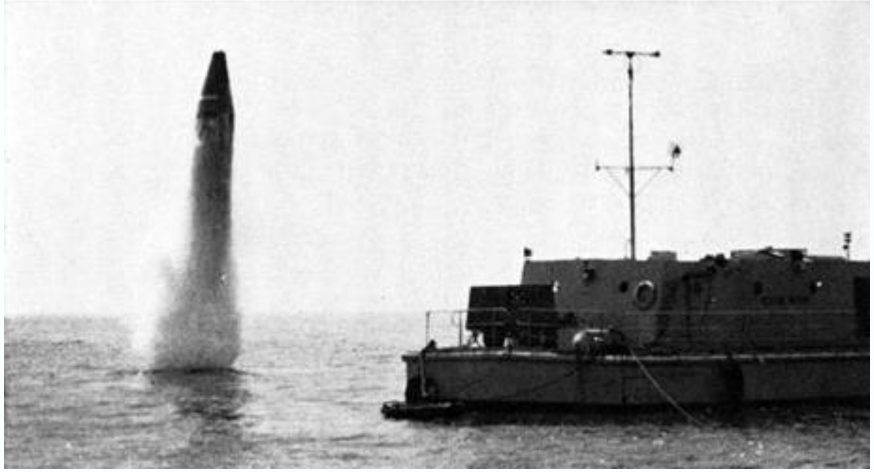
M-1 & M-2 SLBM

- M-1 was the 1st French SLBM. It was a 2-stage, solid-fueled missile with inertial guidance.
- It was armed with a single 500 kT MR41 nuclear warhead. The M-2 had the same warhead.
- The P10 first stage of the M-1 and M-2 also was used as the second stage on France's larger, land-based IRBM.
- The primary difference between the M-1 and M-2 was a 2,000 kg (4,400 pound) increase in the solid propellant carried in the second stage, which increased missile range from 2,414 km (1,500 miles) for the M-1 to 3,058 km (1,900 miles) for the M-2.
  - The M-2 also has updated electronics and improved penetration aids.



Source: adapted from Aviation Week & Space Technology magazine, 9 July 1973, p13.

M-1 & M-2 SLBM



M112 prototype SLBM test.
Source: Aviation Week & Space Technology magazine, 29 May 1967

- 1967: Underwater test launch of a prototype SLBM (the M112) was conducted from an submerged platform.
- 1968: M-1 1st launch from test submarine *Gymnôte 2* (Q-251 / S655).
- M-1 was in service for four years, from 1972 to 1975.
  - The first two French SSBNs originally were equipped with the M-1 SLBM
  - *Le Redoubtable* (S611) started France's 1st deterrent patrol on 28 January 1972, armed with M-1 missiles.
- M-2 replaced the M-1 and was in service for five years, from 1974 – 1978.
  - *Le Foudroyant* was the only SSBN originally equipped with the M-2 SLBM.
  - The first two SSBNs originally equipped with M-1 SLBMs were retrofitted with the M-2 system during their normal overhauls.
- M-2 was replaced by the M-20 starting in 1977.

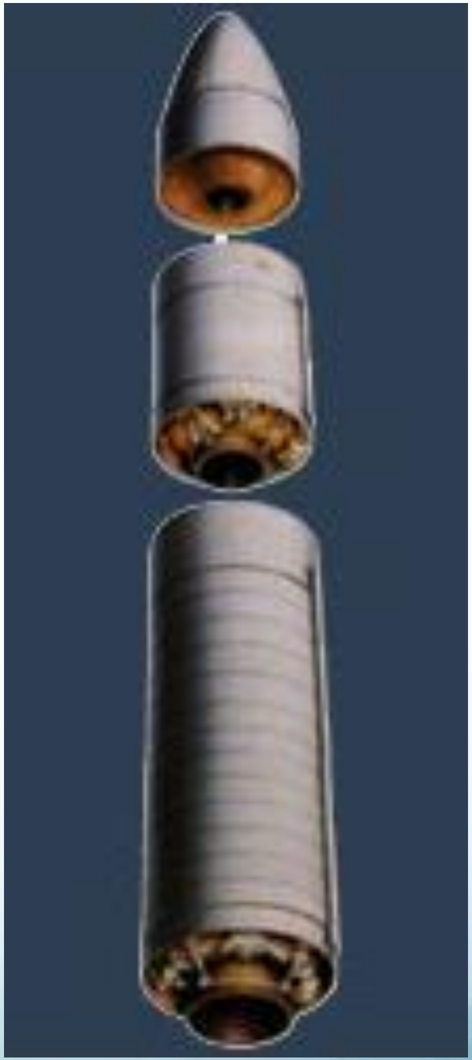
M-20 SLBM

- M-20 was the third French SLBM. It was derived from and replaced the M-2 SLBM aboard Redoutable-class SSBNs.
  - It was a two-stage, solid-fueled missile with inertial guidance and a range of about 3,000 km (1,864 mi).
- M-20 was the 1st French SLBM armed with a thermonuclear warhead: one 1.0 - 1.2 MT TN60, which was considered an "interim" warhead.
  - The TN60 was the 1st French nuclear warhead that was radiation hardened to improve its ability to survive Soviet anti-ballistic missile defenses. It also was equipped with penetration aids (decoys).
- 1977: M-20 entered service as original equipment on the fourth boat, *L'Indomptable,* and later on *Le Tonnant.*
  - The three earlier SSBNs subsequently were retrofitted with the M-20 system during their normal overhauls.
- Later in 1977, the lighter-weight TN61 nuclear warheads replaced the TN60.
- The M-20 was replaced by the M-4 starting in 1985 and completing in 1991, when the *Le Redoutable* was decommissioned.
- The M-20 had a service life of 14 years.

M-20 SLBM.
Source Wikimedia Commons / Rama

M-4 SLBM

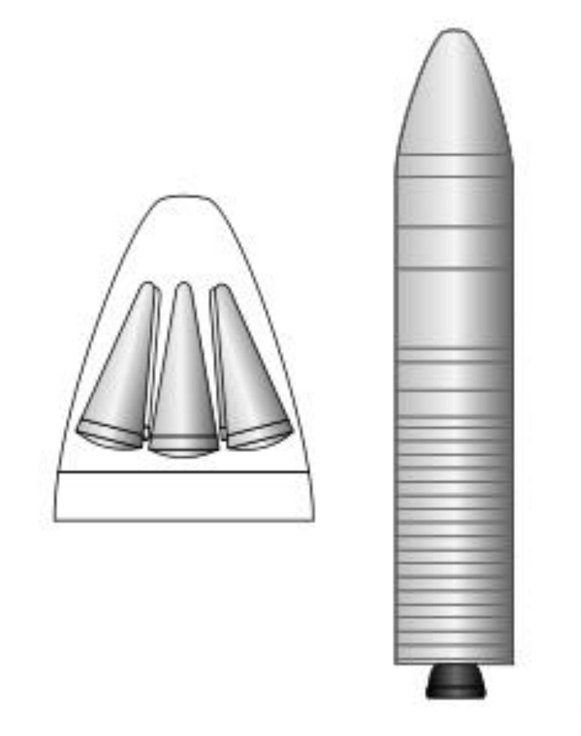
- M-2 replaced the M-2 SLBM aboard five of the six Redoutable-class SSBNs (not *Le Redoutable (*S611) itself).
- 1^{st} 3-stage French SLBM and 1^{st} equipped with MIRV (multiple, independently targeted reentry vehicle) warheads.
  - Initially armed with up to six 150 kT TN70, and later TN71, thermonuclear warheads.
  - Inertial guidance system plus a payload bus guidance system to control the release of the multiple warheads.
- Range: M-4A; 4,000 km (2,485 mi.); M-4B: 5,000 km (3,100 mi).
- Development tests of the M-4 were carried out by the test submarine *Gymnôte 2* from 1980 – 1984.
- 1985: M-4 with TN70 warheads entered service on *Le Inflexible* (S615), which was designed from the start for the M-4 SLBM.
- Four other Redoutable-class SSBNs were overhauled during the period from 1985 – 1993 to handle the M-4.
- 1987: TN71 warheads introduced.
- 2008: M-4 was removed from service when the last Redoutable-class SSBN, *Le Inflexible,* was decommissioned.
- Service life of the M-4 was almost 23 years.



M-4 3-stage SLBM.
Source: http://www.nuclearfiles.org/

M-45 SLBM

- Derived from the M-4 SLBM.
- M45 has a longer range (6,000 km vs. 4,000 – 5,000 km), increased accuracy, and new TN75 MIRV warheads with improved penetration capabilities (stealth features and more decoys) and radiation hardening intended to help defeat the Soviet anti-ballistic missile (ABM) defenses.
- The TN75 is an even more compact, lighter weight warhead than the TN70/TN71.
    - TN75 was tested several times before July 1991, when France temporarily ceased testing its nuclear weapons.
    - TN75 likely was tested again during France's final series of nuclear tests that started in 1995.
- 1995: 1st submerged M-45 launch was conducted by *Le Triomphant* in February.
- Deployed only on SNLE-NG Triomphant-class SSBNs.
    - It is believed that France purchased only enough missiles and warheads for three SSBNs, which is the minimum number it requires to be continuously available.
- 1997: 1st M-45 nuclear deterrent patrol on *Le Triomphant*.
- 2016: The last M-45 SLBMs were retired when *Le Téméraire* entered the shipyard in December for its mid-life refit and conversion for the M-51 SLBM.
- Service life of the M-45 was 19 years.



M-45 SLBM & MIRV warheads.
Source Wikimedia Commons / Rama

M-51 SLBM

- Design work started on the M-5 SLBM in 1992. The program was redefined and the missile was renamed M-51 in 1996.
- November 2006: 1st test launch at Centre d'essais de lancement de missiles (CELM) in Biscarosse, France.
- January 2010: 1st test launch from a submerged submarine, *Le Terrible*.
- M-51.1, with up to six TN75 MIRV warheads, entered service on *Le Terrible* later in 2010.
- M-51.2 has up to 10 TNO (Tête nucléaire océanique) maneuverable warheads, extended range, a highly accurate stellar navigation system to augment the standard inertial navigation system and a better penetration capability. M-51-2 was flight tested in 2012 and started replacing M-51.1 in 2015.

Source: https://missilethreat.csis.org/missile/m51/

Source: https://thenortheasttoday.com

M-51 SLBM

- The TNO weapons concept was validated during the final series of French nuclear tests in 1995. In addition, warhead design and functionality were validated through: (a) simulation on the CEA Direction des Applications Militaires (DAM) Tera 100 supercomputer, (b) inertial confinement tests at the Laser Mégajoule facility near Bordeaux, and (c) radiographic examination.
- When *Le Téméraire* completes its IA M51 overhaul & refueling in 2018, all French SSBNs will be armed with M-51 SLBMs, presumably all M-51.2.
- M-51.3 is an upgraded version that is expected to enter service with the current SSBN fleet in 2025 and also serve on the next generation of French SSBNs.

M-51 SLBM

M-51 SLBM & *Le Triomphant* SSBN. Source: http://www.hisutton.com/Nuclear%20Missile%20Submarines.html

Nuclear-powered fast attack submarines (SSN / SNA*)

* The French name for a fast attack nuclear submarine is SNA, for “Sous-marin nucléaire d'attaque.”

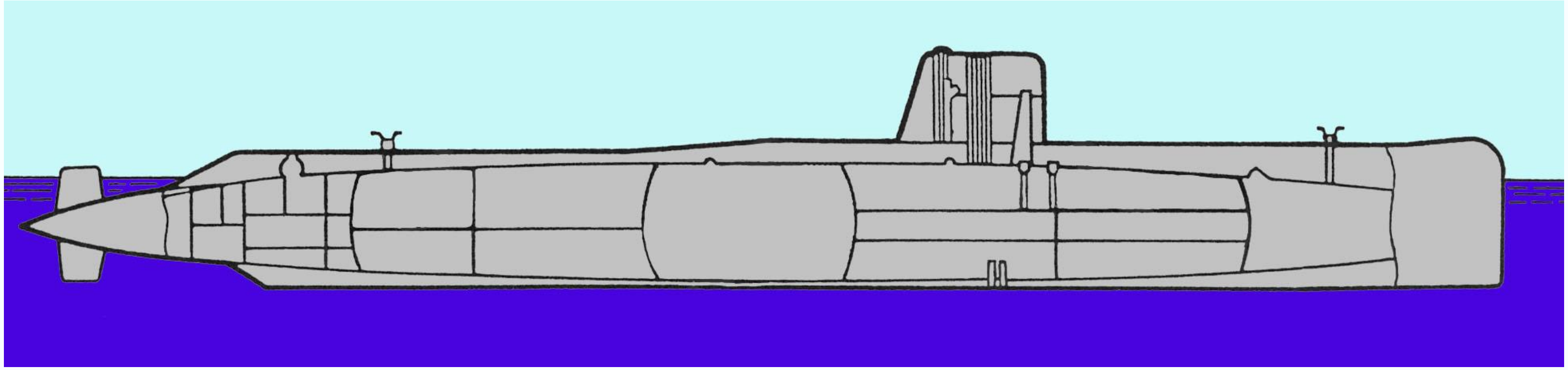
Fast attack submarines (SSN/SNA)

Class	# in Class	Length	Beam	Displacement (tons)	Reactor	Shaft hp	Max speed (kts)	Years delivered	Years in service
Q-244	1	113.75 m (373 ft)	10 m (33 ft)	4,868 (surf), 5,990 (sub)	1 x pressurized heavy water reactor (PHWR)	Not known	17	Not completed. Hull converted to diesel-electric *Gymnote 2* SLBM test sub	
Rubis / Améthyste	6	73.6 m (241.5 ft)	7.6 m (24.9 ft)	2,400 (surf), 2,660 (sub)	1 x PWR CAS48, 48 MWt	9,400 (est)	25	1983 - 93	1983 - present
Barracuda (Suffren)	6 (plan)	99.5 m (324 ft)	8.8 m (28.9 ft)	4,650 (surf), 5,300 (sub)	1 x PWR, Improved K15 150 MWt (est)	30,000 (est)	> 25	1st expected 2018 - 2019	2021 earliest

The French name for a fast attack nuclear submarine is SNA, for “Sous-marin nucléaire d'attaque.”

Q-244

France's 1st nuclear submarine (almost)



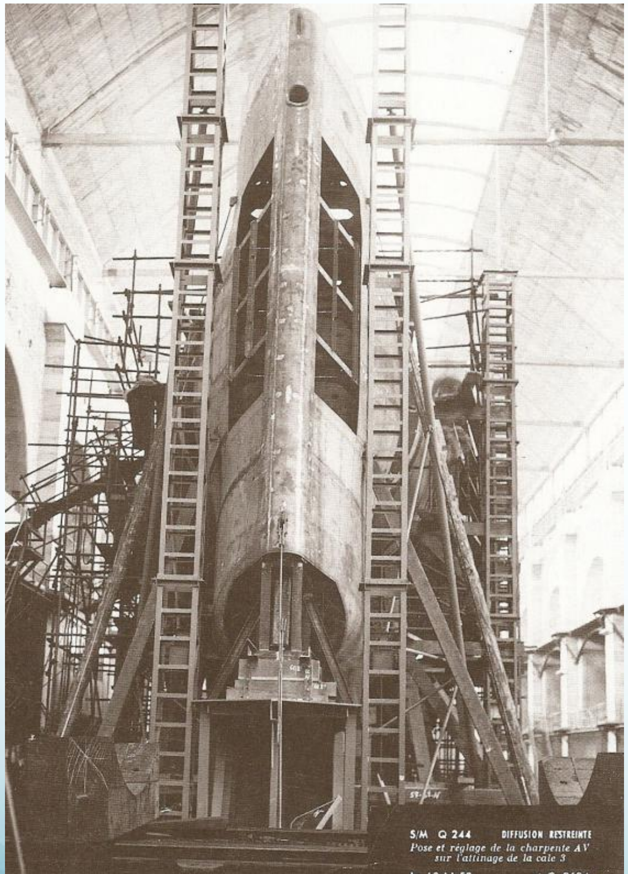
Source: http://sous-marin.france.pagesperso-orange.fr/Q244.htm

- The Q-244 was intended to be France's first nuclear-powered submarine.
  - 2 Jul 1955: Construction began in Cherbourg.
  - 1958: Construction was stopped when it was determined that the planned heavy water reactor would be too large for the submarine. Other reactor technical issues and material supply chain issues (zirconium and heavy water) contributed to the decision.
  - 1959: The Q-244 project was finally abandoned
- Propulsion:
  - In the mid-1950s, France was unable to purchase enriched uranium for the submarine reactor and did not have a domestic uranium enrichment capability. Hence, it was decided to develop a natural uranium fueled reactor, cooled and moderated by heavy water.
  - France did not produce significant amounts of heavy water until December 1967. It is believed that the heavy water needed for the submarine reactor would have been imported from Norway (which France did for its two Celestin land-based heavy water reactors).

Q-244

France's 1st nuclear submarine (almost)

January 2, 1955, the Q-244 under construction in Cherbourg Arsenal



Source: http://forummarine.forumactif.com/t4981-sna-classe-rubis

- Armament: 8 x 550 mm (21.6 in) torpedo tubes; storage for 20 torpedoes.
- Maximum safe depth: 200 m (656 ft.)

Partially-completed Q-244 out of drydock

Source: http://www.graptolite.net/sous-marins/Q244.html

Rubis / Améthyste-class SSN

Source: www.The-Blueprint.com

- The first French SSN design program, SNC68, which started in 1968, proposed construction of eight larger submarines: Displacement: 4,200 – 5,200 tons; Length: 91 - 100 m; Speed: 28 - 29 knots. This program was abandoned in 1969 and work was redirected to the smaller Rubis-class subs.
- The six-boat Rubis-class is the 1st-generation French SSN (SNA) designed by DCNS (Direction des Constructions Navales) and built at the DCNS Cherbourg shipyard between 1983 – 1993.
- The first four Rubis-class SSNs were optimized for anti-surface warfare on a small platform that had export potential.
  - The use of low-enriched uranium (LEU) nuclear fuel complied with international nuclear proliferation restrictions.
  - HY-80 steel hull.
  - The compact design limited the use of machinery quieting measures; no rafting.

Rubis / Améthyste-class SSN

- Propulsion: 1 x CAS-48 integral PWR rated @ 48 MWt with LEU "Carmel" fuel.
  - 2 x 3.15 MW turbo-alternators driving a single electric motor (7 MW, 9,400 shp) and a single screw. Auxiliary diesel-electric propulsion.
  - The CAS-48 reactor can operate on natural circulation at lower (cruising) speed, reducing self-generated noise.
  - Reactor service life for the SSN operating cycle is about 7 years between refueling.
- Armament: 4 x 533 mm (21 in) torpedo tubes; storage for 14 weapons
  - Originally armed with L5 active/passive homing torpedoes and mines.
  - Modernized to use to F17 anti-ship torpedoes & Exocet SM-39 anti-ship cruise missiles.

Rubis / Améthyste-class SSN

- Operational issues:
  - Operationally, the original four Rubis-class SSNs were relatively noisy, with high flow noise and machinery noise.
  - The Améthyste program started in 1982 to develop an anti-submarine warfare (ASW) version of the Rubis SSN with a re-designed forward hull for lower flow noise and rafting of the major machinery.
    - Améthyste was an acronym for AMElioration Tactique, HydrodYnamique, Silence, Transmission, Ecoute ("Tactical, hydrodynamics, silence and transmission improvements").
    - The small hull and cramped interior spaces still limited the ability to apply silencing technologies. However, improvements were made over the original Rubis-class boats.
    - The two improved SSNs, *Améthyste* and *Perle,* were both longer that the original Rubis-class boats, 73.6 meters (241 ft) as compared with 72 meters (236 ft). The Améthyste program included upgrades to the sonar, reshaping of the hull form and bow to improve silencing and additional upgrades of the electronics.
    - These two boats were launched in 1988 and 1990.
    - Two additional *Améthyste* boats were planned, but were cancelled in 1992.
  - With the upgrades tested and proven, the original four boats were rebuilt to the same standards between 1989 and 1995.

Rubis / Améthyste-class SSN

- Operational issues (cont'd):
  - These SSNs are designed to operate at seas 220 days per year. To enable this, they have two crews that periodically exchange roles, similar to SSBN crews.
  - In 30 March 1994, the seawater cooling system for one of the two main condensers failed on the *Emeraude* (S604) while it was taking part in naval exercises in the Mediterranean off Toulon. Pressure built up in the affected main condenser, which ultimately exploded, sending steam and debris into the engine room. The submarine's captain and nine crew in the engine room died. The submarine was able to surface and return to port with the diesel engine and batteries.

Rubis / Améthyste-class SSN

Perel (S606) in drydock

Note the unusual propeller on *Perle*. Source: https://www.reddit.com/r/WarshipFans/

Proposed Canadian version of an Améthyste-derivative SSN

- In June 1987, Canada issued a White Paper detailing a program to acquire 8 to 12 SSNs.
- In response, France offered an Améthyste derivative (the “Canada-class”) with the following features:
  - 80 meters (261 feet) length; surface displacement of 2,590 tons.
  - Able to dive to 350 meters (1,150 feet)
  - Six torpedo tubes; with storage for 22 torpedoes vs. four tubes and 14 torpedoes on *Rubis / Améthyste*.
  - Endurance of 70 days.
  - A strengthened sail and a spike on the periscope for breaking through 1 m (39 in) of ice.
- France was competing against a UK offer to deliver Trafalgar-class SSNs with PWR1 nuclear plants.
- Canada canceled its SSN procurement plans in April 1989.

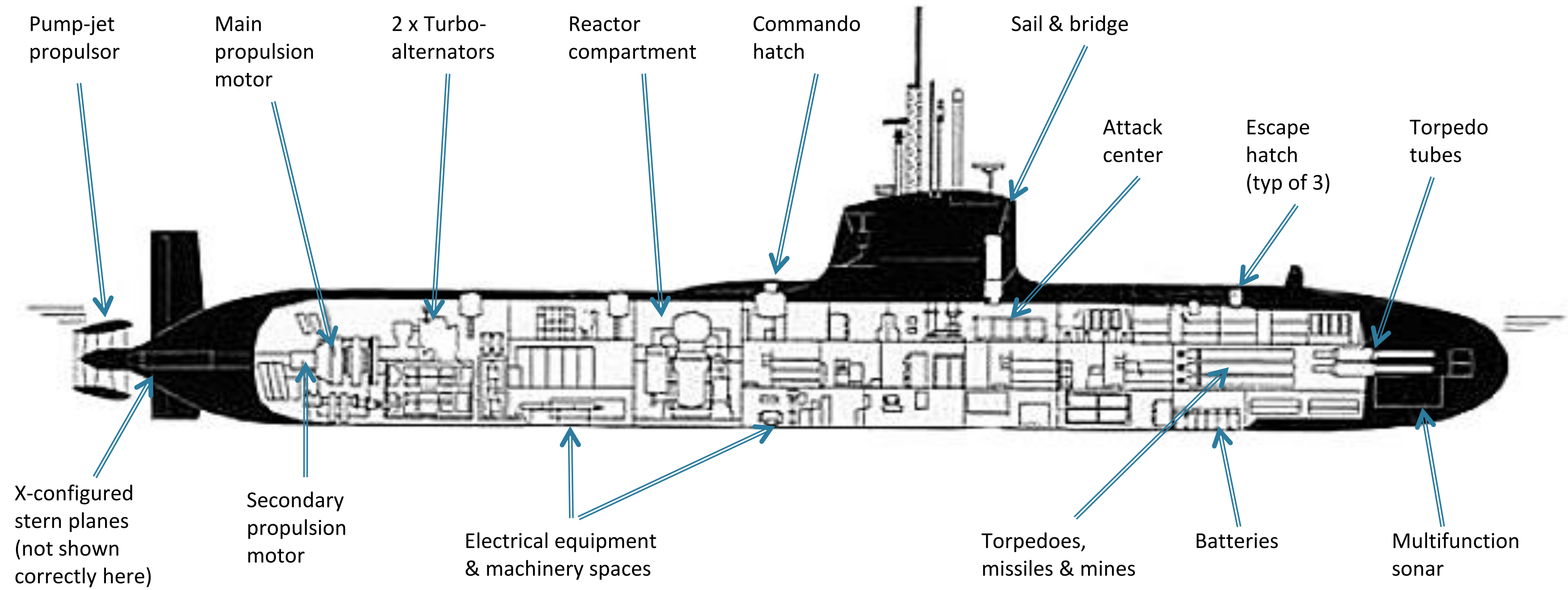
Rubis / Améthyste-class SSNs vs. US Carrier Strike Groups (CSG)

- 2015: *Saphir* (S602) vs. *USS Theodore Roosevelt* (CVN-71)
  - In From 22 January to 5 February 2015, the Rubis-class SSN *Saphir* participated in a COMPTUEX (composite training unit exercise) off Florida with US Carrier Strike Group (CSG) 12, which was preparing for a long deployment.
  - The CSG included the Nimitz-class aircraft carrier *Roosevelt* and the following escort vessels:
    - One Ticonderoga-class cruiser
    - Three Arleigh Burke-class Flight IIA destroyers
    - Likely one or more SSNs
  - In the second phase of the exercise, while serving as a member of the adversary force, *Saphir* avoided detection, penetrated the defense screen around the aircraft carrier and scored simulated torpedo hits on the *Roosevelt* and one or more escort vessels.
- 1998: *Casabianca* (S602) vs. *USS Dwight D. Eisenhower* (CVN-69)
  - During the *Péan* multi-national exercise with the *Eisenhower* CSG, *Casabianca* scored simulated torpedo and Exocet SM39 anti-ship cruise missile hits on the *Eisenhower* and the escorting Ticonderoga-class cruiser *Anzio* (CG-68).
  - This exercise occurred during *Eisenhower's* 1998 deployment to the Mediterranean and Arabian Sea, June – December 1998.
  - The *Eisenhower* CSG included the following escort vessels:
    - Cruiser – Destroyer Group 8, comprised of two Ticonderoga-class cruisers (including *Anzio*), two Arleigh Burke-class Flight I destroyers, and two Spruance-class destroyers
    - One Los Angeles Flight I SSN (*USS Atlanta*).

Barracuda-class SSN

- Expected to be a 6 boat class; as confirmed in France's 2019-2025 defense White Paper.
  - Originally designated SNA-NG (Sous-Marins Nucleaires d'Attaque Nouvelle Generation).
  - Will replace Rubis / Améthyste-class SSNs on a 1-for-1 basis.
- Designed by French shipbuilder DCNS. The Barracuda definition phase started in 1998 and the design phase in 2002.
- Barracuda-class SSN's are being built at DCNS Cherbourg shipyard and are expected to be launched at approximately 2-year intervals over a 12 year period.
  - The keel for the lead boat, *Suffren*, was laid on 19 December 2007.
  - The construction program has been delayed by several years.
  - The lead boat, *Suffren*, may be launched in 2018, but likely would not be delivered to the French Navy until 2019 - 2020.
- In 2010, France's national audit court, the *Cour des Comptes*, estimated that the unit production cost of a Barracuda-class SSN was € 1,093 million (in 2009 Euros, about $1.5 B).
  - The 5th Barracuda-class SSN was ordered in May 2018.

Barracuda-class SSN



Source: Adapted from DCN

Barracuda-class SSN

- Design features:
  - HY- 130 or equivalent steel hull
  - Larger interior volume than Rubis / Améthyste-class
  - Extensive use of machinery isolation and other sound-quieting techniques that were not possible in the Rubis / Améthyste-class
  - X-configured tail planes, pump-jet propulsor
  - Anechoic tiles on the hull
  - Photonic mast instead of a conventional periscope
  - SYCOBS (SYstem de COmbat Barracuda-SSBN) tactical combat system and SGN-3E navigation system, which also have been retro-fitted on all Le Triomphant-class SSBNs by 2018.
  - Mobile pod (similar to US Dry Deck Shelter) can be attached aft of the sail to accommodate equipment for 12 commandos.
- The Barracuda SSN is designed for a maximum operational availability of 265 days per the year, including two distant patrols a year.
  - A Barracuda operates with a 60-person crew, including 12 officers. Like the Rubis / Améthyste-class SSNs, Barracuda-class SSNs will have two crews that periodically exchange roles, similar to SSBN crews.

Barracuda-class SSN

- Propulsion: 1 x integral PWR NSSS that is similar to the RES prototype reactor, which is an evolutionary development of the existing K15 PWR.
  - The K15 integral PWR is rated @ 150 MWt with a secondary steam plant delivering about 21.5 MW (30,000 shaft horsepower) to the propulsion system. This is comparable to the propulsion power of a US Los Angeles Flight I-class SSN, which is a much larger boat than a Barracuda-class SSN and capable of > 30 knots.
  - Barracuda's smaller hull diameter [8.8 m (28.9 ft) vs. 12.5 m (41 ft) for a Le Triomphant-class SSBN] requires a more compact NSSS than the existing K15 installations on the SSBNs and the *Charles de Gaulle* CVN.
  - Hybrid electric propulsion at economical cruise speeds; turbo-mechanical propulsion for higher speeds; driving a single pump-jet; also two emergency electric motors.
  - Reactor service life for the SSN operating cycle will be longer than the seven year cycle for Rubis / Améthyste-class; Barracuda is expected to to have operate for about 10 years between refueling.
- Armament: 4 x 533 mm (21 inch) torpedo tubes with an automated ordnance loading system; storage for 20 weapons, including:
  - F21 heavy-weight torpedoes,
  - Exocet SM-39 anti-ship cruise missiles,
  - MdCN (SCALP Naval) land-attack cruise missiles,
  - FG29 mines, and
  - A3SM anti-aircraft / anti-helicopter missiles.

Barracuda-class SSN

Construction at DCNS Cherbourg shipyard

- The Barracuda SSN is built in a modular fashion at DCNS Cherbourg center.
- Completed modules are moved from a manufacturing space to the main building way for integration.
- Twenty one steel hull segments comprise the pressure hull of a Barracuda SSN, with the segments measuring about 3 m (9.84 ft) long and 9 m (29.5 ft) in diameter.

Barracuda hull segment being moved. Source: DCNS

Barracuda sail under construction. Source: DCNS

Barracuda-class SSN

Construction at DCNS Cherbourg shipyard

Source: DCNS

Barracuda-class SSN

Construction at DCNS Cherbourg shipyard

Barracuda stern section showing X-control surfaces. Source: DCNS

Barracuda-class SSN

Construction at DCNS Cherbourg shipyard

Barracuda lead boat *Suffren*, circa 2016. Source: DCNS

Barracuda-class SSN

Construction at DCNS Cherbourg shipyard

This may be one of the first photos of the externally complete Barracuda-class lead boat, *Suffren*, May 2018.
Source: le marin via http://gentleseas.blogspot.com/2018/05/launch-of-french-barracuda-ssn-delayed.html

Barracuda-class SSN

Notional concept drawing

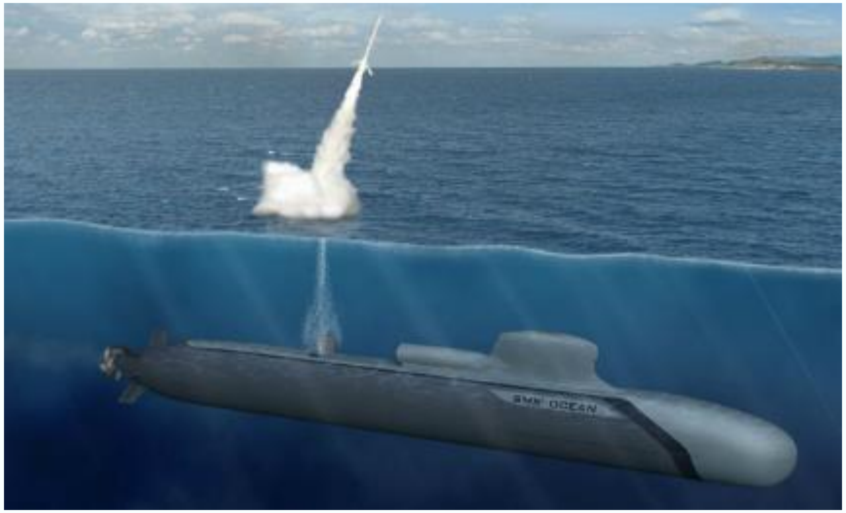
Source: Marine Nationale (French Navy) graphic / navyrecognition.com

Next generation French attack sub?

Source: DCNS

- Oct 2014: DCNS introduced its concept for a next-generation French multi-role attack sub, *SMX Ocean,* that will be suitable for deployment in anti-surface warfare (ASuW), anti-submarine warfare (ASW), anti-air warfare (AAW), land attack and Special Forces missions
- 4,765 ton sub (surfaced), 5,300 ton (submerged), based on the *Barracuda* SSN hull form; including support for launching & recovering unmanned underwater vehicles (UUVs) & divers, including internal provisions for 16 special operations force (SOF) personnel, a a lockout chamber for 8 SOF divers, and a "commando pod" for SOF vehicles and equipment mounted aft of the sail.
- Basic submarine parameters: overall length 100 m (330 ft.); beam 8.8 m (28.9 ft.); and maximum operational depth 300 m (984 ft.).

Next generation French attack sub?



Source: https://www.naval-technology.com

- Propulsion: conventional, air-independent propulsion (AIP); not nuclear.
  - Combination of diesel engines, lithium-ion batteries and fuel cells.
  - Designed for an endurance of 18,000 nautical mile (29,000 km), 3 month autonomous voyages at an average speed of 10 kts.
  - Maximum underwater endurance on AIP fuel cells: 21 days.
  - Two deployable thruster pods provide for maneuverability without the main engine.
- Armament:
  - 4 x 533 mm torpedo tubes for F21 heavy-weight torpedoes, Exocet SM-39 anti-ship cruise missiles, and A3SM anti-aircraft / anti-helicopter missiles; also mines.
  - Also fitted with multiple large, modular Vertical Launch System (VLS) tubes, each with six vertical launch cells for land-attack cruise missiles, unmanned aerial systems (UAS), or other devices.

Submarine-launched tactical weapons

Torpedoes,
Tactical missiles

French submarine-launched torpedoes

Weapon	Years in service	Weight	Length	Diam	Speed / Propulsion	Range / guidance	Warhead
L-5 Mod 3	1960 – late-1980s	935 kg (2,061 lb)	4.3 m (14.1ft)	533 mm (21 in)	30 kts Electric / silver-zinc battery	9.5 km (5.1 naut. mi) Guidance: active / passive terminal homing	High-explosive,200 kg (440 lb)
F17 Mod 2	1988 to present	1,397 kg (3,079 lb)	5.38 m (19.4 ft)	533 mm (21 in)	22 or 40 kts Electric / silver-zinc oxide battery	22 km (11.9 naut.miles) @ 40 kts Guidance: Wire-guided, passive / active terminal homing	High-explosive, 250 kg (551 lb)
F21 Artemis	IOC in 2018 - 2019	1,500 kg (3,307 lb)	6 m (19.6 ft)	533 mm (21 in)	> 50 kts Electric / silver oxide – aluminum battery	Guidance: Fiber optic wire-guided, passive / active and wake homing terminal homing	Similar to UGST

L5 Mod 3 torpedo

- The L5 torpedo came in several versions. The Mod 3 version could be launched from submarines and surface ships.
- Initial Operating Capability (IOC) was in 1971. On submarines, the L5 Mod 3 was a replacement for the shorter-range, slower L3 acoustic homing anti-submarine torpedo that was developed in the late 1950s and entered service in 1960.
- The ECAN L5 Mod 3 torpedo was equipped with active and passive homing.
- Basic design parameters:
  - Weight: 935 kg (2,061 lb)
  - Diameter: 533 mm (21 in)
  - Length: 4.3 m (14.1 ft)
  - Propulsion: Electric, silver-zinc battery
  - Speed: 35 knots (65 kph, 40 mph)
  - Maximum range: 9.5 km (5.1 naut. miles)
  - Maximum operating depth: 550 m (1,800 ft)
  - Warhead: 200 kg (440 lb) high-explosive
- The L5 Mod 3 was replaced on submarines by the F17 Mod 2 torpedo.

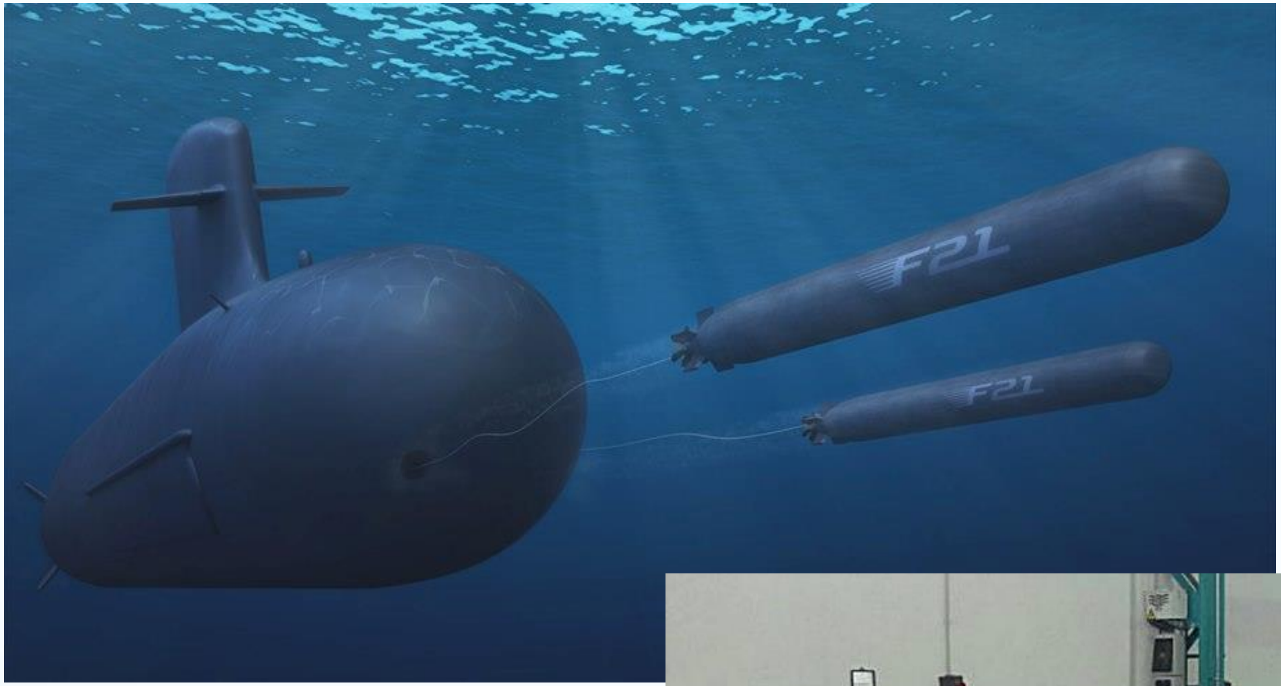
F17 Mod 2 torpedo

- Developed by DCNS Naval Group (ECAN, Saint-Tropez) starting in 1973, originally at a caliber of 550 mm (21.65 inches) and deployed on submarines and surface ships in various models since 1973.
  - The F17 Mod 2 was developed later with a caliber of 533 mm (21 inches).
  - Earlier E15 torpedoes were converted to the F17 standard.
- The F17 Mod 2 version is France's current generation of heavyweight submarine-launched torpedo, intended for use against submarine and surface targets. IOC was 1987.
- Wire-guided (traditional wire) with active and passive acoustic terminal homing, with a shallow-water operating mode.
- Basic design parameters:
  - Weight: 1,397 kg (3,079 lb)
  - Length: 5.38 m (19.4 ft)
  - Propulsion: Electric, silver-zinc oxide battery
  - Speed: The torpedo can be fired at two different speed settings: low speed [24 knots (44.4 kph, 27.6 mph)] or high speed [40 knots (74 kph, 46 mph)]. Either the torpedo travels the entire distance at one speed, or it begins the approach at the slower speed and accelerates to high speed in the terminal homing phase.
  - Range: 22 km (11.9 naut. mi) @ 40 knots
  - Maximum operating depth: 600 m (1,969 ft)
  - Warhead: 250 kg (551 lb) high-explosive
- In 2003, the unit price of an F17 Mod 2 torpedo was estimated to be $1.2 M.
- It is being replaced by the F21 Artemis torpedo.

F21 Artemis torpedo

- This is France's current generation of 533 mm (21 inch) high-speed, heavyweight, submarine-launched torpedo. Launch can be done in swim-out or push-out modes.
- Developed by DCNS Naval Group (ECAN, Saint-Tropez) with Thales and Atlas Elektronik.
  - Initial tests began in 2013, with qualification testing continuing into 2018.
  - Will replace the F17 Mod 2 torpedo on all French submarines.
- Fully digital; guided by fiber-optic wire and by an autonomous passive / active acoustic and wake homing capability; for use against surface and submarine targets in oceanic and coastal waters.
  - The guidance package, designed by Thales, is claimed to deliver good performance in very noisy coastal areas with dense maritime traffic.
- Basic design parameters:
  - Weight: 1,500 kg (3,307 lb)
  - Length: 6 m (19.6 ft)
  - Propulsion: Electric, with a small auxiliary battery for initial operation to move the torpedo beyond a "safety zone" around the launching submarine, then power is provided by the silver oxide-aluminum (AgO-Al) primary battery.
  - Speed: > 50 knots (> 93 kph, > 58 mph)
  - Maximum range: 57 km (31 naut. miles)
  - Warhead: PBX B2211 high-explosive, detonated by acoustic proximity / impact fuse.
- The French Navy has ordered 93 F21 torpedoes; also ordered by Brazil.

F21 Artemis torpedo



Source: DCNS via
http://www.deagel.com/library/F21-
torpedo_m02017062300009.aspx

Source: DCNS via http://weaponews.com/news/29362-the-french-fleet-successfully-
tested-a-new-torpedo-f21.html

French submarine-launched tactical missiles

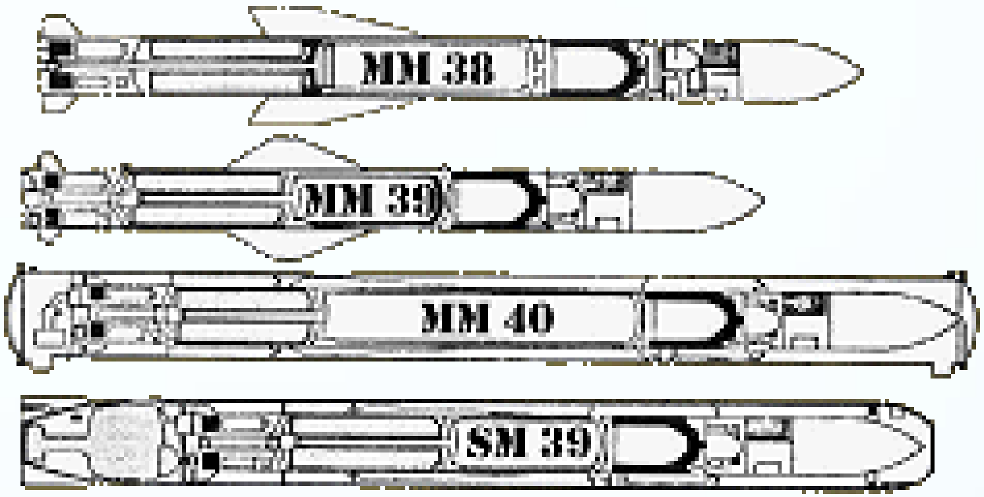
Missile type	Years in service	Weight	Length	Diam (D) / Span (S)	Speed	Range	Guidance	Warhead
SM39 Exocet anti-ship cruise missile	1983 - present	655 kg (1,444 lb) missile only; 1,345 kg (2,965 lb) with VSM *	4.69 m (12.3 ft.) missile only; + VSM *	D=350 mm (13.8 in); S=1.13 m (3.7 ft.) missile only	Mach 0.9	50 km (27 mi)	Inertial + terminal active radar homing	Conventional shaped charge 165 kg (364 lb)
MdCN land-attack cruise missile	2019 (planned)	1,400 kg (3,086 lb) + VSM *	6.5 m (21.3 ft.) missile only; + VSM *	D=500 mm (19.7 in); S=2.85 m (9.4 ft.) missile only	Mach 0.9; 1,000 kph (621 mph)	About 1,000 km (621 mi.)	Inertial + radio-altimeter + GPS + terminal IR homing	Conventional unitary warhead, weight TBD (several hundred kg)
A3SM Mica medium-range anti-aircraft missile	Unveiled 2012, under development	112 kg (247 lb) missile only; + VSM *	3.1 m (10.2 ft.) missile only; + VSM *	D=160 mm missile only	Mach 3	20 km (12.4 mi)	Inertial + terminal infra-red homing	Conventional 12 kg (26.4 lb)
A3SM Mistral 2 short-range anti-aircraft missile	Unveiled 2012, under development	19.5 kg (43 lb)	1.86 m (6.1 ft.)	D=90 mm (3.5 in) S=180 mm (7.0 in)	Mach 2.5	6.5 km (4 mi)	Infra-red homing	Conventional 2.95 kg (6.5 lb)

* VSM = *véhicule Sous marin = missile capsule*

SM-39 Exocet

anti-ship cruise missile

- The SM.39 is the encapsulated submarine launched version. The MM.38 and MM.40 are the ship-to-ship versions. The last member of the family is the AM.39; the air-to-ship version.
- The submarine-launched missile is housed inside a water-tight launch capsule (VSM or *véhicule Sous marin*), which is hydraulically launched from a submarine 533 mm (21 in.) torpedo tube. On leaving the water, the capsule is ejected as the missile's rocket motor ignites.



Source: http://www.century-of-flight.net/Aviation%20history/

- Missile basis parameters: Length: 4.69 meters (12.3 ft), diameter: 350 mm (13.8 in), wingspan: 1.13 meter (3.7 ft), missile weight: 655 kg (1,444 lb); warhead weight: 165 kg (364 lb); range: 50 km (27 mi); speed: Mach 0.9
- Guidance is inertial + terminal active radar homing.
- The air-launched version sank HMS *Sellafield* during the 1982 Falklands War.
- This missile has been sold by France to many export customers worldwide.

SM-39 Exocet

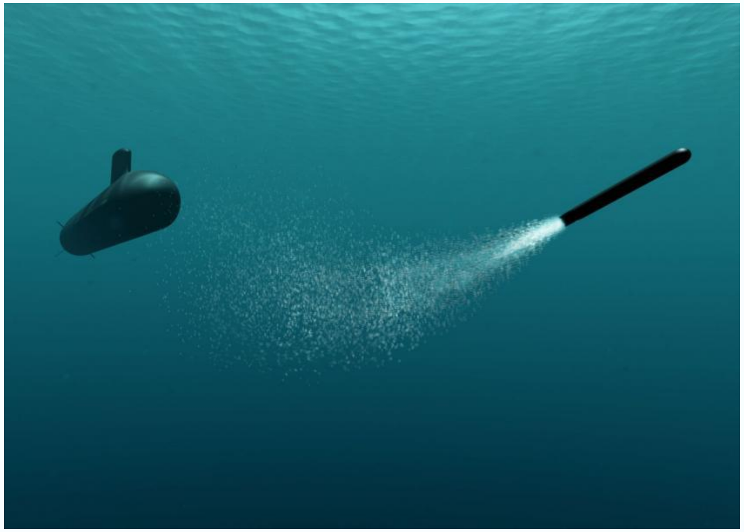
anti-ship cruise missile

Exocet submerged launch sequence. Source: MBDA Missile Systems

MdCN (SCALP Naval)

(Missile De Croisière Naval – naval cruise missile)

- Developed by the French firm MBDA, MdCN is a naval variant of the air-launched Storm Shadow/ SCALP land-attack cruise missile. The MdCN version for surface ships was first deployed in 2017; submarine deployment is expected in 2019.
- The submarine-launched version is encapsulate and launched from a 533 mm (21 in.) torpedo tube. This version was first tested from an underwater platform in June 2011 and from a submarine in October 2012. It will equip Barracuda-class SSNs and Scorpion-class conventional subs.
- Rocket booster + small Turbomeca Microturbo TR50 turbojet engine for cruise flight.
- The missile is subsonic, with a maximum speed of about 1,000 kph (621 mph) and a maximum range of about 1,000 km (621 mi.).

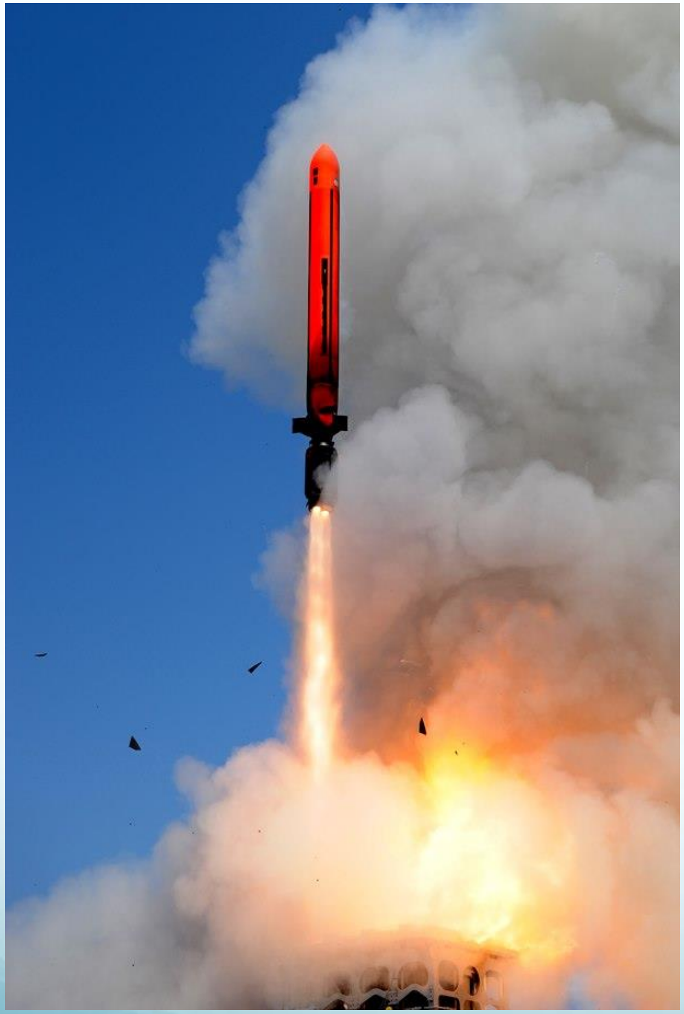


MdCN launched from a submarine. Source: DCNS

MdCN test launch from a submerged platform.
Source: DGA (Delegation Generale pour l'Armement)

MdCN (Scalp Naval)

(Missile De Croisière Naval – naval cruise missile)



MdCN rocket booster firing. Source: MBDA / DGA

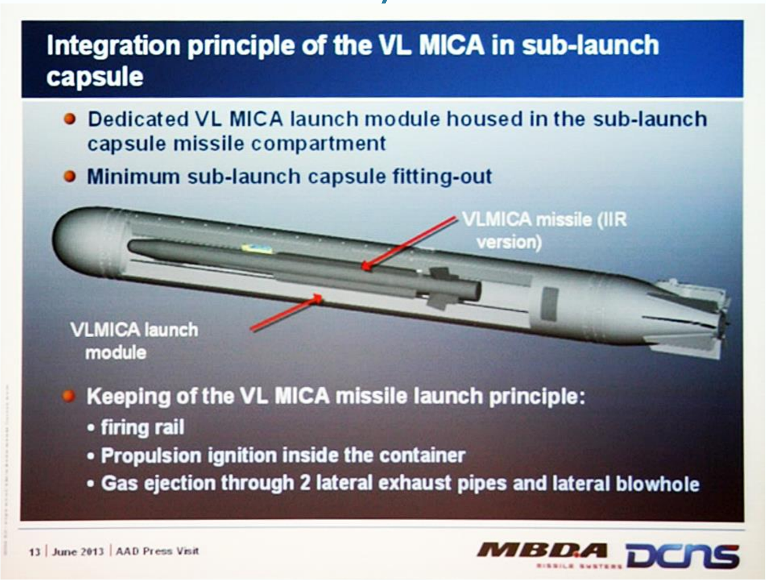
MdCN missile in cruise flight configuration. Source: MBDA

- Navigation system: integrated inertial, radio-altimeter and GPS for enroute navigation, with an imaging infra-red (IR) seeker for terminal guidance.
- Warhead: unitary warhead for use against soft to moderately hardened targets

A3SM

Arme Anti-Aérienne pour Sous Marins
(Anti-Air Weapon for Submarines)

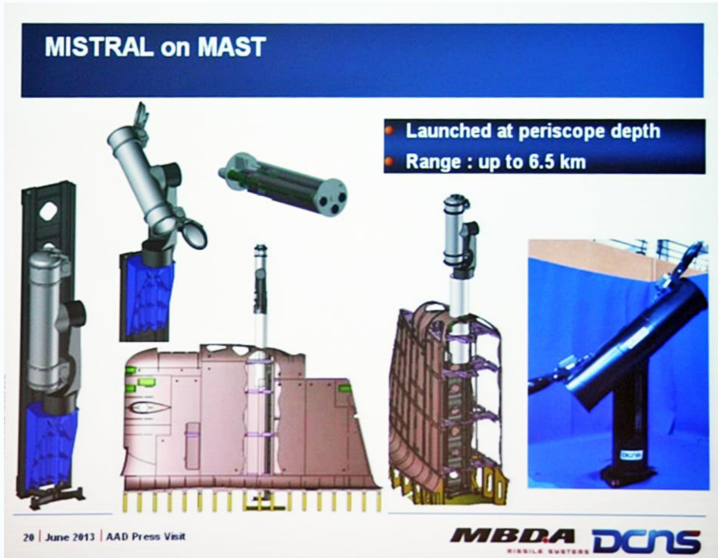
- A3SM is a family of submarine-launched weapons developed by the French firms MBDA and DCNS for use against anti-submarine helicopters and maritime patrol aircraft.
- Two versions were unveiled at Euronaval 2012: (1) an encapsulated “underwater vehicle” launched from a 533 mm (21 in.) torpedo tube, and (2) a smaller, mast-mounted version.

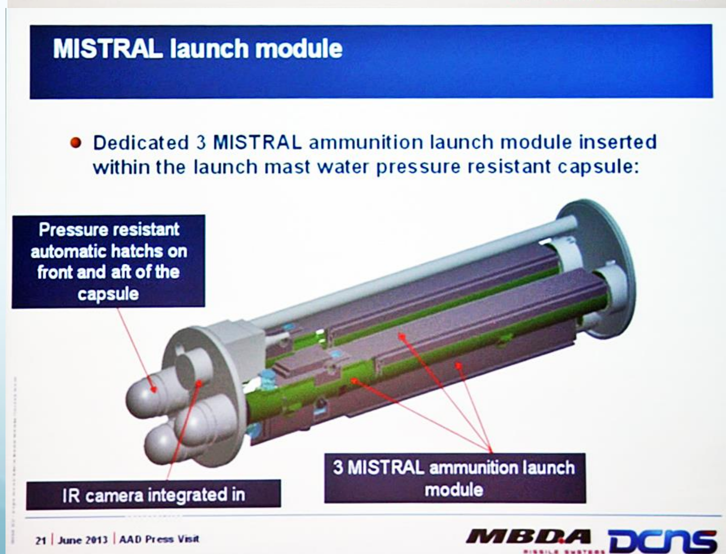


Source: MBDA / DCNS / http://www.navyrecognition.com/

- The A3SM “underwater vehicle” is similar to the VSM for the SM39 Exocet missile. It can be launched from any depth. Following launch, the rocket-powered capsule maneuvers underwater to align the missile with its intended target. When the capsule breaches the surface, the Mica missile is fired and flies free of the capsule.
- Mica is a medium range (20 km, 12.4 miles), Mach 3, autonomous infra-red (IR) guided missile with a 12 kg (26.4 pounds) warhead. It acquires its target after launch.

A3SM





Source: MBDA / DCNS / http://www.navyrecognition.com/

- The mast-mounted version has an extendable mast with a watertight container that houses an infra-red (IR) targeting camera and three Mistral 2 missiles. When extended at periscope depth, the launch container is opened above water, pointed in any direction to acquire the intended target with the IR camera, and a missile is launched after it has locked-on to the target.
- Mistral 2 is a lightweight, short-range (6.5 km, 4 miles), Mach 2.5, IR guided missile with a modest warhead (about 2.95 kg, 6.5 pounds).
- Not yet deployed, but both A3SM versions are designed to be employed on all French submarines with minimum modifications.

Nuclear-powered aircraft carrier

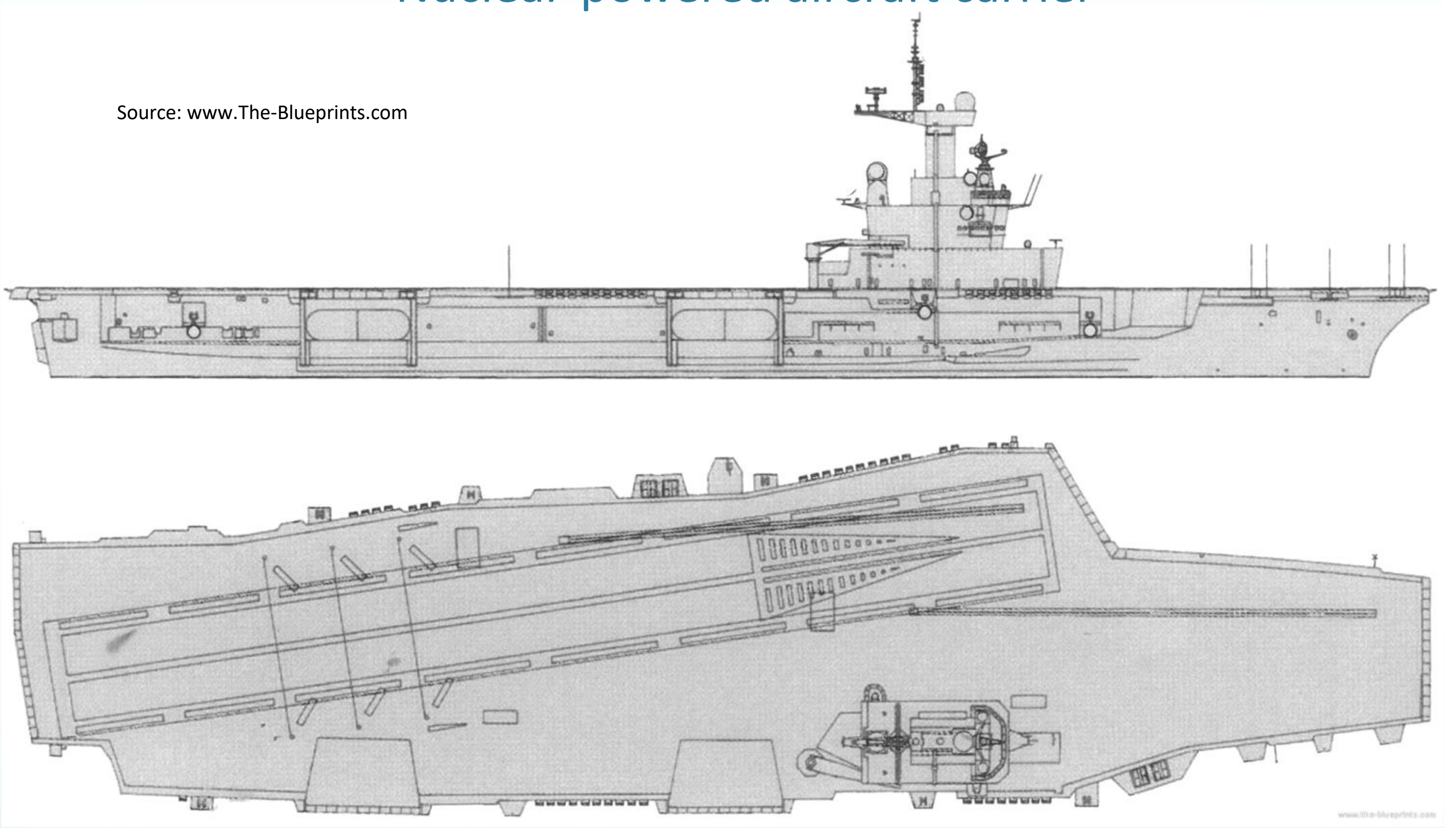
Charles de Gaulle (R91)

Nuclear-powered aircraft carrier

- The aircraft carrier *Charles de Gaulle* was the first French nuclear-powered surface ship.
  - Originally proposed in 1972 as a nuclear-powered helicopter carrier.
  - The nuclear-powered aircraft carrier was proposed in 1980, funded in 1983, and the keel was laid in April 1989 at the DCN Brest Arsenal Shipyard. Originally it was to be named *Richelieu.*
  - The ship was commissioned as *Charles de Gaulle* on 18 May 2001 and assigned to operate out of the port of Toulon, on the Mediterranean.
  - The ship carries a crew of about 1,950
  - Construction cost was estimated at USD $2.8 billion.
- Propulsion: 2 x K15 integral PWRs rated @ 150 MWt each.
  - 2 x GEC Alsthom steam turbines deliver a combined output of 82,000 shp (61 MW), driving 2 x shafts.
  - The *Charles de Gaulle* top speed is about 27 knots. Its conventionally-powered predecessor, *Clemenceau*, achieved 32 knots.

Charles de Gaulle (R91)

Nuclear-powered aircraft carrier



Class	# in Class	Length	Beam	Displacement (tons)	Reactor	Shaft hp	Max speed (kts)	Year delivered	Years in service
Charles de Gaulle	1	261.5 m (857.9 ft)	64.4 m (211.3 ft) overall	42,000 (full load)	2 x PWR, K15, 150 MWt each	82,000	27	2001	2001 - present

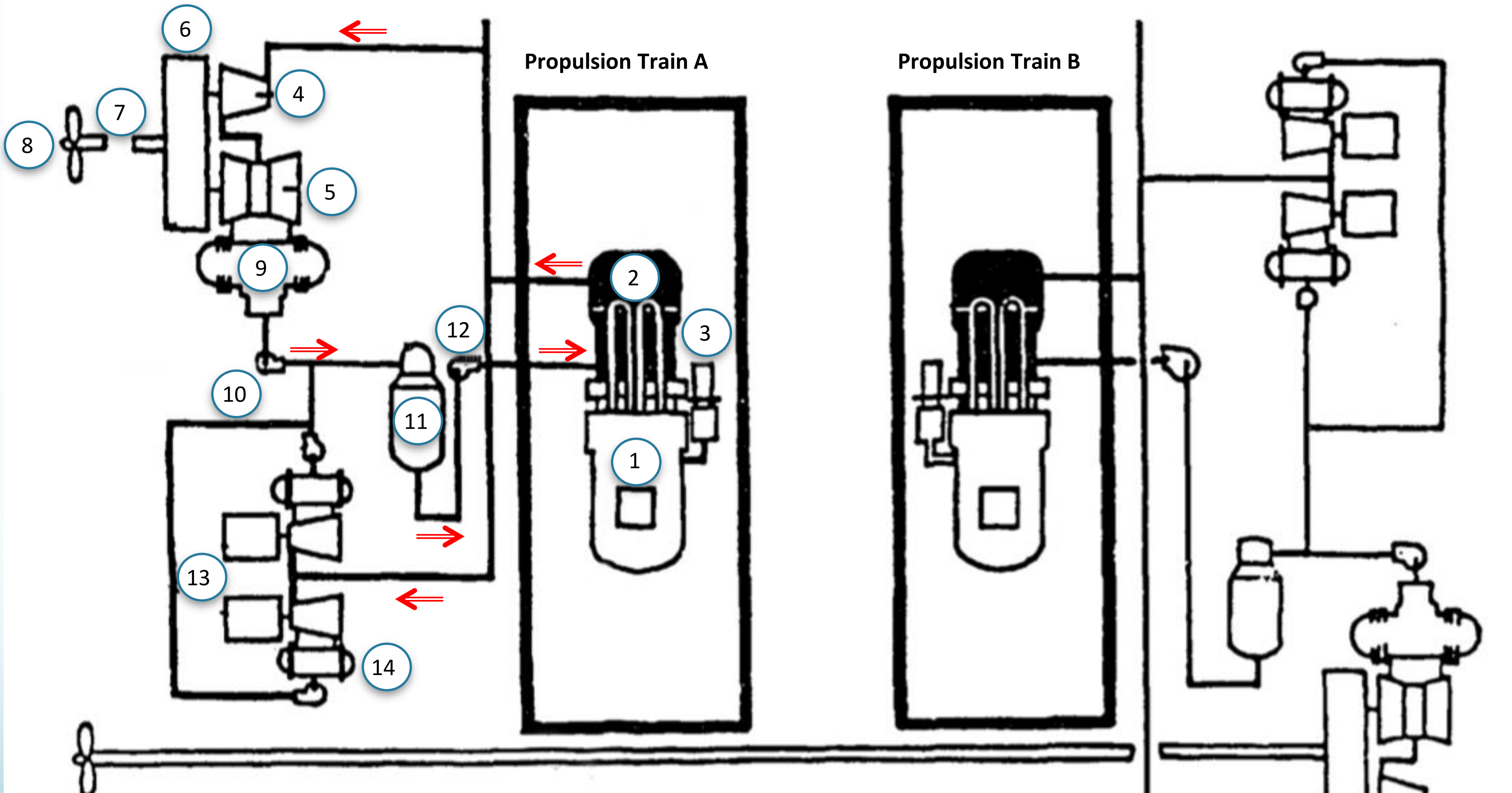
Charles de Gaulle (R91)

Nuclear-powered aircraft carrier

Charles de Gaulle at its home port, Toulon, France. Source: http://www.skyscrapercity.com/

Charles de Gaulle (R91)

Nuclear propulsion plant configuration with two K15 integral PWRs

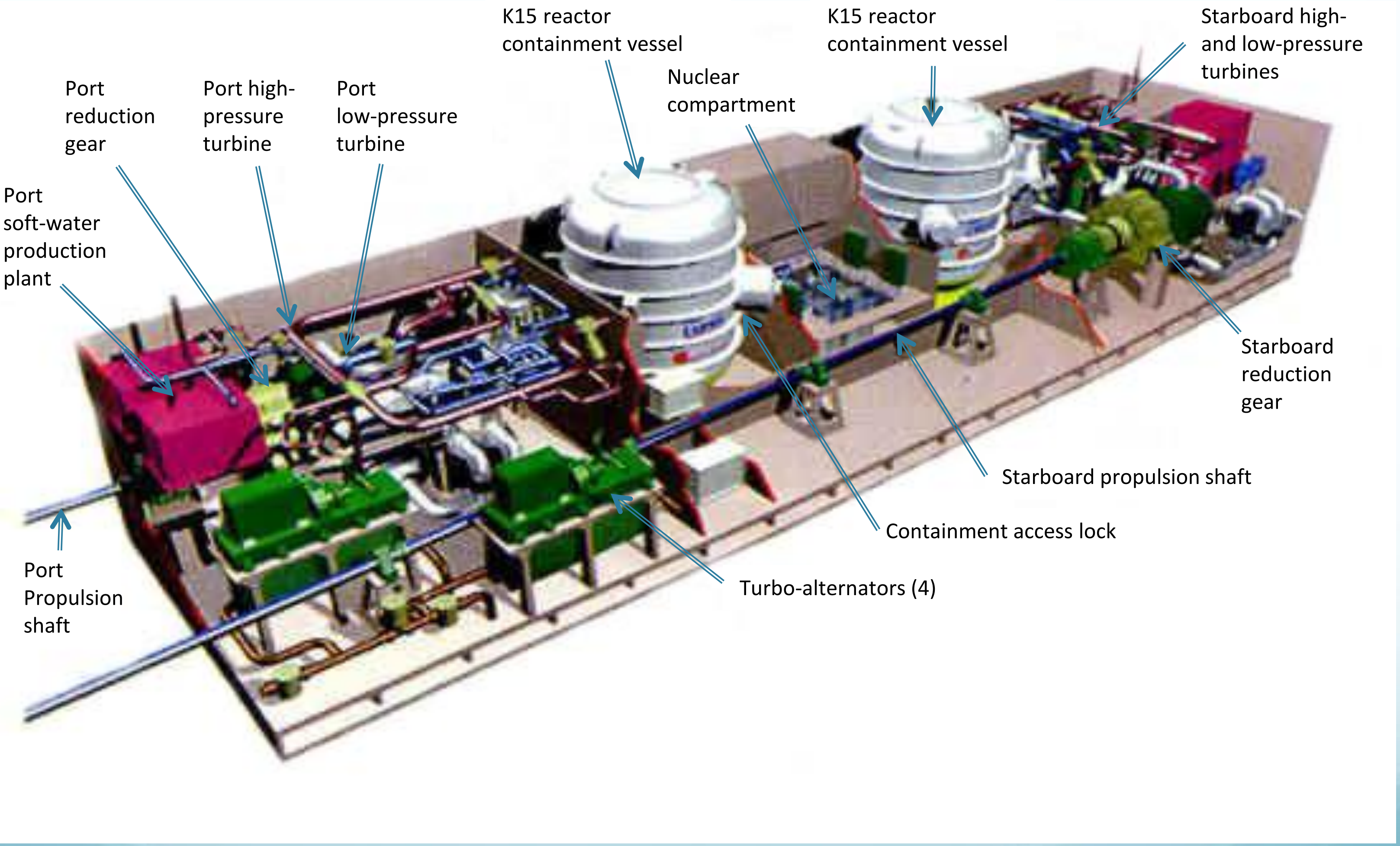


Legend: 1 – Reactor, 2 – Steam generator, 3 – Primary pump, 4 – HP turbine, 5 – LP turbine, 6 – Reduction gear, 7 – Propeller shaft, 8 – Propeller, 9 – Main condenser, 10 – Condensate pump, 11 – Deaerating feed tank, 12 – Feedwater pump, 13 – Turbine generators, 14 – TG condensers and condensate pumps

Source: adapted from http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/27/073/27073072.pdf

Charles de Gaulle (R91)

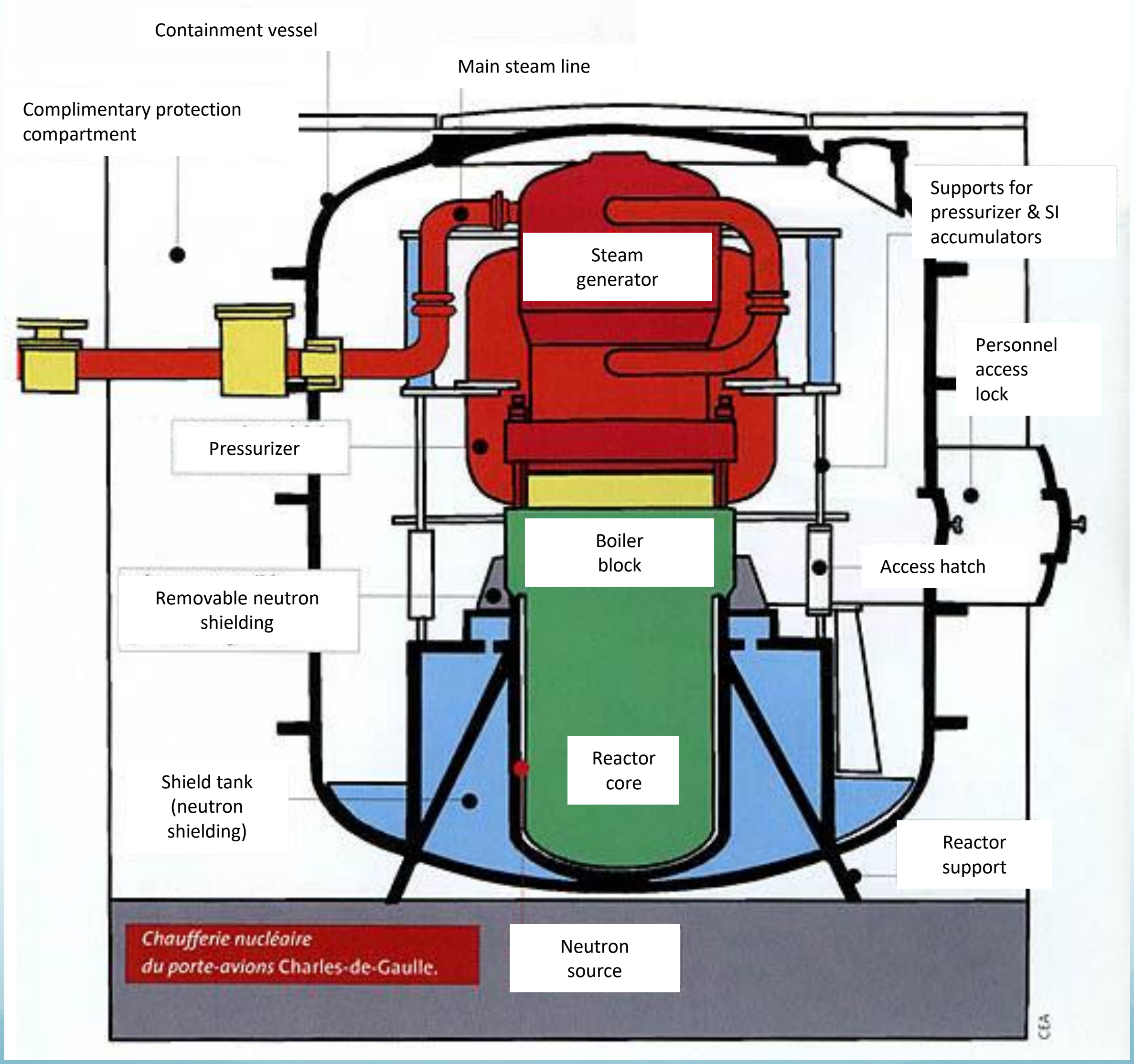
Nuclear propulsion plant configuration with two K15 integral PWRs



Source: adapted from http://forummarine.forumactif.com/t1226p285-pa-r91-charles-de-gaulle

Charles de Gaulle (R91)

K15 integral PWR configuration on *Charles de Gaulle*



Source: adapted from La Gazette Nucléaire n°175/176 juin 1999

Charles de Gaulle (R91)

Nuclear-powered aircraft carrier

- Armament:
  - Air wing with up to 40 aircraft and helicopters of various types.
    - Fighters: Dassault Rafale M
    - Airborne early warning: E-2C Hawkeye
  - Anti-air defenses: 4 x Sylver (MBDA Aster) 8-cell missile launchers, 2 x Sadral 6-cell short-range missile launchers and 8 x 20 mm dual-purpose cannons.
- Operational matters:
  - The two reactors went critical for the first time on 25 May and 10 June 1998, respectively; about four years after CDG was launched. Sea trials began about 18 months later, in November 1999.
  - *CDG* is the only non-American aircraft carrier in the world qualified to operate US naval aircraft (F-8E Crusader jet fighters and E-2C Hawkeye airborne early warning and control aircraft).
  - September 2007: The first major overhaul and refueling began nine years after initial criticality and lasted 15 months, until December 2008.
    - *CDG* sailed about 450,600 km (280,000 miles) and spent 900 days at sea on the initial core.
    - The hangar deck serves as a fuel unloading / refueling hall.

Charles de Gaulle (R91)

Nuclear-powered aircraft carrier

- Operational matters (cont'd):
  - February 2017: *de Gaulle* started its second major overhaul to refuel the reactor and modernize the ship. The overhaul is expected to take 18 months and should extend the life of the ship for another 20 years, until at least 2039. Ship improvements will include:
    - New Thales Smart-S Combat Management System, including new sensors and communications systems
    - Upgraded navigation system
    - Improved NATO interoperability
    - Improved support for the Rafael fighter, including new landing & guidance system
  - Since commissioning in 2001, *CDG* has sailed the equivalent of 30 times around the world (about 1,200,000 km, 745,000 miles) and performed 41,000 catapult launches.

Charles de Gaulle (R91)

Nuclear-powered aircraft carrier

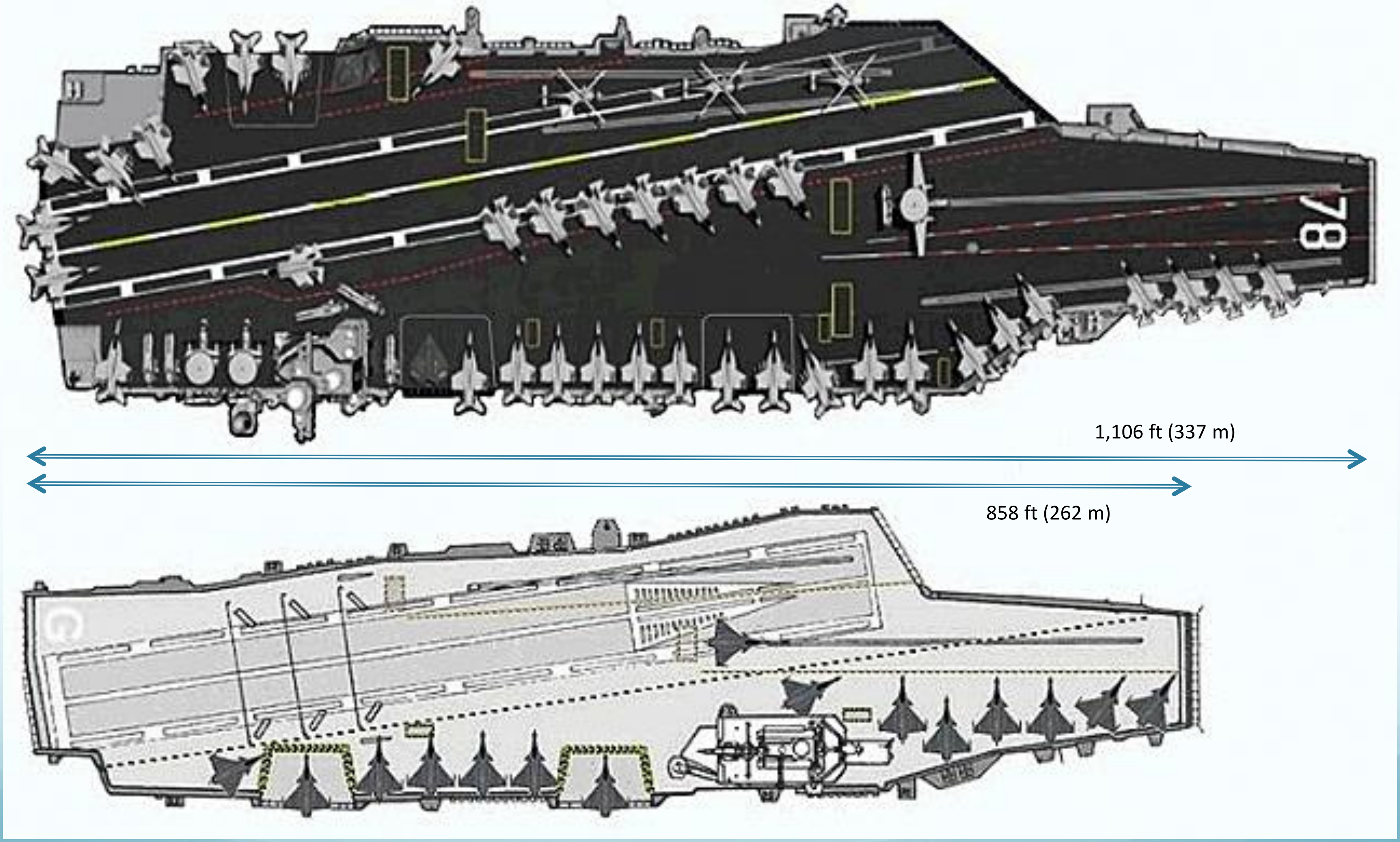
Source: http://news.usni.org/2015/01/07/

Left: French Rafael M fighters & US Navy E-2D Hawkeye airborne early warning aircraft on *Charles de Gaulle*; Above: C-2 Greyhound cargo aircraft landing; Below: Rafael M fighter on deck.

Source, 2 photos, above: https://upload.wikimedia.org/

CVN Comparison

USS. Gerald R. Ford (CVN-78) & *Charles de Gaulle* (R91)



Source: adapted from diefenbakertechnology.blogspot.com

A 2nd French aircraft carrier?

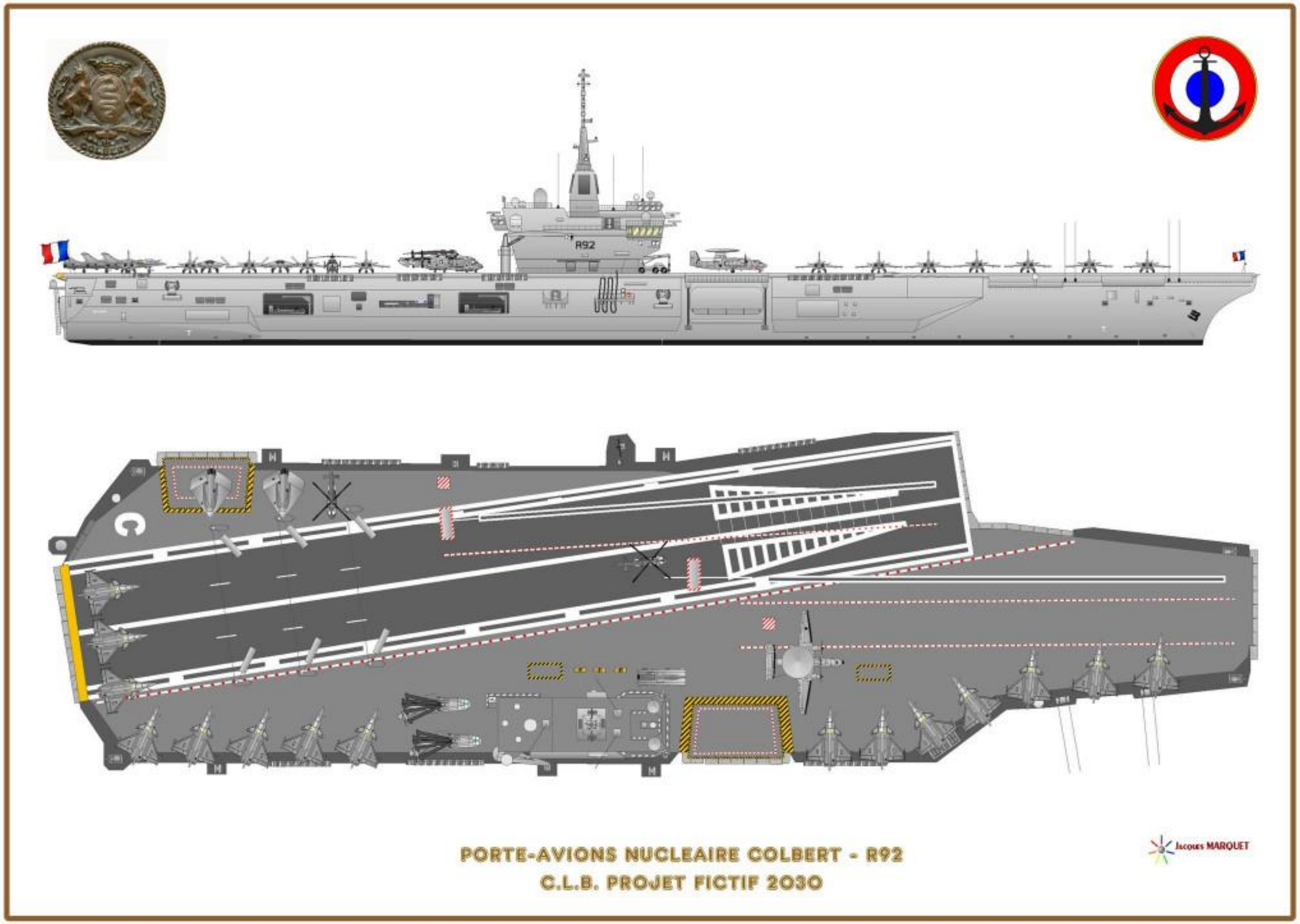
(Concept for "R92 Colbert")

- Since decommissioning the conventionally-powered aircraft carriers *Clemenceau*, in 1997, and *Foch*, in 2000, France has had only a single aircraft carrier, the nuclear-powered *Charles de Gaulle*. Required maintenance and overhaul and other factors limit the operational availability of the single aircraft carrier.
- In 2017, the French newspaper *L'Opinion* reported* that France again may have raised plans to build another nuclear-powered aircraft carrier.
- According to the newspaper:
  - The new ship will be needed to replace the aircraft carrier *Charles de Gaulle (CDG).*
  - The new vessel's preliminary design can be started during the next five years.
  - Some experts believe that work on the new aircraft carrier could start as soon as 2020, and the vessel could be delivered by 2035.
  - It is likely that the new vessel will be built in Saint-Nazaire, not in Brest, where *CDG* was constructed.
  - The two K15 reactors on *CDG* each are rated at 150 MWt and deliver barely enough power for the aircraft carrier. Designers of the future French aircraft carrier will need to decide whether they will equip the ship with three K15 reactors or develop a new reactor (i.e., a K15+). It will be necessary to coordinate with the plans for a new reactor for the future third-generation SSBN, which will replace the Le Triomphant-class SSBNs in the late 2030s.
  - There are few supporters in the French Navy and industry for a non-nuclear aircraft carrier.

* Source: https://maps.southfront.org/france-meets-with-some-difficulties-in-design-of-its-new-aircraft-carrier/

A 2nd French aircraft carrier?

(Concept for R92 Colbert)



Source: Twitter / FauteuilColbert via
https://maps.southfront.org/france-meets-with-some-difficulties-in-design-of-its-new-aircraft-carrier/

French disposition of decommissioned nuclear submarines

Dismantling and deconstructing retired nuclear vessels

- "Dismantling" and "deconstructing" are two completely independent processes:
  - Dismantling referring to the operations linked to nuclear safety.
  - Deconstructing deals with the disposition of the hull after removal of the nuclear reactor.
- The DGA (French Armament Procurement Agency) is the project contractor for dismantling and DCNS is the project manager.
  - All dismantling operations take place at the DGA's facilities in the military harbor of Cherbourg.
    - First the reactor core and certain nuclear waste are removed. This is a several month operation.
    - Equipment in the reactor compartment is decontaminated, fluids are drained, and connections to equipment and systems in other parts of the sub are severed and sealed. This operation takes about 10 – 12 months.
    - The sealed 700 ton reactor compartment is cut from the sub and removed to an interim storage location on the military base at Cherbourg. This operation takes about three months.
    - The bow and stern sections of the submarine are then repositioned with computer-controlled "walkers" and welded together. The whole entity is then put back to water and the hull is kept along a quay, waiting to be "deconstructed".
  - All of the Redoutable-class SSBNs have completed the dismantling process. The first-in-class, *Le Redoutable*, was converted into a museum ship in 2002.

Dismantling and deconstructing retired nuclear vessels

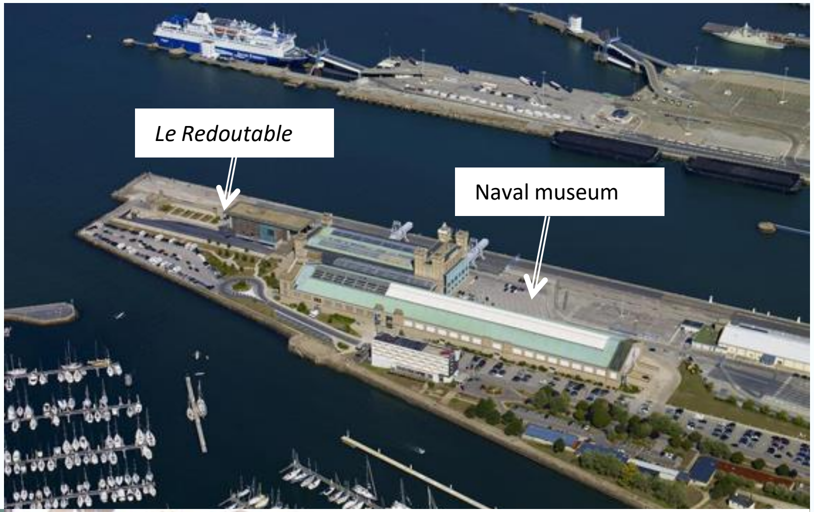
- After dismantling, management of the remaining hull with the reactor compartment removed no longer raises any nuclear safety issues.
- In 2016, the French defense procurement agency, Direction Générale de l'armement (DGA), contracted with DCNS to deconstruct the five remaining Redoutable-class SSBBN hulls. Work on the first hull will begin in 2018 and the last should be completed by 2027.

Reactor compartment removed. Source: DCNS

- Reactor compartment interim storage is intended to last for decades. The decreasing radioactivity of the reactor's activated or contaminated metallic materials will allow safer and more economic processing in the future. By mid-2018, the first reactor, from *Le Redoutable*, has been stored for 24 years.
- Eventually, all nuclear materials and equipment will be removed from the reactor compartment, cut up and conditioned, and placed into waste barrels and delivered to ANDRA (French National Agency for Radioactive Waste Management) for final disposition. These operations will be carried out on the DCNS Cherbourg site in a new facility dedicated to the final dismantling and disposition of the reactor compartments.

Cité de la Mer naval museum, Cherbourg

- France's 1st nuclear submarine, the SNLE *Le Redoutable* (S611), was dismantled and converted in 2002 to a museum ship for the Cité de la Mer naval museum in Cherbourg. The reactor section was removed and replaced by a steel tube.
- This is the only SSBN in the world that is available for public tours



Source, two bottom photos: DCNS; top photo: https://cherbourg-titanic.com/

French non-propulsion marine nuclear applications

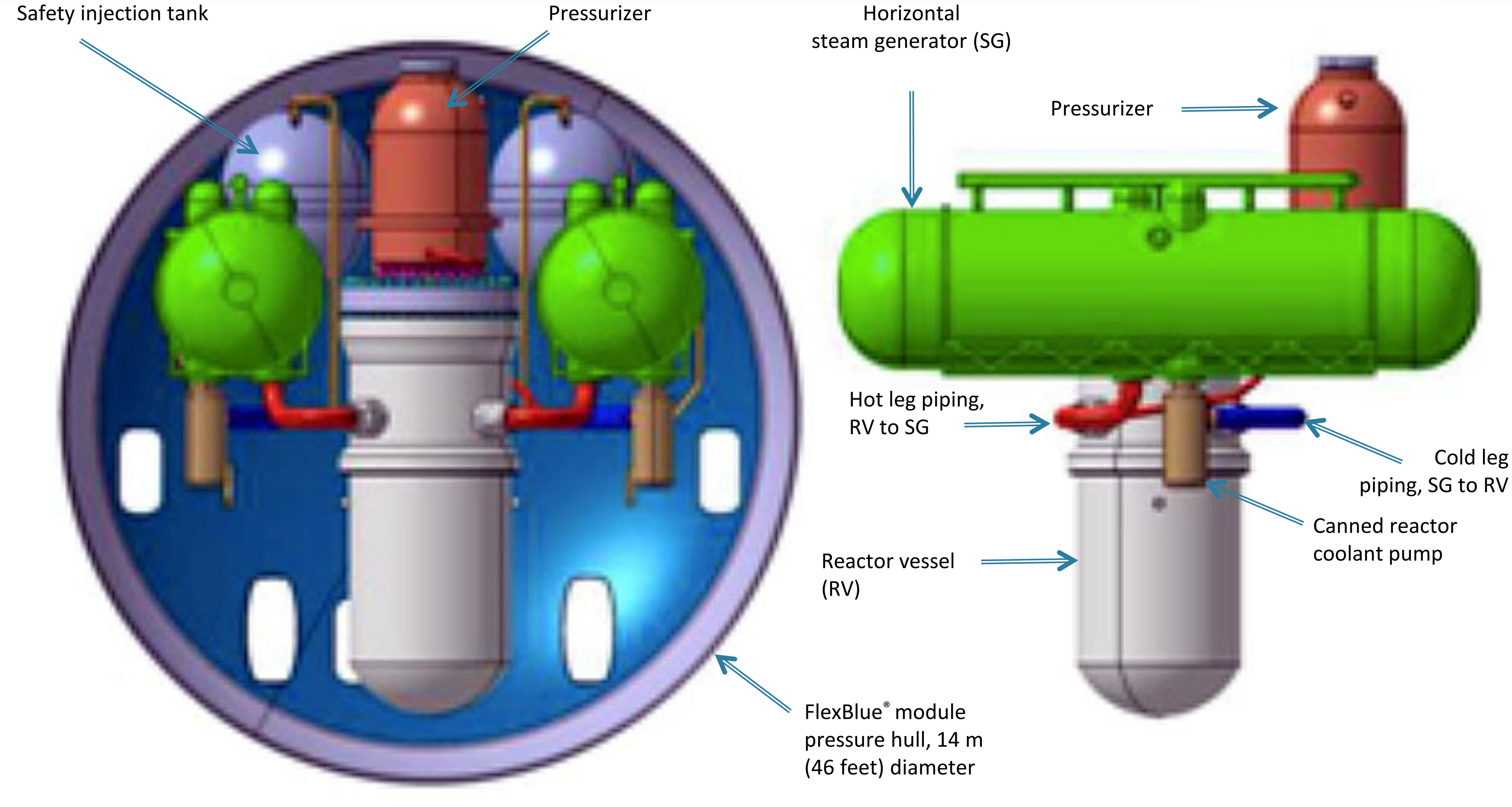
Flexblue®

- Flexblue® is small pressurized water reactor (PWR) packaged as a "transportable and immersed nuclear power system" (TINPS) that is designed for siting on the sea floor.
- The design was developed by DCNS and Areva-TA based on their experience as the designer and constructor of French nuclear-powered submarines and naval reactors:
  - The original concept unveiled in 2008 was to be based on the K15 naval reactor, redesigned to operate with standard 17 x 17 civilian PWR nuclear fuel with an enrichment of < 5%, and safety systems that make greater use of passive safety features, including the passive ocean heat sink available to a reactor sited on the sea floor.
  - A range of electric power outputs have been cited; from 50 – 250 MWe. In 2016, the Flexblue® description by the International Atomic Energy Agency (IAEA) lists a reactor thermal power of 530 MWt (3.5 times the power rating of the K15), with a net electrical output of 160 MWe.
  - Over time, the physical size of a Flexblue® module has grown. In 2016, the dimensions were given as 146 m (479 feet) long and 14 m (46 feet) in diameter. This is slightly larger than the size of a Le Triomphant-class SSBN, which measures 138 m (453 feet) long, 12.5 m (41 feet) in diameter, with a submerged displacement of 14,335 tonnes (15,801 tons).
- Standardized Flexblue® modules will be manufactured in shipyards and factories.

* IAEA, "Advances in Small Modular Reactor Technology Developments", 2014

Flexblue®

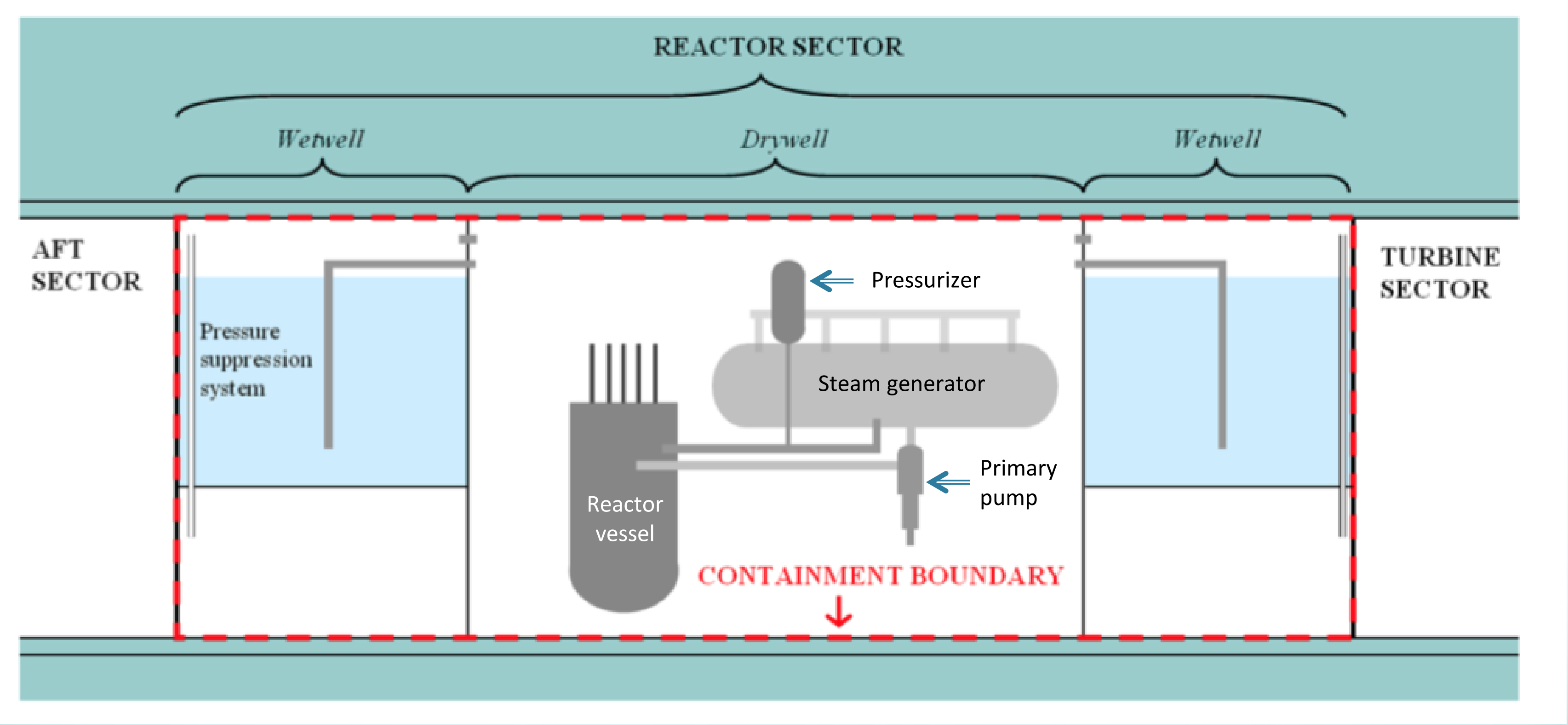
Two-loop PWR NSSS general arrangement



Source: adapted from https://www.knepublishing.com/index.php/KnE-Energy/article/view/475/1693

Flexblue®

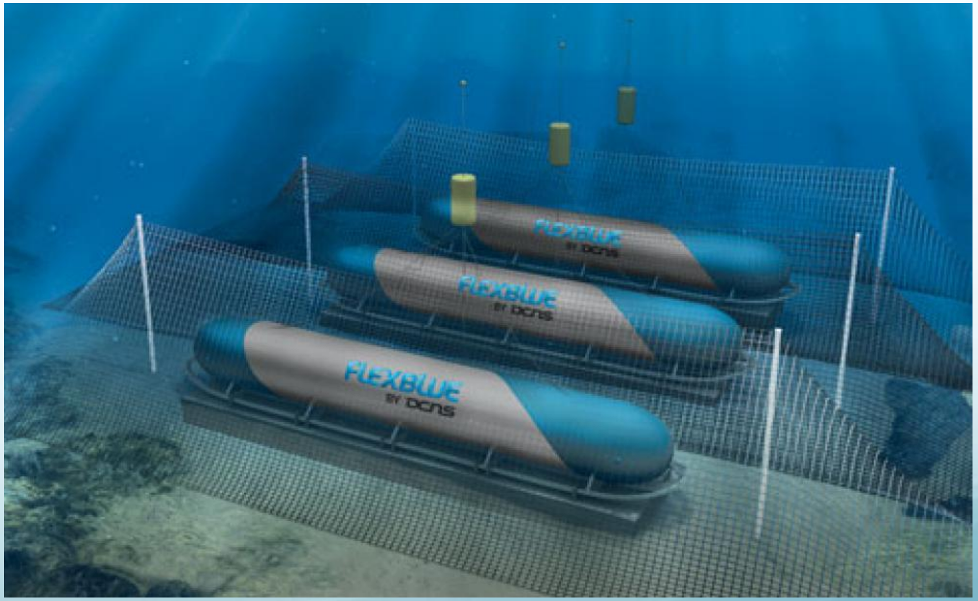
Containment general arrangement



Source: DCNS via IAEA, “Advances in Small Modular Reactor Technology Developments”, 2014

FlexBlue® deployment

- A FlexBlue® module is carried by ship to the intended location 5 - 15 km (3.1 – 9.3 miles) offshore and then is lowered to a prepared site on the sea floor, where it is anchored at a depth between 40 - 100 m (131 - 328 feet).
- Multiple modules can be connected to an underwater electrical grid to deliver power via submarine cables to the mainland.



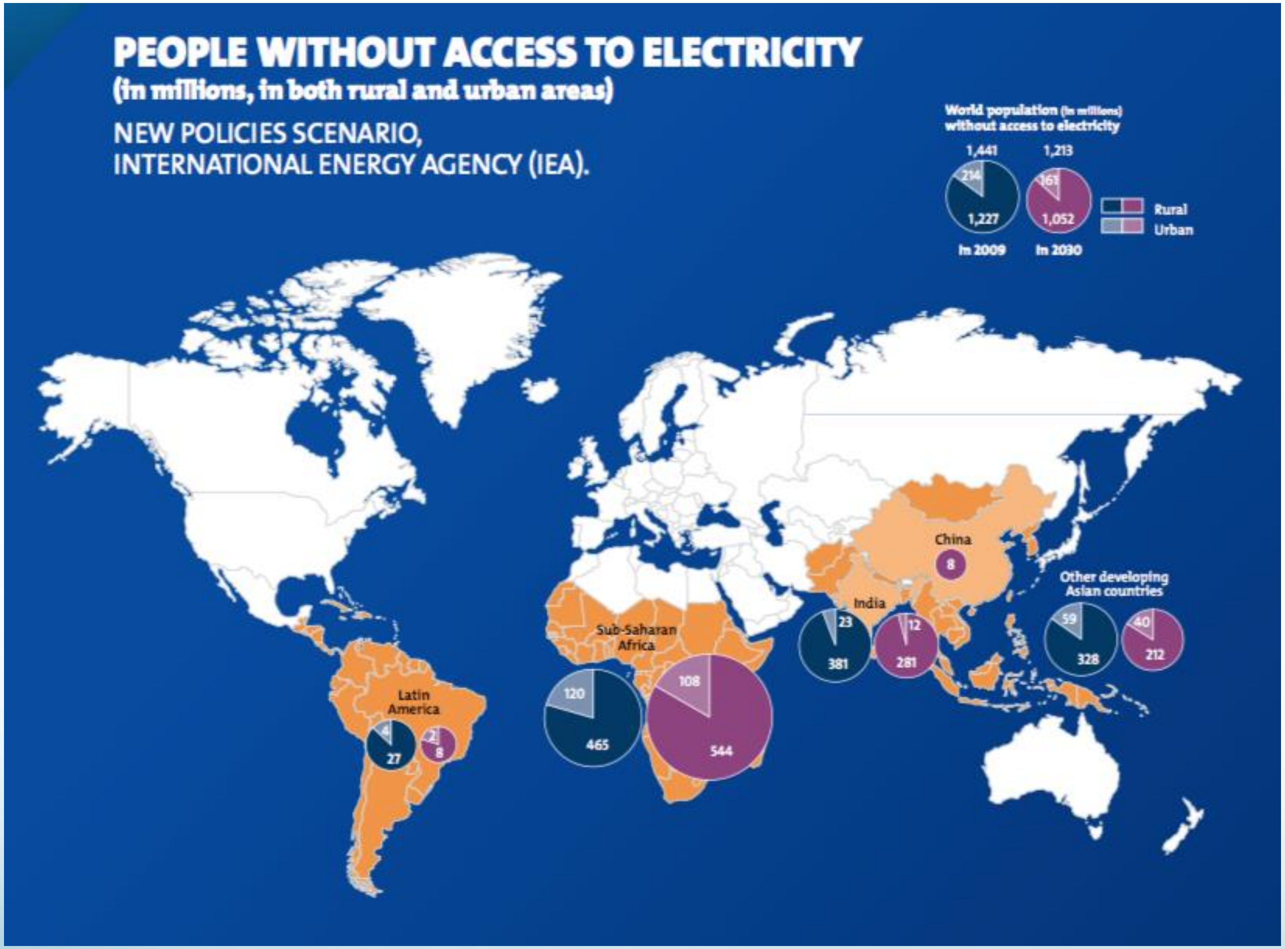
Source, three graphics: DCNS

Flexblue®

Refueling and decommissioning

- The FlexBlue® power production cycle lasts 38 months. Then refueling is required. Major overhauls of the modules are scheduled every 10 years.
- If required, an in situ FlexBlue® module will be accessible via underwater vehicle (i.e., for inspection, minor servicing or repair)
- Three refueling options have been considered:
  - **Basic option:** Retrieve the FlexBlue® module from the seabed and sail it back to a nuclear-qualified shipyard (i.e., to Brest or Toulon, where facilities for nuclear submarine refueling exist). The goal is to be able to accomplish refueling and routine servicing in about one month in the shipyard and then return the refueled module to its original seabed site.
  - **Special purpose refueling vessel**: Bring the Flexblue® module up to the surface and conduct the refueling at sea, aboard the special purpose refueling vessel.
  - **Module replacement**: Retrieve the FlexBlue® module from the seabed and replace it immediately with another module (new or refueled). Sail the retrieved module back to a shipyard for refueling and servicing.
- An overhaul requires retrieving the module and delivering it to a shipyard for an extended servicing period.
- At the end of its service life (about 60 years), a module will be retrieved and delivered to a nuclear-qualified shipyard for dismantling and deconstruction using the same processes as are being employed now on decommissioned French nuclear submarines.

FlexBlue® target market



The FlexBlue® marine nuclear power plant is intended for deployment in coastal and oceanic regions, particularly where the existing electrical infrastructure is poor. In these regions, the oceanic ultimate heat sink site conditions at 100 m (328 ft) depth do not vary greatly around the world.

Source: http://www.uxc.com/smr/Library%5CDesign%20Specific/Flexblue/

French marine nuclear power current trends

France current trends

- **New build**
  - Barracuda-class SSN new-build has commenced at DCN Cherbourg. The lead ship is expected to be launched in 2018.
- **Phase-out / replacement**
  - All Rubis / Améthyste-class SSNs are expected to be replaced on a 1-for-1 basis once delivery of Barracuda-class SSNs starts, sometime after 2018.
- **Refurbishment / modifications**
  - The three older Le Triomphant-class SSBNs have been undergoing "AI M51" mid-life overhauls to get updated to the *Le Terrible* standard. The last boat, *Le Téméraire* (S617), will complete its overhaul in 2018. Then, all Le Triomphant-class SSBNs will have modern combat and navigation systems and can operate the latest M51.2 SLBM, F21 torpedo and Exocet anti-ship cruise missile.
- **Operations**
  - Improved multi-mission SSN capabilities will be available as the Barracuda-class SSNs start entering the fleet in a couple of years.
- **New weapons development**
  - Development of the M51.2 SLBM with the new-generation TNO warhead is complete and has been deploying on upgraded SSBNs starting in 2015.

France current trends

- **New submarine development**
  - A program to develop the third-generation SSBN is expected to start in the early 2020s.
  - Development of a multi-mission conventional sub with air-independent propulsion has been proposed by DCNS: *SMX Ocean.*
- **New marine reactor development**
  - The new PWR for Barracuda-class SSNs is a derivative of the K15 reactor that has been operational in Le Triomphant-class SSBNs since 1997 and the and the aircraft carrier *Charles de Gaulle* since 2001.
  - It was intended that a prototype of this reactor would have been tested in in new RES reactor facility being built at Cadarache. The RES facility is many years behind schedule. While RES appears to be largely complete in mid-2018, initial criticality of the new reactor has not yet occurred.
- **Final disposition of retired nuclear vessels**
  - The current dismantling and deconstruction process will continue to be managed at DCNS Cherbourg.
  - The Rubis-class SSNs will start retiring as the new Barracuda-class SSNs enter the fleet. Dismantling and deconstruction of the six Rubis-class SSNs should occur during the 2020s.

France current trends

- **Non-propulsion marine applications**
  - Prospects for the Flexblue® "transportable and immersed nuclear power system" are uncertain. This is the only seafloor sited nuclear power plant design that is not being developed by Russia or China.
- **Technical support to other nations**
  - France is supporting Brazil's efforts to develop an indigenous nuclear submarine manufacturing capability.
    - France's DCNS is a 49% partner in Sociedade de Proposito Especifico (SPE), which will build Brazil's nuclear submarines at the new shipyard being built at Itaguai.
  - France won the international competition to transfer conventional submarine technology to Australia and assist in developing the local submarine manufacturing and support infrastructure.
    - Australia's conventional "Shortfin Barracuda" SS will share many design features and systems with the French Barracuda SSN.

Germany

Civilian nuclear prototype
bulk ore carrier / research vessel

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

German marine nuclear timeline

Nov 1961
GKSS contracted for construction of *Otto Hahn*
13 Jun 1964
Otto Hahn launched
Nov 1967
CNSG 1 initial criticality at GKSS
1968
Geesthacht KSH gas-cooled reactor consortium formed
Aug 1968
CNSG 1 initial criticality aboard *Otto Hahn*
11 Oct 1968
Otto Hahn commissioned

1940s	1950s	1960s	1970s	1980s	1990s	2000s	2010s

5 May 1955
Allied occupation of West Germany ends; West German sovereignty restored
18 April 1956
GKSS founded to develop nuclear ship propulsion
1958
German Ministry of Scientific Research initiated research on a marine gas-cooled reactor

1970
Work on the marine Geesthacht KSH gas-cooled reactor discontinued
1970
Otto Hahn 1st port of call: Casablanca, Morocco
1972
Otto Hahn 1st refueling
1974
GKSS mission broadened to industry-wide nuclear safety
Feb 1979
Otto Hahn decommissioned

3 October 1990
German Unity Day; end of the unification process

2011
GKSS was renamed Helmholtz-Zentrum Geesthacht Zentrum für Material und Küstenforschung GmbH (Centre for Materials and Coastal Research)

Beginning of the marine nuclear program in post-war West Germany

- The Bonn–Paris conventions were signed in May 1952 and came into force after the 1955 ratification. The conventions put an end to the Allied occupation of West Germany. The conventions came into force during the last meeting of the Allied High Commission, which took place in the United States Embassy in Bonn, on 5 May 1955.
  - The conventions prohibited Germany from manufacturing warships, with the exception of smaller ships for defense purposes.
  - The prohibited warships were defined as follows:
    - Warships > 3,000 tons displacement
    - Submarines > 350 tons displacement
    - All warships which are driven by means other than steam, diesel or petrol engines or by gas turbine or by jet engines
  - Nuclear-powered warships were prohibited.
- After high-level negotiations, the declaration of sovereignty was issued by the former occupying powers on 5 May 1955. The Federal Republic was free to engage in reactor physics and build reactors. In August, a small group of delegates attended the first Geneva conference, where many aspects of peaceful uses of nuclear energy were openly discussed.

Source: "Development of nuclear power in Germany," The Journal of the British Nuclear Energy Society, Vol. 7, No. 4, October 1968, https://www.nuclearinst.com/write/bnes/BNES-VOL%207-4.PDF

Beginning of the marine nuclear program in post-war West Germany

- On the West German north coast, Hamburg, Bremen, Schleswig-Holstein and Lower Saxony founded Gesellschaft für Kernenergieverwertung in Schiffbau und Schiffahrt (GKSS) at Geesthacht, near Hamburg, with the aim of developing nuclear ship propulsion. (GKSS = Society for the Utilization of Atomic Energy in Shipbuilding and Shipping Ltd.)
- The Geesthacht establishment was the driving force that led to the construction of the *Otto Hahn*, Europe's first nuclear powered merchant ship.
- The establishment in 1974 of reactor safety as an independent research area at GKSS marked the transition from an initial focus on marine applications of nuclear power to the wider field of research into nuclear reactor safety issues.
- This transition continued into the following decades. In 2011, GKSS was renamed Helmholtz-Zentrum Geesthacht Zentrum für Material und Küstenforschung GmbH (Centre for Materials and Coastal Research).

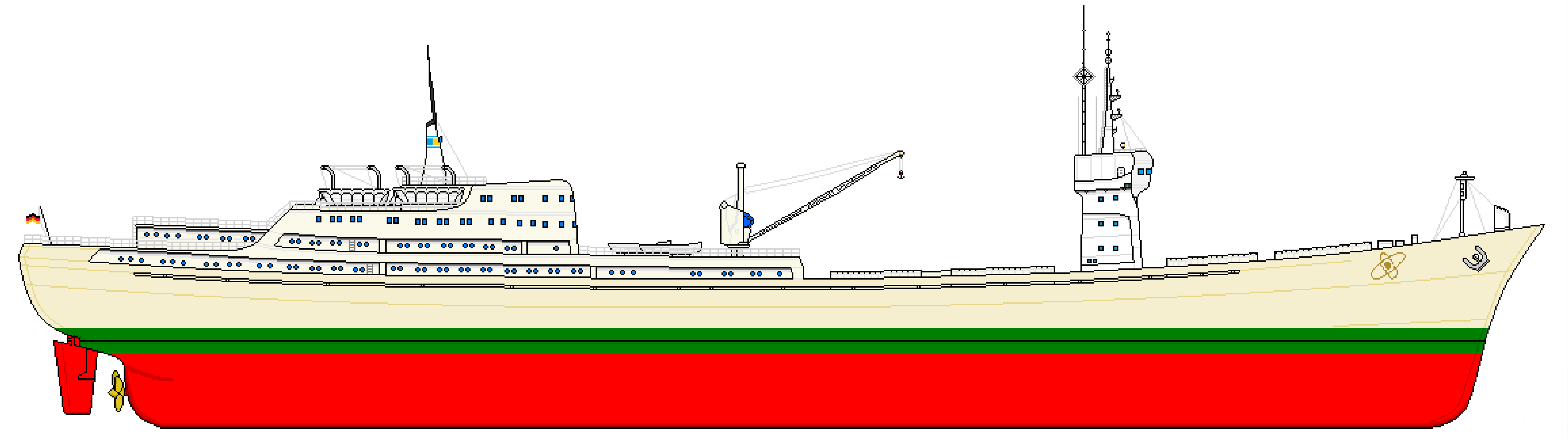
Source: "Development of nuclear power in Germany," The Journal of the British Nuclear Energy Society, Vol. 7, No. 4, October 1968, https://www.nuclearinst.com/write/bnes/BNES-VOL%207-4.PDF

A West German SSN?

- In their 2016 book, “Quieter, Deeper, Faster – Innovations in German Submarine Construction,” authors Jürgen Rohweder and Peter Neumann described German efforts in the 1960s to acquire nuclear submarines. They reported:
  - “In August 2008, under the headline “*Desirous Dreams*,” the SPIEGEL reported the findings of Alexander Lurz, a young historian, in the British national archives. He had uncovered the once-secret report of the British Ambassador to NATO, Frank Roberts, after a meeting with NATO’s Supreme Commander in Europe, General Lauris Norstad. The SPIEGEL story indicated that the Adenauer Government and its Defense Minister, Franz Josef Strauss, wanted nuclear submarines for the Navy.” Roberts’ report was dated 26 April 1960.
  - Key points related to the German interest in SSNs:
    - Germany had been putting pressure on the US for more than two years (from the late 1950s) to acquire nuclear submarines.
    - After the most recent request in 1960, the US had replied with a firm “No”.
    - General Norstad felt that an ocean-going German nuclear submarine with unlimited endurance was the last thing NATO wanted from Germany. There was no military justification for it.
    - At the time, the German maritime industry did not have the technical capability to build a nuclear-powered submarine and there was no formal nuclear submarine design program. Twenty years later, Germany was building advanced conventional submarines for the German Navy and international customers.

Otto Hahn

Germany's prototype civilian bulk ore carrier + research vessel

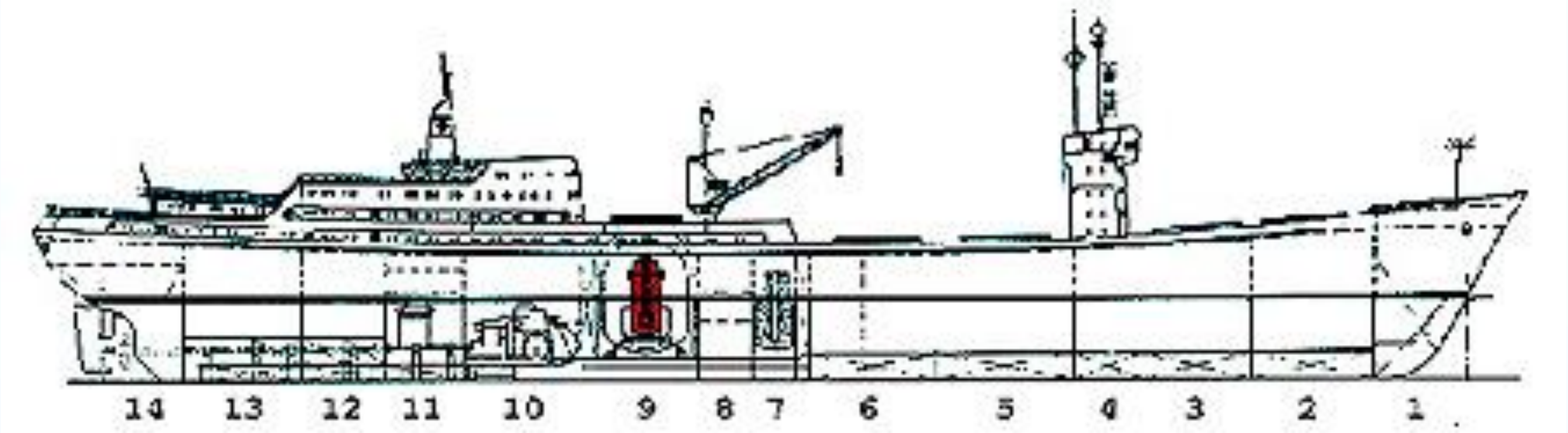


Source: adapted from Alexander van Maanen, http://www.shipbucket.com/drawings/6537

- GKSS was the owner and operating authority for the nuclear-powered ore freighter *Otto Hahn*. Development of the ship began in 1960 under the supervision of German physicist Erich Bagge. He was one of the founders and the head of GKSS.
- In November 1961, GKSS contracted with Howaldtswerke Deutsche Werft AG of Kiel to construct the *Otto Hahn*. The keel was laid on 31 August 1963 and *Otto Hahn* was launched on 13 June 1964. The reactor was installed in 1968 after preliminary testing at GKSS in 1967. The ship was completed on 1 October 1968 and commissioned on 11 Oct 1968.
- Length: 172 m (564.5 ft) ; beam 23.4 m (76.8 ft); full load displacement: 25,790 tons; maximum speed: 15.7 kts

Otto Hahn

Germany's prototype civilian bulk ore carrier + research vessel

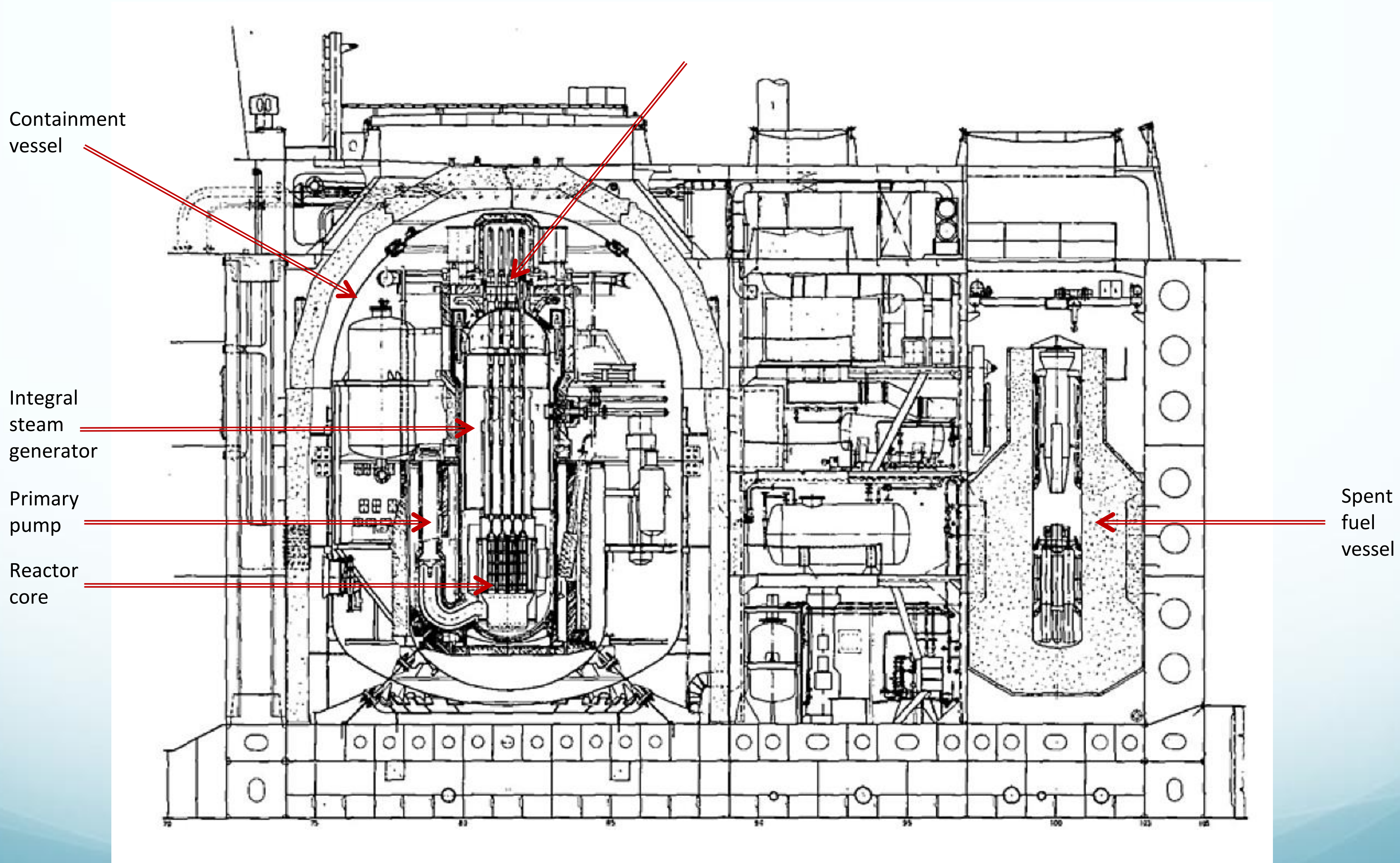


Source: adapted from Radiationworks.com

- Reactor: 38 MWt integral PWR (reactor & three steam generators in a common vessel)
  - The reactor was designed and manufactured by Deutsche B&W and Internationale Atomreaktorbau GmbH (Interatom) is a slightly modified version of the Babcock & Wilcox (B&W) Consolidated Nuclear Steam Generator 1 (CNSG I).
  - Located amidship, inside a steel containment vessel.
  - Fuel: UO_2 pellets in Zr-4 fuel rods; 3.5% and 6.6% enrichment; average core enrichment: 4.03%
  - Reactor core: Hexagonal core cross-section, comprised of 12 square section “central” fuel elements with control rods and 4 triangular corner fuel elements without control rods.
  - Initial criticality at GKSS, Geestacht: November 1967; and onboard *Otto Hahn*: August 1968
  - Core life: 900 full-power days (21,600 equivalent full-power hours); refueled in 1972.
- Propulsion: Steam turbine delivered 11,000 shp, driving a single shaft.

Otto Hahn

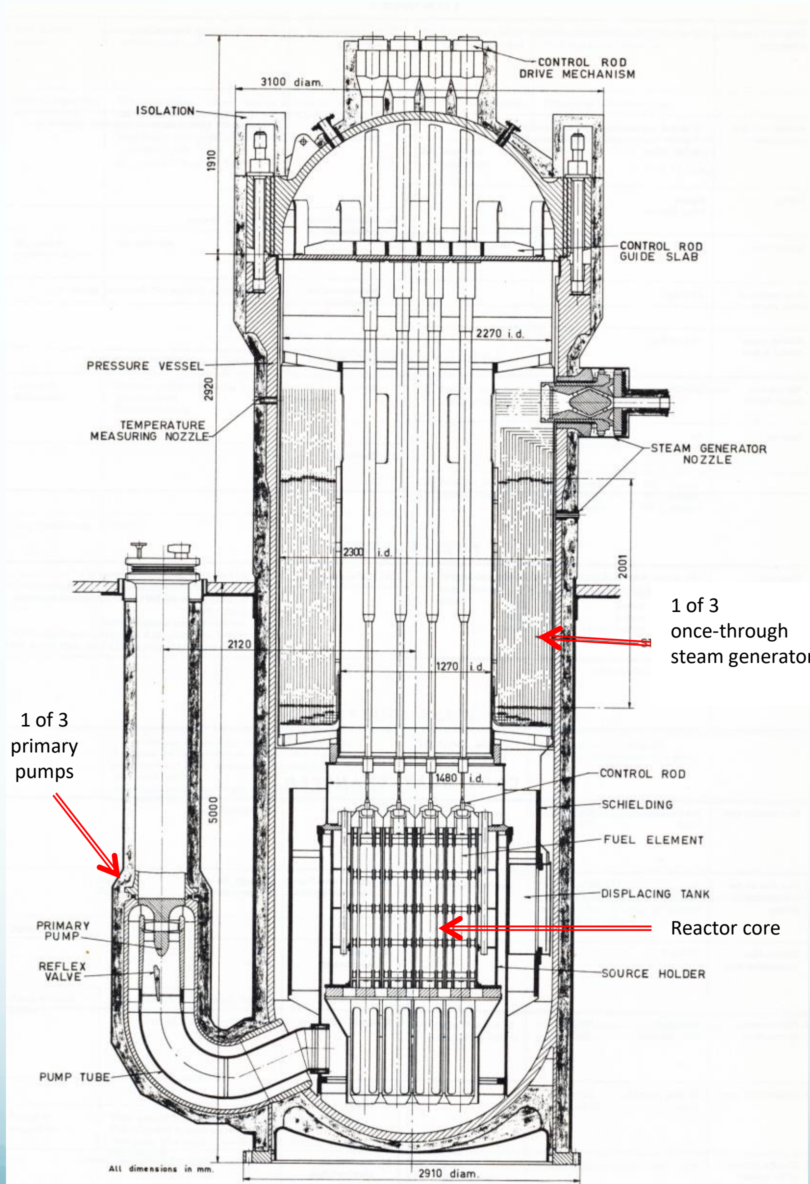
CNSG I reactor plant shipboard layout



Source: adapted from P. von Dobschuetz, "*Dismantling of NS Otto Hahn*"

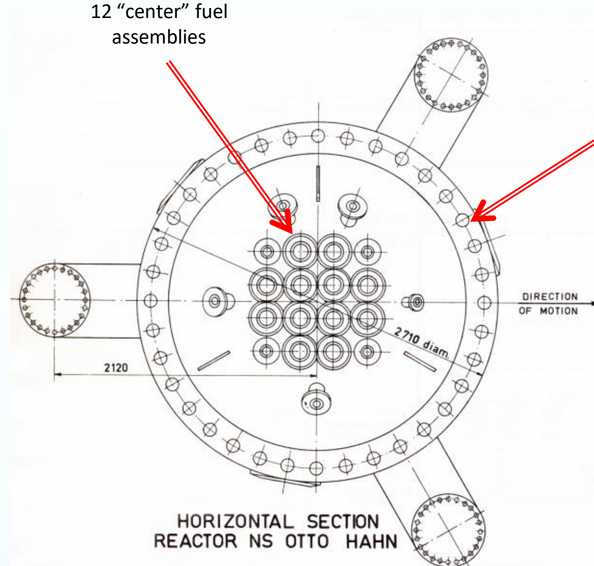
Otto Hahn

CNSG I integral PWR arrangement



VERTICAL SECTION REACTOR NS OTTO HAHN

Control rod drive mechanisms in the 12 "center" fuel assemblies

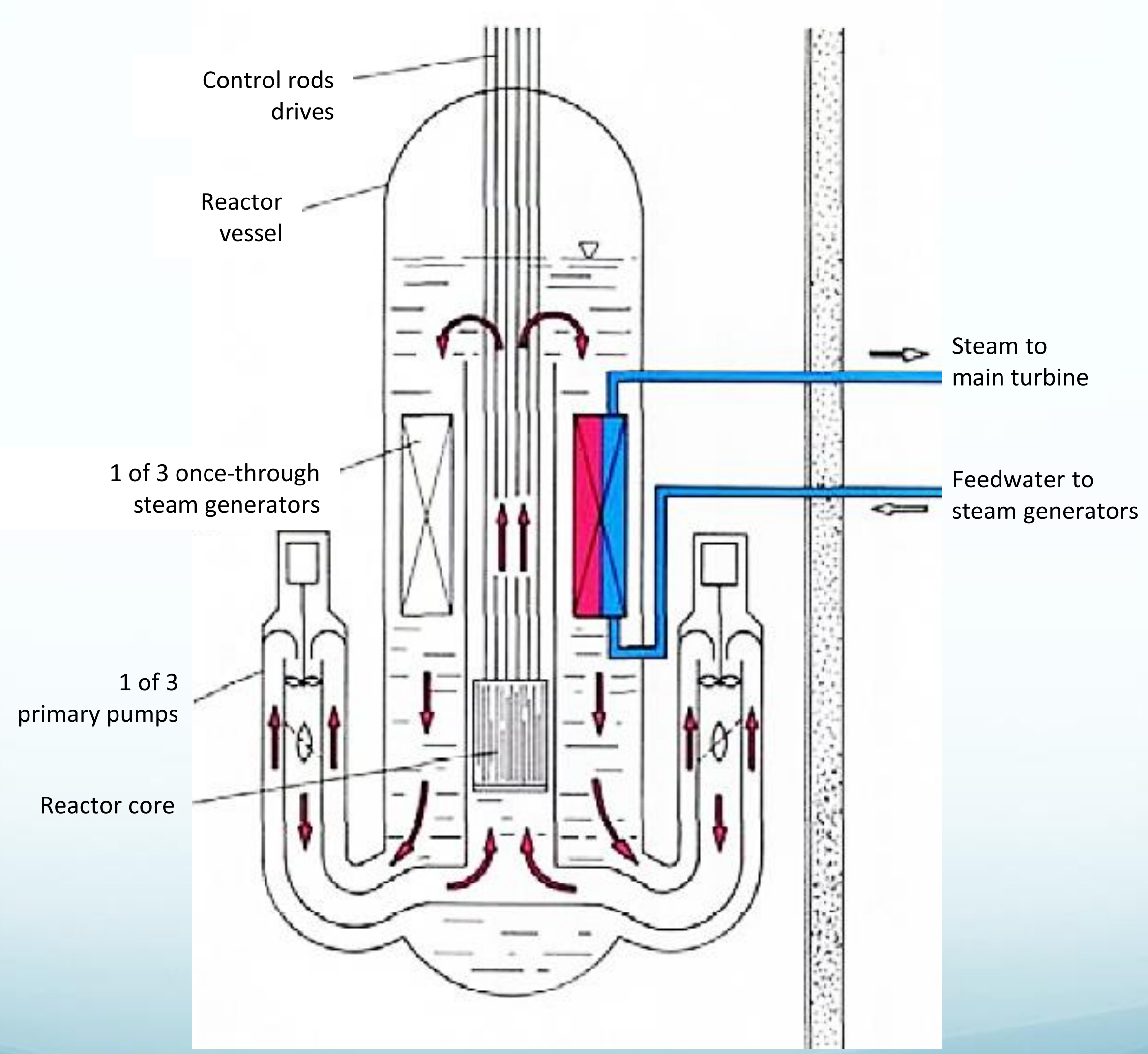


1 of 3 primary pumps

Source: adapted from IAEA Directory of Nuclear Reactors, Volume IX, Power Reactors, 1971

Otto Hahn

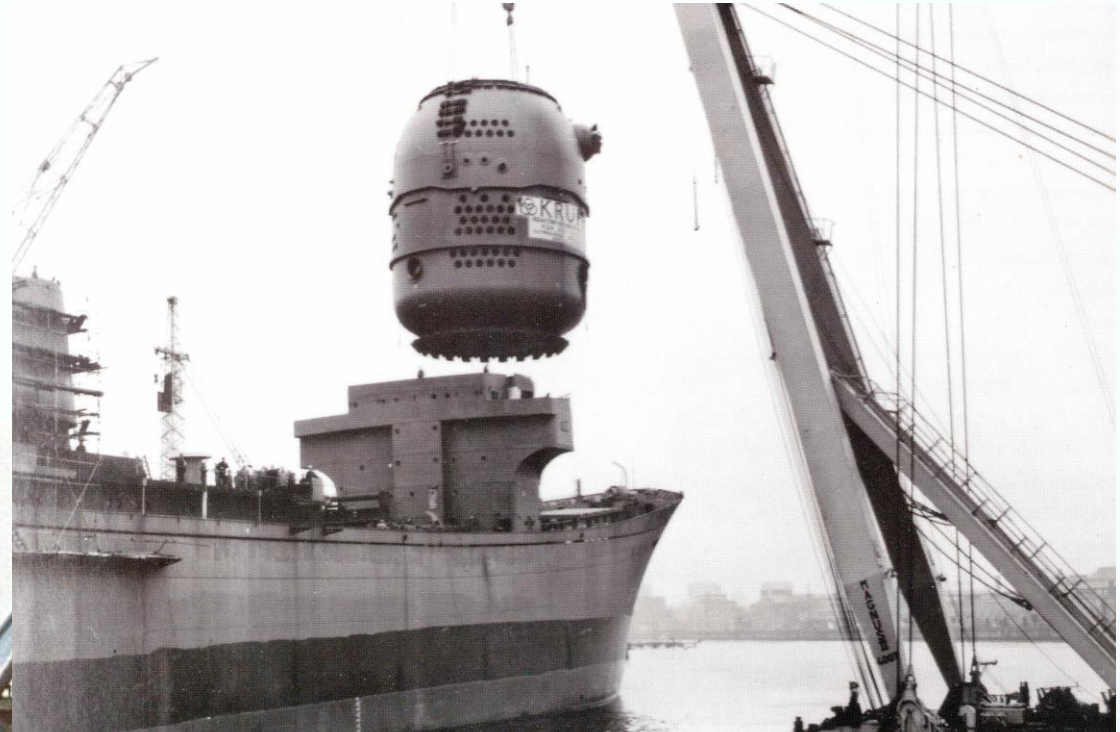
CNSG I coolant flow paths



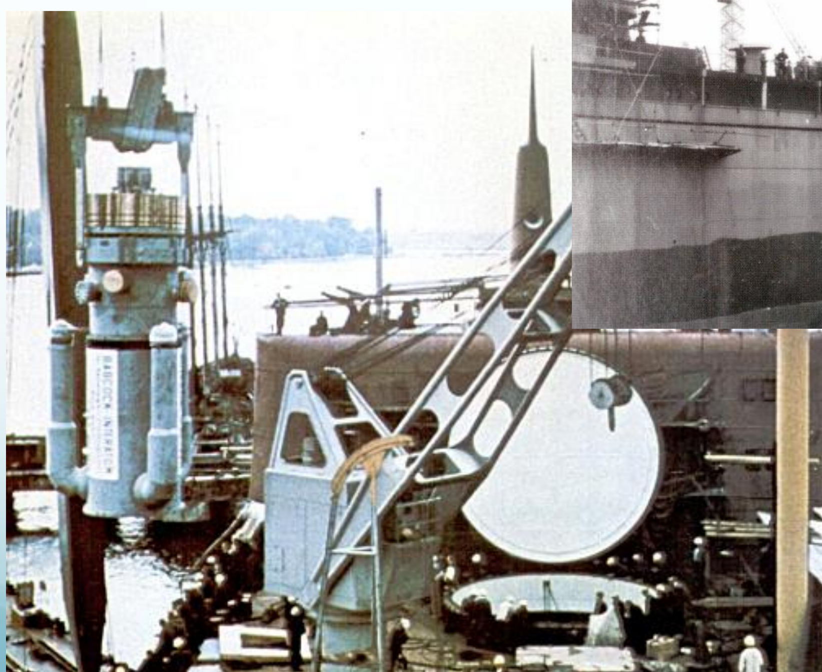
Source: adapted from P. von Dobschuetz, "Dismantling of NS Otto Hahn"

Otto Hahn

Installing the containment vessel and the reactor



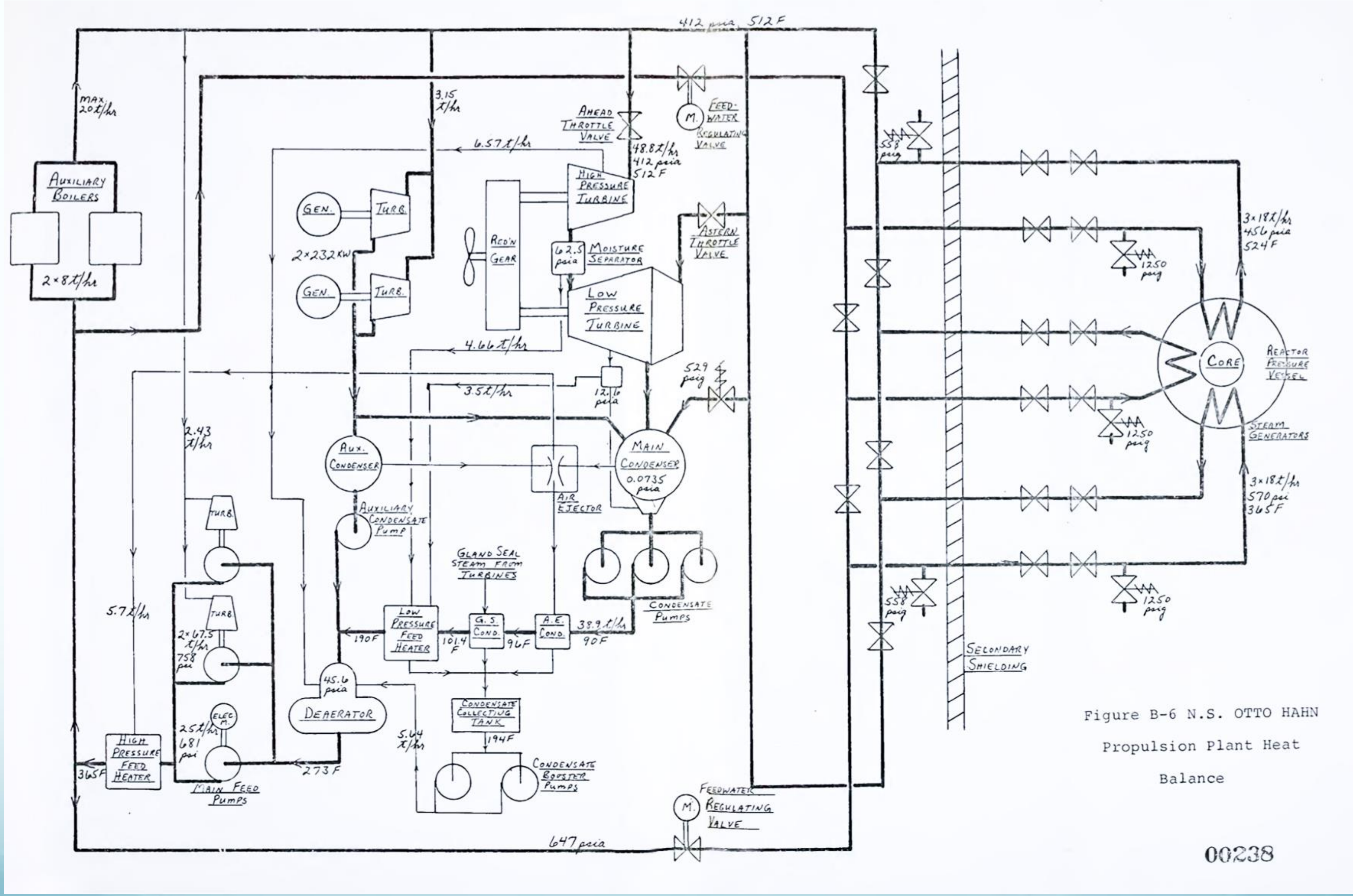
Above: Containment vessel being loaded aboard *Otto Hahn*. Source: Archives HDW/TKMS via J. Rohweder & P. Neumann, "*Quieter, Deeper, Faster – Innovations in German Submarine Construction*," E.S. Mittler & Sohn, 2015/2016.



Left: CNSG 1 integral PWR being loaded aboard *Otto Hahn*. Source: New Scientist and Science Journal, 13 May 1971, p. 380

Otto Hahn

Nuclear propulsion system process flow diagram



Source: James R. Bauman, "Analysis of past, present and future applications of nuclear power for propulsion of marine vehicles," Massachusetts Institute of Technology, 1972

Otto Hahn

Germany's prototype civilian bulk ore carrier + research vessel

Otto Hahn cruising off Capetown, South Africa. Source: GKSS

Source: www.shipspotting.com

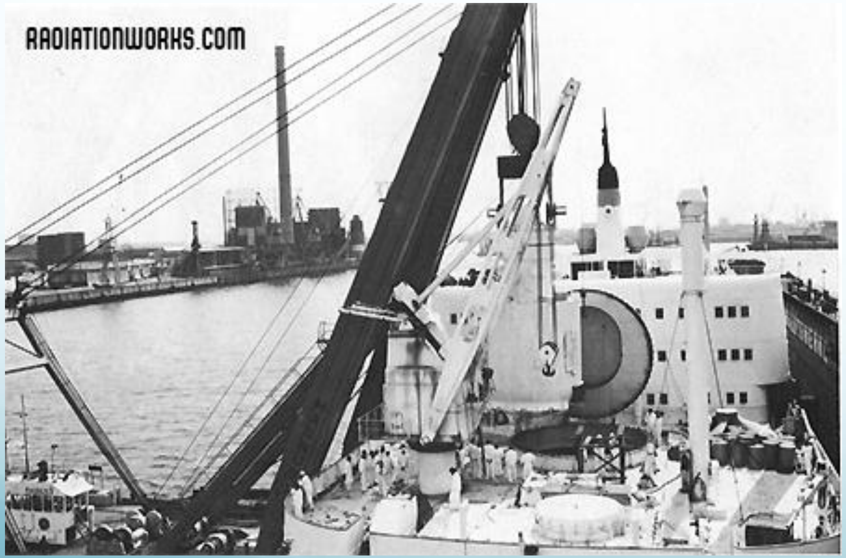
- Operation:
  - Intended primarily as a research vessel. Accommodated 36 scientists + 63 crew.
  - 1970: 1st port of call: Casablanca, Morocco
  - 1972: 1st refueling after cruising 250,000 miles (402,336 km).
  - By the mid-1970s, GKSS studies showed that it was not possible to operate nuclear-powered freighters in an economically efficient manner. Following this re-evaluation of the potential of nuclear-powered shipping, the *Otto Hahn* was finally decommissioned in February 1979 after 10 years of trouble-free operation.
  - *Otto Hahn* cruised 400,000 miles (643,738 km) on the 2nd core, for a total of 650,000 miles (1,046,074 km) on nuclear power, visiting 33 ports in 22 countries. Access to some ports was limited.

Otto Hahn

Removing the reactor during decommissioning

- 1979 - 1982: The nuclear propulsion plant was removed and replaced with a diesel propulsion plant and the ship was converted to a container ship. It was re-commissioned as *MS Trophy* in 1983 and continued operating until being scrapped in 2009.

Above: Otto Hahn reactor control room.



Above & bottom right: Removing the reactor during decommissioning.
Source, three photos: http://www.radiationworks.com/ships/nsottohahn.htm

Geesthacht KSH

Marine closed-cycle gas-cooled reactor (CCGCR) prototype

- In 1958, as part of the 3rd German Nuclear Program, the German Ministry of Scientific Research initiated a long-range development program for a High Temperature Reactor (HTR) operating with a closed-cycle helium gas turbine.
  - The reactor was to be applicable for both a central station power plant and a maritime propulsion system.
  - The program was in collaboration with Swiss gas-turbine manufacturers, Escher-Wyss in particular.
- 14 May 1968: By a letter of intent from KSH (Kernkraftwerk Schleswig-Holstein mbH) to Gutenhoffnungshütte (GHH), the world's closed-cycle gas-cooled reactor (CCGCR) was ordered.
  - The order called for the construction of the 25 MWe CCGCR prototype on the site of the research center at Geesthacht, at a cost of DM 76 million.
  - While construction of this prototype was being prepared, planning was initiated for development for a larger 600 MWe CCGCR plant with a 48% thermal efficiency.
- In early 1970 the German Science Ministry's High-Temperature Reactor Committee restudied the Geesthacht project, and shortly, in May 1970, GHH indicated to KSH that they were not able to fulfill the contract for the design and construction of the plant.
- The real cause for terminating the Geesthacht project is uncertain, but GHH gave as the reason the difficulties encountered in fuel element design and fabrication, and also in development of the helium turbo-machinery.

Source: S. C. Juo & R.T. Schneider, "Closed Cycle Gas Turbine Systems in Europe," Report R-3-77, Office of Naval Research, 11 March 1977, http://www.dtic.mil/dtic/tr/fulltext/u2/a040250.pdf

Geesthacht KSH

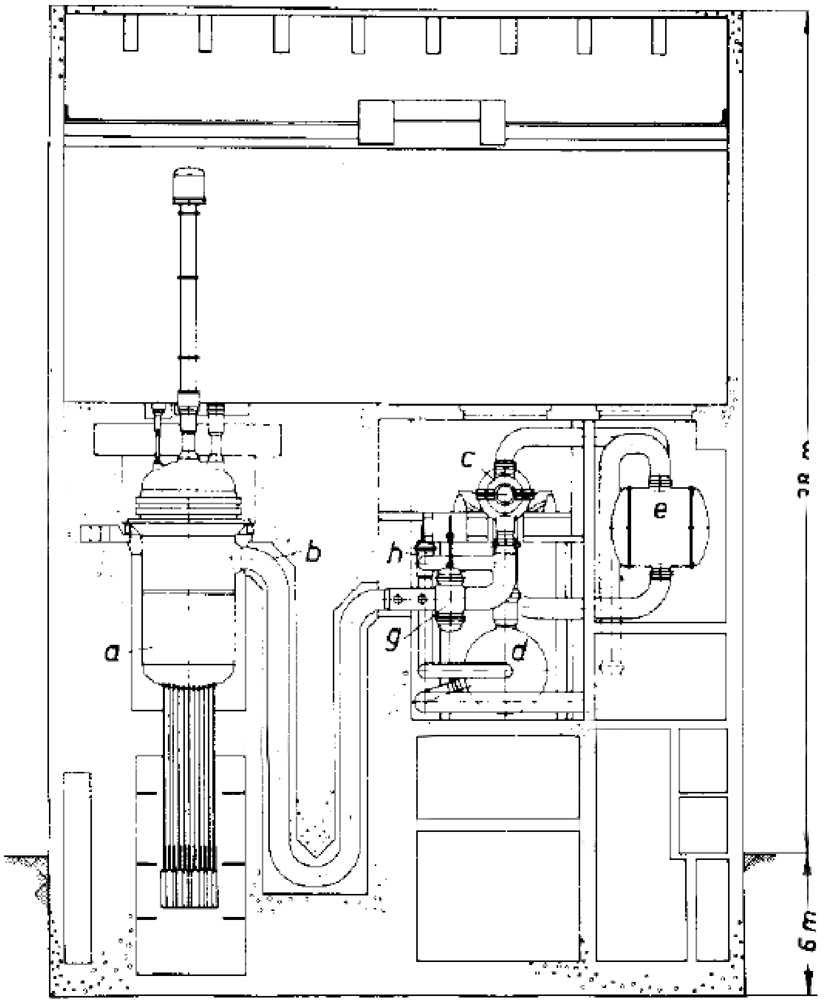
Marine closed-cycle gas-cooled reactor (CCGCR) prototype

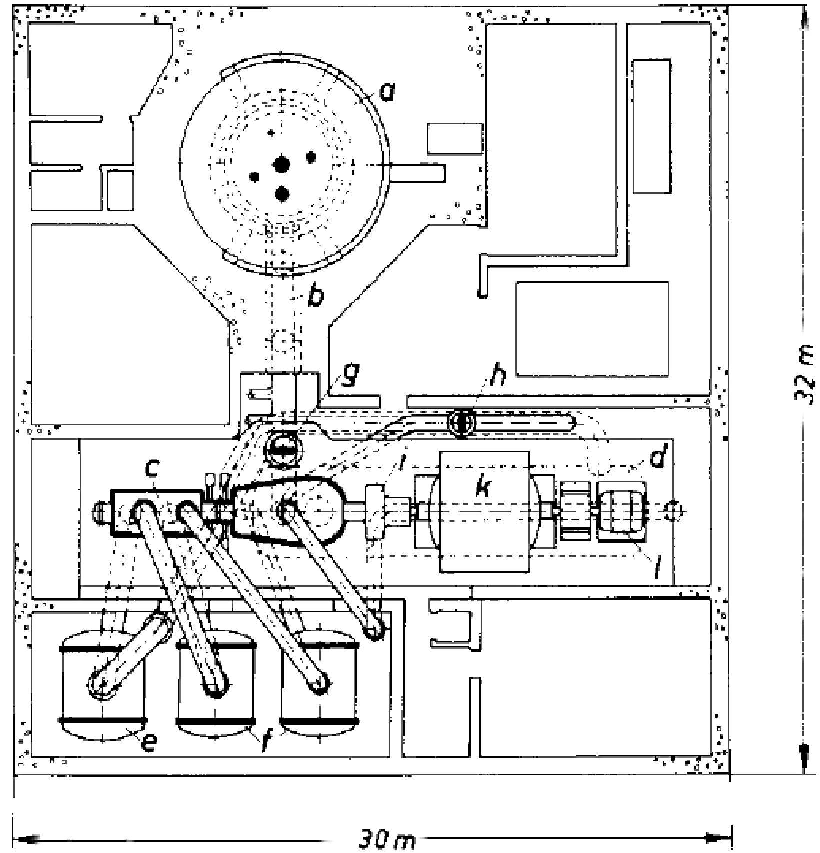
- Reactor details:
  - The reactor was rated at 64 MWt, operating with a thermal efficiency of 39%.
  - The reactor core consisted of 657 cylindrical graphite fuel elements similar to those of the General Atomics Peach Bottom prototype, but without the purge channels.
  - Each fuel element was made up of a graphite sleeve enclosing a graphite matrix containing fissile (highly-enriched UO_2, about 90% enriched) and fertile (thorium) coated particles similar to those used in the US in the General Atomics Fort St. Vrain high-temperature gas-cooled reactor (HTGR).
  - The active core was surrounded by a graphite reflector.
  - The helium coolant pressure was 367.5 psia; core outlet temperature was 1355°F (735°C).
  - Core lifetime was about 900 days.
- Had the Geesthacht KSH prototype been built as scheduled, it would have been a major milestone in the history of nuclear power development, demonstrating for the first time the use of a gas turbine for generating output power from a nuclear reactor.
- The larger 600-MWe CCGCR never got past the preliminary design phase.

Source: D. C. Current, Status of maritime gas cooled reactors," Pennsylvania State University, August 1973, https://calhoun.nps.edu/bitstream/handle/10945/16818/statusofmaritime00curr.pdf?sequence=1

Geesthacht KSH

Prototype plant elevation & plan views



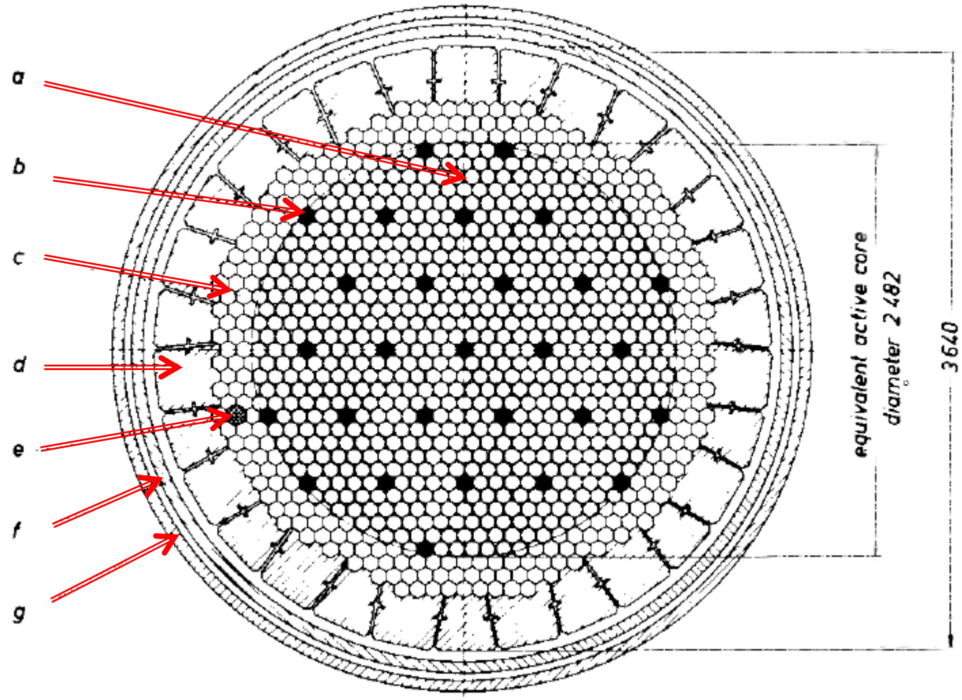


a = Reactor
b = Concentric pipe
c = Turbo machinery
d = Heat exchanger
e = Precooler
f = Intercoolers
g = Hot gas valve
h = Cold gas valve
i = Gear
k = Generator
l = Starting motor

Source: K. Bammert & E. Bohm, “Nuclear Power Plants With High temperature Reactor and Helium Turbine,” American Society of Mechanical Engineers, 1969

Geesthacht KSH

Reactor core layout

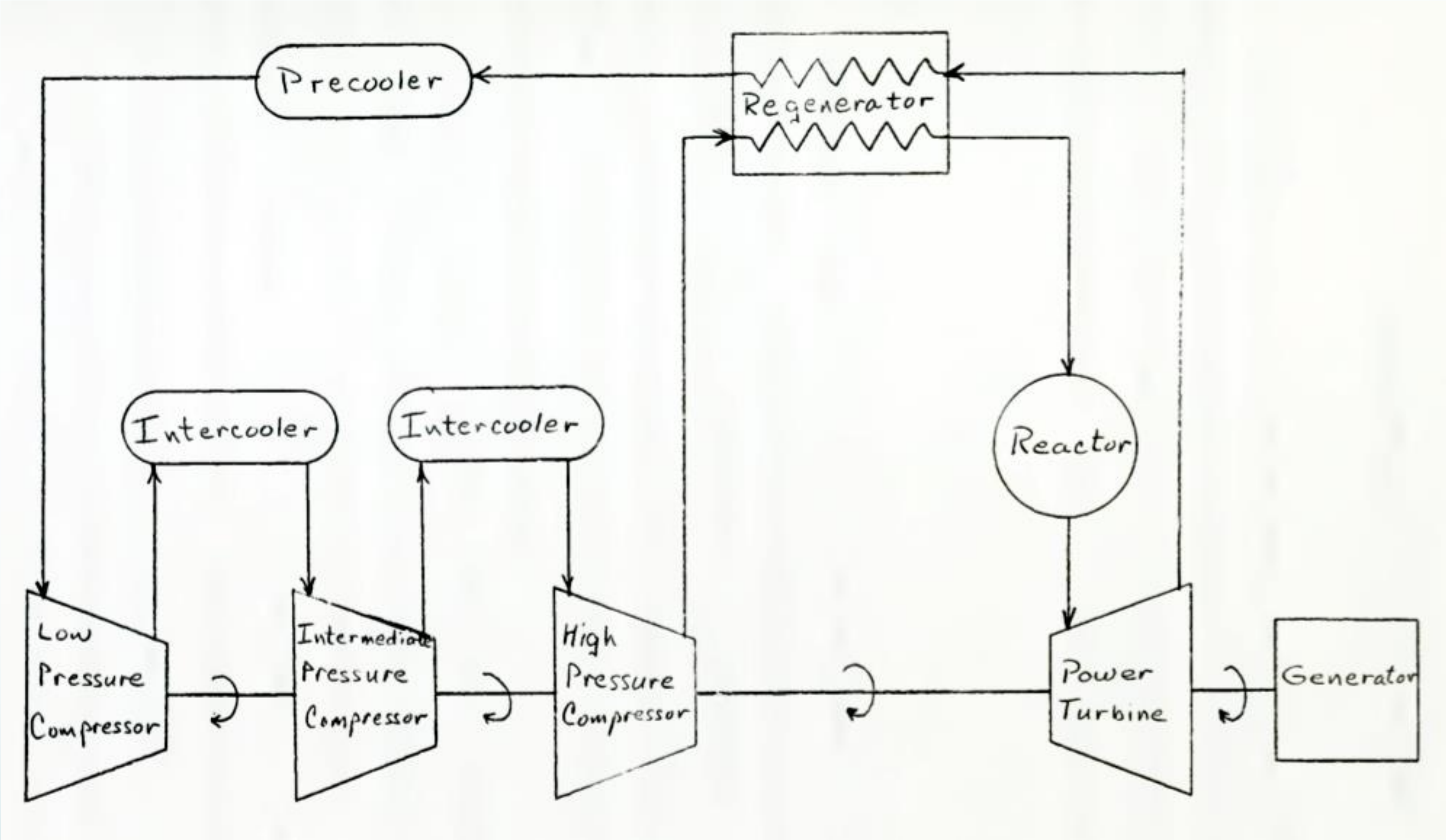


a = fuel element
b = control rod
c = reflector element
d = reflector block
e = charge position
f = thermal shield
g = pressure vessel

Source: K. Bammert & E. Bohm, "Nuclear Power Plants With High temperature Reactor and Helium Turbine," American Society of Mechanical Engineers, 1969

Geesthacht KSH

Power conversion cycle



Source: Current, Donavon C., "Status of maritime gas-cooled reactors," The Pennsylvania State University, Department of Nuclear Engineering, August 1973

Italy

Active development programs in the 1950s – 70s
for naval nuclear submarines and
a nuclear-powered naval logistics support ship

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

Italian marine nuclear timeline

1940s | 1950s | 1960s | 1970s | 1980s | 1990s | 2000s | 2010s

1952
National Committee for Nuclear Research (CNRN) formed
mid-1950s
Preliminary plans developed for an Italian SSN
1959
Minister of Defense, Giulio Andreotti announced plans to build an SSN, *Guglielmo Marconi*
1959
Construction of CNRN's Casaccia Research Centre began.

1960
CNRN reorganized to form National Committee for Nuclear Energy (CNEN)
December 1962
Minister of Defense Andreotti affirmed plans to build SSN *Guglielmo Marconi*
1963
U.S refused to transfer nuclear submarine technology to Italy
1964
SSN project cancelled, refocused on a naval logistics support vessel, *Enrico Fermi*

1970
Definition of the industrial team for *Enrico Fermi* was complete
1970 - 71
US refused to supply uranium. France offered to "rent" uranium for the Italian naval reactor program
Feb 1979
Enrico Fermi project cancelled.

Italy

Timeline for the Italian naval nuclear program

- **1952:** The Italian government created the National Committee for Nuclear Research (CNRN)
- **mid-1950s**: Preliminary plans were developed for an Italian nuclear-powered fast attack submarine.
- **1959**: Minister of Defense, Giulio Andreotti, announced plans to build a nuclear submarine to be named *Guglielmo Marconi*.
- **1959**: Construction of CNRN's Casaccia Research Centre began
- **1960**: Italian government transformed CNRN into the National Committee for Nuclear Energy (CNEN), which was closely linked to industry and responsible for designing and building commercial nuclear plants, fuel-cycle facilities, and naval nuclear-powered vessels.
- **22 December 1962**: At a launching ceremony for an Italian Navy cruiser, Minister of Defense Andreotti said, "We want to bring forward as soon as possible the project of construction of a nuclear submarine that will meet the aspirations of our Navy and also represent a step forward towards that technical project to which we must all cooperate."

Italy

Timeline for the Italian naval nuclear program

- **18 Sep 1963**: Minister of Defense Andreotti spoke in the Italian Parliament of the commitment, "to provide a nuclear-powered surface unit, a first step towards the construction of the atomic submarine, which remains the ultimate goal."
  - In the US, Naval Reactors opposed the Italian naval nuclear program on two main points:
    - Large amounts of classified nuclear propulsion technology would have to transferred to the Italian government and industry to enable their nuclear ship program to proceed. Protecting these data was a US national security issue.
    - Naval Reactors felt that Italy did not have the necessary technology infrastructure for the safe application of naval nuclear propulsion technology.
  - Italy was not going to get US S5W reactors or access to the naval reactor technology needed for the planned Marconi-class SSNs.
- **1964**: Andreotti announced that the nuclear ship program would focus on a naval logistics support vessel to be named *Enrico Fermi*.

Italy

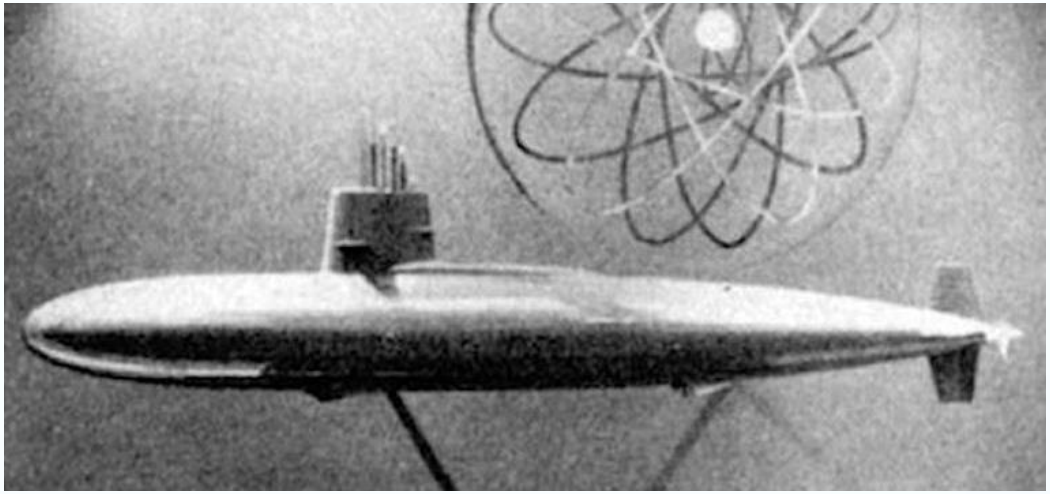
Timeline for the Italian naval nuclear program

- **9 Dec 1966**: Cooperation agreement executed between CNEN and the Italian Navy for the *Enrico Fermi* nuclear ship program.
- **1970**: Definition of the industrial team and contractual arrangements for constructing the *Enrico Fermi* seemed almost complete.
  - FIAT submitted an offer for manufacturing the nuclear power plant.
  - Over 90% of the nuclear plant components, including all the internal reactor parts, were to be built by the Italian national industry.
  - Reactor physics experiments were nearing completion at CNEN critical facilities at Casaccia Research Center. CNEN computational code validation was showing favorable results against benchmarks.
- **1970 – 71** timeframe: France agreed to provide (rent) two tons of enriched uranium produced at their enrichment plant to Italy for the *Enrico Fermi.* The US had refused to provide uranium for this ship.
- **1971:** The *Enrico Fermi* nuclear ship project was cancelled
- Italy never built or operated a nuclear-powered vessel.

Guglielmo Marconi

Nuclear-powered fast attack submarine

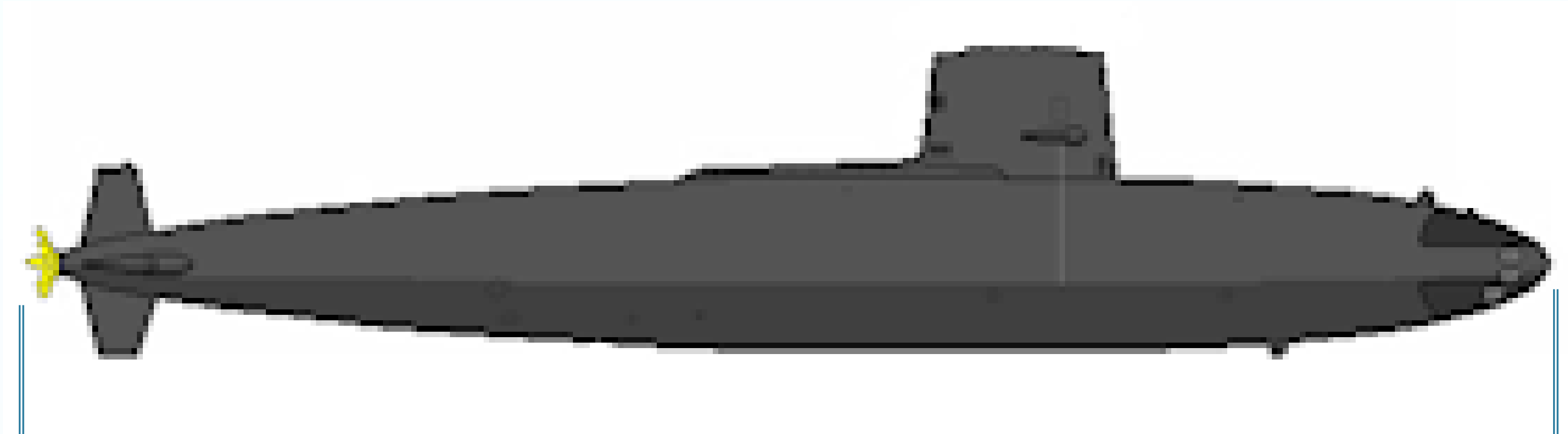
- Originally planned as a class of two subs, with a "solid of revolution" hull design based on the *USS Albacore*.
- Basic ship design parameters were: length: 83 meters (272 ft); maximum diameter: 9.55 m (31.3 ft), displacement: 2,300 tons (surfaced), 3,400 tons (submerged).



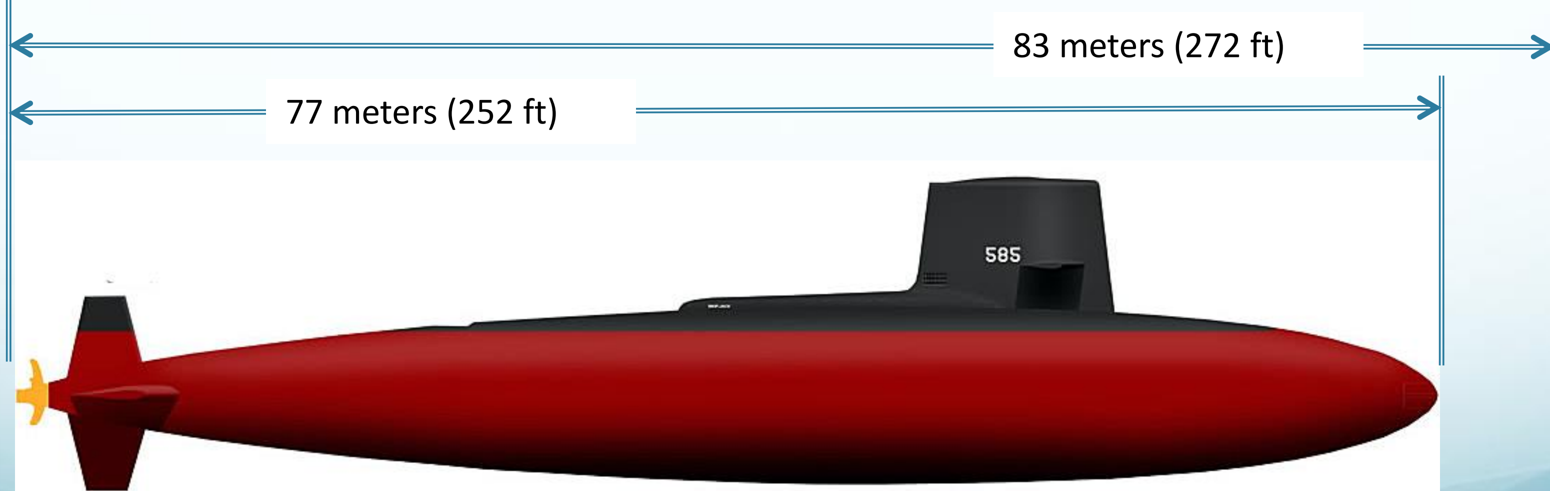
Source: adapted from http://www.globalsecurity.org/military/world/europe/its-marconi.htm

- The Marconi design looked very much like a US Skipjack-class SSN that had been lengthened in the bow by 6 meters (20 ft); with the forward planes mounted on the sail, and a cruciform rudder and stern plane arrangement.
- Propulsion: The Italian Navy intended the reactor plant to be a Westinghouse S5W PWR.
  - The propulsion plant was expected to deliver 15,000 shaft horsepower to drive a single 5-bladed screw, providing a maximum speed of about 30 kts.
  - Core life was to be sufficient to enable 12,000 hours of submarine operation, which probably translates to core life of 3,000 – 4,000 equivalent full power hours.
- Armament: 6 x 533 mm torpedo tubes, with storage for 30 torpedoes.
- US refused to supply the reactor. The *Marconi* SSN project was cancelled in 1963-1964.

Comparison of *Guglielmo Marconi* and *USS Skipjack*



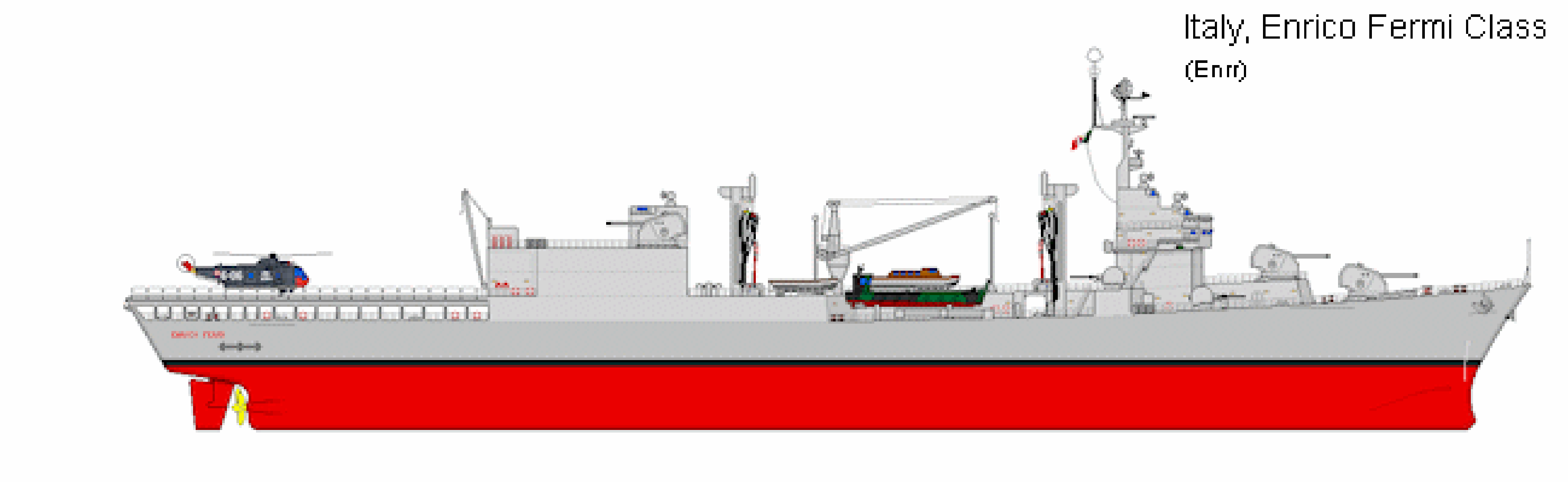
Source: adapted from http://www.globalsecurity.org/military/world/europe/its-marconi.htm



Source:www.subsim.com

N/S Enrico Fermi

Nuclear-powered naval logistic support ship



Source: http://www.globalsecurity.org/military/world/europe/its-fermi.htm

- Basic ship design parameters were: displacement: 18,000 tons; length: 175 meters (574 ft); and speed: 20 knots.
- An 80 MWt PWR would power the ship, providing about 22,000 shp (16.4 MW) for propulsion.
  - The reactor was to be designed by Comitato Nafcionale Energia Nucleare (CNEN, the Italian Committee for Nuclear Energy)
- This ship was never built. The *Enrico Fermi* program was cancelled in 1971.

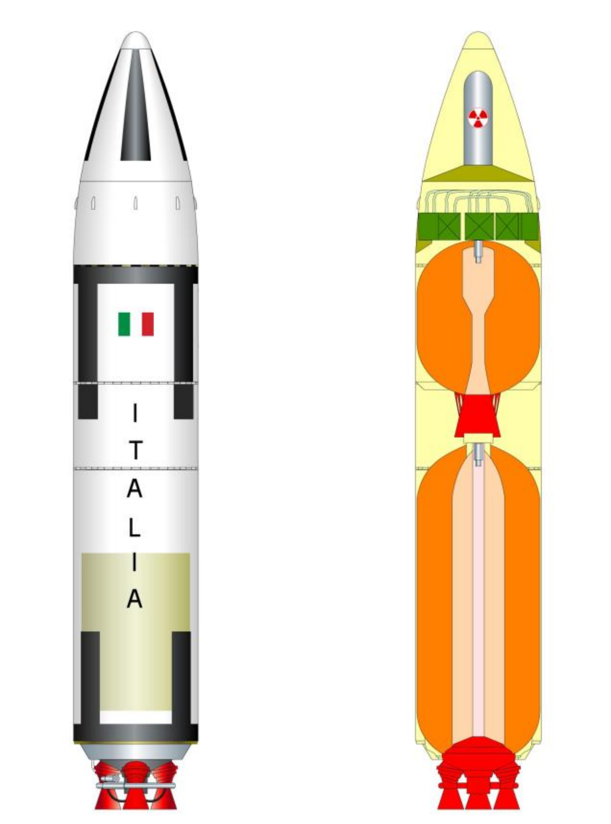
Alfa

Italian Navy intermediate range ballistic missile

- After cancellation of plans for the NATO Multilateral Force, Italy decided to take steps toward an independent nuclear deterrent.
  - In 1971, the Italian Navy began the project for developing an indigenous intermediate range ballistic missile named Alfa.
  - Officially it was called a, "technology program intended to develop high-power solid-propellant boosters for civil and military applications."
  - The Alfa missile was to be carried on submarines and major surface combatants.
  - In anticipation of the NATO MLF, Italy had modified its cruiser *Giuseppe Garibaldi* with four launch tubes for Polaris missiles.

Missile	Weight	Length	Diameter	Range
Alfa	8,000 kg (18,000 lb)	6.5 m (21 ft)	1.37 m (54 in)	1,600 km (990 mi)
Polaris A1	13,063 kg (28,800 lb)	8.69 m (28.5 ft)	1.37 m (54 in)	1,931 km (1,200 mi)

- The Alfa missile first stage motor was fired eight times in static tests. Three Alfa test missiles with inert second stages were launched from Salto di Quirra in Sardinia. All flights were successful.
- The program was abandoned at this stage. Under US pressure Italy signed the Nuclear Non-proliferation Treaty as a non-nuclear state on 2 May 1975.



Source: Wikipedia, Giuseppe De Chiara 1968

Sweden

Former interest in a nuclear-powered attack submarine

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

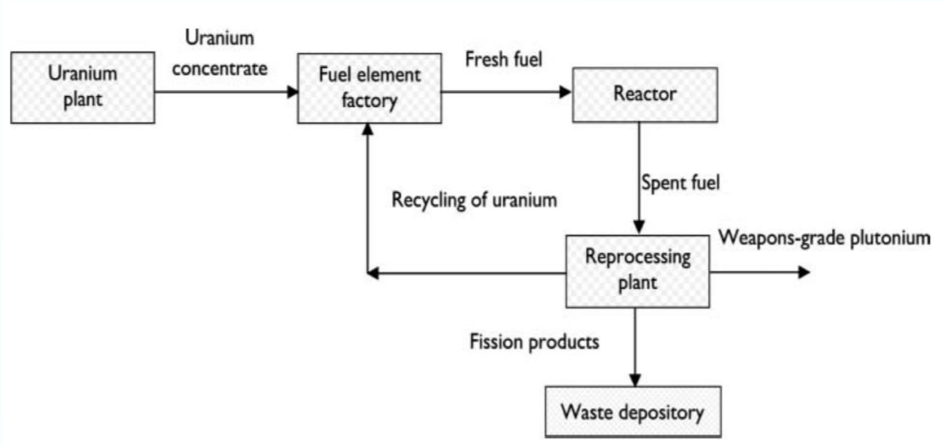
Developing Sweden's nuclear infrastructure

- Sweden initiated a nuclear weapons research program in 1945, shortly after the end of WW II. That mission went to the newly established Swedish National Defense Research Establishment (FOA).
- November 1945: The Atomic Committee (Atomkommittén, AC) was founded. AC was an advisory committee of experts with the mission to plan and prioritize alternative pathways for the development of civilian nuclear energy in Sweden.
- One of the first tasks that AC gave FOA was to acquire uranium. Extracting uranium from Sweden's Kolm-type shale was part of a plan for self-sufficiency. Swedish uranium reserves were deemed to be one of the richest in Western Europe.
- AC and FOA chose a reactor technology using Swedish natural uranium, moderated by heavy water acquired from Norway, to produce plutonium for nuclear weapons. There was no plan for a domestic uranium enrichment capability.
- FOA suggested focusing on civilian nuclear power development that could accommodate plutonium production for nuclear weapons in the framework of civilian nuclear power.
- 1947: AB Atomenergi (AE), which was largely government-owned, was founded with the purpose of developing civilian nuclear power.

Source: Thomas Jonter, "The Swedish Plans to Acquire Nuclear Weapons, 1945–1968: An Analysis of the Technical Preparations," Science & Global Security, 18:61–86, 2010

Developing Sweden's nuclear infrastructure

- The intended Swedish nuclear fuel cycle is shown in the the adjacent diagram.
- The reactor in this diagram was a natural uranium-fueled, heavy water cooled and moderated reactor. This was the "Swedish line" of reactors.

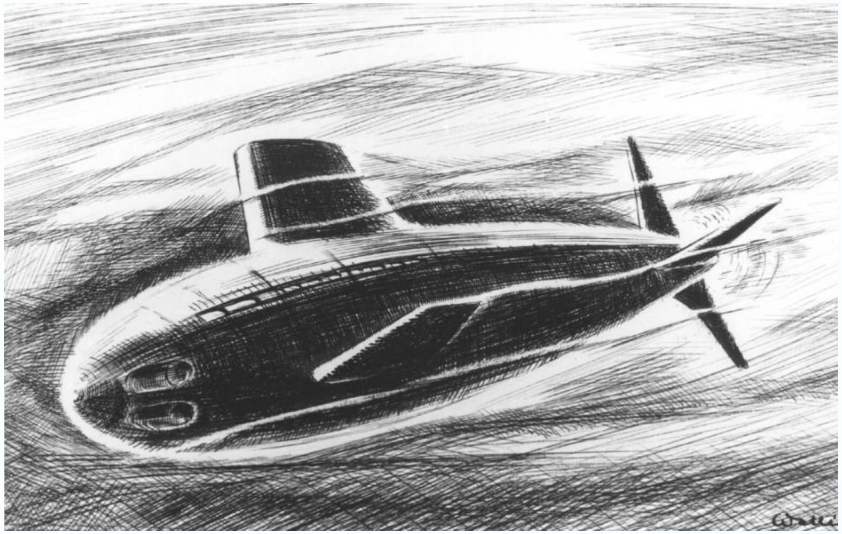


- The first such reactor was Ågesta, which was constructed between 1957 – 1962 and started commercial operations in 1964.
- That's the same time period when FOA was developing plans for a Swedish nuclear-powered attack submarine (an SSN). However, a natural uranium-fueled, heavy water-cooled and-moderated reactor was not suitable as the basis for a compact submarine reactor, as demonstrated by the French with their Q-244 submarine.
- Later in the 1960s, the Swedish Parliament shelved the nuclear weapons option and Sweden signed the Non-Proliferation Treaty (NPT) in 1968.

Source: Thomas Jonter, "The Swedish Plans to Acquire Nuclear Weapons, 1945–1968: An Analysis of the Technical Preparations," Science & Global Security, 18:61–86, 2010

Sweden’s planned SSN

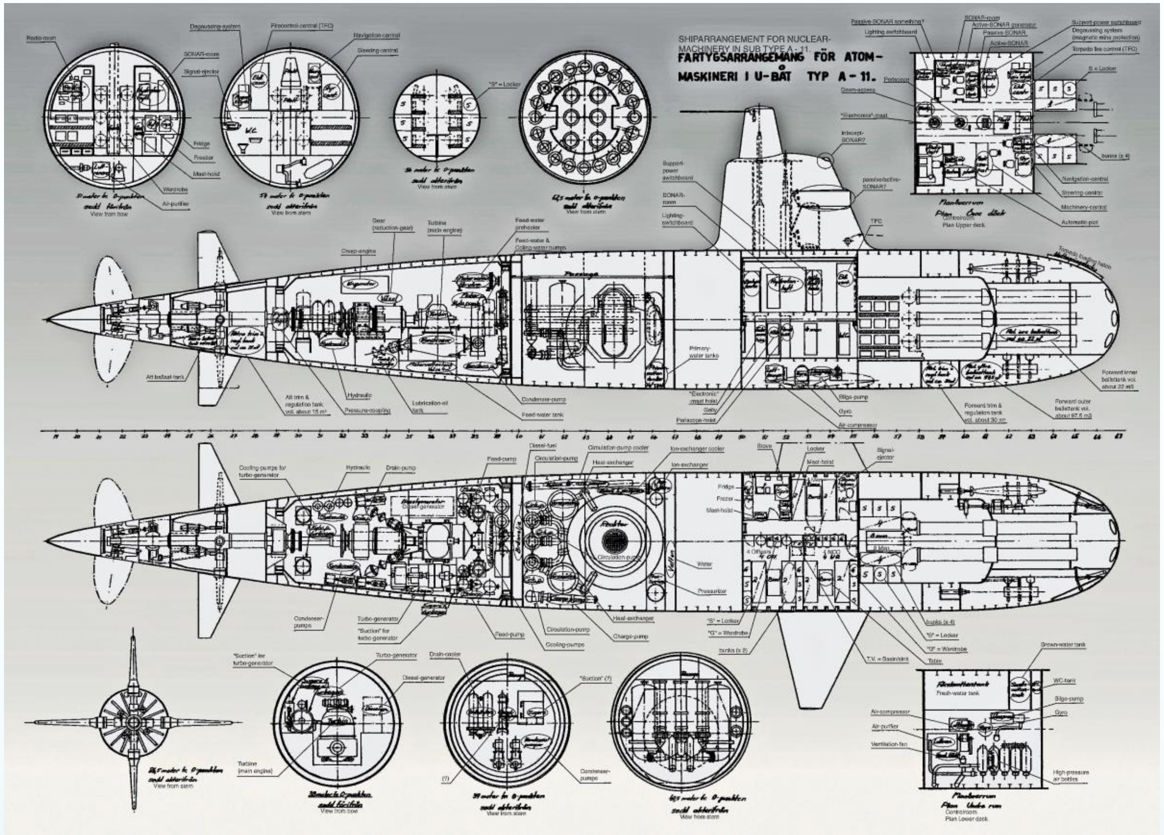
- In 2017, naval analyst H. I. Sutton reported on a Swedish nuclear-powered attack submarine program that began in 1957 and continued until 1964 under that auspices of the National Defense Research Establishment (FOA).
- Swedish design studies yielded the smallest SSN designs developed by any nation, ranging from 660 to 1,170 tons surface displacement. That’s less than 1/3 to 1/2 the displacement of a French Rubis-class SSN.



- The very small size of these SSNs required significant compromises in radiation shielding for the reactor compartment, which was focused on protecting the crew. The sides of the reactor compartment were minimally shielded, meaning that the reactor could not safely be operated in port. Therefore, an onboard diesel generator would be used for maneuvering in port. Crew passage through the access tunnel over the reactor compartment (to reach the aft engine room) had to be done quickly. The maximum time in the aft engine room was 3.5 hours per day.
- The plans for the SSN, known as the A-11A, and the associated NEPTUN reactor, never got beyond the design stage and both were abandoned in 1964. Issues affecting the cancellation included the changing nuclear policy in Sweden and the likelihood that the cost of the new SSN class would exceed the Swedish Navy's financial resources.

Source: H.I Sutton, Covert Shores, “Swedish SSN,” http://www.hisutton.com/Swedish_SSN.html

A-11A SSN circa 1957

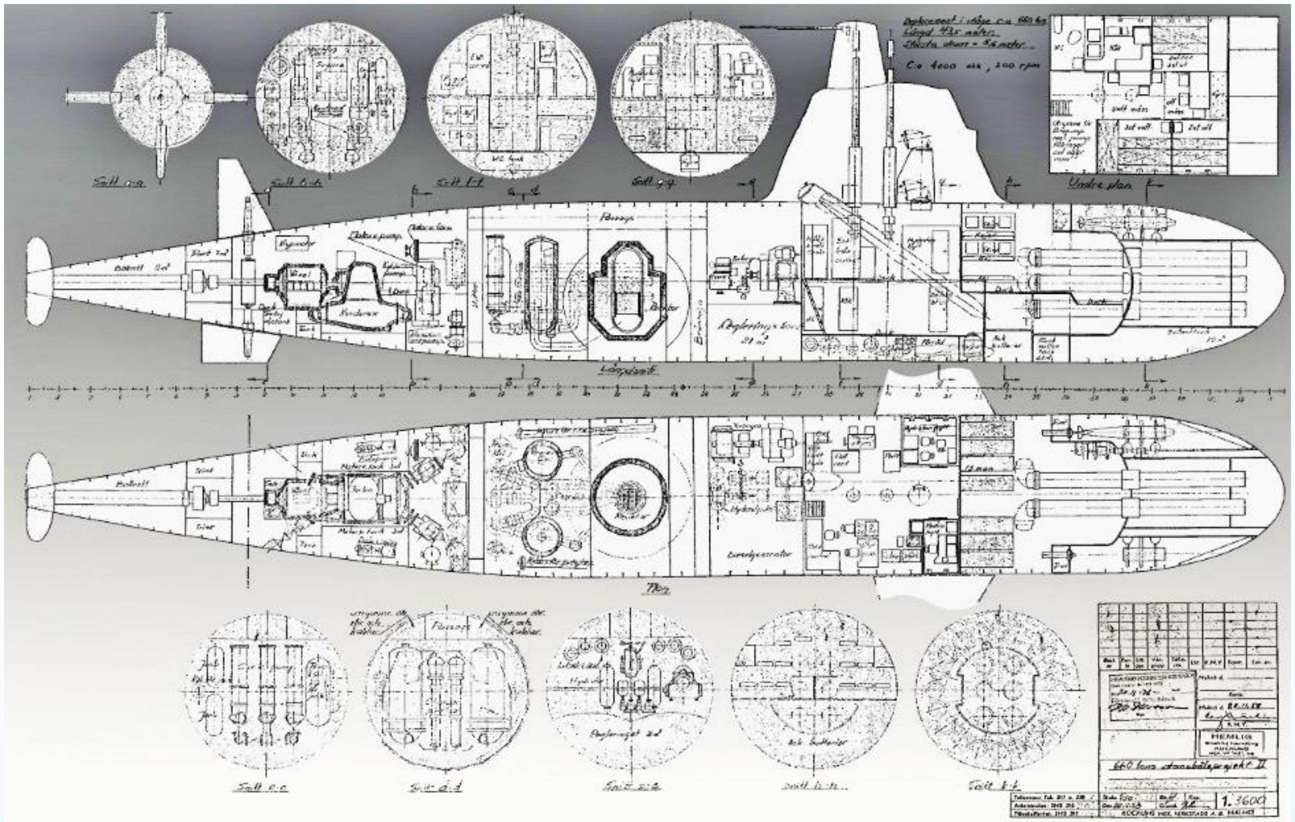


- Surface displacement: 965 tons
- Length: 48.5 m (159.1 ft)
- Hull diameter: 6.4 m (21 ft)
- Maximum speed: > 25 knots
- Crew: 20

- Teardrop-shaped hull
- Cruciform tail fins
- Large variable-pitch propeller
- 6 x 533 mm (21 in) torpedoes & 20 x 400 mm (15.75 in) torpedoes in a rotary magazine in the bow, outside the pressure hull.

Source: H.I Sutton, Covert Shores, “Swedish SSN,” http://www.hisutton.com/Swedish_SSN.html

A-11A SSN circa 1958

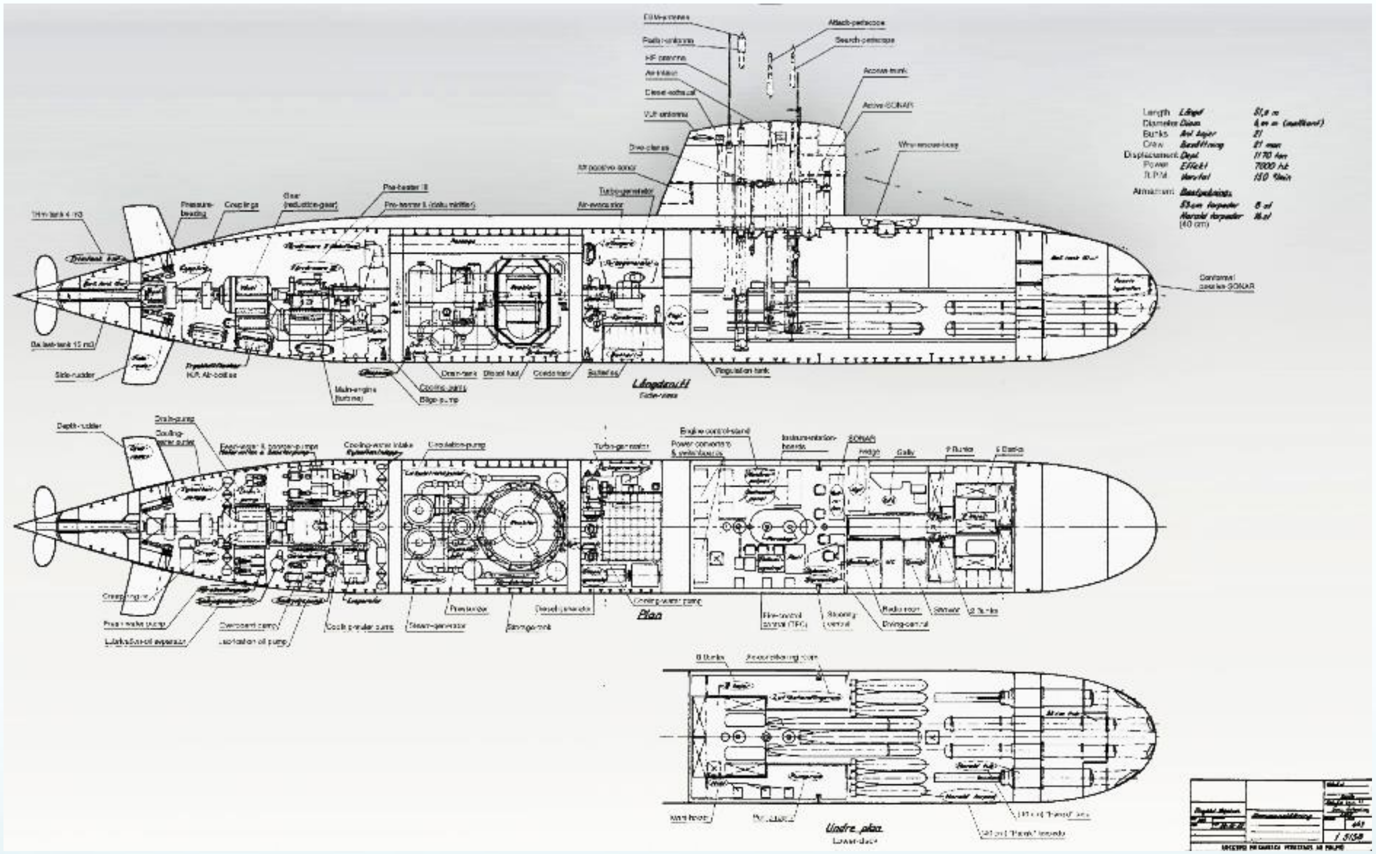


- Surface displacement: 660 tons
- Length: 43.5 m (142.7 ft)
- Hull diameter: 5.6 m (18.4 ft)
- Propulsion power: 4,000 shp (3 MW)
- Reactor power: 21 MWt (est)

- Cylindrical hull mid-section
- Cruciform tail fins
- Smaller fixed propeller
- 6 x 533 mm (21 in) torpedoes & 20 x 400 mm (15.75 in) torpedoes in a rotary magazine in the bow, outside the pressure hull.

Source: H.I Sutton, Covert Shores, “Swedish SSN,” http://www.hisutton.com/Swedish_SSN.html

A-11A SSN circa 1962



- Surface displacement: 1,170 tons
- Length: 51.2 m (168 ft)
- Hull diameter: 6.04 m (19.8 ft)
- Propulsion power: 7,000 shp (5.22 MW)
- Reactor power: 36 MWt (est)
- Crew: 21

- Full length cylindrical hull
- X-tail fins
- More conventional propeller
- 4 x 533 mm (21 in) torpedo tubes, 8 torpedoes (4 loaded in tubes, 4 reloads)
- 2 x 400 mm (15.75 in) torpedo tubes, 16 torpedoes

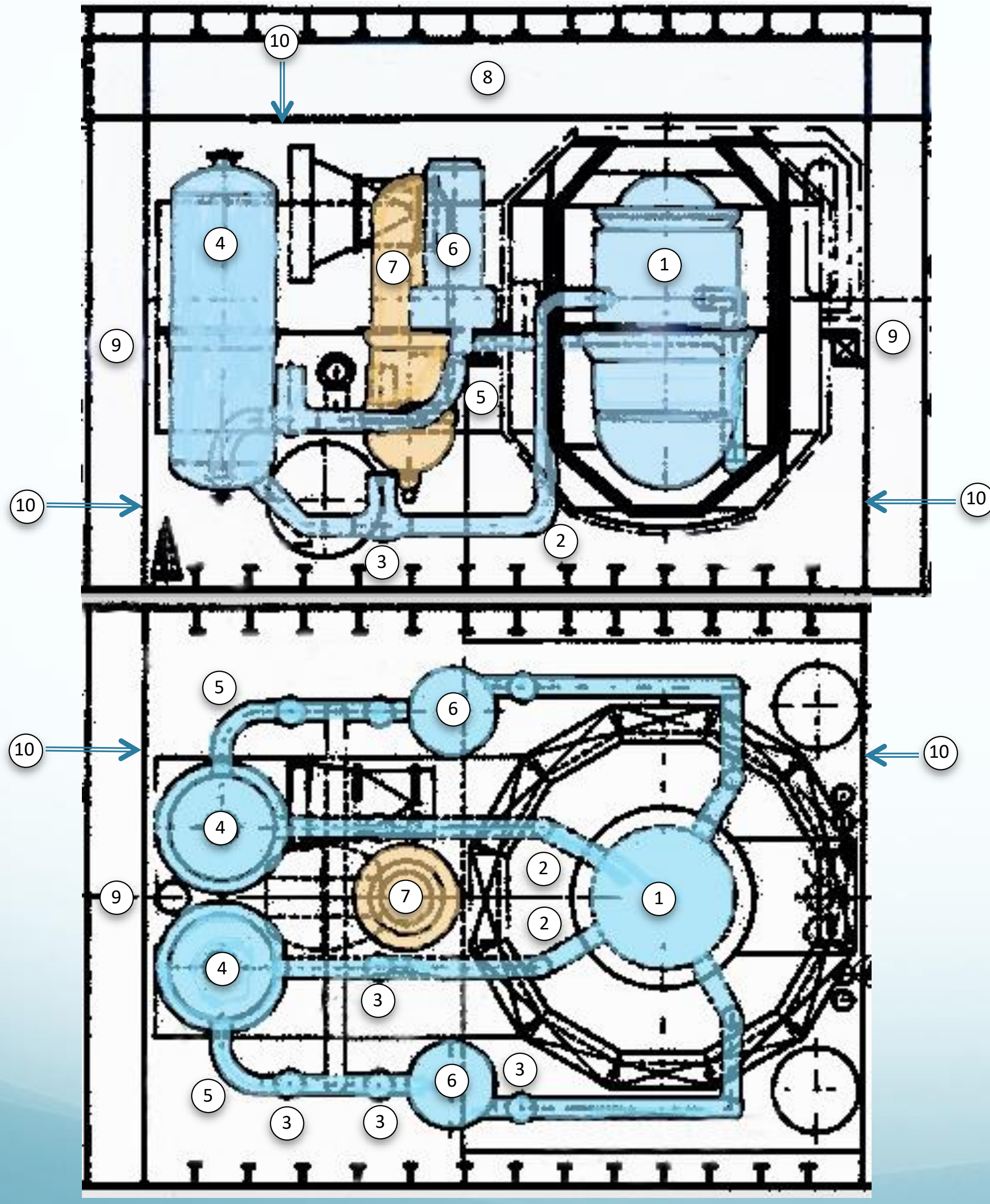
Source: H.I Sutton, Covert Shores, “Swedish SSN,” http://www.hisutton.com/Swedish_SSN.html

NEPTUN marine reactor

- The NEPTUN nuclear reactor was intended for use in a small (nominally 5,000 shp) marine propulsion system to be developed by the joint venture NAVALATOM Group, formed by the main Swedish shipyard, Kockoms AB, and Stal-Laval AB.
  - This nuclear propulsion installation was intended primarily for surface ships (both civilian and military), and was adapted by the Swedish Navy for use on submarines. The Navy only funded a third of the budget and the whole project was unclassified.
- Propulsion power requirements for the A-11A SSN ranged from 4,000 to 7,000 shp, which corresponds approximately to a reactor power ranging from 21 to 36 MWt.
- The Swedish nuclear weapons program in the late 1950s – early 1960s was focused on natural uranium-fueled, heavy water cooled and moderated, pressurized water reactors (the "Swedish line"), like the Ågesta Nuclear Plant.
  - This type of reactor, with a relatively large natural uranium core, was not well suited for use in a very compact marine reactor for a very small SSN. France's first nuclear submarine project, the Q-244, was cancelled in 1959 during construction. The primary issue was that the designers were unable to fit the same type of reactor (natural uranium-fueled, heavy water cooled and moderated) on the much larger Q-244 submarine.
- NEPTUN appears to be a simple, light water-cooled PWR. If so, it would have required at least low-enriched uranium fuel. Sweden did not have a domestic source for enriched uranium.

A-11A SSN reactor compartment arrangement

circa 1962



1	NEPTUN reactor vessel
2	Hot leg piping
3	Main loop stop valve
4	Steam generator
5	Cold leg piping
6	Primary pump
7	Pressurizer
8	Personnel fore-aft access tunnel
9	Shield water tank
10	Containment boundary

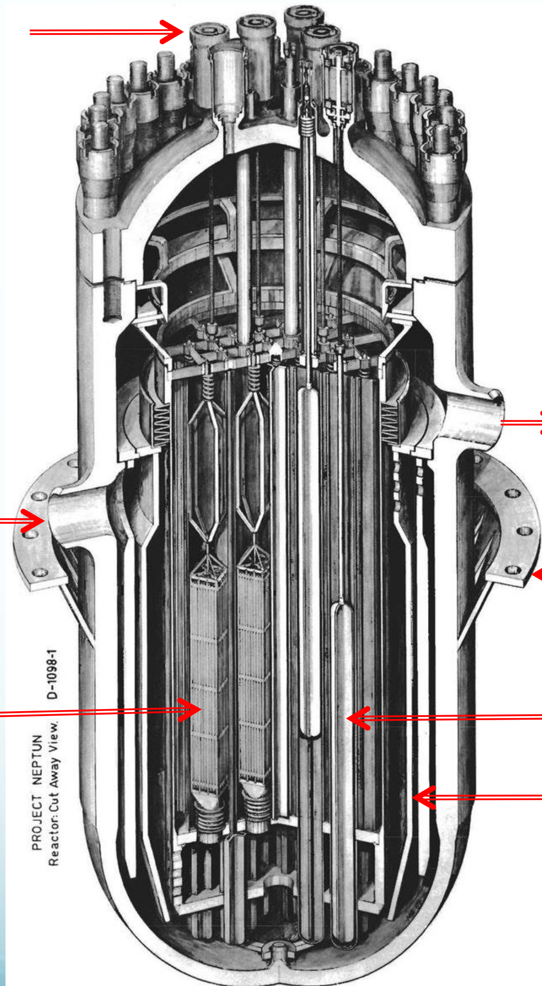
Source: adapted from Navalatom via H.I Sutton, Covert Shores, “Swedish SSN,” http://www.hisutton.com Swedish_SSN.html

NEPTUN marine reactor

Rod drive mechanism penetrations on reactor vessel head

Cold leg return to reactor vessel

Fuel elements



Hot leg to steam generator

Vessel Support flange

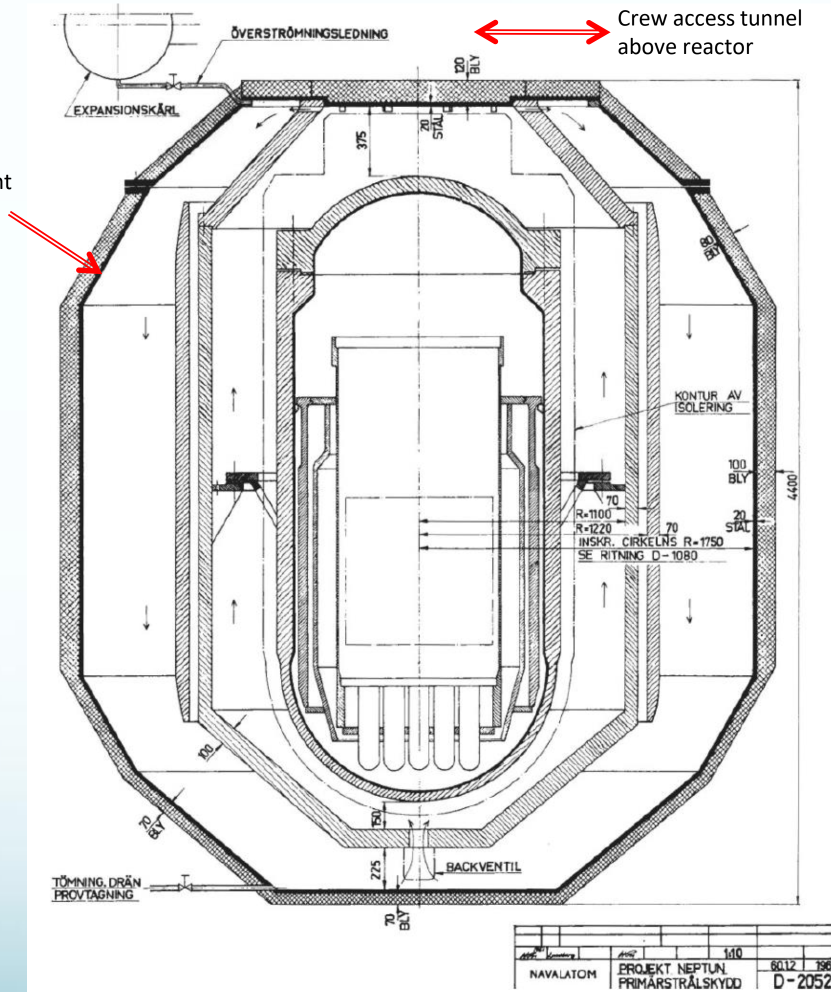
Control rod

Core shroud

Containment boundary

Shielding & containment structures circa 1962

Crew access tunnel above reactor



Source: Navalatom via H.I Sutton, Covert Shores, "Swedish SSN," http://www.hisutton.com/Swedish_SSN.html

Netherlands

NERO marine reactor &
Fast container ship study

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

NERO

PWR nuclear ship propulsion plant

- Developed by the Netherlands Reactor Centre from 1961 to 1967, with funding from Euratom.
- The NERO was a 2-loop PWR intended for use initially with a 22,000 shp propulsion system. The reactor was scalable for propulsion applications up to 120,000 SHP.
  - Each primary loop contained a vertical U-tube steam generator, a horizontal U-tube steam superheater, a canned induction motor-driven main coolant pump, two loop isolation valves and a check valve to prevent reverse flow.
  - An electrically-heated pressurizer maintained primary system pressure maintains at 2,130 psia
  - Primary flow through the core is single pass with internal recirculation (recirculation ratio 2.59) within the reactor vessel provided by 30 jet pumps located peripherally between the core and the vessel wall. The use of these jet pumps reduces external flow rate so that smaller, more compact loops can be used, and provides sufficient natural circulation of the coolant to remove core decay heat to the upper plenum of the vessel in the event pumping power is lost.
  - Primary coolant core inlet/outlet temps are 554 °F (290 °C) / 571.4 °F (300 °C)
  - Steam conditions at the outlet of the superheater are 582 psia, 545 °F (285 °C), 62 °F (34 °C) superheated
- Use of the superheater results in several advantages:
  - No moisture separators are needed upstream of the turbine throttle valve,
  - The problem of condensate flashing in the steam lines during power maneuvers is eliminated,
  - Throttle valve erosion at low power levels is greatly reduced,
  - Cycle thermal efficiency increases several percent
  - Turbine operating life is increased

NERO

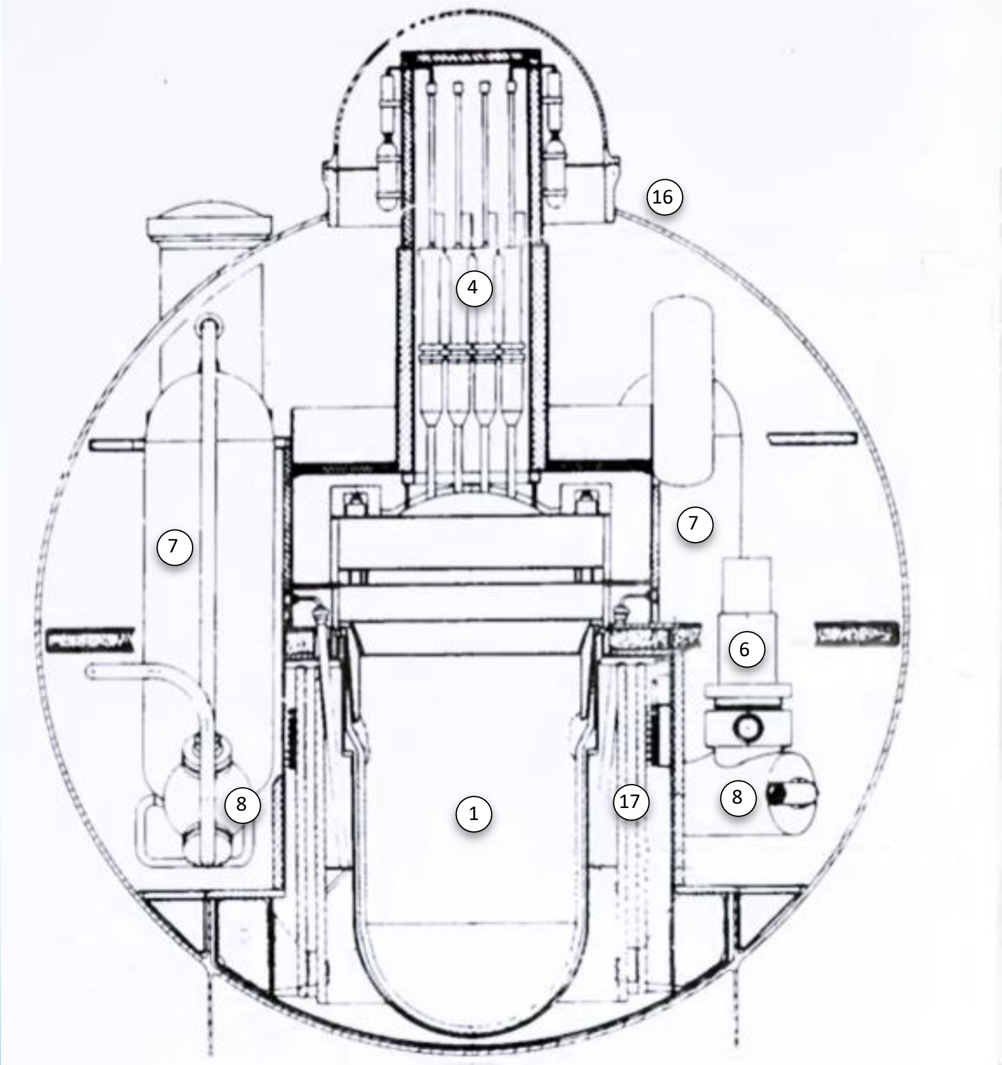
PWR nuclear ship propulsion plant

- Reactor:
  - The 63 MWt core consists of 12 identical, hexagonal fuel elements. Each fuel element contains 282 zircaloy-4 clad fuel rods.
  - Fuel was LEU, 6 w/o uniformly enriched UO_2 fuel pellets.
  - Burnable poison was incorporated in the fuel pellets to achieve long core life without fuel shuffling or excessive control rod movement; there were two radial burnable poison zones.
  - Core life is designed to be 26,400 equivalent full power hours; approximately 4 calendar years of ship operation;
  - Refueling is batchwise to minimize refueling time.
- A fully automatic control system sensing steam pressure and coolant temperatures moves control rods to maintain constant coolant core outlet temperature, permitting faster maneuvering rates with smaller pressurizer in-and out-surges.
- Containment:
  - All radioactive fluids are contained inside the 29 ft 7 in. inside diameter spherical containment vessel.
  - Secondary shielding consisting of lead, concrete and polyethylene is situated both inside and outside the containment vessel.
  - The weight of the entire reactor system, including shielding and containment vessel, is 1,060 tons.

Source: Adapted from James R. Bauman, “Analysis of past, present and future applications of nuclear power for propulsion of marine vehicles,” Massachusetts Institute of Technology, 1972

NERO

PWR nuclear ship propulsion plant

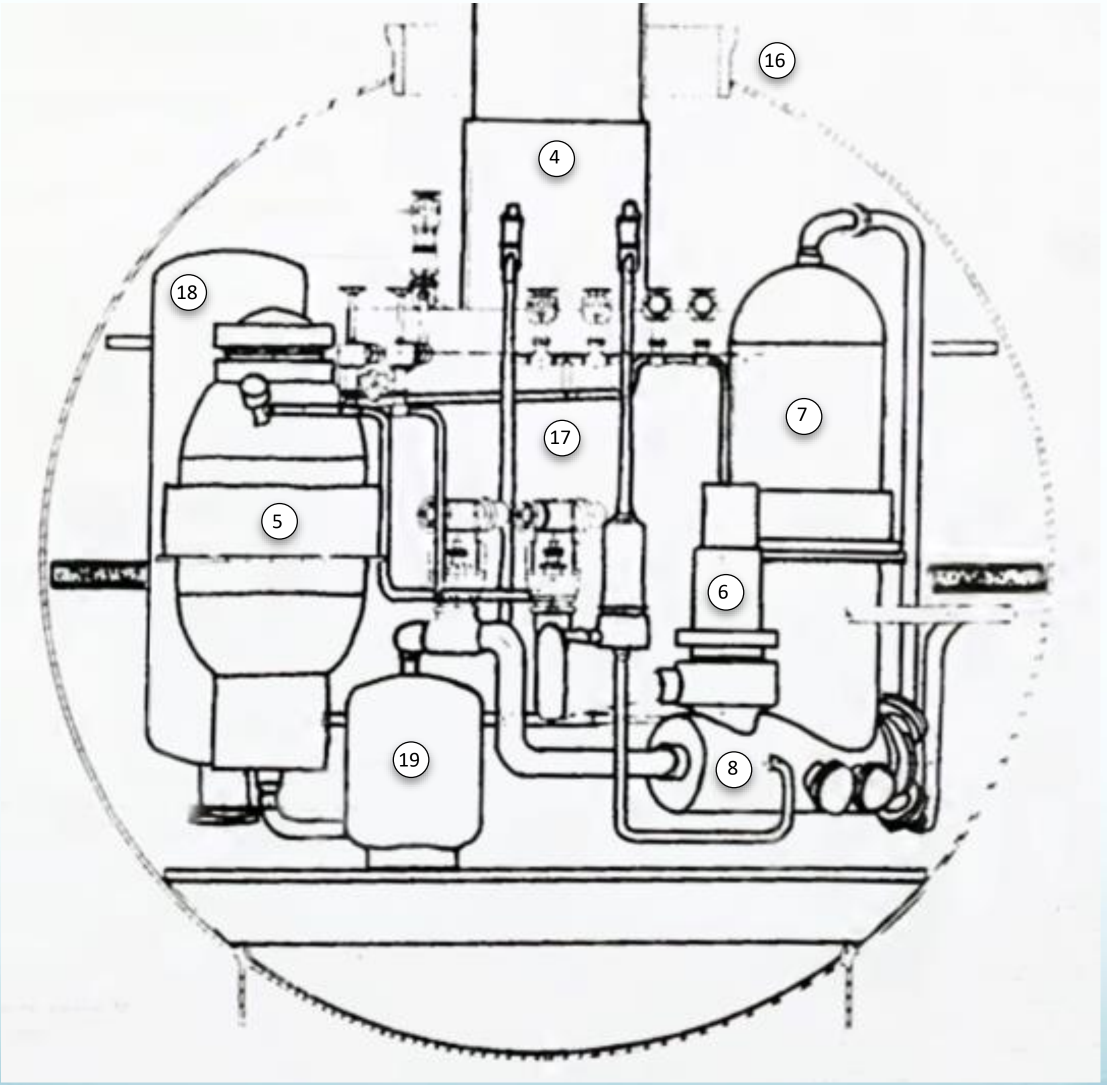


1 Reactor vessel
2 Jet pump
3 Reactor core
4 Control rod drive
5 Pressurizer
6 Primary pump
7 Steam generator
8 Superheater
9 Main steam line
10 Main turbine
11 Reduction gear
12 Main condenser
13 Sea water cooling
14 Feedwater pump
15 Feedwater line
16 Containment
17 Shield tank

Source: Adapted from James R. Bauman, "Analysis of past, present and future applications of nuclear power for propulsion of marine vehicles," Massachusetts Institute of Technology, 1972

NERO

PWR nuclear ship propulsion plant



1 Reactor vessel
2 Jet pump
3 Reactor core
4 Control rod drive
5 Pressurizer
6 Primary pump
7 Steam generator
8 Superheater
9 Main steam line
10 Main turbine
11 Reduction gear
12 Main condenser
13 Sea water cooling
14 Feedwater pump
15 Feedwater line
16 Containment
17 Shield tank
18 Blow-off tank
19 Drain tank

Source: Adapted from James R. Bauman, "Analysis of past, present and future applications of nuclear power for propulsion of marine vehicles," Massachusetts Institute of Technology, 1972

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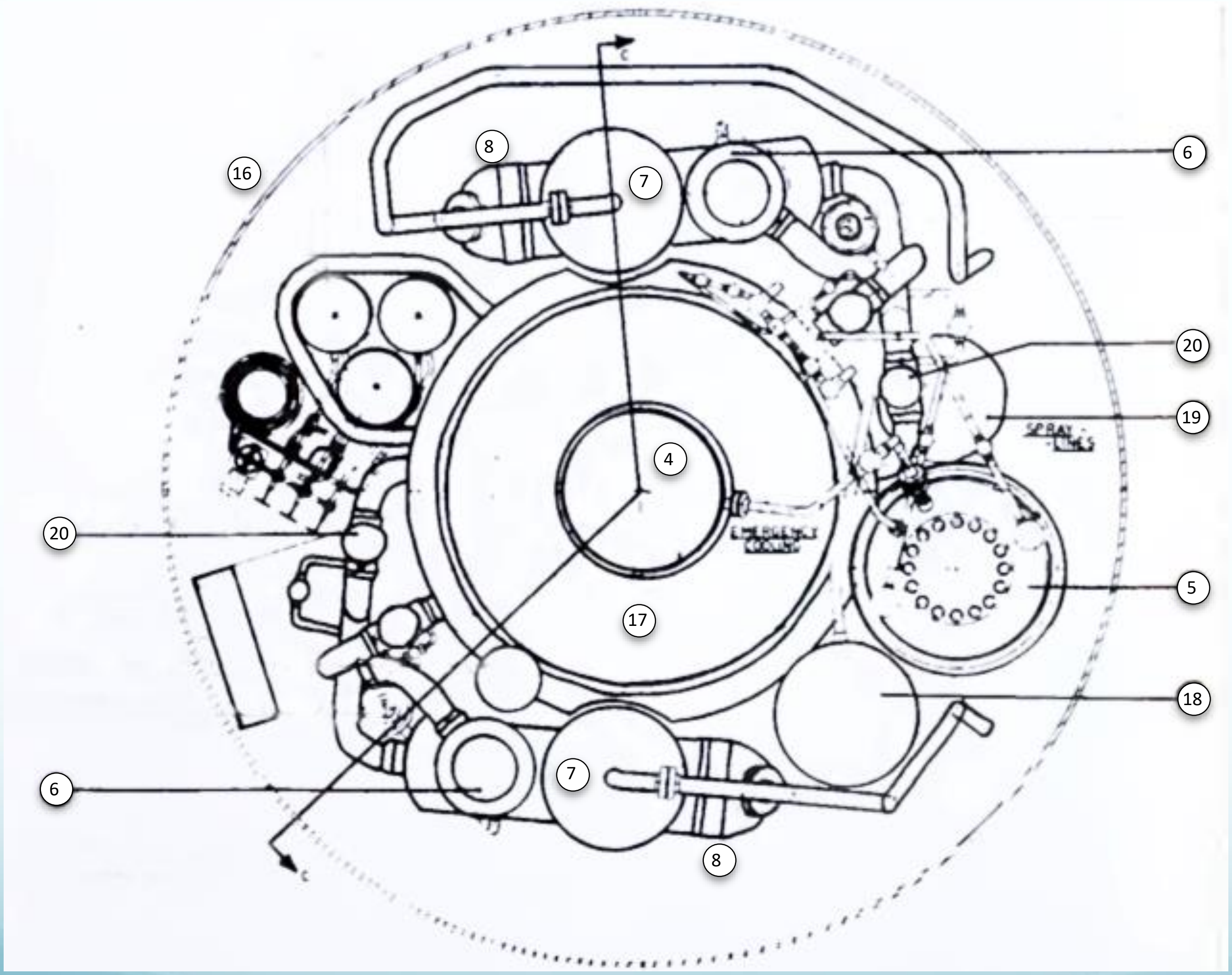

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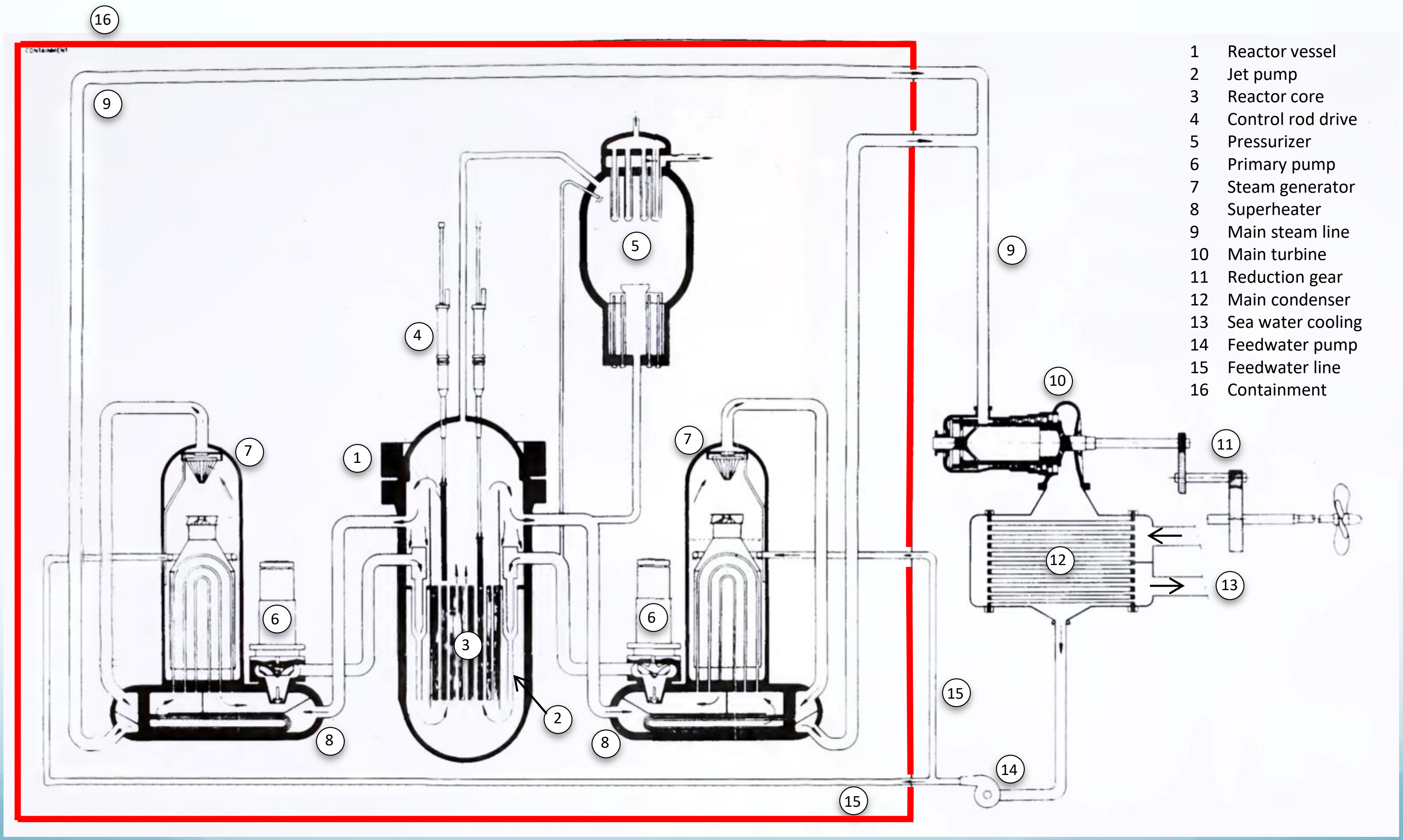
14 Feedwater pump
15 Feedwater line
16 Containment
17 Shield tank
18 Blow-off tank
19 Drain tank
20 Main loop stop valve

Source: Adapted from James R. Bauman, "Analysis of past, present and future applications of nuclear power for propulsion of marine vehicles," Massachusetts Institute of Technology, 1972

NERO

PWR nuclear ship propulsion plant process diagram



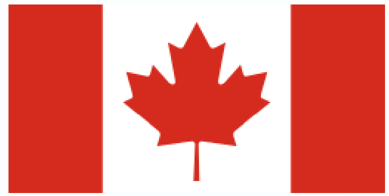
Source: Adapted from James R. Bauman, "Analysis of past, present and future applications of nuclear power for propulsion of marine vehicles," Massachusetts Institute of Technology, 1972

RCN & Rotterdam Dockyard

PWR nuclear propulsion plant

- In 1969, Reactor Centrum Nederland and the Rotterdam Dockyard Company undertook design evaluations of two PWR nuclear propulsion plants rated at 120,000 shp for a 30 knot containership. Eight conventionally-powered vessels of this type recently had been ordered in the US, sparking interest in this market segment.
- The design effort consisted of detailed extrapolations of Westinghouse (loop type) and earlier B&W CNSG (integral type) PWR designs to deliver 120,000 shp and marrying these extrapolated designs to the ship with a minimum of ship redesign.
- The principal conclusions reached during this design effort were:
  - Both nuclear plants increased light ship weight by 2,400 tons due to the heavy reactor and propulsion plant components and associated ship structural stiffening and collision protection provisions, plus 3,000 tons of additional permanent ballast for ship stability.
  - The candidate nuclear propulsion plants required a bit more space than a conventional propulsion plant, slightly decreasing the space available for cargo.
  - There was no clearly decisive technical advantage for choosing one of the reactor types over the other. The choice of loop-type reactor or integral-type PWR could be made based mainly on differences in capital costs and life-cycle operating and maintenance costs.
- The project did not beyond the study phase.

Source: James R. Bauman, "Analysis of past, present and future applications of nuclear power for propulsion of marine vehicles," Massachusetts Institute of Technology, 1972



Canada

Former interest in
a Coast Guard heavy nuclear icebreaker,
a Naval SSN fleet,
an auxiliary "nuclear battery" for conventional submarines, and
the SAGA-N commercial nuclear submarine

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

Sovereignty over the Canadian Arctic

- Canada's intermittent interest in marine nuclear power has been driven largely by its concern about demonstrating Arctic sovereignty.
- The primary concern is that a lack of Canadian surveillance, control, and physical presence in its northern waters might seriously imperil its claims to ownership.
- In 1986 the Canadian government officially claimed the Northwest Passage as internal Canadian waters through the application of straight baselines.
- The US has refused to acknowledge Canadian sovereignty over these waters, claiming instead that the Northwest Passage is an international strait open to shipping, and its use does not requiring permission from Canada for transit.
- The 1987 *"Challenge and Commitment: A Defence Policy for Canada"* was a plan to plug the 'commitment capability gap' that had arisen between Canada's commitments to collective defense and national security, and the Canadian Forces' ability to meet these responsibilities.

Nuclear-powered vessel studies

- The Canadian government studied, but did not proceed with the acquisition of, any of the following nuclear-powered vessels:
  - 1970 – 1980s: A nuclear-powered polar icebreaker for the Canadian Coast Guard, to support economic development in the Canadian Arctic
  - 1987: 10 to 12 nuclear attack submarines (SSNs) at a price of $CAD 8 billion for the Canadian Navy, as announced in the Government's *Defence White Paper.*
    - The UK or France were the candidate suppliers. In May 1989, the SSN program was cancelled.
  - Late-1980s: "Nuclear battery", which was a small autonomous marine powerplant to augment the normal power system on Canada's Oberon-class diesel-electric submarines.
- A joint Canadian – French consortium attempted to develop a commercial mini-sub, SAGA-N, powered by a "nuclear battery" to support Arctic exploration and saturation diving operations.
  - The project was thwarted, largely on financial grounds by tax issues with the Canadian Department of National Revenue.

Nuclear-powered polar icebreaker study

- From the 1970s to the early 1980s, the Canadian Department of Transport (DOT), which includes the Canadian Coast Guard, investigated the design of a “Class 10” nuclear-powered icebreaker, with acquisition in the 1990s.
- In 1976, the Cabinet funded the design of a Class 10 nuclear-powered icebreaker with an “hybrid” powerplant, described as gas turbines powered by nuclear reactors, delivering a total propulsion power of 112 MW (150,000 hp).
  - All reactor proposals were from outside of Canada: US, UK, France, Switzerland & Germany.
  - Rolls-Royce offered a PWR for use on the proposed nuclear icebreaker, along with through-life maintenance and refueling services. The R-R nuclear propulsion plant design was reported to deliver 45 – 67.5 MWe. That implies a reactor power in the range of 145 – 210 MWt. Two Rolls-Royce reactors would have been needed on the polar icebreaker.
  - By 1980, all reactor vendors had dropped out except the French, which offered to transfer marine nuclear technology to Canada.

Nuclear-powered polar icebreaker study

- The project was cancelled in the early 1980s for several reasons, including:
  - Commercial exploitation of Canada’s Arctic resources was occurring slower than expected, and thereby weakening the business case for the Class 10 icebreaker.
  - Canada’s lack of a marine nuclear regulatory infrastructure led to delays in negotiating with the reactor vendor.
  - Acquisition of marine nuclear technology for a single ship came at a very high price.
  - Only the Soviet Union had actual experience operating a nuclear propulsion plant on an icebreaker.

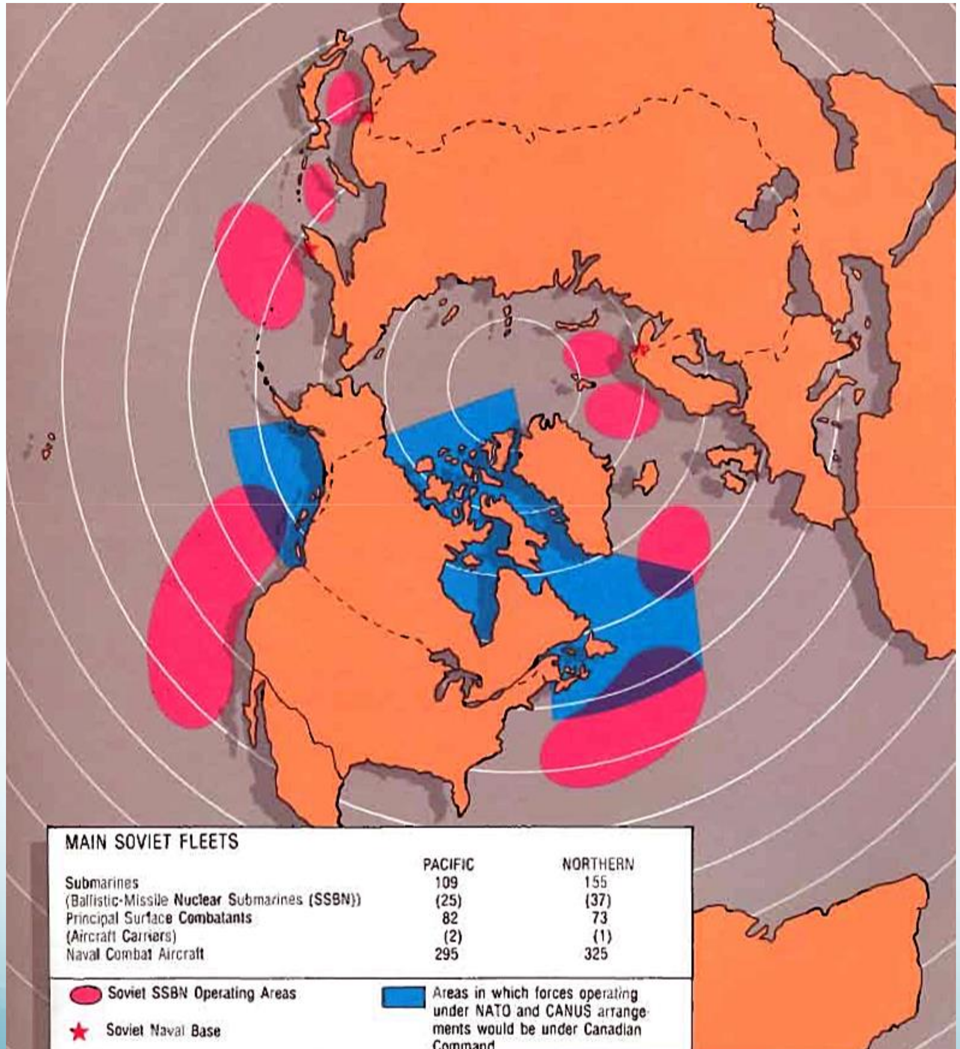
Nuclear submarine fleet plans

Canada’s 1987 defense white paper

- In June 1987, the Canadian defense white paper, *“Challenges and Commitment – A Defense Policy For Canada”* recommended the purchase of 10 to 12 nuclear-powered attack submarines, with the goals of building up a three-ocean Navy and asserting Canadian sovereignty over its Arctic territorial waters.
  - Submarine purchase was to be made under a technology transfer agreement.
  - The choice of the type of submarine was to be confirmed before summer 1988. The candidates were a French Rubis /Améthyste-derivative SSN and the UK Trafalgar-class SSN.
- The strongest American opposition to the U.K.-Canadian SSN deal came from Naval Reactors, which did not support the nuclear propulsion technology transfer from the UK (which was based on US-provided naval reactor technology) to Canada.
- The plan to purchase nuclear submarines was finally abandoned in May 1989.
- Canada also planned to acquire Arctic underwater surveillance capabilities, possibly similar to the US SOSUS. This plan also was abandoned.
- The Canadian Forces eventually acquired four of the UK Royal Navy's diesel-electric *Upholder / Victoria*-class subs in 1998, which they continue to operate as of mid-2018.
  - Unreliability has limited the operational utility of these submarines.

Nuclear submarine fleet plans

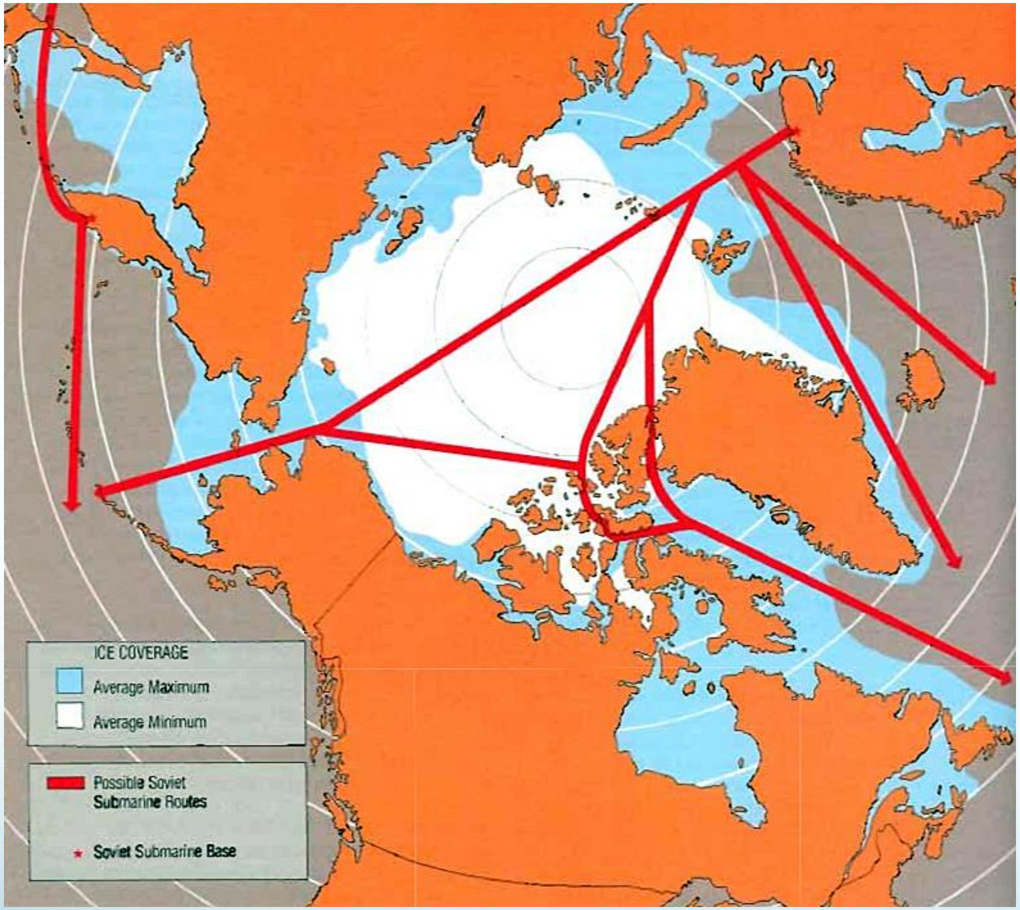
Canada's 1987 defense white paper



- This figure from the 1987 defense white paper shows regions of the Arctic (blue) where Canada expected that forces operating under NATO and CANUS arrangements would be under Canadian command (i.e., while they are in Canada's claimed Arctic territorial waters)
- The red regions denote Soviet SSBN operating areas. The Soviet submarine bases at Murmansk, Petropavlovsk and Vladivostok are shown on the map.

Nuclear submarine fleet plans

Canada's 1987 defense white paper



- This figure from the 1987 defense white paper illustrates possible routes taken by Soviet nuclear submarines transiting through the Arctic between the Atlantic and Pacific Oceans, passing through Canada's claimed Arctic territorial waters on some of the routes.
- Average Arctic ice coverage circa 1987 also is shown on the map (it's a bit more than the averages in 2018).

Nuclear submarine fleet plans

Canada's 1987 defense white paper – rationale for SSNs

- Submarines are essential to meet current and evolving long-range ocean surveillance and sea control requirements in the Atlantic, Pacific and the Canadian Arctic.
  - Nuclear-powered submarines (SSNs) are uniquely capable anti-submarine platforms.
  - SSNs can maintain high speeds for long periods, enabling them to reach operational patrol areas faster and stay there longer.
  - SSNs can shift more rapidly from one area to another to meet changing circumstances.
  - An SSN is a "vehicle of maneuver," while a diesel-electric sub is a "vehicle of position."
  - Through there mere presence, SSNs can deny an opponent the use of sea areas.
  - SSNs are the only proven vehicle, today and for the foreseeable future, capable of sustained operations under the Arctic ice.
- Given the vast distances in the three ocean areas in which Canada requires maritime forces, and the SSNs unlimited endurance and flexibility, the Government decided to acquire a fleet of nuclear-powered submarines to enhance the overall effectiveness of the Canadian Navy.
  - A program of 10 to 12 SSNs will permit submarines to be on station on a continuing basis in the Canadian areas of responsibility in the northeast Pacific, the North Atlantic and the Canadian Arctic.
  - The Canadian nuclear-powered SSNs would not be nuclear-armed.
- The cost of acquiring the SSN fleet would be offset by not acquiring a third batch of air defense frigates at roughly equal cost. The resulting Canadian naval force would be more balanced.

SAGA-N

Commercial nuclear-powered mini-submarine

Source: http://www.geocaching.com/

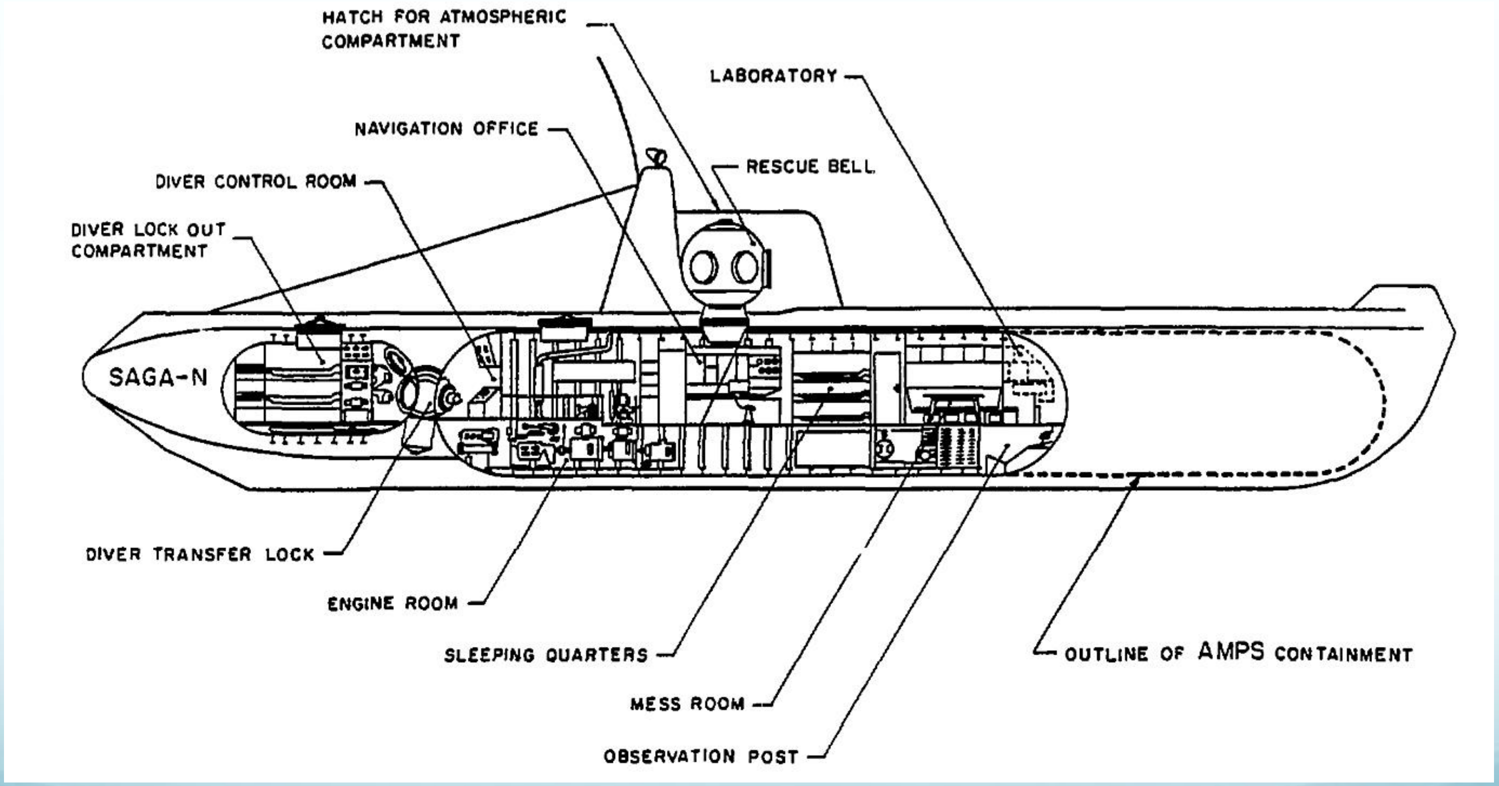
Source: http://www.anciencomex.com/

- The SAGA-1 (Submarine of Assistance to Great Autonomy) mini-sub was designed by Jacques Yves Cousteau and built in France.
  - Displacement: 600 tons
- A consortium named International Submarine Transportation Systems (ISTS) planned to complete the sub, fit it with a 1.5 MWt AMPS nuclear plant based on the *Slowpoke* reactor designed by Canadian firm Energy Conversion Systems (ECS), and re-christen the sub SAGA-N.
- Intended to support long-duration saturation diver operations at depths to 450 m (1,476 ft) and other work site operations to 600 m (1,969 ft), both at submerged ranges to 556 km (300 nautical miles).
- Carries a crew of six + seven divers.
- Mission time limited by the endurance of the crew.
- Brought to Canada in 1988 for integration with AMPS, originally expected to be completed by 1995.

SAGA-N

Commercial nuclear-powered mini-submarine

SAGA-N was not completed because the Canadian Department of National Revenue disallowed a research tax credit and demanded that the consortium pay more than $44 million in Canadian taxes. This led to a significant diplomatic battle between France & Canada and project cancellation.



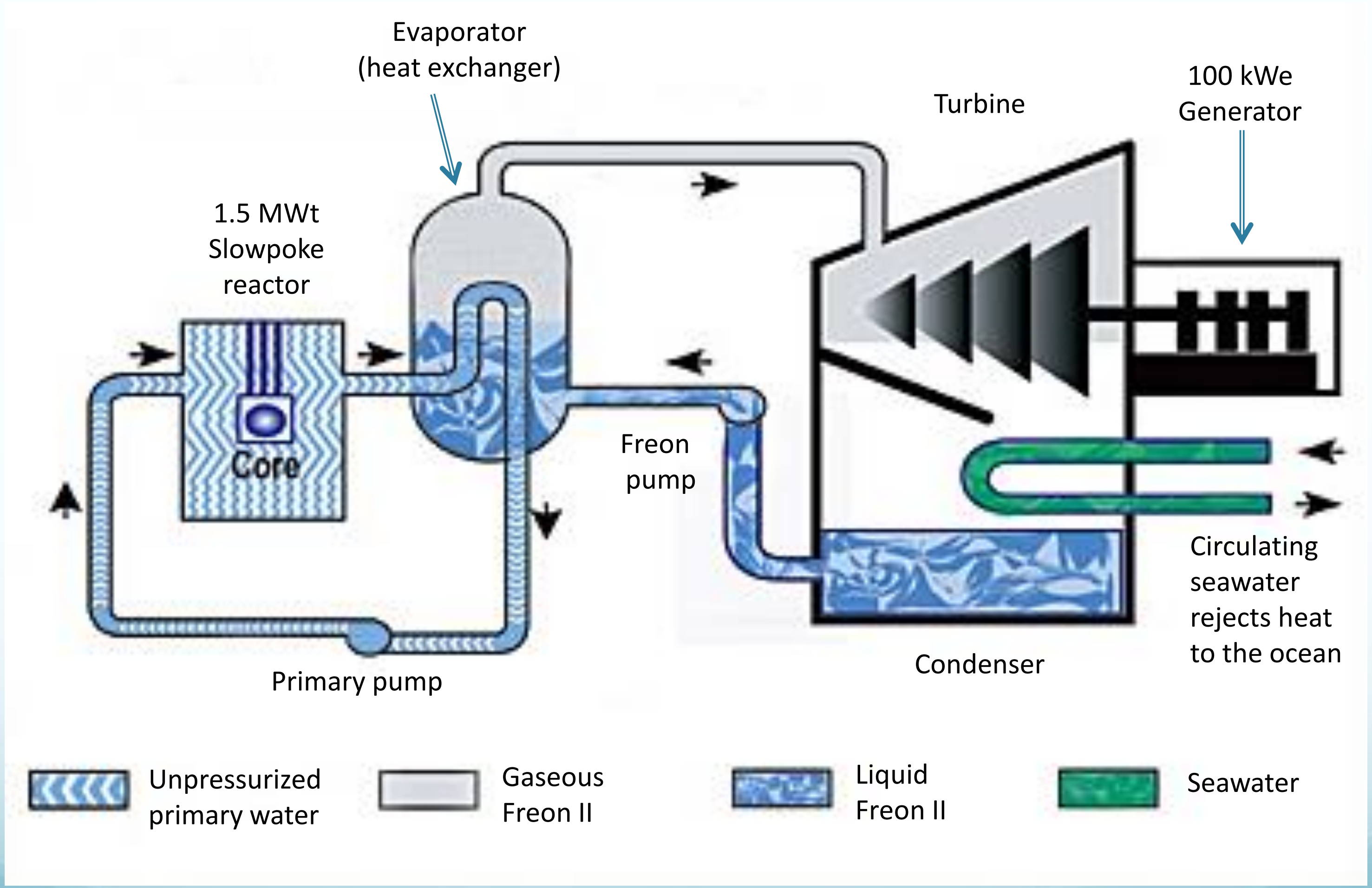
Source: SAGA-N, a nuclear-powered submarine vehicle for commercial operation, Hewitt, J.S.; Wilkins, P.; Kastner, G.A., Proceedings of the Canadian Nuclear Society sixth annual conference, 1985

Autonomous Marine Power Source (AMPS)

- For the SAGA-N mini-sub, AMPS was to be rated at 1.5 MWt
  - Slowpoke (Safe LOW-POwer Kritical Experiment) reactor developed by Canadian firm Energy Conversion Systems (ECS)
  - About 9 kg of ceramic UO_2 fuel enriched to 20%
  - Cooled and moderated by unpressurized light water at an average operating temperature of about 90° C (194° F)
  - Core life is about seven years
  - Inherent safe shutdown on loss of core cooling
- Low-temperature Rankine-cycle secondary heat transport and power conversion system using Freon II coolant.
  - Two turbine generators produce 100 kWe.
- AMPS is housed in a steel containment vessel that is part of the SAGA-N pressure hull.
  - If the submarine sinks, a rupture disk will burst and equalize containment pressure with sea pressure so the containment vessel does not implode.
- Designed to conform to space and weight limits on the order of 30 cubic meters (1,059 cubic feet) and 70 metric tons.

Autonomous Marine Power Source (AMPS)

simplified process flow diagram



Source: adapted from http://www.world-nuclear.org/Nuclear-Basics/

Oberon-class submarine

Conventional submarine conversion with AMPS

- Three new-construction Oberon-class diesel-electric subs were purchased by Canada from the UK, and based at Halifax during the period 1965-2000.
- In the mid-1980s the Canadian government studied the possibility of fitting each sub with an AMPS-type nuclear auxiliary power source.
- AMPS was not implemented on the Oberon-class subs.

Source: http://www.saoc-central.ca/_html/_ocs/_ocs.html

- Functionally, the Canadian AMPS "nuclear battery" is similar to the Russian VAU-6 auxiliary nuclear power plant (ANPP) that was implemented on the Project 651E *Nerka* (Juliett-class submarine B-68) and the Project 20120 *Sarov* (experimental submarine B-90).