60 Years of Marine Nuclear Power: 1955 - 2015

Part 4: Other Nuclear Marine Nations

Peter Lobner

August 2015

Foreword

This is Part 4 of a rather lengthy presentation that is my attempt to tell a complex story, starting from the early origins of the U.S. Navy's interest in marine nuclear propulsion in 1939, resetting the clock on 17 January 1955 with the world's first "underway on nuclear power" by the *USS Nautilus*, and then tracing the development and exploitation of nuclear propulsion over the next 60 years in a remarkable variety of military and civilian vessels created by eight nations.

I acknowledge the great amount of work done by others who have posted information on the internet on international marine nuclear propulsion programs, naval and civilian nuclear vessels and naval weapons systems. My presentation contains a great deal of graphics from many internet sources. Throughout the presentation, I have made an effort to identify all of the sources for these graphics.

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

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

Best regards,

Peter Lobner
August 2015

Other nuclear marine nations

- United Kingdom
- France
- China
- Germany
- Japan
- India
- Other nations with an interest in marine nuclear power technology: Brazil, Italy, Canada, Australia, North Korea, Israel, Pakistan, Iran

United Kingdom

Naval nuclear submarines (SSN & SSBN)

UK’s current nuclear vessel fleet

mid-2015

- The UK operates an all-nuclear fleet of submarines comprised of the following three classes:
  - Four Trafalger-class SSNs
  - Three Astute-class SSNs, which will be replacing the older Trafalger-class boats on a one-for-one basis
  - Four Vanguard-class SSBNs
- The UK does not operate any nuclear-powered naval or commercial surface vessels.

Technology enablers for the UK nuclear submarine program

- 1946: The U.S. Atomic Energy Act (the McMahon Act) severely limited the transfer of restricted nuclear information and materials from the U.S. to any other nation.
- 1956: UK Naval Nuclear Propulsion Program (NNPP) formed
- mid-1950's: Series of exchange visits to define a framework for renewed nuclear collaboration between the U.S. and the UK.
  - Progress was aided by the UK's first atom bomb test in 1952 and first hydrogen bomb test in 1957
- 1958: US-UK Mutual Defense Agreement (MDA)
  - The original MDA included export of a complete Westinghouse S5W submarine nuclear power plant & fuel for the 1st UK nuclear submarine, *HMS Dreadnought*.
  - The MDA is renewed every 10 years.
  - Use of U.S. enrichment services to enrich UK-supplied uranium was reportedly formalized in a 1984 amendment to the MDA
  - In the latest update negotiated and agreed in July 2014, Article III of the treaty was modified to authorize transfer of new reactor technology, spare parts, replacement cores and fuel elements. This will directly benefit the UK's Successor submarine program (Vanguard SSBN replacement).

Technology enablers for the UK nuclear submarine program

- 11 December 1962: Nassau Agreement (Polaris Sales Agreement)
  - Under this Agreement between President John F. Kennedy & UK Prime Minister Harold Macmillan, U.S. was to provide the UK with a supply of nuclear-capable Polaris missiles, launch tubes, and fire control system under the terms of the Polaris Sales Agreement.
    - Equipped with British warheads
    - UK would build five (later four) FBM submarines
    - U.S. would gain an FBM naval base in Holy Loch, Scotland
  - UK's Polaris missiles were part of a 'multi-lateral force' within the North Atlantic Treaty Organization (NATO) and could be used independently only when 'supreme national interests' intervened.
    - Lacking the “dual-key” system, the UK Polaris force was independent.
- March 1982: Trident Sales Agreement
  - Patterned after the 1962 Polaris Sales Agreement
  - Agreed by President Ronald Reagan & UK Prime Minister Margaret Thatcher.
  - The UK leases 58 Trident II (D-5) missiles from a common pool managed by the U.S.

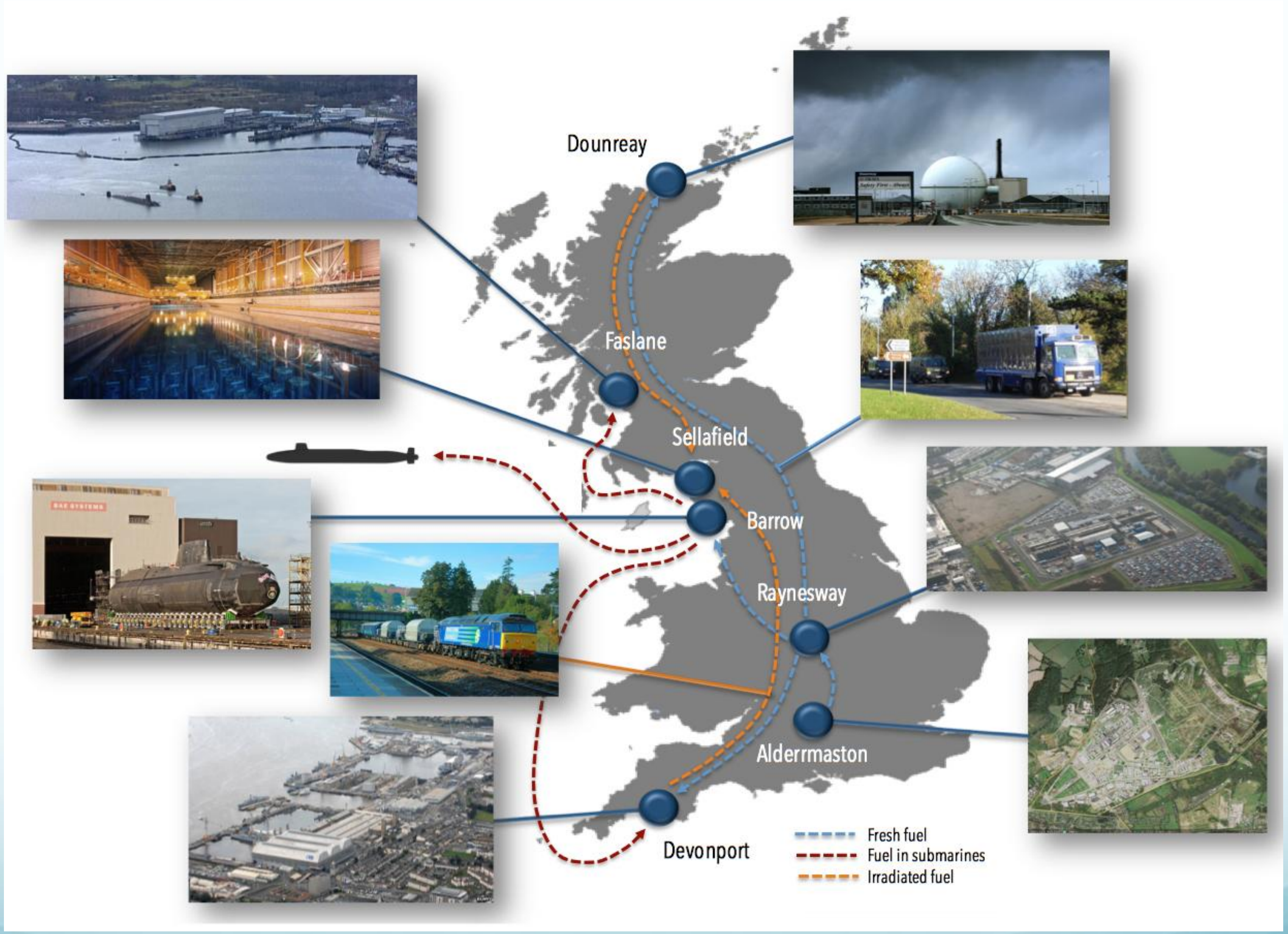
UK naval nuclear propulsion program infrastructure

- Atomic Weapons Establishment (AWE) Aldermaston, Reading
  - Stores and processes HEU for initial fabrication into reactor fuel for the NNPP. UK has 80 or more years worth of HEU for use in NNPP.
  - New Enriched Uranium Facility (Project Pegasus) expected to be operational in 2020.
- Rolls-Royce Marine Power Operations, Ltd., Raynesway, Derby
  - Reactor design and fuel fabrication. Includes 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.
  - Rolls-Royce is the technical authority for the UK “Nuclear Steam Raising Plant” (NSRP)
- Vulcan Naval Reactor Test Establishment (NRTE), Dounreay, Scotland
  - NNPP prototype reactors and related facilities operated by Rolls-Royce on behalf of MoD.
- BAE Systems Maritime Devonshire Dock Complex, Barrow-in-Furness
  - Reactor core assembly and commissioning on new construction submarines.

UK naval nuclear propulsion program infrastructure

- HM Naval Base (HMNB) Clyde, Faslane, Scotland
  - Provides facilities for the operation, maintenance, and repair of all classes of UK submarines.
- Devonport Royal Dockyard and HMNB Devonport, Plymouth
  - Submarine defueling and refueling.
- Nuclear Decommissioning Authority's Sellafield site, Cumbria
  - Long-term irradiated fuel storage
- Uranium Enrichment:
  - All UK submarine reactors operate on highly-enriched uranium (HEU) fuel.
  - UK produced its military HEU at the Capenhurst Gaseous Diffusion Plant between 1952 and 1962.
  - In addition, the UK received about 13 tons of HEU from the U.S.
  - Uranium enrichment services are not currently needed to support the UK naval nuclear propulsion program.

Key facilities in the UK NNPP

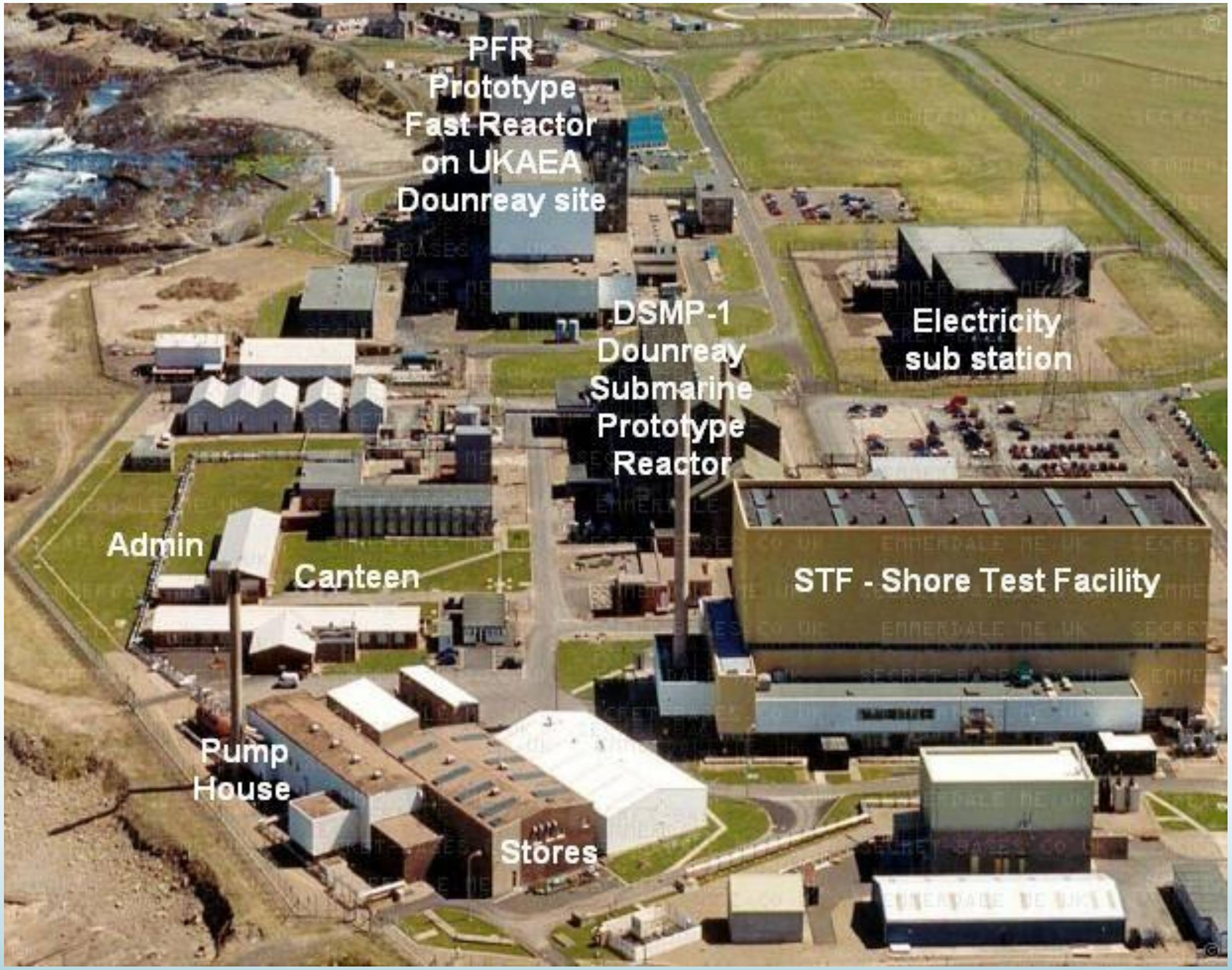


Source: The UK Naval Nuclear Propulsion Programme and Highly Enriched Uranium, Dr Nick Ritchie, University of York, UK, February 2015

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 propulsion plants 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 Ministry of Defense (MoD).

Vulcan Naval Reactor Test Establishment (NRTE)



Source: secret-bases.co.uk (from MoD / Rolls-Royce / UKAEA / NRTE)

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).
- Shore Test Facility (STF) houses 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: 2002 - present
  - In January 2012, a fuel cladding leak was detected in STF. This led to early refueling of *Vanguard* and may require replacement of the cores in other subs operating Core H.
  - STF continues to operate with Core H under the Vulcan Trials Operation and Maintenance (VTOM) program, which is scheduled to be completed in 2015.
  - After completion of VTOM, it is expected that STF operations will cease pending a final decision on it's disposition.

UK submarine reactors

- Except for the 1st UK nuclear sub, *HMS Dreadnought*, which used a U.S.-provided Westinghouse S5W PWR, the reactor plants for all other UK nuclear submarines have been manufactured by Rolls-Royce Marine Power Operations, Ltd. (formerly Rolls-Royce and Associates), Derby, UK.
- PWR1
  - The PWR1 NSSS was based on the Westinghouse S5W NSSS. PWR1 delivers comparable output: about 15,000 shaft horsepower (11 MW), implying a reactor power of about 78 MWt.
  - Core 1 (A) was the original core on Valiant & Churchill-class SSNs & Resolution-class SSBNs, and replaced the original S5W core on Dreadnought.
  - Core 2 (B) was the original core on Swiftsure-class SSNs and the replacement core on Valiant & Churchill-class SSNs & Resolution-class SSBNs
  - Core 3 (Z) is the original core on Trafalger-class SSNs
- PWR2
  - The PWR2 NSSS delivers about 27,500 shaft horsepower (20.5 MW), implying a reactor power of about 145 MWt.
  - Core G was the original core on Vanguard-class SSBNs.
  - Core H is the original core on Astute-class SSNs and the replacement core on Vanguard-class SSBNs.
    - Rolls-Royce claims a ten-fold improvement in core life over the first U.S. and UK core designs, which was about 5,500 equivalent full power hours on *Dreadnought's* Westinghouse S5W core.
    - The reactor will not need to be refueled during the vessel's 25-30 year service life.
- PWR3
  - Planned for use on the future Vanguard replacement SSBN
  - In May 2011, the UK MoD Defense Board said the PWR3 would be 'based on a modern U.S. plant' and U.S. support provided 'independent peer review of the UK's NNPP capability and helped to optimize its PWR3 concept design.'

UK submarine reactors

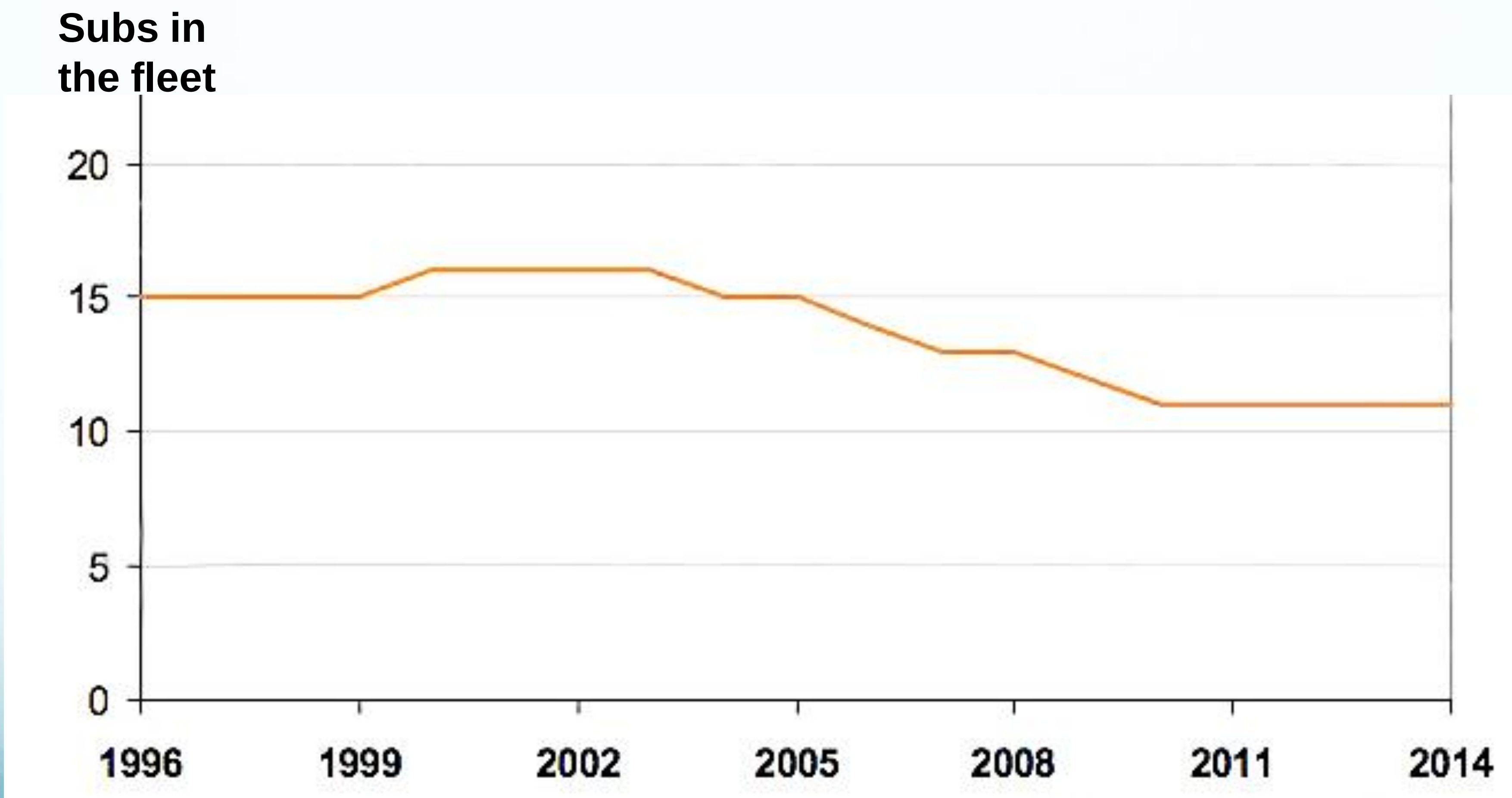
as of mid-2015

PWR	ROLLS-ROYCE PWR 1 REACTOR PLANT																							ROLLS-ROYCE PWR2 REACTOR PLANT										
STATUS	DECOMMISSIONED																			IN SERVICE												IN BUILD		
CLASS			VALIANT		RESOLUTION				CHURCHILL			SWIFTSURE						TRAFALGER								VANGUARD				ASTUTE					
REACTOR CORE	HMS DREADNOUGHT	DS / MP1 PROTOTYPE @ VULCAN	HMS VALIANT	HMS WARSPITE	HMS RESOLUTION	HMS RENOWN	HMS REPULSE	HMS REVENGE	HMS CHURCHILL	HMS CONQUEROR	HMS COURAGEOUS	HMS SWIFTSURE	HMS SOVEREIGN	HMS SUPERB	HMS SCEPTRE	HMS SPARTAN	HMS SPLENDID	HMS TRAFALGER	HMS TURBULENT	HMS TIRELESS	HMS TORBAY	HMS TRENCHANT	HMS TALENT	HMS TRIUMPH	SFT PROTOTYPE @ VULCAN	HMS VANGUARD	HMS VICTORIOUS	HMS VIGILANT	HMS VENGANCE	HMS ASTUTE	HMS AMBUSH	HMS ARTFUL	HMS AUDACIOUS	HMS ANSON	HMS AGAMEMNON
S5W	O/F																																		
CORE A	RF	ORIGINAL FIT																																	
CORE B		REFUEL										ORIGINAL FIT																							
CORE Z		RF										REFUEL						ORIGINAL FIT																	
CORE G																									ORIGINAL FIT										
CORE H																									REFUEL					ORIGINAL FIT					

O/F = Original fit; RF = Refuel

Source: adapted from Rolls-Royce

Trend of UK submarine fleet size (SSNs + SSBNs)



Source: UK Defense Statistics Compendium (1996 – 2012)
Statistical Bulletin 4-01-2013

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)	3500 (surf), 4000 (sub)	S5W	15,000 (est.)	28	Apr 1963	Apr 1963 - 1980
Valiant	2	86.8 m (285 ft)	10.1 m (33.3 ft)	4400 (surf), 4900 (sub)	PWR1 Core 1/2	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)	4400 (surf), 4900 (sub)	PWR1 Core 1/2	15,000 (est.)	29	Jul 1970 – Nov 1971	Jul 1970 – Apr 1992
Swiftsure	6	82.9 m (272 ft)	9.8 m (32 ft)	4400 (surf), 4900 (sub)	PWR1 Core 2/3	15,000 (est.)	>28	Apr 1973 – Mar 1981	Apr 1973 – Dec 2010
Trafalgar	7	85.3 m (280 ft)	9.8 m (32 ft)	4800 (surf), 5300 (sub)	PWR1 Core 3	15,000 (est.)	>28	May 1983 – Oct 1991	May 1983 - present
Astute	3 + 7 (plan)	96.9 m (318 ft)	11.3 m (37 ft)	7000 (surf), 7400 (sub)	PWR2 Core H	27,500	29	Aug 2010 -	Aug-2010 - present

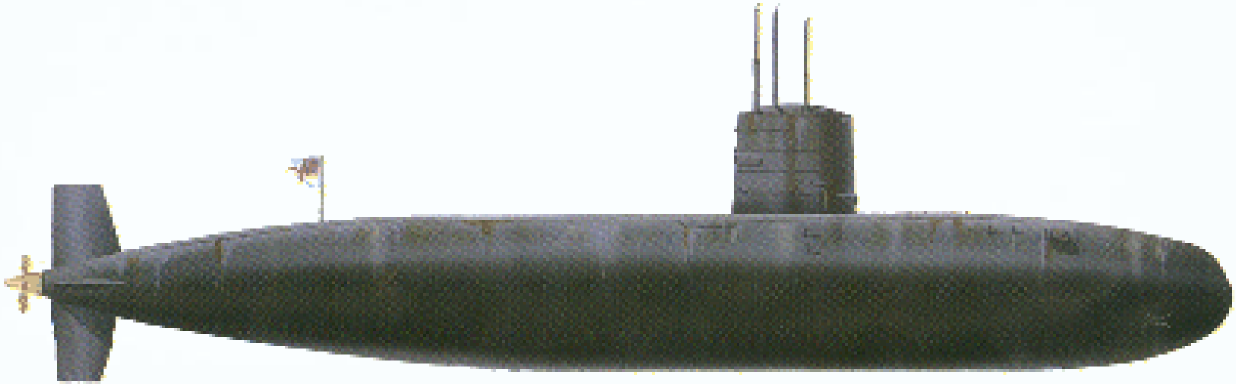
HMS Dreadnought (S101)

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.
  - Built by Vickers Ltd, Shipbuilding Group, Barrow-in-Furness
  - Keel was 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 steam turbines with a combined rating of 15,000 hp (11MW); driving a single propeller
  - Reactor operating life for the initial Westinghouse core was about 5,500 equivalent full-power hours
  - Refueled with Rolls-Royce PWR1 Core 1 (A)
- Armament: 6 x 533 mm torpedo tubes; stowage for up to 24 torpedoes; also mines.
- Operational matters:
  - *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.
  - *Dreadnought* was decommissioned in 1980, and currently is laid up in "afloat storage" pending final disposition.

Valiant-class SSN



Source: BritSub

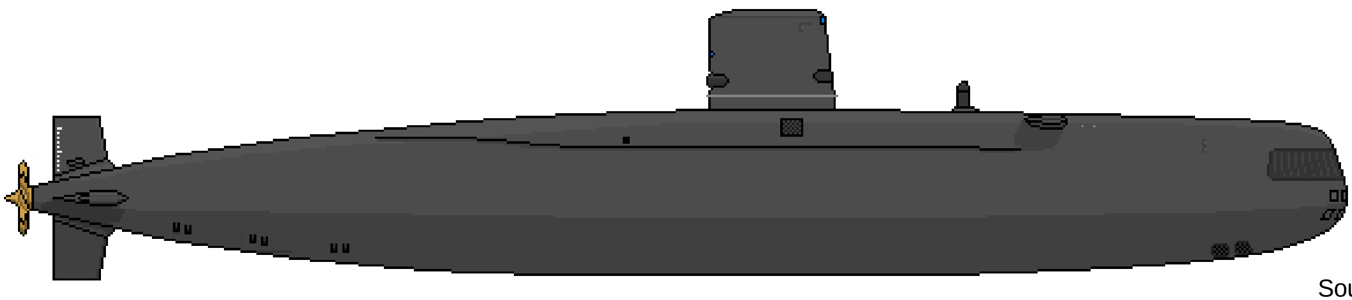
- The two boats in this class were the 1st all-British designed nuclear-powered subs.
  - Built by Vickers Ltd, Shipbuilding Group, Barrow-in-Furness
  - Introduced "rafting" to isolate large, rotating machinery from the hull (a WW II German idea) and thereby provide better sound quieting than in contemporary U.S. nuclear subs.
  - 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 steam turbines with a combined rating of about 15,000 hp (11MW); driving a single propeller
  - Refueled with PWR1 Core 2 (B)
- Armament: 6 x 533 mm torpedo tubes; storage for 24 torpedoes; later upgraded to include Harpoon anti-ship cruise missiles; also mines

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.
  - These subs were decommissioned by 1994 after cracks were discovered in the primary coolant system.
  - They are laid up in “afloat storage” pending final disposition.

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

Churchill-class SSN

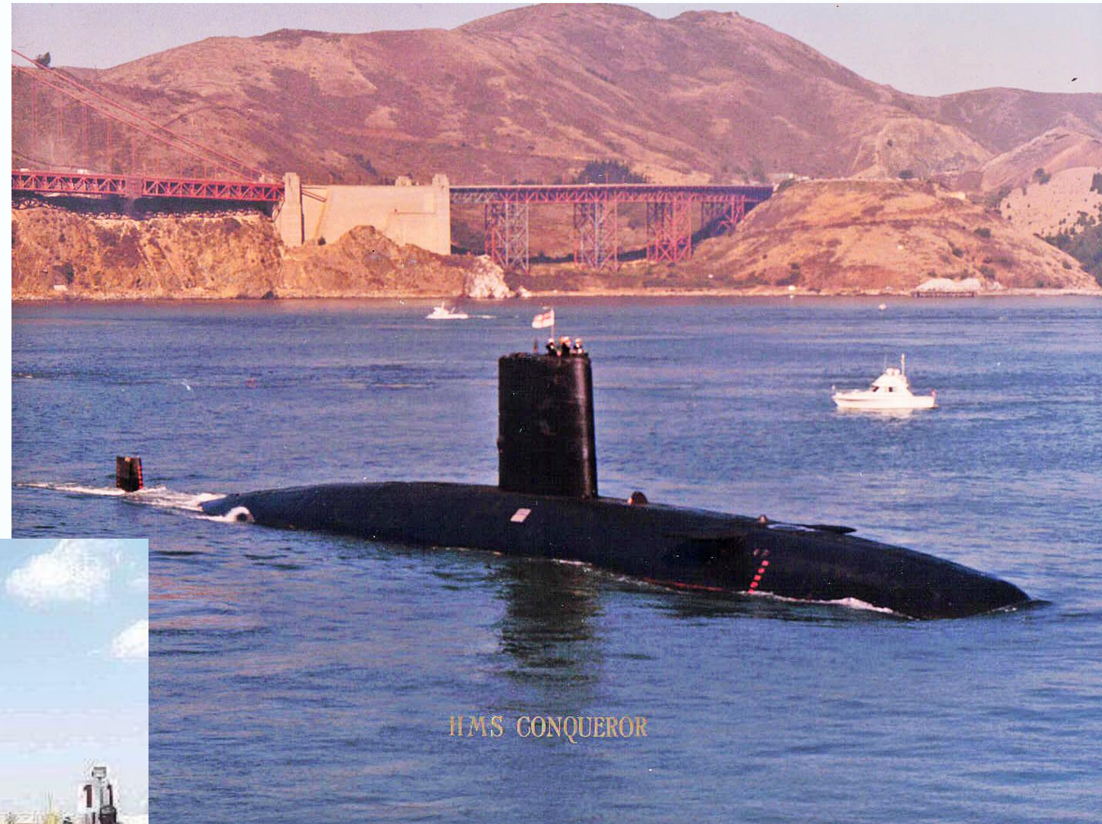


Source: BritSub

- Three boats in the class. *Churchill* & *Courageous* were built by Vickers Ltd, Shipbuilding Group, Barrow-in-Furness. *Conqueror* was built by Cammell Laird in Birkenhead.
- Propulsion: 1 x Rolls-Royce PWR1, Core 1 (A) rated @ about 78 MWt; 2 x steam turbines with a combined rating of about 15,000 hp (11MW); driving a single propeller
  - Refueled with PWR1 Core 2 (B)
- Armament: 6 x 533 mm torpedo tubes; stowage for 26 weapons; Mark 8 and Tigerfish torpedoes, Harpoon anti-ship cruise missiles; also mines
- Operational issues:
  - *Churchill* conducted trials on the first full-size submarine pump-jet propulsor.
  - These subs have been decommissioned
    - *Churchill* and *Conqueror* are laid up in “afloat storage” pending final disposition.
    - *Courageous* is a museum ship in Devonport Dockyard.

HMS Conqueror

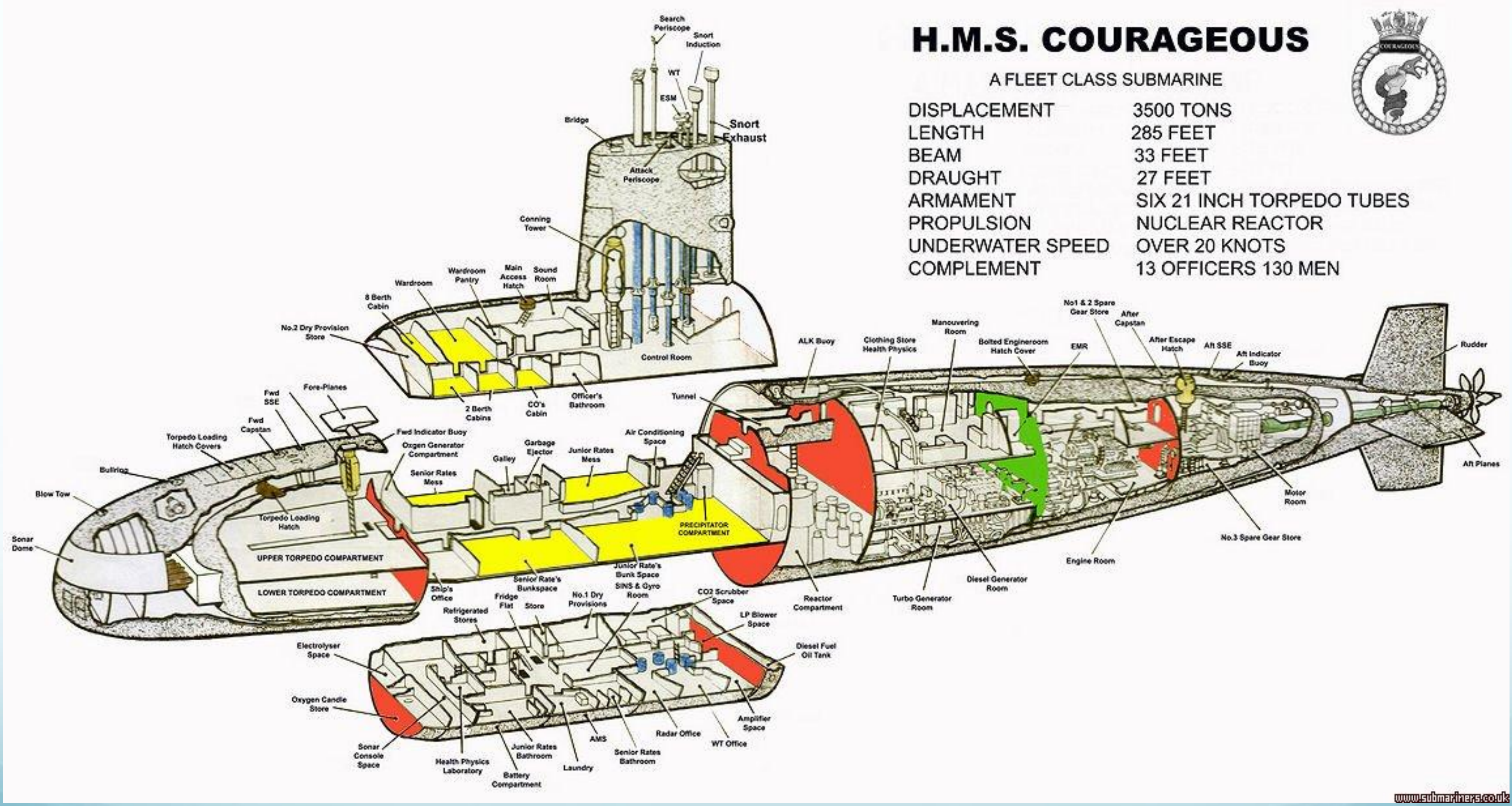
HMS Conqueror is the only nuclear-powered submarine known to have engaged and sunk an enemy ship with torpedoes, sinking the Argentine cruiser *General Belgrano* during the 1982 Falklands War.



Conqueror passing Golden Gate Bridge

Source, two photos: http://www.rnsubs.co.uk/Boats/BoatDB2/

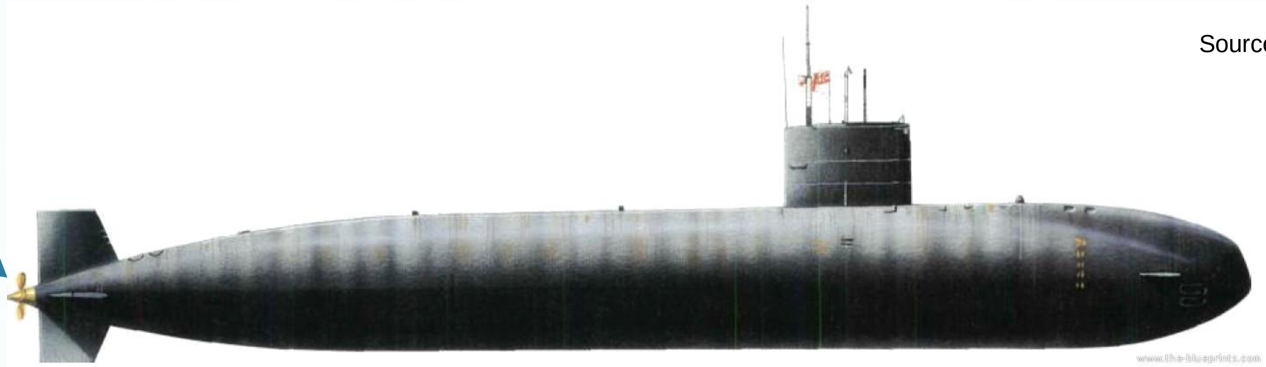
Churchill-class SSN cutaway



Source: submariners.co.uk

Swiftsure-class SSN

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



Source: The-Blueprints.com

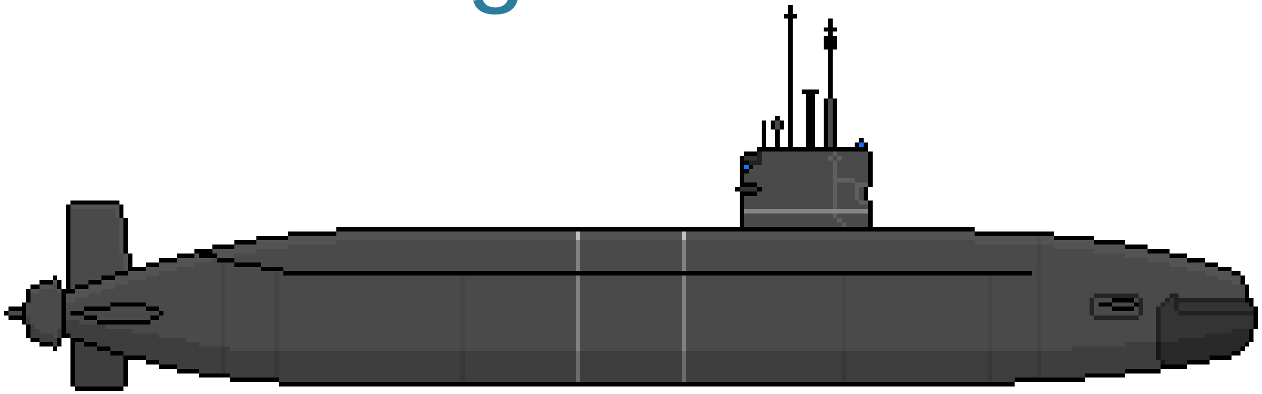
- Six boats in the class, built by Vickers Ltd, Shipbuilding Group, Barrow-in-Furness.
  - Based on Valiant-class with various improvements (flank sonar arrays & towed sonar).
  - Hull maintained its diameter for a greater length than in previous UK classes, similar to contemporary U.S. Permit-class subs.
- Propulsion: 1 x Rolls-Royce PWR1, Core 2 (B) rated @ about 78 MWt; 2 x steam turbines at a combined rating of about 15,000 hp (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 U.S. Navy licensed the main shaft flexible coupling arrangement for use in U.S.-built submarines.
  - Refueled with PWR1 Core 3 (Z).
- Armament: 5 x 533 mm torpedo tubes; Spearfish torpedoes, Harpoon anti-ship cruise missiles, and on some boats, Tomahawk land-attack cruise missiles.
- Operational matters:
  - *Splendid* became the 1st British ship armed with American-built 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.
  - These subs have been decommissioned and are laid up in “afloat storage.”

Swiftsure-class SSN

HMS Spartan with Dry Deck Shelter
Source: http://www.rnsubs.co.uk/Boats/BoatDB2/

http://www.military-today.com/navy/swiftsure_class.htm

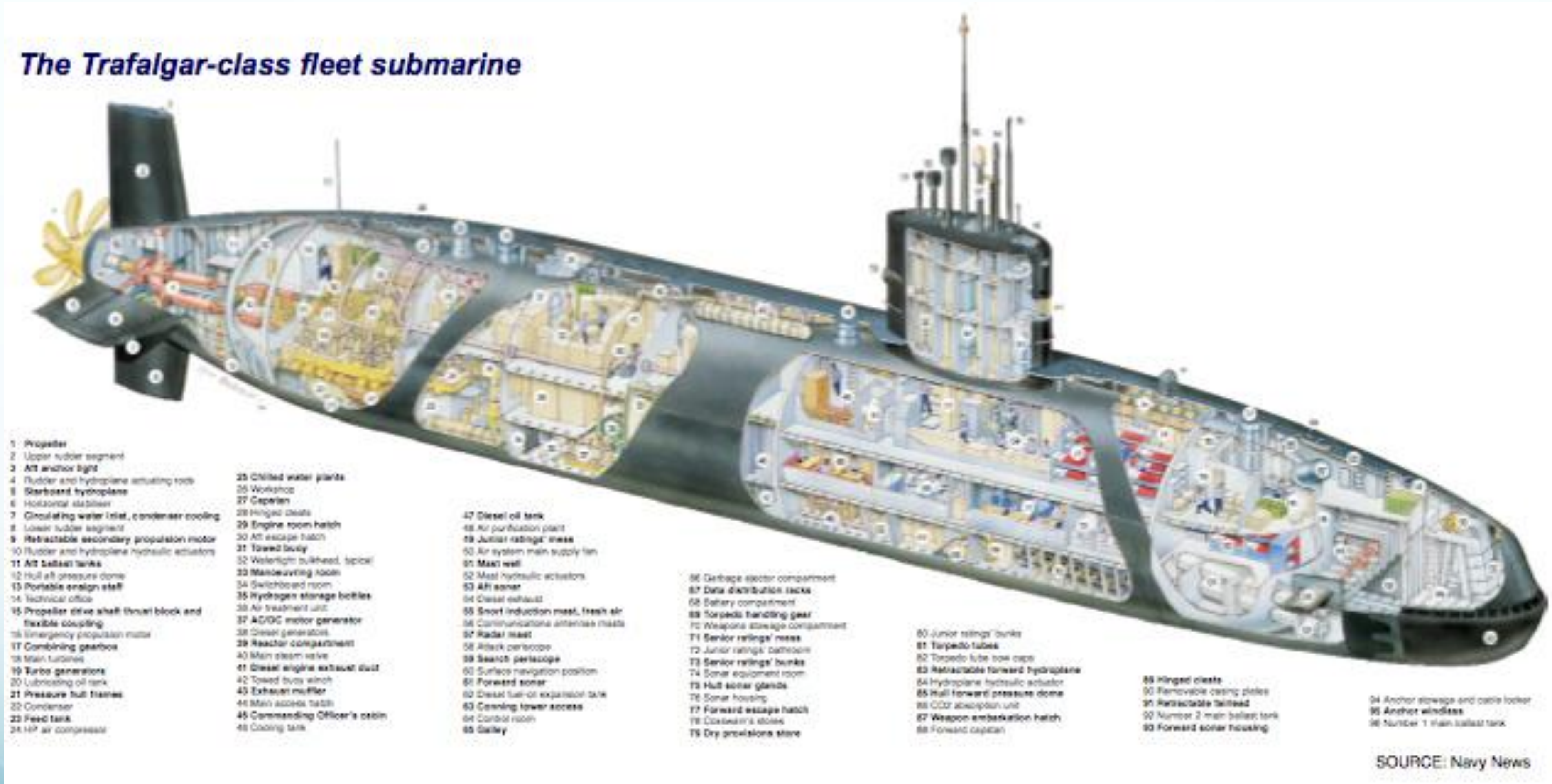
Trafalger-class SSN



Source: wolfsshipyard.com

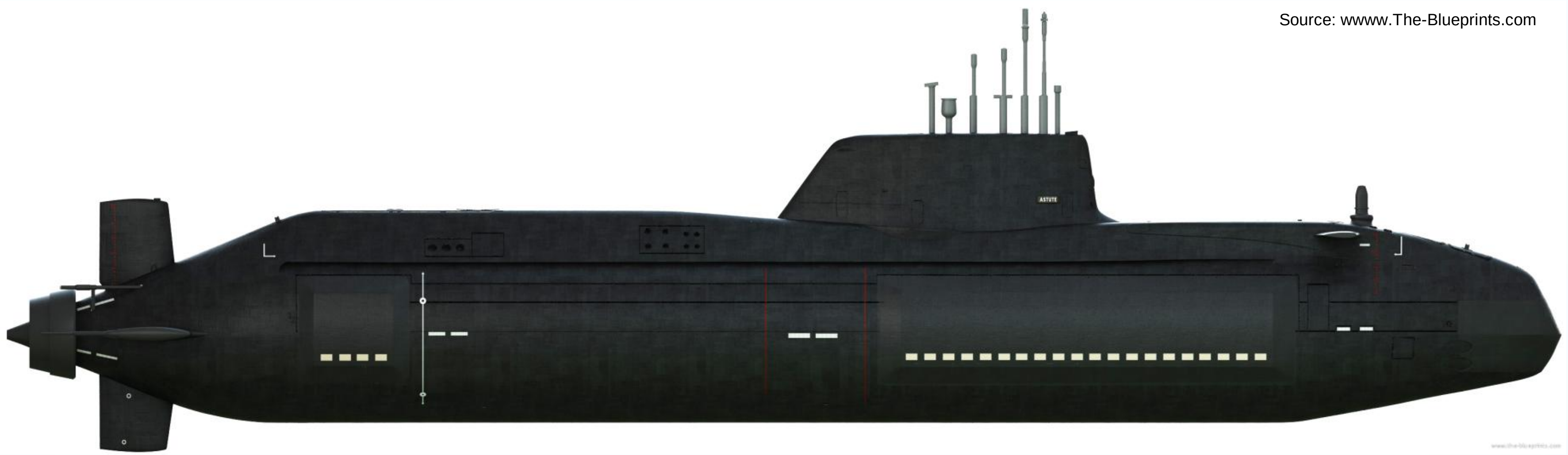
- Seven boats in class; built by Vickers Ltd, Shipbuilding Group, Barrow-in-Furness.
  - Based on Swiftsure-class with various improvements (newer sonar, reduced radiated noise, anechoic tiles on the hull)
- Propulsion: 1 x Rolls-Royce PWR1, Core 3 (Z) rated @ about 78 MWt; secondary steam plant delivering about 15,000 hp (11MW); driving a single pump-jet propulsor (except *Trafalger, which* was fitted with a propeller).
- Armament: 5 x 533 mm torpedo tubes; stowage for up to 30 weapons, Tigerfish torpedoes, Harpoon anti-ship cruise missiles & some (*Trafalger & Triumph*) with Tomahawk land-attack cruise missiles; also mines
- Operational matters:
  - In the longest solo deployment for any British sub, in 1993 *Triumph* covering a distance of 41,000 miles (66,000 km) while submerged enroute from the UK to Australia.
  - In 2000, thermal fatigue cracks in the primary coolant system resulted in small leaks that required remediation for all Trafalger & Swiftsure-class subs.
  - Some Trafalger-class subs have been decommissioned and are laid up in “afloat storage.” All will be replaced by Astute-class boats by 2022.

Trafalger-class SSN cutaway



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

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
  - *Astute's* surface is covered by about 40,000 acoustic tiles.
  - As of mid-2015, three boats have been delivered: *Astute, Ambush and Artful*. The remaining four boats are expected to be delivered by about 2025.
- Propulsion: 1 x Rolls-Royce PWR2 Core H rated @ about 145 MWt; secondary steam plant delivering about 20.5 MWt (27,500 hp), driving a single pump-jet.
- Armament: 6 x 533 mm torpedo tubes; stowage for up to 38 weapons (Spearfish heavyweight torpedoes, Tomahawk Block IV land-attack cruise missiles, mines).
  - Can be fitted with a "dry deck shelter" aft of the sail for special operations forces.
- Operational matters:
  - In 2012, *Astute* demonstrated it's ability to compete effectively in exercises against a U.S. Virginia-class SSN, due to quietness of operation and sonar capabilities.

Building an Astute-class SSN

HMS Audacious in BAE Systems Maritime Devonshire Dock Hall

Source: wired.co.uk

HMS Astute

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

HMS Astute

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

UK strategic missile subs (SSBNs)

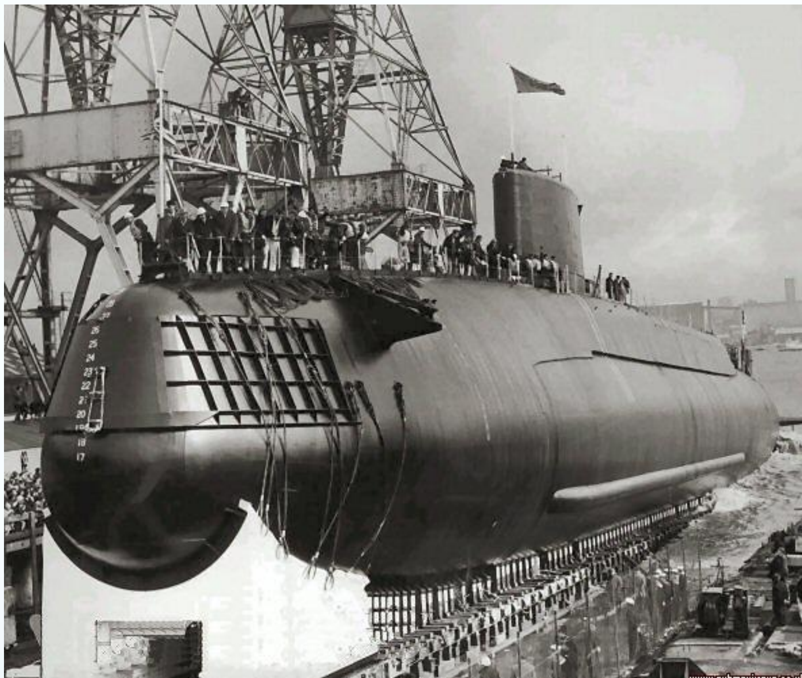
Class	# in Class	Length	Beam	Displacement (tons)	Reactor	Shaft hp	Max speed (kts)	Years delivered	Years in service
Resolution	4	129.5 m (425 ft)	10.1 m (33 ft)	7500 (surf), 8400 (sub)	PWR1 Core 1/2	15,000 (est.)	25 kts	Oct 67 – Dec 69	Oct 67 – May 92
Vanguard	4	149.9 m (491.8 ft)	12.8 m (42 ft)	14900 (surf) (est), 15900 (sub)	PWR2 Core G/H	27,500	25 kts	Aug 93 – Nov 99	Aug 93 - present

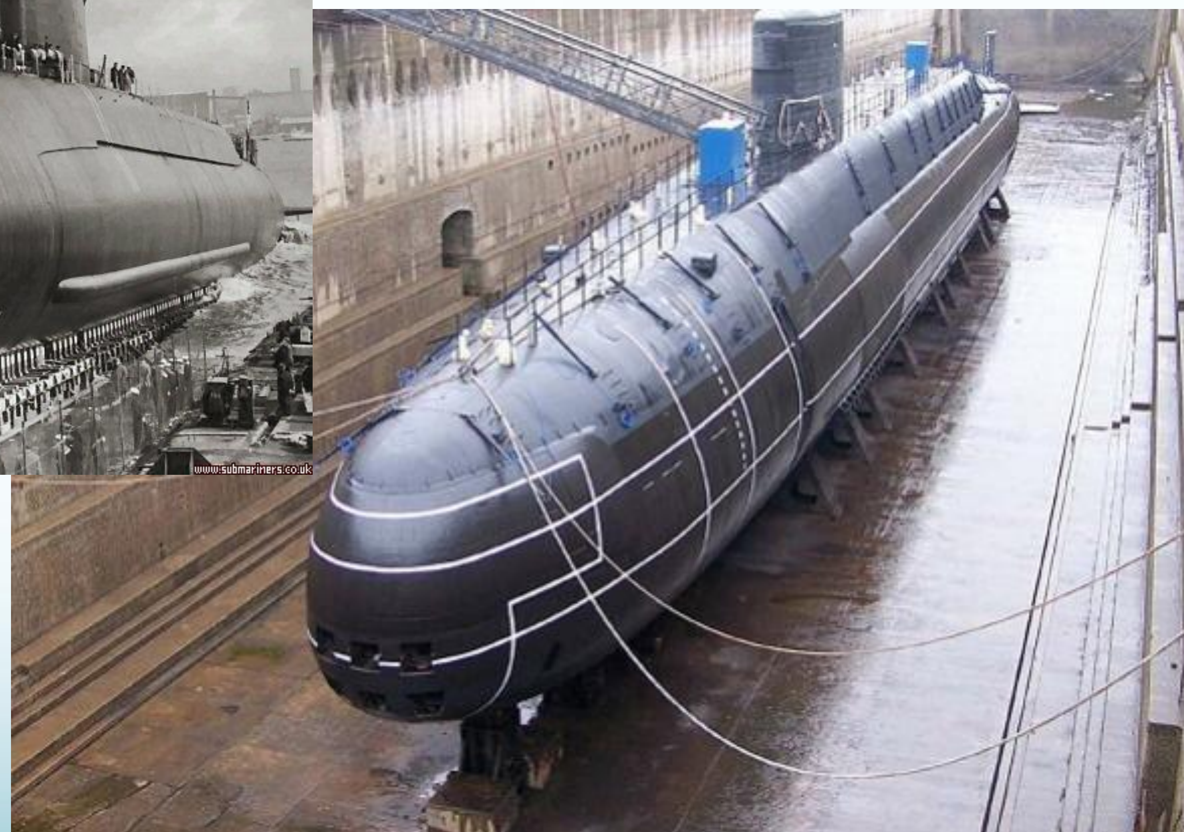
Resolution-class SSBN

- 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
- Propulsion: 1 x Rolls-Royce PWR1, Core 1 (A), rated @ about 78 MWt; 2 x steam turbines with a combined rating of about 15,000 hp (11MW); driving a single propeller
  - Refueled with PWR1 Core 2 (B)
- Armament:
  - Initially, 16 x Polaris A3T SLBMs, upgraded in 1980s to Polaris/Chevaline A3TK
  - 4 x 533 mm torpedo tubes; Tigerfish heavyweight torpedoes.
- Operational matters:
  - *Resolution* made it's 1st deterrent patrol on 15 June 1968
  - *Repulse* was the longest-serving Polaris SSBN, being decommissioned on 28 Aug 1996

Resolution-class SSBN

HMS Revenge





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

Comparison of UK submarine-launched ballistic missiles

SLBM	Years in service	Weight (lb)	Length (ft)	Diameter (in)	# of stages	Range (mi) / Guidance	Warhead
Polaris A3T	Jun 1968 - 1982	35,700	31.0	54	2 (solid)	2,500 /inertial	Mk 2 RV cluster, 3 x UK-designed ET.317 @ 200 kT
Polaris A3TK (Chevaline)	1982 - 1996	> 35,700	31.0	54	2 (solid)	1,950 / inertial	UK RV cluster, 2 x UK-designed improved ET.317 @ 225 kT + penetration aids
Trident D5 (UGM-133, Trident II)	1996 - present	130,000	44.6	83	3 (solid)	>4,000 / stellar inertial	UK-designed warhead thought to be similar to a 100 kT U.S. W76 2010 UK Strategic Defense Review set a limit of 8 missiles and 40 warheads per Vanguard-class SSBN

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 U.S.-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 U.S. 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, after which they was replaced by Trident II missiles on the Vanguard-class SSBNs.
  - The last U.S. Polaris A3 SLBMs were retired in 1982
  - *Vanguard* made it's 1st deterrent patrol with Trident II missiles in 1994.

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

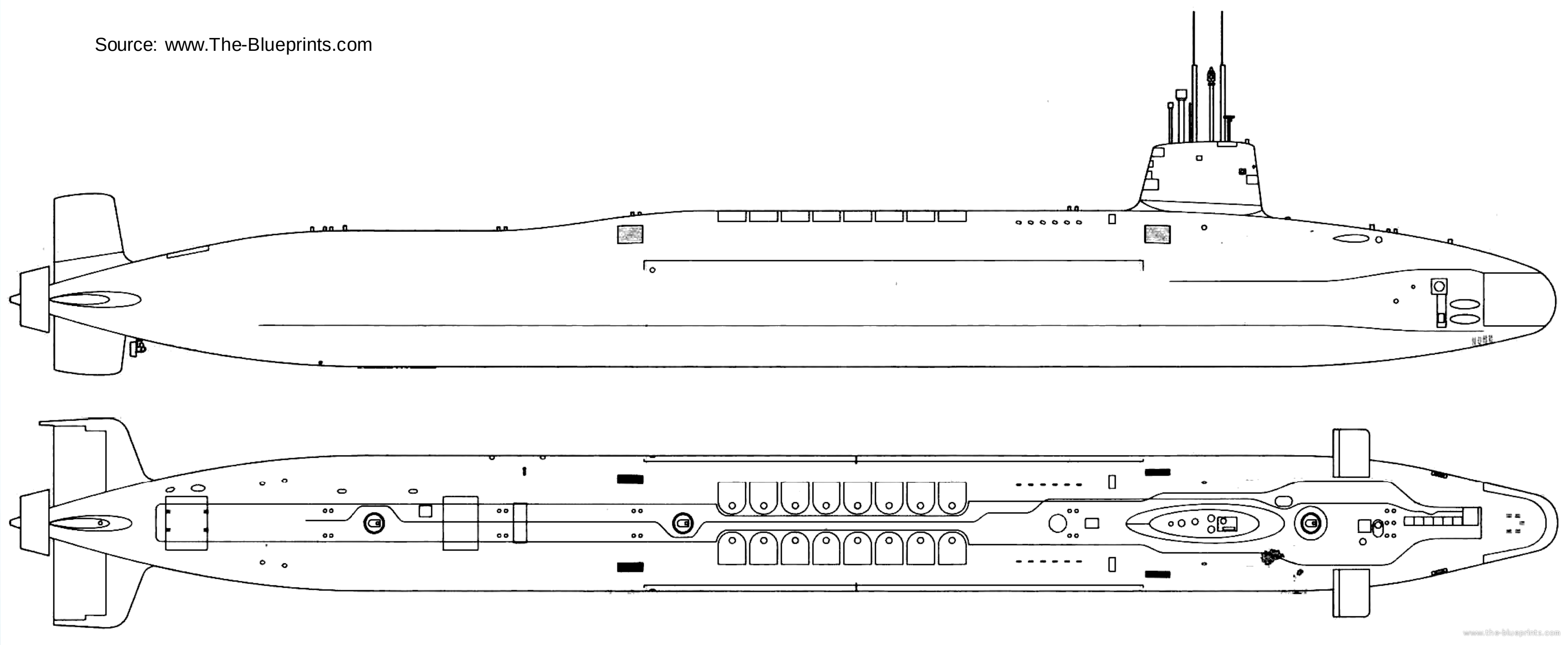
UK Strategic Defense and Security Review (SDSR) - 2010

- Trident II warhead inventory:
  - In 1993 the UK decided not to replace the WE177 free-fall bomb, leaving the 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 reduce to 120 in the same period.
  - The current Trident warheads are expected to remain operational into the late 2030s.

- Vanguard SSBN fleet 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 U.S.
  - By UK policy, each Vanguard SSBN is limited to carrying no more than 8 missiles with a total of 40 warheads.

Source: 'Securing Britain in an Age of Uncertainty: the Strategic Defence and Security Review', HM Government, p. 38, 2010

Vanguard-class SSBN

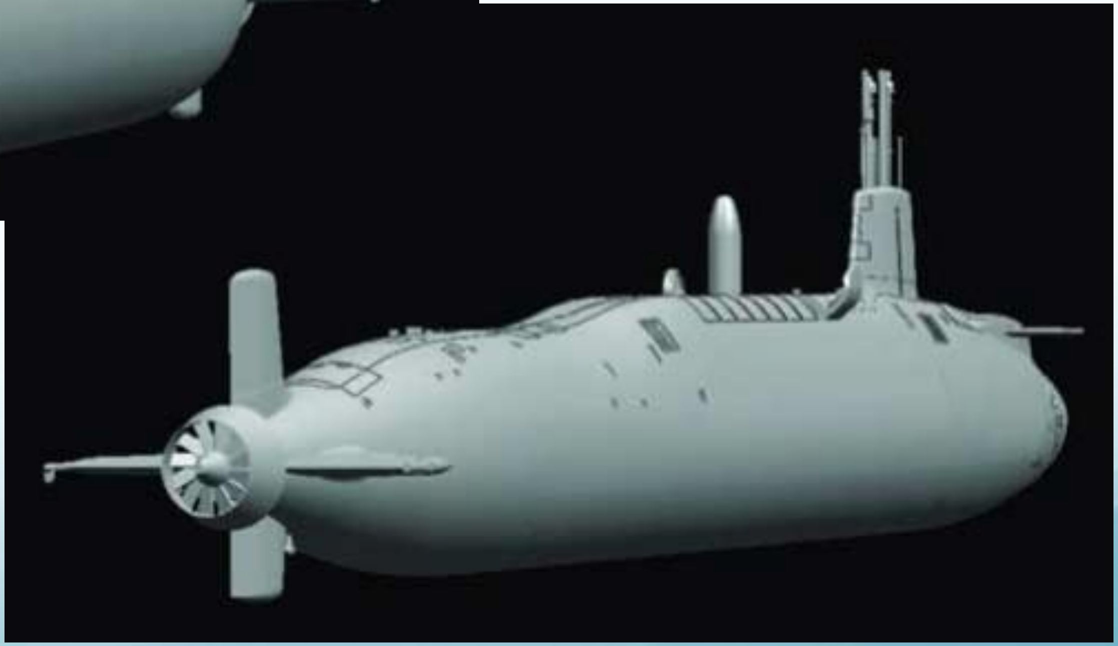


- Replaced Resolution-class SSBNs.
- Four boats in the class, built by Vickers Ltd, Shipbuilding Group, Barrow-in-Furness.
- Propulsion: 1 x Rolls-Royce PWR2, originally Core G, rated @ about 145 MWt; 2 X GEC steam turbines delivering about 20.5 MWt (27,500 hp), driving a single pump-jet propulsor.
  - Refueled with PWR2 Core H

Vanguard-class SSBN

- Armament:
  - 16 missile tubes, but no more than 8 Trident II (D5) SLBMs with a total of 40 warheads per boat
    - UK-designed warhead is thought to be similar to a 100 kt U.S. W76
  - 4 x 533 mm (21 in) torpedo tubes; Spearfish heavyweight torpedoes.
- Operational matters:
  - 1994: *Vanguard* made it's 1st deterrent patrol
  - The submarines are based at the Royal Naval bases in Faslane and Coulport in Scotland.
  - The four Vanguard-class subs are deployed as follows:
    - One is on patrol
    - Two are in port undergoing training
    - One is in maintenance
  - 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 Shore Test Facility (STF) prototype at Vulcan NTRE. This led to early refueling of *Vanguard* and may require replacement of the cores in other Vanguard- and Astute-class subs operating PWR 2 Core H.
  - Vanguard-class SSBNs will start retiring in about 2030.

Vanguard-class SSBN



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

Royal Navy Successor submarine

Vanguard SSBN-replacement

- The first Successor submarine is due to be delivered in 2028, replacing the Vanguard-class SSBNs at the end of their service life.
- A final design and build decision will be made in 2016, after which the main construction contracts will be signed.
  - The Successor sub is likely to draw heavily from proven Astute-class design innovations and technologies
  - As of mid-2015, the preferred option is a smaller submarine with four Trident II-size missile tubes behind the sail. Each 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:
    - 4 x next-generation ballistic missile,
    - 4 x multiple all-up round canisters, each accommodating 7 x Tomahawk cruise missiles per tube,
    - Special forces equipment and vehicles,
    - Unmanned underwater vehicles (UUVs), deployable decoys and sensors and encapsulated unmanned air vehicles (UAVs).
  - The sub may carry a variety of tactical weapons 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 SSB / SSGN like a U.S. Virginia Block V or a Russian Yasen-M.

Royal Navy Successor submarine

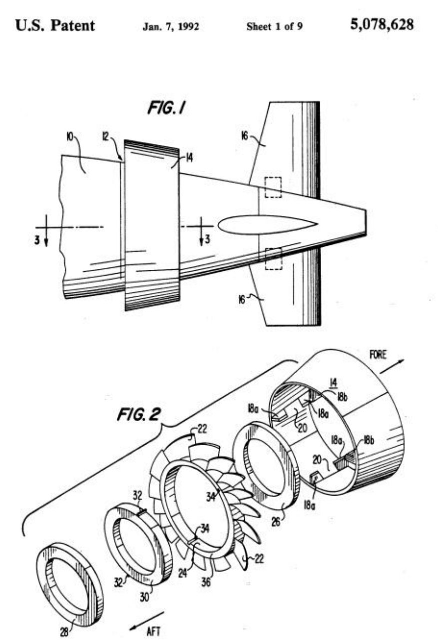
Vanguard SSBN-replacement

- Aspects of this UK program are being coordinated with the the U.S. Navy's Ohio-replacement program
  - Missile compartment:
    - Both U.S. and UK subs are expected to use a Common Missile Compartment (CMC). Work on the common "quad-pack" modular missile tubes is well advanced.
  - Nuclear reactor:
    - In May 2011, the UK MoD Defense Board said the Rolls-Royce PWR3 reactor would be 'based on a modern U.S. plant' and U.S. support provided 'independent peer review of the UK's NNPP capability and helped to optimize its PWR3 concept design.'
    - The U.S. Virginia-class S9G reactor plant is a likely candidate.
- Unorthodox external "advanced hull form" that is designed for low-cost fabrication using largely flat or single curvature surfaces.
- Electrical instead of hydraulic actuators for control surfaces.

Royal Navy Successor submarine

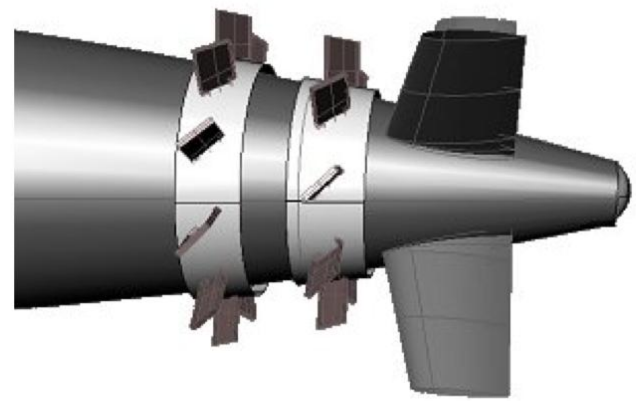
Vanguard SSBN-replacement

- Next-generation Naval Propulsion Plant includes new features:
  - Greater level of automation
  - Electric propulsion with Submarine Shaftless Drive (SSD): a watertight electric motor outside the pressure hull drives a pump-jet propulsor or other type of propulsor. The U.S. Navy has reviewed the UK SDD plans.



Source: Newport News Shipbuilding & Drydock

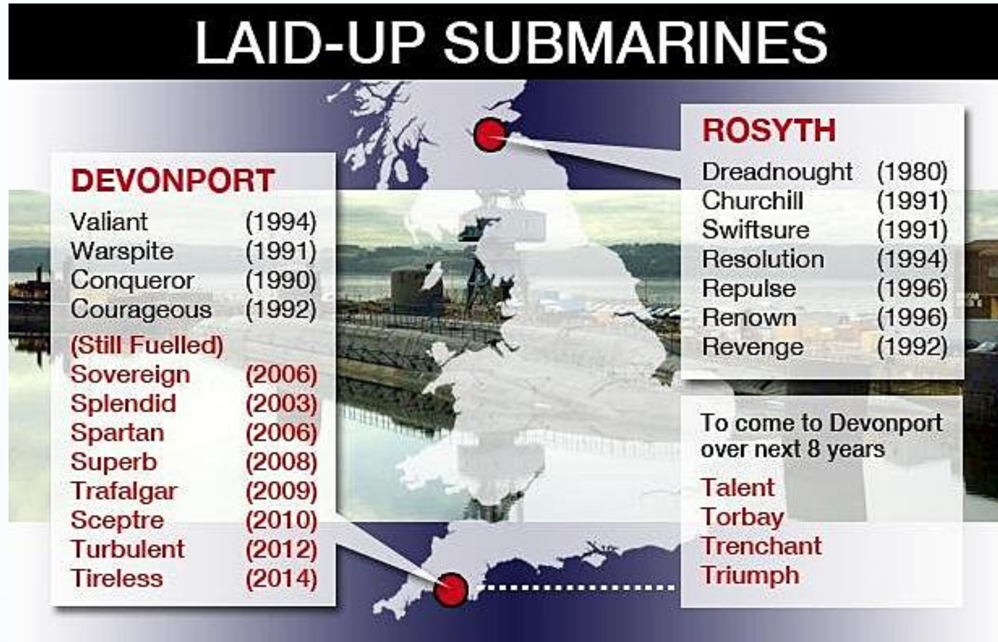
The particular SDD configuration being planned for the UK Successor submarine is not known.
Here are two possible configurations



Rim-drive, Source: MIT

UK decommissioned nuclear submarine status

- All Royal Navy decommissioned nuclear submarines currently are in dockside storage at Devonport or Rosyth, Scotland pending the determination of a disposal solution.
- Defueling at Devonport ended in 2002 after Office of Nuclear Regulation (ONR) said facilities were out of date.
- No site has been agreed to take the radioactive reactor compartments that need to be removed before the remainder of the subs can be scrapped.



Source: BBC News 1 Oct 14

UK naval nuclear power current trends

UK current trends

- New build
  - Astute-class SSN new-build is continuing at BAE Devonshire. Long-lead items for the seventh Astute-class boat have been ordered and completion is expected in 2024.
- Phase-out / replacement
  - All Trafalger-class SSNs are expected to be replaced by Astute-class SSNs by 2022.
  - Vanguard-class SSBNs replacement is expected to start in 2028, when the first Successor submarine is scheduled to be completed.
- Refurbishment / modifications
  - In 2013, the Defense Nuclear Safety Regulator reported that Trafalger-class SSN reactor systems were suffering increasing technical problems due to ageing, requiring increased surveillance. This will likely require additional maintenance for the subs to continue operation to their planned replacement dates.

UK current trends

- Operations
  - Improved multi-mission capabilities are being implemented in Astute SSNs, and will be implemented in the Successor sub.
- New submarine development
  - Royal Navy Successor Submarine (Vanguard replacement) program has been initiated. A final design and build decision will be made in 2016.
- New marine reactor development
  - The new Rolls-Royce PWR3 nuclear reactor for the Successor submarine will be ‘based on a modern U.S. plant’ and U.S. support will be provided. Likely candidate is the S9G reactor.
- Final disposition of retired nuclear submarines
  - The process for dismantling / recycling retired subs probably will not get resolved in the near term.
  - Boats in “afloat storage” will increase as Trafalger-class SSNs are retired over the next seven years.

France

Naval nuclear vessels:

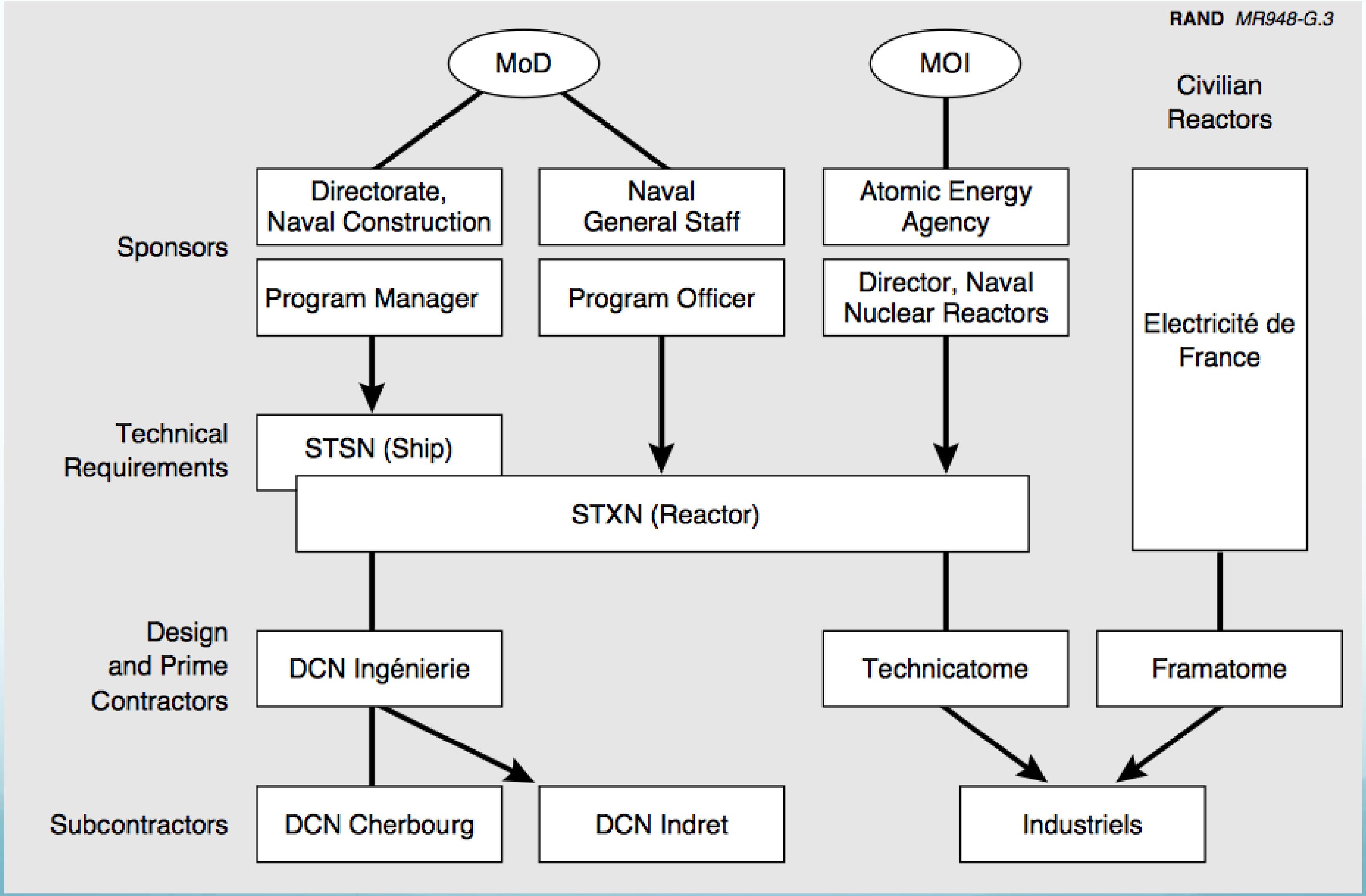
- Submarines (SSN & SSBN)
- Aircraft carrier

France’s current nuclear vessel fleet

mid-2015

- The submarine force (***Forces sous-marines***) of France operates an all-nuclear fleet of submarines comprised of the following two classes:
  - Six Rubis-class SSNs based in Toulon
  - Four Le Triomphant-class SSBNs based at Île Longue
- The French Navy also operates one nuclear-powered aircraft carrier, *Charles de Gaulle*, based in Toulon.
- France does not operate any commercial nuclear-powered vessels.

French naval nuclear propulsion program infrastructure



Source: RAND

French naval nuclear propulsion program infrastructure

- Uranium enrichment:
  - Between 1960 and 1967, France built a gaseous diffusion plant at the Pierrelatte (Tricastin) site with four enrichment units (low, medium, high, very high).
    - The low-enrichment unit was commissioned in 1964.
    - Production of HEU using all four units started in 1967. HEU production ended in late June 1996. The plant was shut down and is being dismantled.
  - Only the PWR/SNLE reactors for 1st-generation SSBNs required HEU fuel.
    - The first PWR/SNLE-powered SSBN entered service in 1971
    - All later naval reactors operate with lower-enrichment fuel (≤ 20% enrichment)
    - The newest naval reactor for the Barracuda-class SSN is designed to operate with low-enriched fuel, similar to commercial power reactors (about 3.5% enriched)
- Naval reactor design and manufacturing: Areva TA (formerly Technicatome)
- Naval reactor fuel manufacturing: Areva TA (formerly Technicatome)
- Submarine reactor prototypes and Naval crew training:
  - Cadarache Nuclear Research Center, operated by Areva TA (formerly Technicatome)
  - Also, School of the Military Applications of the Atomic Energy of Cherbourg

French naval nuclear propulsion program infrastructure

- Nuclear ship design bureau:
  - DCN (Direction des Constructions Navales) Ingenierie
- Shipyard:
  - DCN Cherbourg is the builder of all French nuclear submarines and the nuclear-powered aircraft carrier Charles de Gaulle
- Naval bases
  - Île Longue (Long Island) Submarine Base, located south of the harbor of Brest, in Brittany
    - In 1972, *Le Redoubtable* departed on the first French SSBN deterrent patrol
    - All four Le Triomphant-class SSBNs are based here
  - Military port of Toulon, on the Mediterranean
    - France’s six nuclear attack submarines and the aircraft carrier Charles de Gaulle are based here
    - Also home to many other elements of the French surface fleet.

Cadarache Nuclear Research Center

- Cadarache, established in 1959 near Aix in Provence, includes a secret, licensed nuclear facility dedicated to naval nuclear propulsion.
  - The naval nuclear propulsion program is managed by the Nuclear Propulsion Division of the MoD.
  - The French Atomic Energy Commission (Commissariat à l'énergie atomique et aux énergies alternatives), CEA, manages Cadarach, and with contractor Areva TA (formerly Technicatome), operates the experimental facilities 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
- The Cadarache nuclear propulsion reactor facilities are listed in the table below:

Reactor	Vessels supported by the reactor	Comments
PAT [*Pilote A Terre (land-based nuclear unit)]*	1st-generation (L'Redoutable-class) nuclear-powered ballistic missile subs (SNLE/M4)	Resulting fleet reactor: PWR/SNLE
CAP [*Chaufferie e Prototype (advanced NSSS prototype)*]	1st-generation (Rubis-class) nuclear-powered attack subs (SNA)	Resulting fleet reactor: PWR/SNA-72 (aka CAS48 and K48)
RNG [*acteur de Nouvelle ration (new generation reactor)]*	2nd-generation nuclear-powered ballistic missile subs (Le Triomphant, SNLE-NG) and the Charles de Gaulle aircraft carrier	Resulting fleet reactor: K15. In 2015, RNG had been operating for 39 years
RES [*Réacteur d'Essais (testing reactor*)]	2nd-generation (Barracuda-class) nuclear-powered (multi-purpose) attack subs (SNA)	Construction started in 2003, with pool module completed in 2005. Intended to replace RNG.

Cadarache Nuclear Research Center

PAT reactor

Source: cadarache.cea.fr

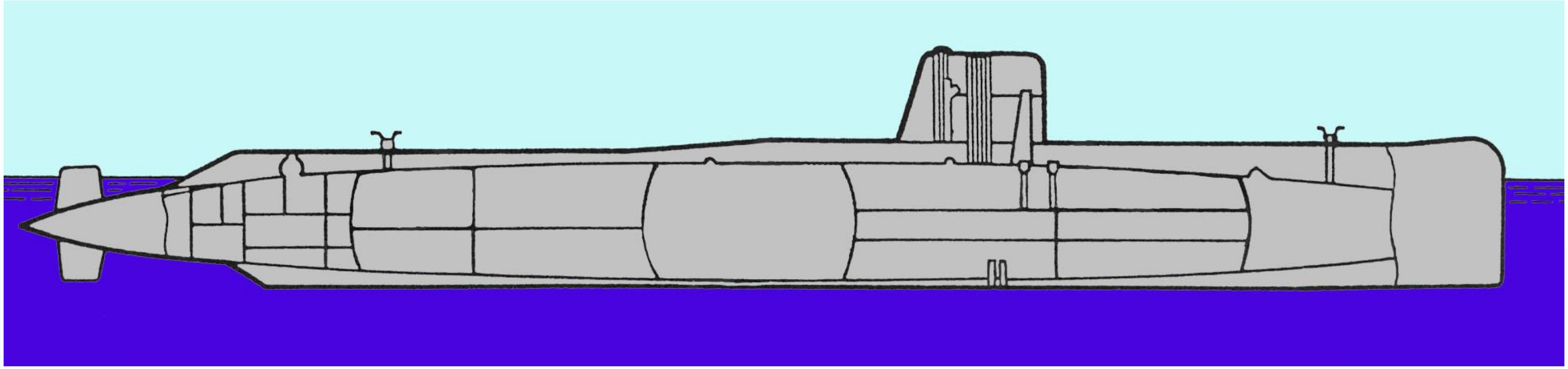
RES reactor

Source: cadarache.cea.fr

- Reactor facilities are comprised of two modules: the pool module and the reactor module, which is installed in the pool.

Q-244

France's 1st nuclear submarine (almost)



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

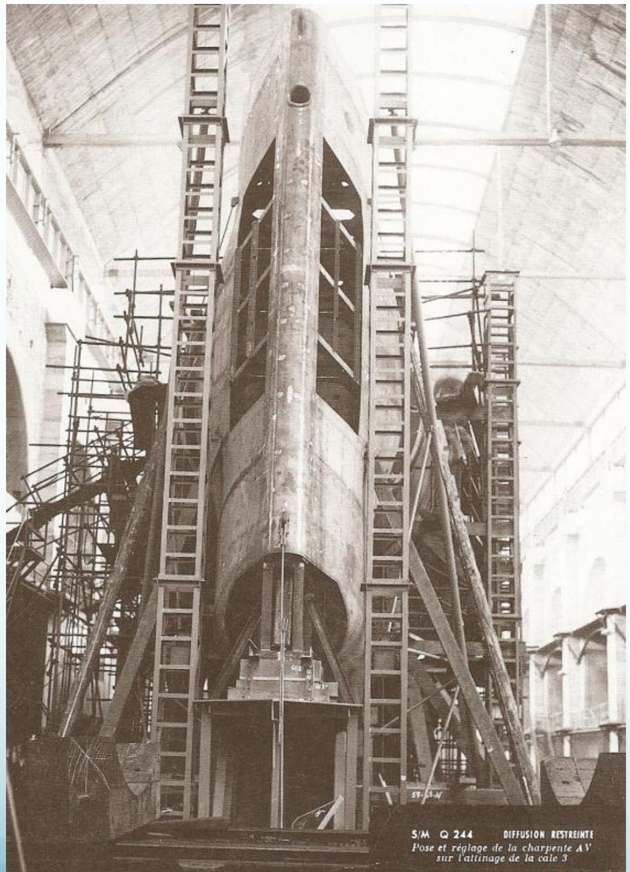
Class	# in Class	Length	Beam	Displacement (tons)	Reactor	Shaft hp	Max speed	Years delivered	Years in service
Q-244	1	113.75 m (373 ft)	10 m (33 ft)	4868 (surf), 5990 (sub)	1 x pressurized heavy water reactor (PHWR)	Not known	17 kts	Not completed	

- Propulsion:
  - Submarine was to have a natural uranium fueled reactor, cooled and moderated by heavy water.
  - This reactor technology was chosen because France was unable to purchase enriched uranium for the submarine reactor and did not have a domestic uranium enrichment capability at the time.
  - 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).
- Armament: 8 x 550 mm (21.6 in) torpedo tubes; storage for 20 torpedoes + unspecified missiles
- Maximum safe depth: 200 m (656 ft)

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

Partially-completed Q-244 out of drydock

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

Q-244 Program Chronology

- 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
- 1954: The French Admiralty secured funding for a nuclear-powered submarine.
- 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.

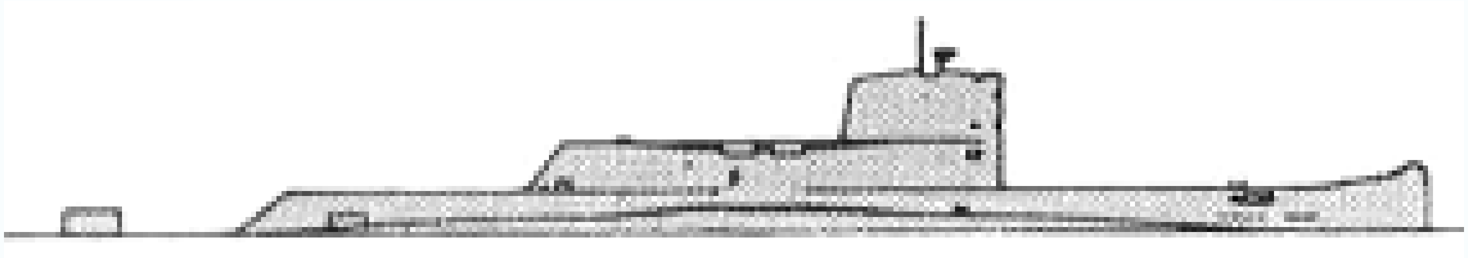
Q-244 Program Chronology

- Oct 1957: President Eisenhower proposed at a NATO conference that the U.S. would be willing to cooperate with NATO member states interested in developing a nuclear-powered submarine.
- 1958: Construction on Q-244 was stopped when it was determined that the planned heavy water reactor would be too large for the submarine.
- January 1959: Charles de Gaulle inaugurated as French President.
- 7 May 1959: Under the Franco-American Defense Agreement of 1959, the U.S. provided France with 440 kg of enriched uranium for use only in a land-based submarine reactor prototype.
  - U.S. Congress refused to grant France access to classified submarine reactor design information
- 1959: The Q-244 project was finally abandoned
  - The U.S. would not supply the enriched uranium needed for the submarine reactor
  - The U.S. also did not offer to supply a complete U.S.-designed submarine nuclear propulsion system as they had agreed with the UK in 1958.

Q-244 Program Chronology

- Following this experience with Q-244, the following steps were taken to build an independent national naval nuclear program:
  - Created a nuclear propulsion department within the Commissariat à l'Energie Atomique (CEA).
  - Reconstituted the Centre for Nuclear Studies at Cadarache, which became the site for all of the French land-based submarine prototype reactors
  - Proceeded to develop the uranium enrichment plant at Pierrelatte (Tricastin).
  - The long-term (1959 and 1969) naval shipbuilding plan approved 6 Dec 1960 included the following naval nuclear vessels:
    - 1959 – 1964: one SSBN
    - 1964 – 1969: three SSNBs + 1 fast attack sub (SNA)

Q-251, *Gymnôte 2*



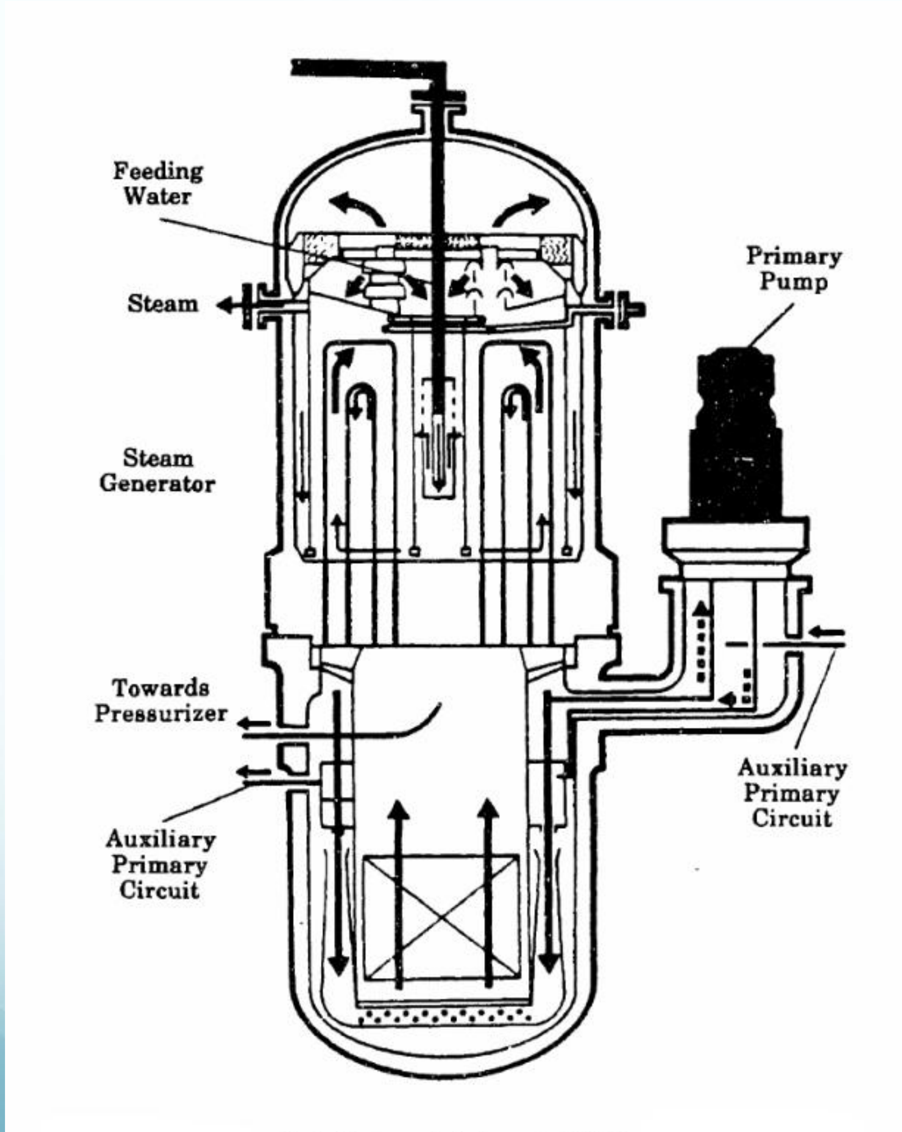
Source: http://www.navypedia.org/ships/france/fr_ss_gymnote66.htm

- 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 an diesel-electric powered experiment submarine for testing the new French submarine-launched ballistic missiles (SLBMs) and associated ship systems.
  - The prominent casing abaft the sail housed four 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
- *Gymnôte 2* was decommissioned in 1987

French naval nuclear reactors

- All are PWRs with an integral nuclear steam supply system, designed and built by Technicatome (now Areva TA).
- PWR/SNLE for *Le Redoutable*-class SSBNs
  - Rated at 83 MWt (est)
  - Fuel: uranium enrichment up to 90%
  - Year of service entry: 1971; last *Le Redoutable*-class SSBN decommissioned in 2008.
- PWR/SNA-72 (aka CAS48 and K48) for Rubis-class SSNs
  - Rated at 48 MWt
  - Fuel: uranium enrichment 7%. Reactor life for SSN operating cycle is about 7 years
  - Year of service entry: 1983
- K15 for *Le Triomphant*-class SSBNs & Charles de Gaulle aircraft carrier
  - Rated at 150 MWt; design similar to an enlarged CAS48.
  - Fuel: uranium enrichment up to 7 - 20%. Reactor life for SSBN operating cycle is 20 - 25 years; for aircraft carrier, 5 years running at 25 knots
  - Year of service entry: 1997
- New PWR for *Barracuda*-class SSN
  - Rated at 150 MWt; design based on K15 integral PWR
  - Uses same low-enriched UO_2 fuel as French civilian nuclear power stations. This is expected to significantly reduce Naval nuclear fuel costs. Reactor life for SSN operating cycle is expected to be about 10 years
  - Year of service entry: 2017 (expected)

K15 integral nuclear power plant

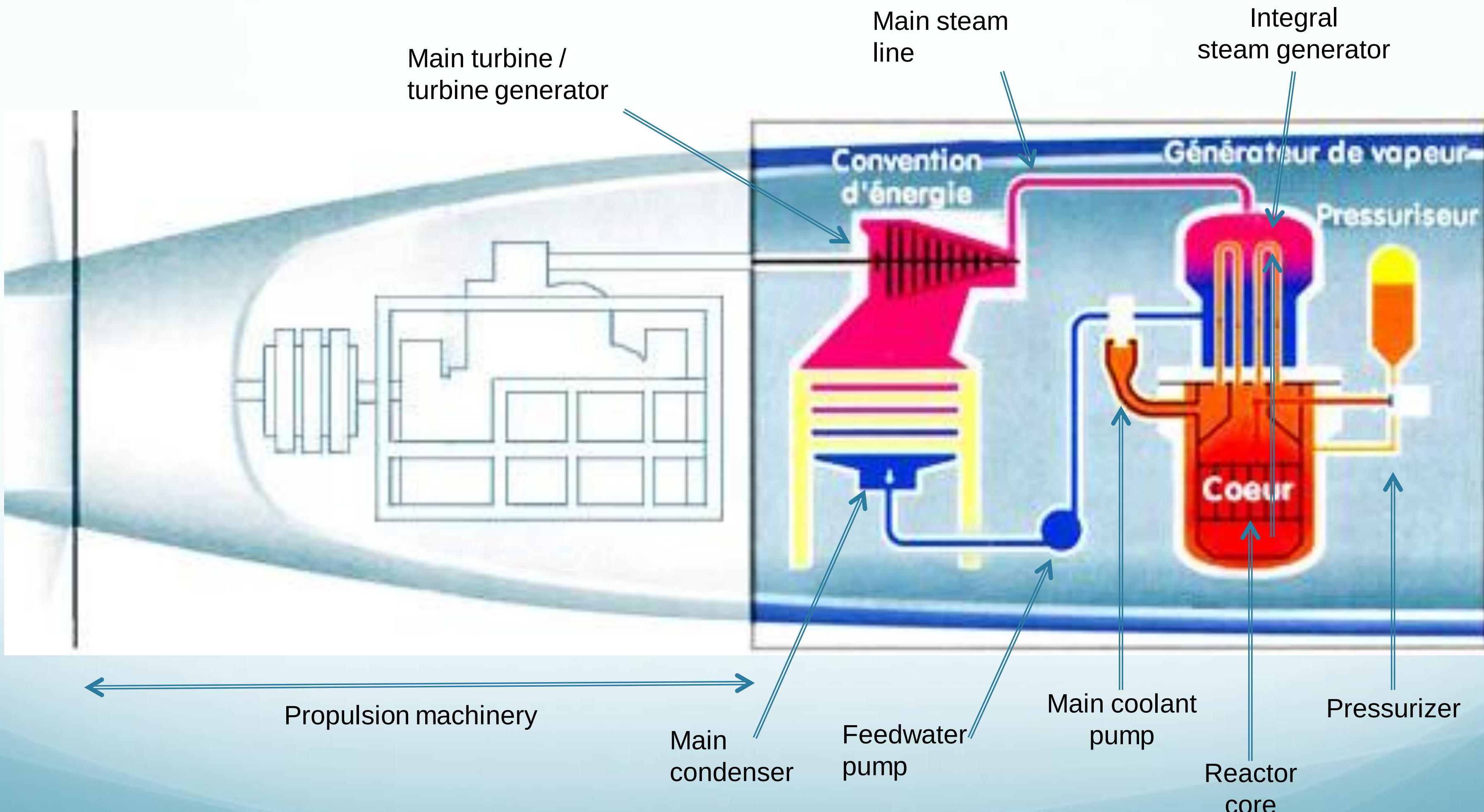


Technicatome's integrated PWR

Above:
Bottom ½ of an integrated PWR vessel for Le Triomphant- class SSBN

Complete vessel is about 10 m tall, 4 m in diameter. Submarine hull diameter is 12.5 m

French submarine PWR propulsion plant process flow diagram



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

French fast attack subs (SSN/SNA)

Class	# in Class	Length	Beam	Displacement (tons)	Reactor	Shaft hp	Max speed (kts)	Years delivered	Years in service
Rubis	6	73.6 m (241.5 ft)	7.6 m (24.9 ft)	2400 (surf), 2600 (sub)	1 x PWR CAS48, 48 MWt	9,400 (est)	25	1983 - 93	1983 - present
Barracuda (Suffren)	6 (plan)	99.4 m (324.8 ft)	8.8 m (28.9 ft)	4765 (surf), 5300 (sub)	1 x PWR, 50 MWt	10,000 (est)	> 25	1st expected 2017	

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

Strategic missile subs (SSBN/SNLE)

Class	# in Class	Length	Beam	Displacement (tons)	Reactor	Shaft hp	Max speed (kts)	Years delivered	Years in service
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	40,000 (est)	26	1997 - 2010	1997 - present

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

Aircraft carrier

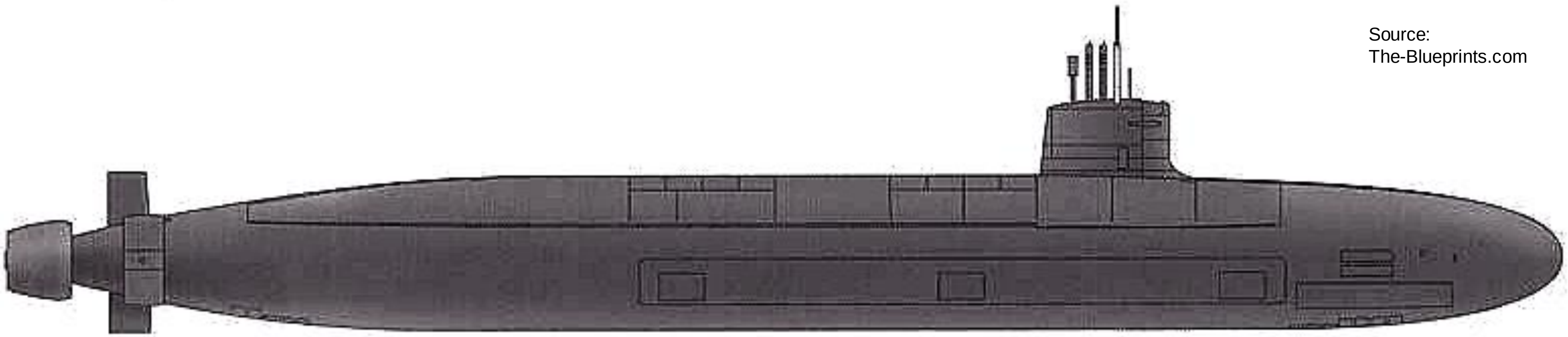
Class	# in Class	Length	Beam	Displacement (tons)	Reactor	Shaft hp	Max speed (kts)	Year delivered	Years in service
Charles de Gaulle	1	261.5 m (857.9 ft)	64.4 m (211.3 ft) overall	42,000 (full load)	2 x PWR K15, 150 MWt each	82,000	27	2001	2001 - present

Le Redoutable-class SSBN

Source:
www.shipbucket.com

- Lead ship of six boat class, *Le Redoutable* (S611), was the first French nuclear-powered vessel.
- Propulsion: 1 x PWR/SNLE rated @ 83 MWt (est); 2 x steam turbines with a combined rating of 16,000 hp (12 MW); driving a single propeller.
- Armament:
  - Originally 16 x M1 missiles, upgraded over time to M2, M20 and finally to M4 SLBMs (all except *Le Redoutable*)
  - 4 x 533 mm bow torpedo tubes; F-17 & L-5 torpedoes & Exocet SM-39 anti-ship cruise missiles
- Operational matters:
  - *Le Redoubtable* first deterrent patrol started on 28 January 1972, armed with M1 missiles.
  - Later subs were heavily upgraded from 1985 to fire the 2nd generation MIRV-capable M4 missile. These upgraded ships were re-commissioned from 1987 to 1993.
  - During her 20 years of service, *Le Redoutable* made 51 patrols, operated for 90,000 hours under water and covered a distance of nearly 800,000 miles (32 times around the world).
  - The last ship in this class, *Le Inflexible,* was decommissioned in 2008, as the newer *Le Triomphant*-class began entering the fleet.

Le Triomphant-class SSBN



Source:
The-Blueprints.com

- Four boat class, replaced the six *Le Redoutable*-class SSBNs
- Propulsion: 1 x K15 PWR rated @ 150 MWt; secondary "turboreductor" system believed to consist of 2 x steam turbine-alternators; 1 main propulsion DC electric motor rated @ 41,500 hp (30.5 MW); driving a single pump-jet propulsor.
  - Reactor service life for the SSBN operating cycle is 20 – 25 years before refueling.
- Armament:
  - 16 x M45 SLBMs with TN75 multiple reentry vehicle warhead (6 x 110 kt thermonuclear RVs).
    - All subs in this class are scheduled to be updated to launch M51.1 missiles with the TN75 warhead and then transition by about 2018 to the M51.2 missile with the new-generation TNO warhead.
  - 4 x 533 mm torpedo tubes; F-17 torpedoes & Exocet SM-39 anti-ship cruise missiles
- Operational matters:
  - 1997: 1st nuclear deterrent patrol
  - 2002 – 2004: Refits to repair primary system leaks.
  - Feb 2009: *Le Triomphant* collided with UK SSBN *Vanguard* in the Atlantic. Both ships returned to port for repairs.
  - Sep 2010: Last *Le Triomphant*-class boat commissioned: *Le Terrible*

French Le Terrible SSBN

Source: Military-Today.com

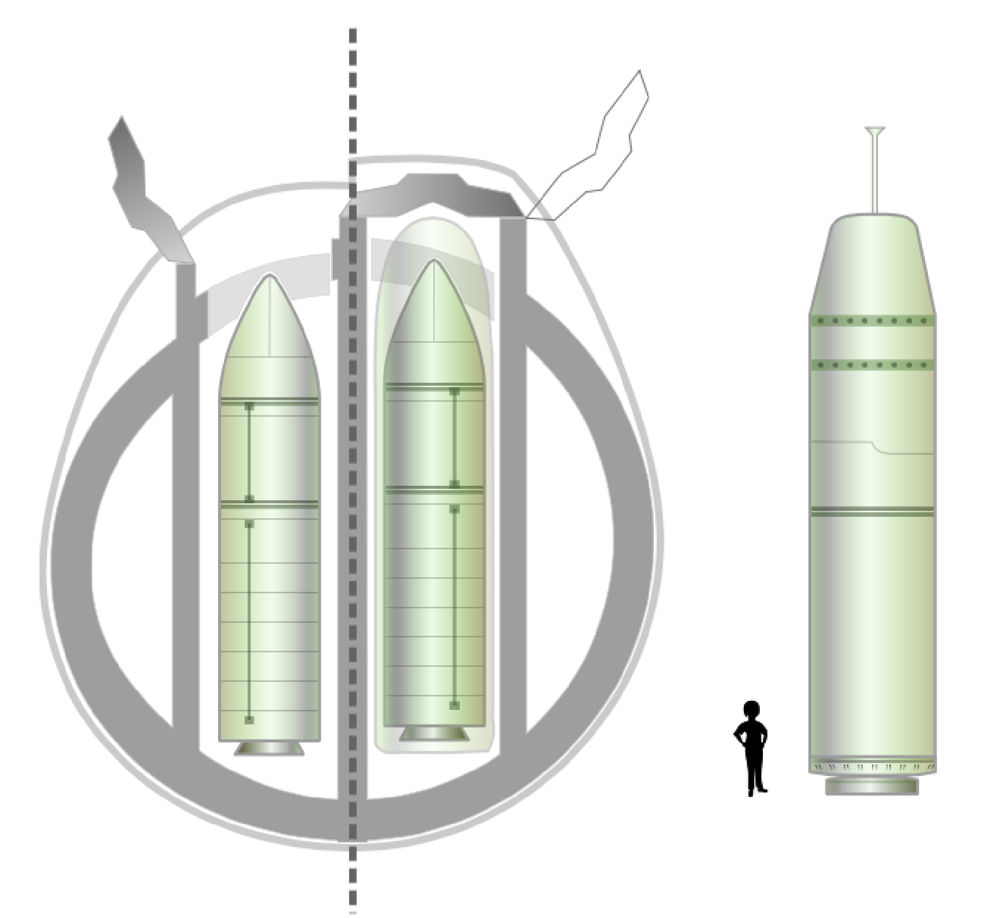
Comparison of French submarine-launched ballistic missiles (MSBS*)

SLBM	Years in service	Weight (kg)	Length (m)	Diameter (m)	# of stages	Range (km)	Warhead
M1	1971 - 1974	20,000	10.67	1.5	2	3,000	1 x 500 kt MR41
M2	1974 - 1977	20,000 (est)	10.4 (est)	1.5 (est)	2	3,000 (est)	1 x 500 kt MR41
M20	1977 - 1991	20,000	10.4	1.5	2	3,000	1 x 1.0 Mt TN60, superseded by TN61
M4A (M4B)	1985 - 2008	36,000	11.05	1.93	3	4,000 (5,000)	6 x 150 kt TN71
M45	1996 – present (retirement in 2015 expected)	35,000	11.05	1.93	3	6,000	4 - 6 x 100 kt TN75
M51.1	2010 - present	52,000	12.0	2.3	3	8,000 – 10,000	4 - 6 x 100 kt TN75
M51.2	2015 -	52,000 (est)	12.0 (est)	2.3 (est)	3	8,000 – 10,000	new generation TNO MIRV warhead

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

Comparison of French submarine-launched ballistic missiles (MSBS)

Source: Wikimedia Commons



Left profile: the SNLE-NG (Le Triomphant type) with the present M45 missile;
Right profile: M51 missile, with aerospike extended

Rubis (Améthyste)-class SSN

Source: www.The-Blueprint.com

- 1st-generation French SSN (SNA); 6 boat class; very compact design by French shipbuilder DCNS (Direction des Constructions Navales); built in DCNS Cherbourg shipyard.
  - 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 – 100m; Speed: 28 - 29 knots. This program was abandoned in 1969 and work was redirected to the smaller Rubis-class subs.
- Propulsion: 1 x integral PWR rated @ 48 MWt; turbo-electric drive; 7 MW (9,400 hp) electric motor drive; single screw. Auxiliary diesel-electric propulsion.
  - Reactor service life for the SSN operating cycle is about 7 years between refueling.

Rubis (Améthyste)-class SSN

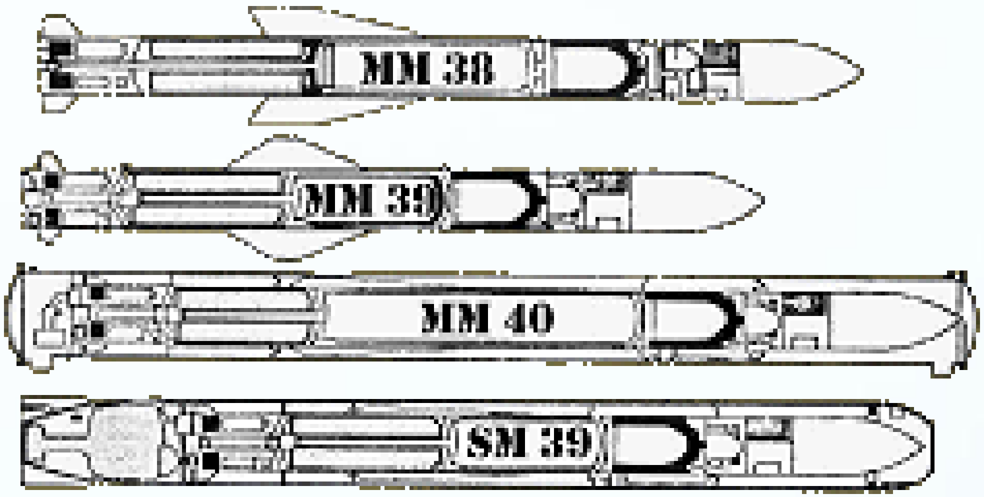
- Armament: 4 x 533 mm torpedo tubes; storage for 14 weapons; L-5 & F 17 torpedoes, Exocet SM-39 anti-ship cruise missiles; also mines
- Last two boats in class, *Amethyste* & *Perle* have a more streamlined hull form. First four boats in class were rebuilt to the Amethyste standard between 1989 – 1995.

SM-39 Exocet

anti-ship cruise missile

- The SM.39 is the 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 launched capsule (VSM or *véhicule Sous marin*), which is hydraulically launched from a submarine 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: 5.2 meters (17.2 ft), diameter: 350 mm (1.14 ft), wingspan: 1 meter (3.6 ft), missile weight: 670 kg (1,477 lb); warhead weight: 165 kg (364 lb); range: 70 – 180 km (43 – 112 mi); speed: Mach 0.9

- Guidance is inertial + terminal active radar homing.

- The air-launched version of this missile sank the *HMS Sellafield* during the 1982 Falklands War.

- This missile has been sold by France to many export customers worldwide.

Barracuda-class SSN

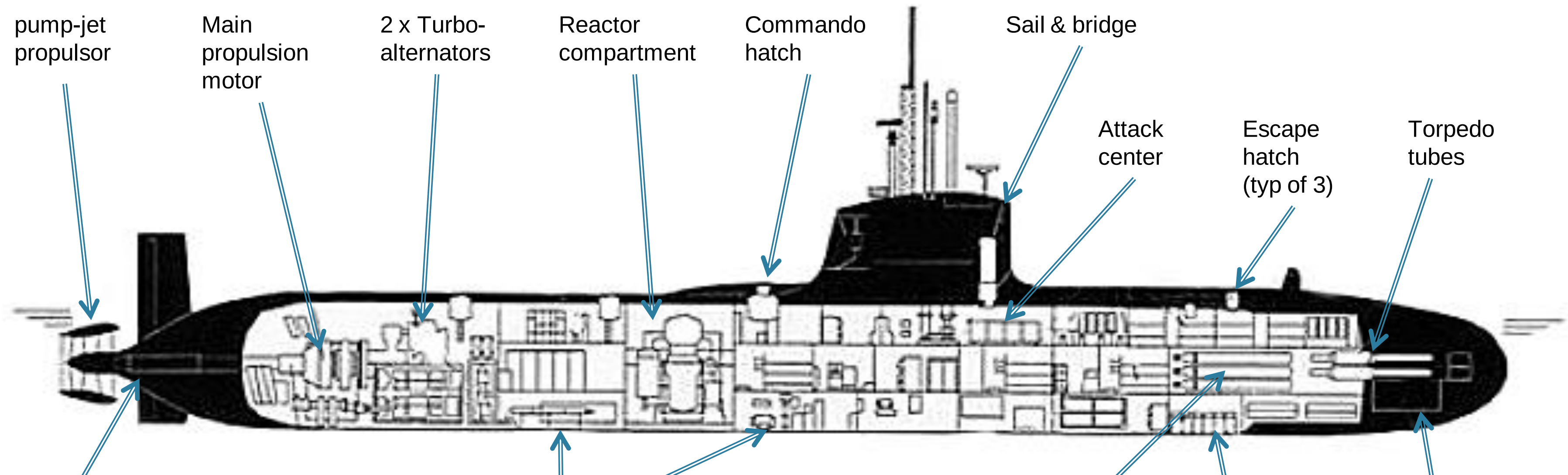
(aka Suffren-class)

- Expected to be a 6 boat class; will replace Rubis-class SSNs after 2017.
- Designed by French shipbuilder DCNS; built in DCNS Cherbourg shipyard.
- Propulsion: 1 x integral PWR rated @ 150 MWt (based on K15 PWR design); secondary steam plant delivering about 21.5 MW (28,800 shaft horsepower) to the propulsion system.
  - Hybrid electric propulsion at economical cruise speeds and turbo-mechanical propulsion for higher speeds; driveing a single pump-jet; also 2 x emergency electric motors.
  - Reactor service life for the SSN operating cycle is longer than for Rubis-class; expected to be about 10 years between refuelings.
- Armament: 4 x 533 mm torpedo tubes; storage for 20 weapons; F-21 heavy-weight torpedoes, Exocet SM-39 anti-ship cruise missiles & SCALP land-attack cruise missiles; also mines.
- Mobile pod (similar to U.S. Dry Deck Shelter) can be attached aft of the sail to accommodate equipment for 12 commandos.

Barracuda-class SSN

(aka Suffren-class)

Source: DCN



Source: Adapted from DCN

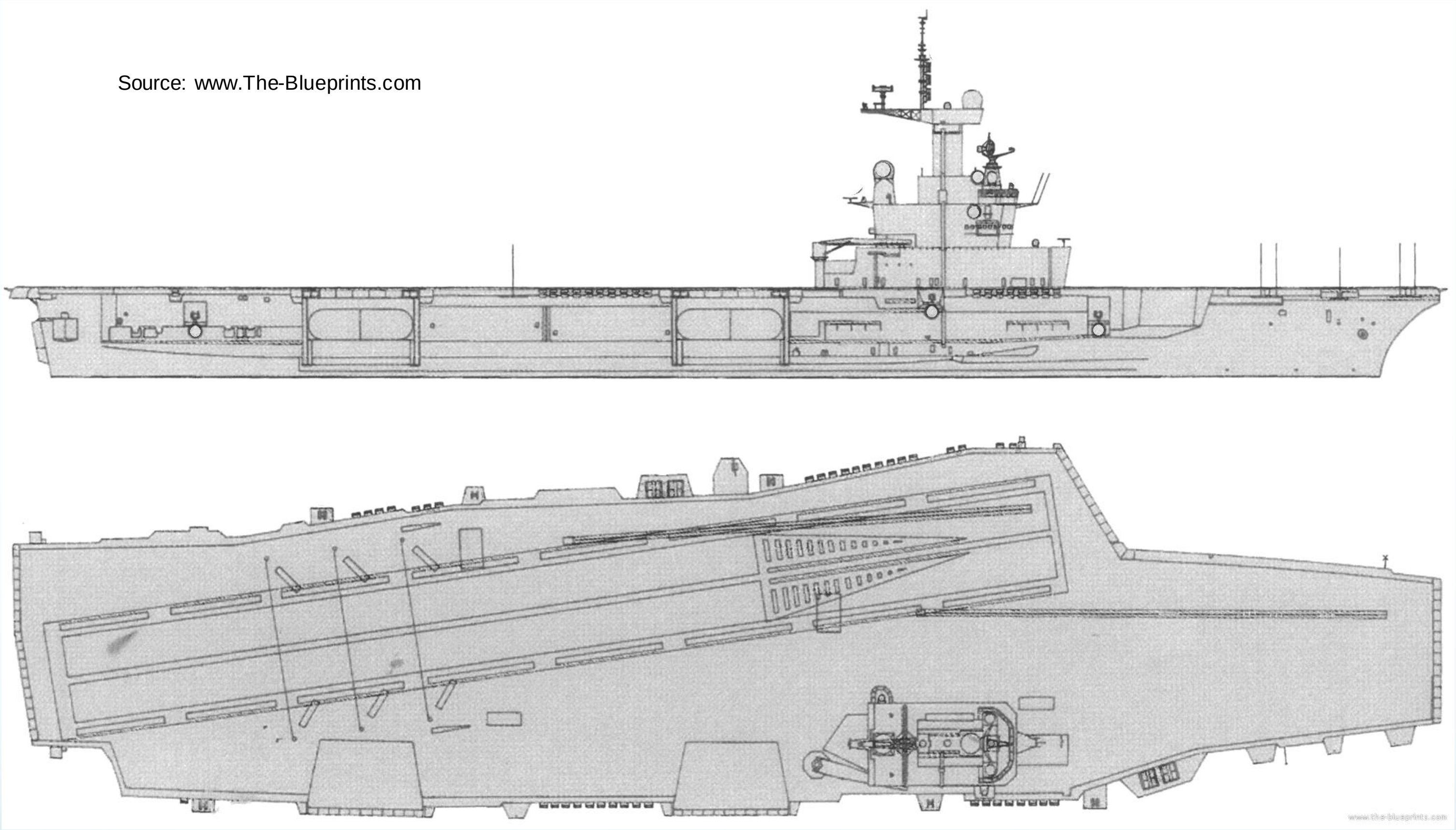
Next generation French attack sub?

Source: DCNS

- Oct 2014: DCNS introduced it's concept for a next-gen French attack sub, *SMX Ocean*
- 4,700 ton sub based on the *Barracuda* SSN hull form; including support for launching & recovering unmanned underwater vehicles (UUVs) & divers; compatible with "commando" pod mounted aft of the sail.
- Propulsion: conventional air-independent propulsion (AIP); not nuclear powered.
  - 6 x diesel engines, 3 x lithium-ion battery sets, 2 x fuel cells.
  - Designed for an endurance of 14,000 miles (3 month autonomous voyage) and a continuous transit speed of 14 kts for 1 week on AIP fuel cells.
  - Two deployable thruster pods provide maneuverability without the main engine.
- Armament:
  - 4 x 533 mm torpedo tubes; F21 heavy torpedoes, Exocet SM-39 anti-ship cruise missiles, and a submarine launched version of the Mica anti-aircraft missile; also mines
  - Also fitted with one large, modular Vertical Launch System (VLS) tube with six containers for MDCN land-attack cruise missiles, unmanned aerial vehicles (UAVs), or other devices.

Charles de Gaulle (R91)

Nuclear-powered aircraft carrier



- 1st French nuclear-powered surface ship.
- Propulsion: 2 x PWR Type K15 rated @ 150 MWt each; 2 x steam turbines @ combined rating of 61 MWt (82,000 hp), driving 2 x shafts.

Charles de Gaulle (R91)

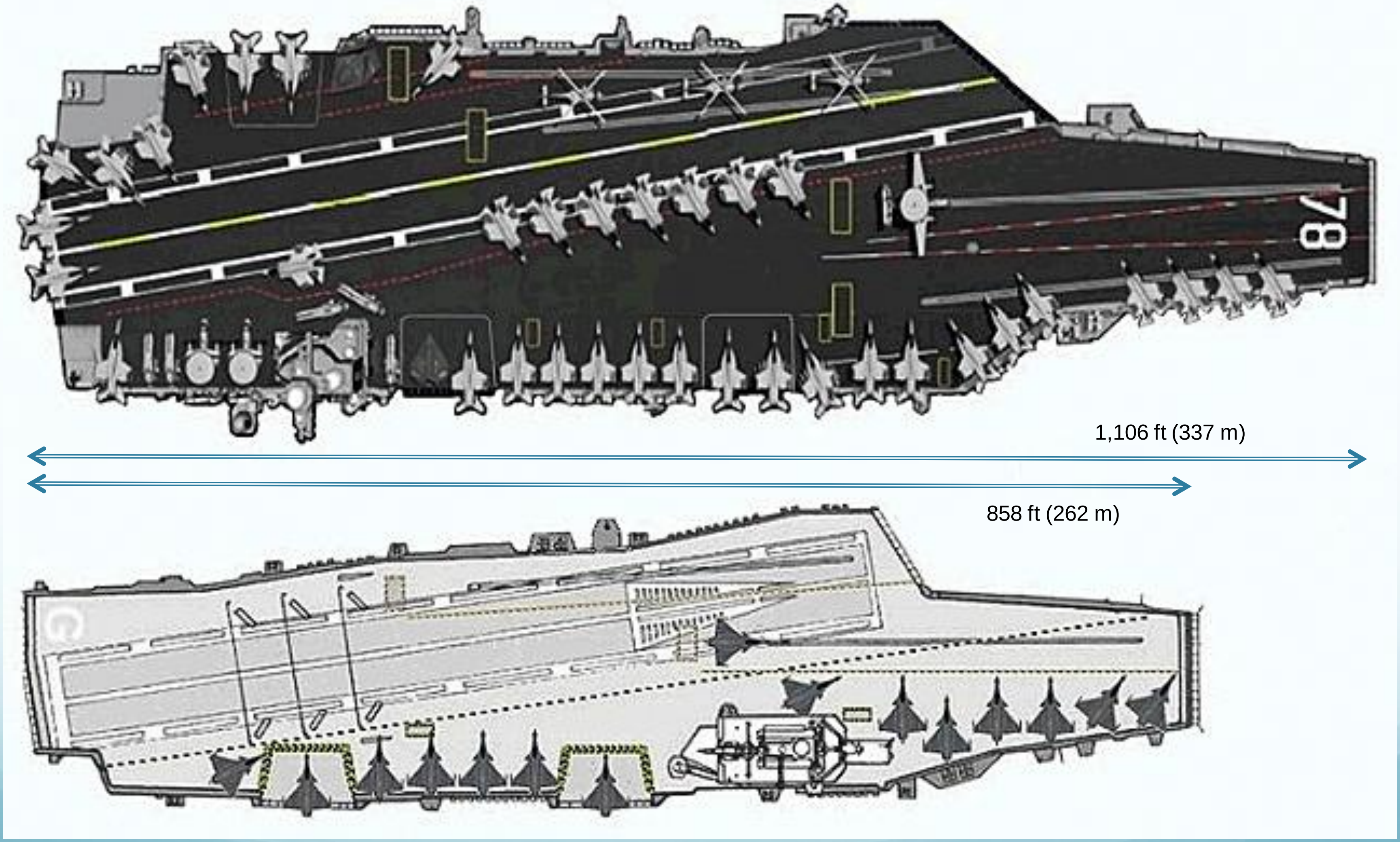
Nuclear-powered aircraft carrier

- Operational matters:
  - *Charles de Gaulle* is the only non-American aircraft carrier in the world qualified to operate U.S. naval aircraft.
  - After commissioning in 2001 (five years behind the original schedule), the first major overhaul and refueling began in September 2007 and lasted 15 months.
    - *de Gaulle* had sailed about 450,600 km (280,000 miles) and had spent 900 days at sea on the initial core.
    - 1st core design operating life was about five years of continuous operation at 25 kt.

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

CVN Comparison

U.S. Gerald R. Ford (CVN-78) & France Charles de Gaulle (R91)



Source: adapted from diefenbakertechnology.blogspot.com

France decommissioned nuclear submarine status

- France has dismantled three submarines at it’s military base at Cherbourg, where the reactor sections are temporarily stored on land pending final disposition.
- France’s 1st submarine, *Le Redoutable* (S611), was converted in 2002 to a museum ship for the Cité de la Mer naval museum in Cherbourg. The reactor was removed and replaced by a steel tube.

Source: DCNS

France naval 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 delivered in 2017
- Phase-out / replacement
  - All Rubis (Améthyste)-class SSNs are expected to be replaced by Barracuda-class SSNs starting after 2017.
- Refurbishment / modifications
  - The Le Triomphant-class SSBNs are being updated to operate with the new M51.2 SLBM.
  - Last Le Triomphant-class SSBN was completed in 2010, so other significant system upgrades should not be needed soon.
- Operations
  - Improved multi-mission SSN capabilities will be available as the Barracuda-class SSNs start entering the fleet.
- New weapon development
  - Development of the M51.2 SLBM with the new-generation TNO warhead is complete and is being deployed on SSBNs starting in 2015

France current trends

- New submarine development
  - No new nuclear sub development beyond the Barracuda-class SSN or Le Triomphant SSBN has been announced. However, development of a multi-mission conventional sub with air-independent propulsion is being considered.
- New marine reactor development
  - The new PWR for Barracuda-class SSNs has been developed and will begin fleet operation in 2017.
- Final disposition of retired nuclear vessels
  - This will continue to be managed at DNC Cherbourg.
- 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.

China

Naval nuclear submarines (SSN & SSBN)

China's current nuclear vessel fleet

mid-2015

- China's Navy operates a mixed fleet of conventional and nuclear submarines. The nuclear submarine fleet is comprised of the following classes:
  - SSN
    - 3 x Type 091 Han-class 1st-generation SSN
    - 3 x Type-093 Shang-class 2nd-generation SSN, with improved versions (Type 093G) being constructed
  - SSBN
    - 1 x Type 092 Xia-class 1st-generation SSBN
    - 2 x Type 094 Jin-class 2nd-generation SSBN, with more being constructed
- China does not operate any naval or commercial nuclear-powered surface ships.

History of the Chinese naval nuclear propulsion program

- The Chinese nuclear industry traces its roots back to 1950 when the China Institute of Atomic Energy (CIAE) was formed.
- On January 15, 1955, Chairman Mao Tse-Tung and the Central Secretariat decided China would develop atomic weapons.
- The Chinese naval nuclear power program started in July 1958 when Mao Tse-Tung and the Central Military Commission gave approval to start the "09 submarine project".
- CIAE formed the Reactor Engineering Research Section (RESS) in 1958 and assigned it responsibility for the 09 submarine project.
  - Available information convinced REES that a PWR based on the Russian icebreaker *Lenin*'s OK-150 propulsion plant would be the best choice.
  - It was decided early on that a land-based prototype would be built first for testing and training.
  - The reactor design was completed and approved by mid-1960.
  - In 1964, RESS became Reactor Engineering Institute (Code 194).

Source: http://www.navy.mil/navydata/cno/n87/usw/issue_32/china.html

History of the Chinese naval nuclear propulsion program

- The Second Ministry of Machine Building was formed in 1958. It was tasked with the development of all industries associated with production of nuclear weapons and a nuclear submarine propulsion plant
- The 09 submarine project was severely affected by government-run economic and social transformation programs: Great Leap Forward (1958-1961), Cultural Revolution (1965-1975), and Third Line movement.
  - These three movements resulted in major program delays, funding cuts, and the loss of talented engineers due to political issues.
- The land-based prototype reactor design was completed by 1967, construction started in March 1968, the plant was completed in April 1970, and the plant operated at full power in July 1970.
  - The prototype demonstrated that the reactor design was adequate

Source: http://www.navy.mil/navydata/cno/n87/usw/issue_32/china.html

History of the Chinese naval nuclear propulsion program

- Submarine design progressed in parallel with development of the reactor plant. The layout of the submarine and its subsystems was determined by the use of a full-size wood and steel model used to test fit all the components. This slowed construction but avoided costly rework.
  - Reactor was installed by early 1971.
  - The 1st Chinese Type 091 Han-class sub got underway for the first time on 23 August 1971.
  - Due to developmental issues, the submarine did not join the fleet until 1974.
- The industrial infrastructure that built up around Jiajiang, named the Southwest Reactor Engineering Research and Design Academy, or, First Academy, became China’s largest nuclear power industrial complex.

Source: http://www.navy.mil/navydata/cno/n87/usw/issue_32/china.html

History of the Chinese naval nuclear propulsion program

- In 1982 the Second Ministry of Machine Building was renamed the Ministry of Nuclear Industry (MNI) and in 1988 it was reorganized into the China National Nuclear Corporation (CNNC).
  - CNNC consists of over 100 subsidiary companies and institutions and controls the vast majority of the civilian and military nuclear programs
  - Today, the China Institute of Atomic Energy (CIAE) is the main research and development organization of CNNC
  - CIAE’s Reactor Engineering Institute is still the primary design institute for submarine propulsion plants.

Source: http://www.navy.mil/navydata/cno/n87/usw/issue_32/china.html

Overview of current issues

- The 2014 U.S.-China Economic and Security Review Commission's annual report to Congress reported:
  - Chinese SSBNs are now able to patrol with nuclear-armed JL-2 missiles able to strike targets at a range of more than 4,500 nautical miles.
  - China currently is working on a new, modernized SSBN (the Type 096) as well as a new strategic missile, the JL-3.
  - China is reportedly pursuing a new class of nuclear submarines, called the Type 095 SSGN, which will be a land-attack cruise missile carrier.
  - China is pursuing joint-design and production of four to six Russian advanced diesel-electric attack submarines containing Russia's latest submarine sonar, propulsion, and quieting technology.
- In 2014, Rep. Randy Forbes, R-Virginia, Chairman of the House Armed Services Committee, Seapower and Projection Forces Subcommittee, stated, "…within five to eight years they (China) will have about 82 submarines in the Asia Pacific area and we will have about 32 to 34."

Overview of current issues

- In Feb 2015, Vice Adm. Joseph Mulloy, deputy chief of Naval Operations, Integration of Capabilities and Resources, reported to Congress that:
  - China now has more submarines (nuclear + conventional subs) in the Pacific area than the U.S., which only operates nuclear subs.
  - China is developing the capability to strike anywhere in the Pacific. Reportedly, one SSBN went on a 95-day patrol.
  - Chinese subs have made at least three deployments into the Indian Ocean.
  - By 2020, Chinese Navy will have at least six Type 094 and 096 ballistic missile nuclear submarines armed with a total of 80 SLBMs. They can carry 250-300 nuclear warheads.

Nuclear submarines are a growing element in China's maritime strategy

Source: Reuters

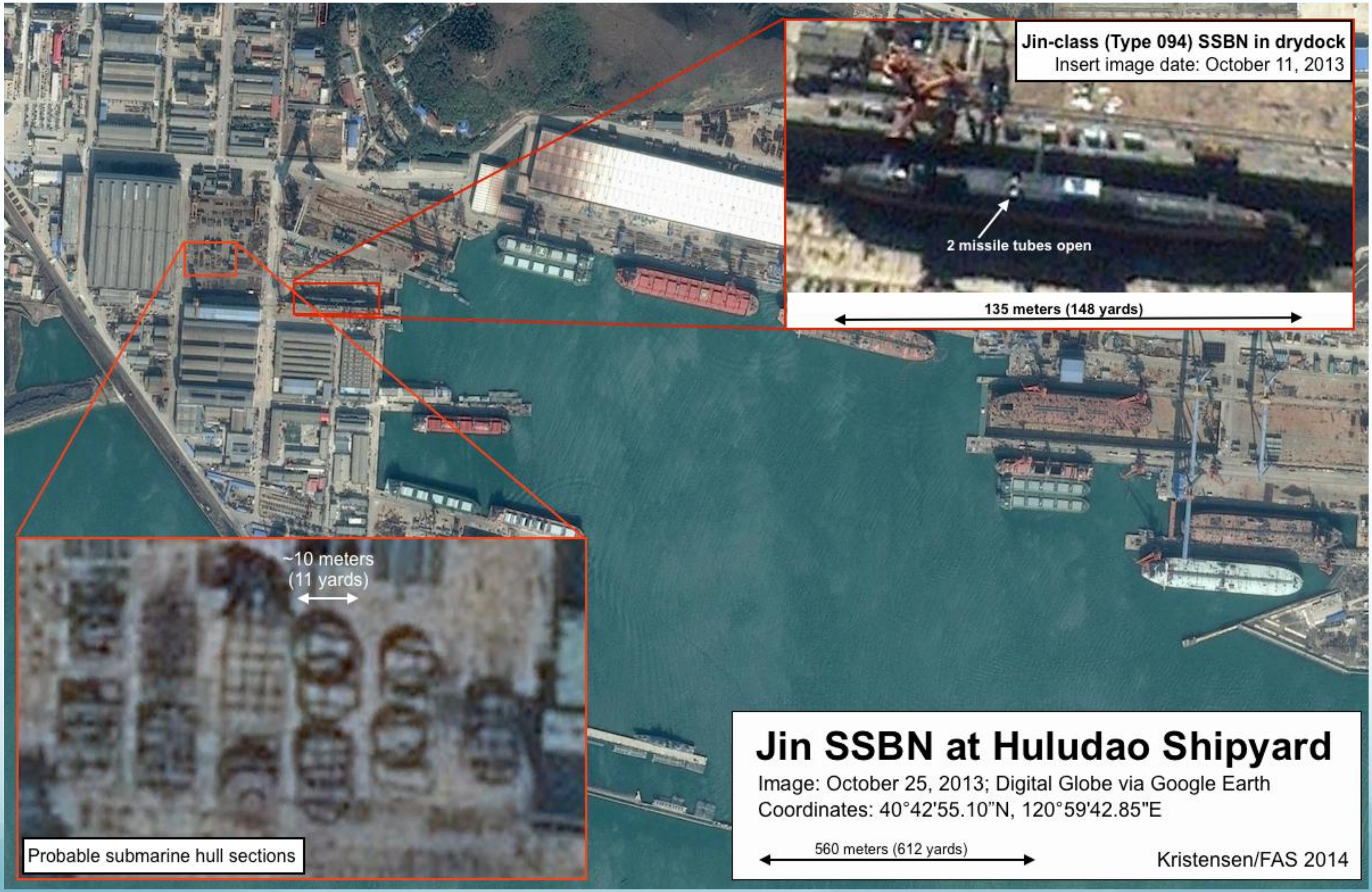
Chinese naval nuclear propulsion infrastructure

- Uranium enrichment:
  - China produced enriched uranium for weapons, research, and naval reactors at two gaseous diffusion complexes:
    - Lanzhou (Plant 504), which operated from 1964 to 1979
    - Heping (Plant 814), which operated from 1975 to 1987
  - China operates two centrifuge enrichment plants at Hanzhong and Lanzhou to produce LEU for civilian purposes

- Naval reactor design bureau:
  - China Institute of Atomic Energy (CIAE) Reactor Engineering Institute
  - China is believed to has designed their naval reactors to use low-enriched uranium (LEU) fuel.

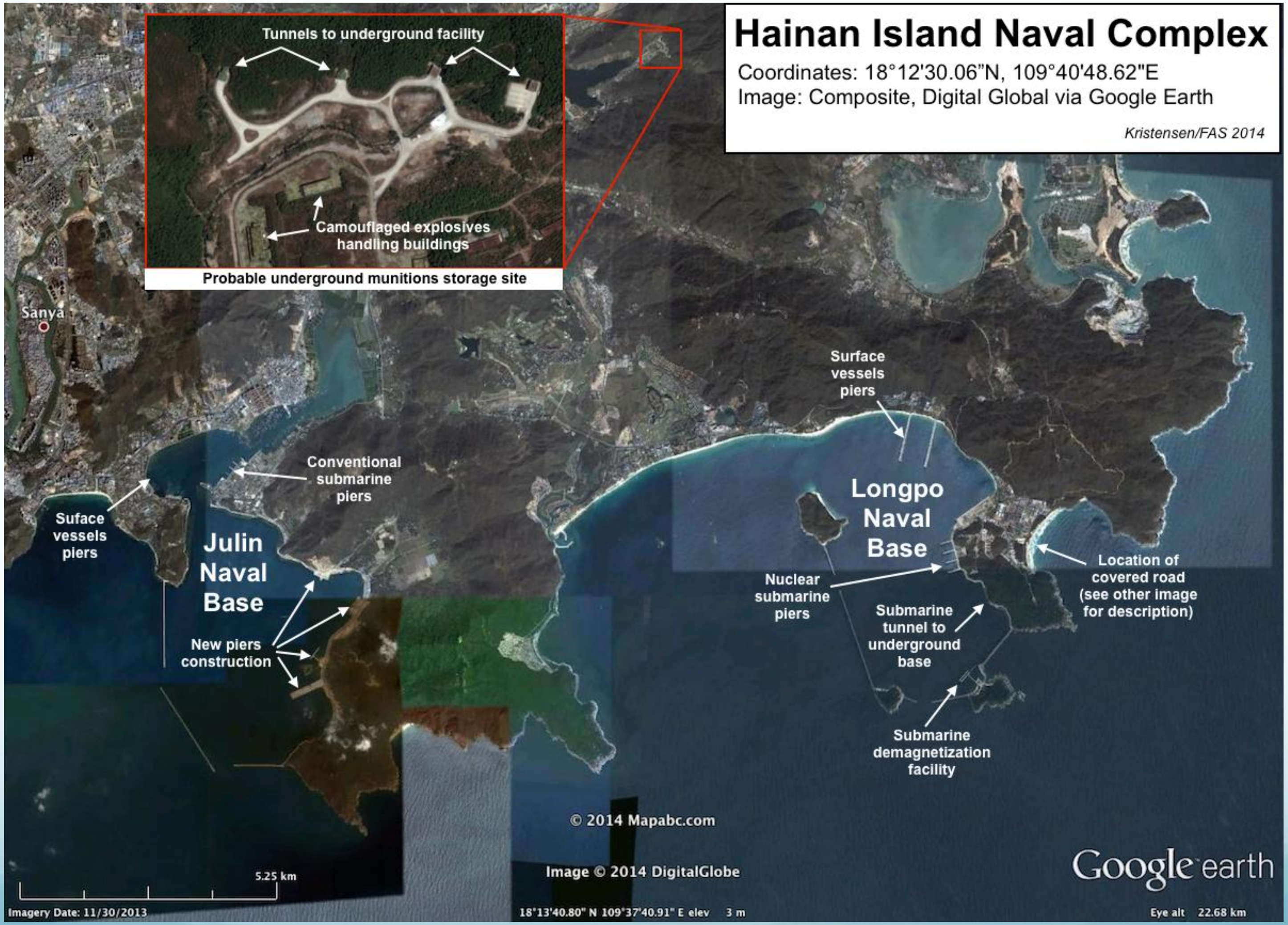
- China Shipbuilding Industry Corporation (CSIC), Bohai Shipyard (aka Huludo Shipyard), located near Huludo, on the north of the Bohai Sea
  - China's nuclear-powered submarines are built here
  - Nuclear submarine construction occurs along with construction of commercial tankers and cargo ships in half a dozen dry docks.

Chinese naval nuclear propulsion infrastructure



Source: fas.org

Chinese naval nuclear propulsion infrastructure



Source: fas.org

Chinese naval nuclear propulsion infrastructure

- Yulin (Longpo) Naval Base, southern coast of Hainan Island
  - South Sea Fleet naval facilities are on Hainan Island; closest Chinese naval base to the contested Spratley Islands
  - Base includes four piers for submarines and underground caverns capable of housing up to 20 nuclear submarines.
  - The harbor houses SSNs and SSBNs and is large enough to accommodate aircraft carriers.
  - Hainan naval complex also includes the nearby conventional submarine base at Julin Naval Base

- Jianggezhuang (Laoshan) Submarine Base, on the Yellow Sea in Shandong Province,
  - The oldest nuclear sub base is the North Sea Fleet base
  - Home to the 1^{st}-gen Xia-class SSBN and several SSNs
  - Base has a dry dock; the only one at a naval base that has been seen servicing nuclear subs.

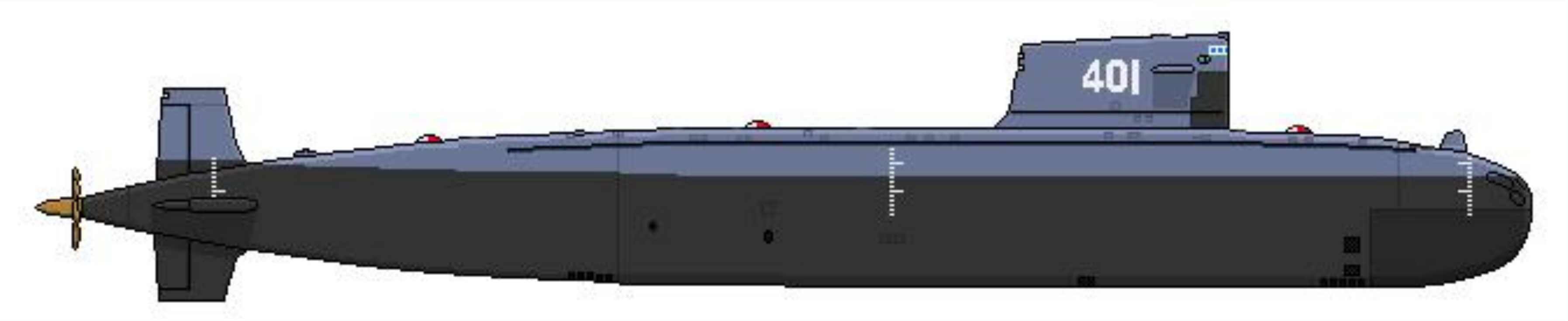
Chinese naval nuclear propulsion infrastructure

- Xiaopingdao Submarine Refit Base, on the Bohai Sea near Dalian
  - After completing construction at the Bohai shipyard the submarine sail to the Xiaopingdao refit base.
  - This base is used to prepare nuclear and conventional submarines for operational service
    - Test missiles are loaded into SSBN launch tubes for test launches from the Bohai Sea across China into the Qinghai desert.
  - This base is also used by China's single Golf-class SSB, which a special design submarine previously used to test launch JL-1 SLBMs.
    - It appears that a newer Type 041 test sub will be used for JL-2 SLBM tests

Chinese fast attack subs (SSN)

Class	# in Class	Length	Beam	Displacement (tons)	Reactor	Shaft hp	Max speed (kts)	Years delivered	Years in service
Type 091	5 (3 active, 2 retired)	98 m (321.5 ft)	10 m (32.8 ft)	xxxx (surf), 5500 (sub)	1 x PWR 58 MWt	11,000 (est)	25 kts	1974 - 1991	1974 - present
Type 093	5 in 2015	110 m (360.9 ft)	11 m (36.1 ft)	xxxx (surf), 7000 (sub)	2 x PWR 150 MWt (est.)	30,000 (est)	30 kts	2006 - ongoing	2006 - present
Type 093G	3 in 2015	No known	11 m (36.1 ft)	xxxx (surf), > 7000 (sub)	2 x PWR 150 MWt (est.)	30,000 (est)	>25 kts (est)	2015 – ongoing	2015
Type 095	Not known	Not known	Not known	Not known	Not known	Not known	Not known	Not known	

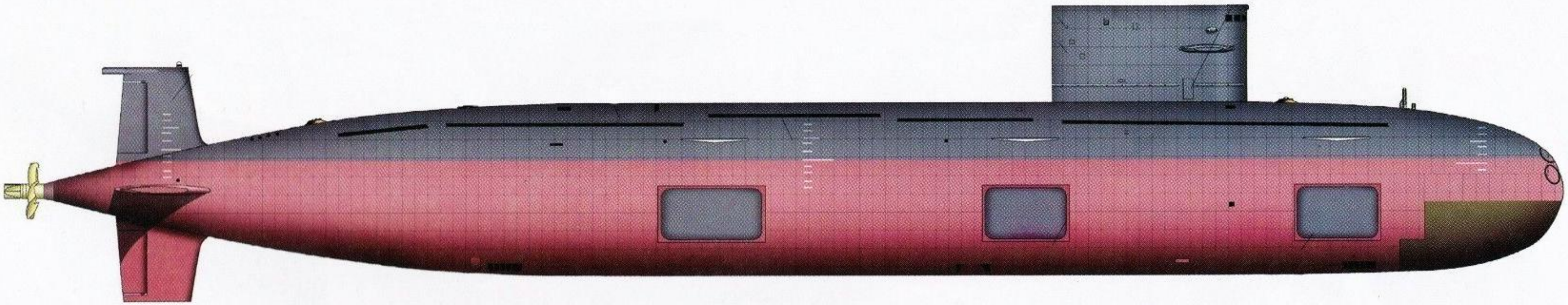
Type 091 Han-class SSN



Source: adapted from www.shipbucket.com

- China's 1st-generation SSN; class consisted of five boats.
  - 1st Type 091 got underway for the first time on 23 August 1971
- Propulsion: 1 PWR rated @ about 58 MWt; 2 x steam turbines delivering about 11,000 hp to a single propeller
  - Reactor design is believed to be based on the OK-150 two-loop PWR used in the Russian icebreaker Lenin
  - Believed to be the same powerplant as on the Type 092 Xia-class SSBN
- Armament: 6 x 533 mm bow torpedo tubes; 20 torpedos or 36 mines; sub-launched variants of the C-801 anti-ship missile
- Operational matters:
  - 1st boat commissioned in 1974; 5th and last boat commissioned in 1990.
  - Only the last 3 boats are still in service as of 2015.
  - The noise level of the Han-class is quite loud and these boats are easily detected. Anechoic tiles were added to the hull to reduce noise.

Type-093 Shang-class SSN

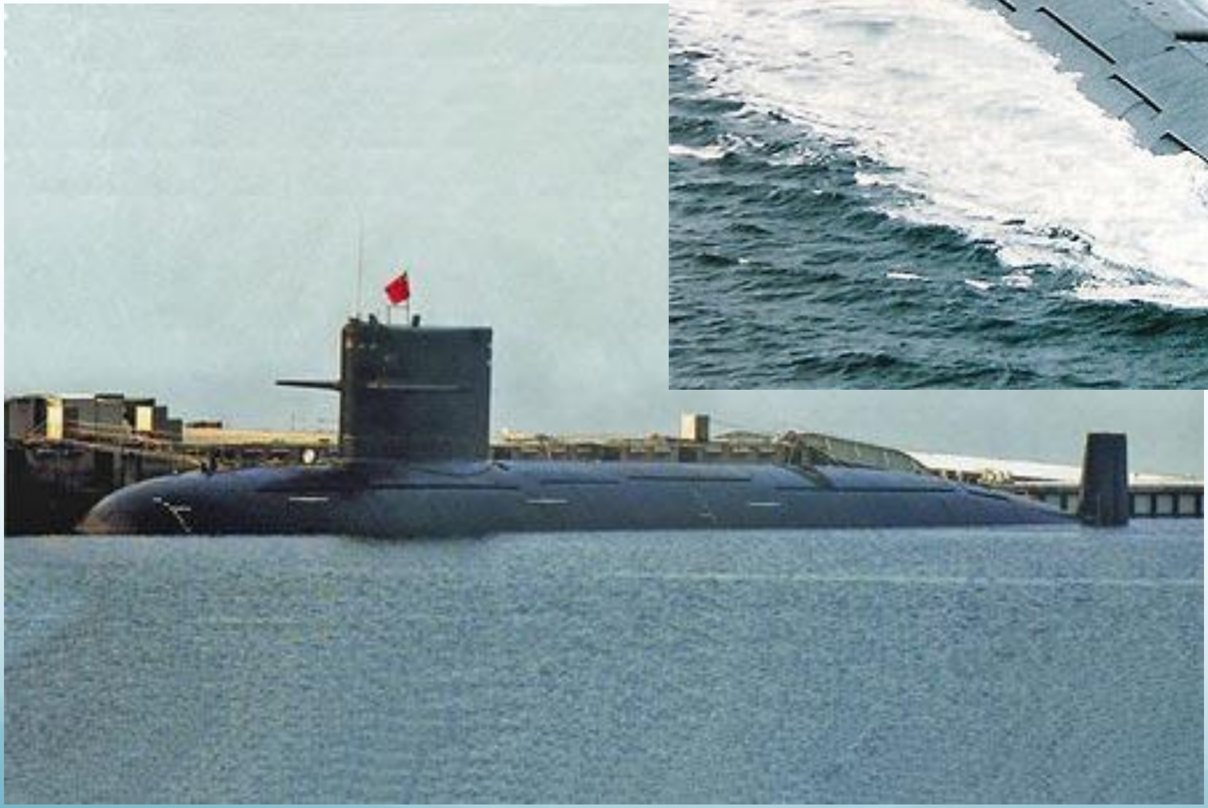


Source: adapted from www.club.china.com

- China's 2nd-generation SSN; based on the Soviet-era Victor III SSN
  - Construction of the first unit began in 1994, but it was not launched until 2002.
  - Believed to be a class of five boats.
- In comparison to a U.S. Los Angeles class sub, Type 093 length is the same; beam is slightly larger, and submerged displacement slightly greater (about 7,000 tons).
- Propulsion: Several sources suggest 2 x PWRs, like Russian Victor III SSN. While less likely, it has been speculated that an advanced high-temperature gas-cooled reactor is used.
  - Secondary steam plant would have to deliver horsepower comparable to a Los Angeles Flight I-class sub (30,000 shaft horsepower) to achieve the attributed maximum submerged speed of about 30 kts. This implies a total reactor power output of about 150 MWt.
- Armament: 6 x 533 mm (or possibly 650 mm) torpedo tubes; various torpedoes & anti-ship cruise missiles
- Operational matters:
  - 2009: USN Office of Naval Intelligence (ONI) listed the Type 093 as being noisier than a Russian Project 671 RTM (V*ictor III*), which entered service in 1979.

Type-093 Shang-class SSN

Source: robertnyakundi.wordpress.com

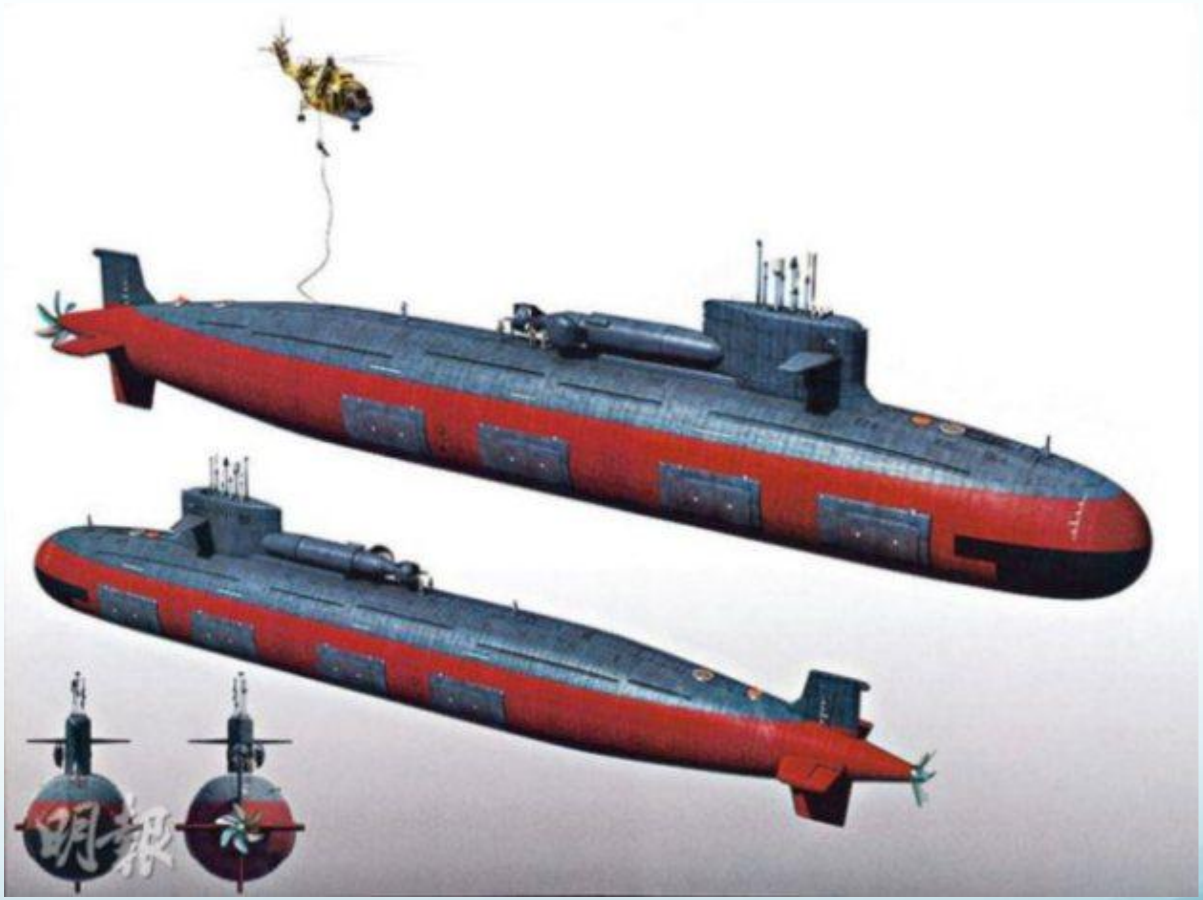


Possible improved Type 093T

- Possible upgraded version, Type 093T, was described on 17 Mar 2015 in an article in the Chinese State-run *Reference News.*

- The accompanying diagram of the sub shows a deck-mounted "wet" hanger capable of holding a mini- sub for special operations forces (SOF).

- The hangar, it was claimed, is intended to accommodate only the first two-thirds of the mini-sub, which "… enters [the] dock space as simple as an ink pen cap."



Possible improved Type 093G

- 3 April 2015, a drawing, possibly from a Taiwanese source, purports to show a new, longer version of the Type 093, with vertical launching system (VLS) tubes behind the sail and a pump-jet propulsor.
- In April, *China Daily* reported that three advanced Type 093G attack submarines were being readied for commissioning this year.
- In May 2015, the Chinese Navy announced that it is preparing to commission three new, longer Type 093G nuclear-powered attack submarines with VLS for cruise missiles such as the Russian Klub (Club) or Chinese YJ-18.

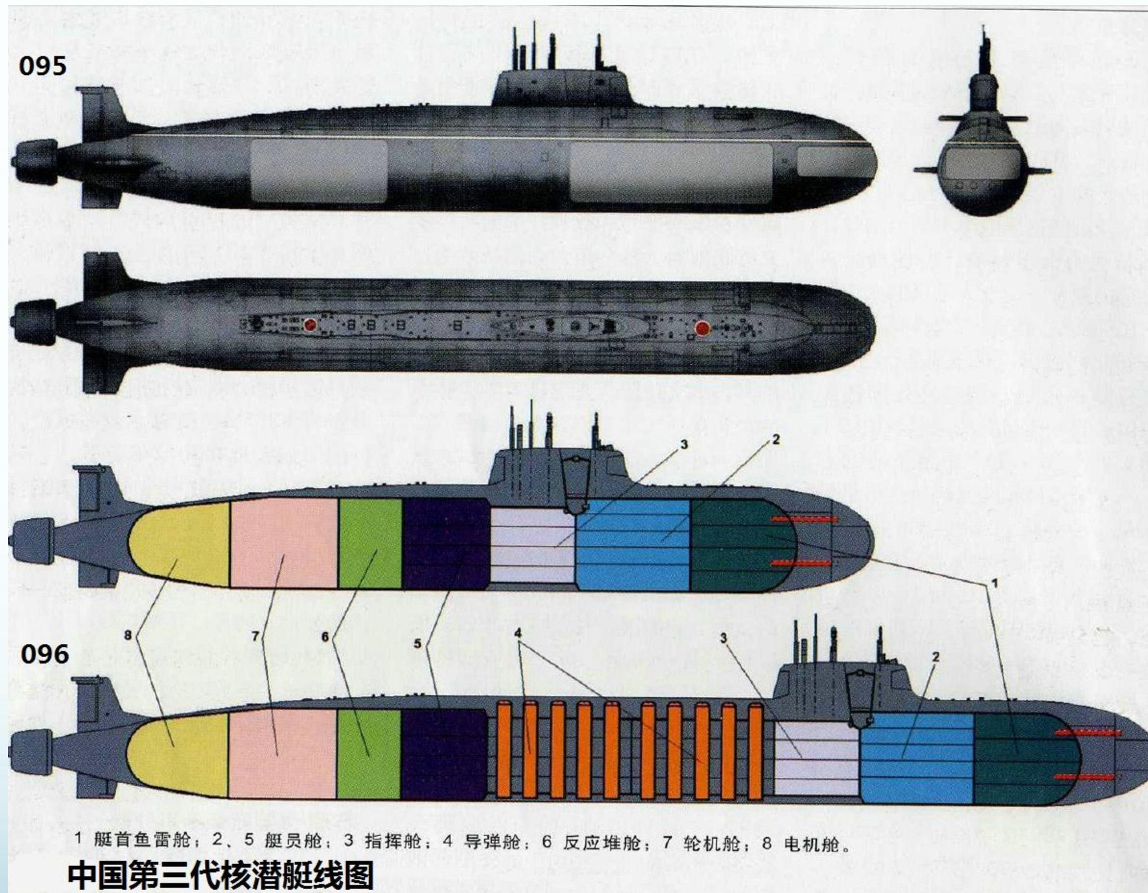
Speculative arrangement of a Type 093G SSGN

Source: http://gentleseas.blogspot.com

Type 095 multi-mission SSN

- China's 3rd-generation SSN currently being developed is expected to feature:
  - Multi-mission capabilities, including removable deck-mounted shelters for special operations forces & equipment
  - A version with a large number of VLS tubes for cruise missiles
  - Advanced nuclear reactor
  - Longer-life reactor core
  - Advanced sonar suite, including flank sonar panels and towed-array sonar
  - Lower acoustic signature
  - Pump-jet propulsor

Speculative SSN & SSGN versions of Type 095

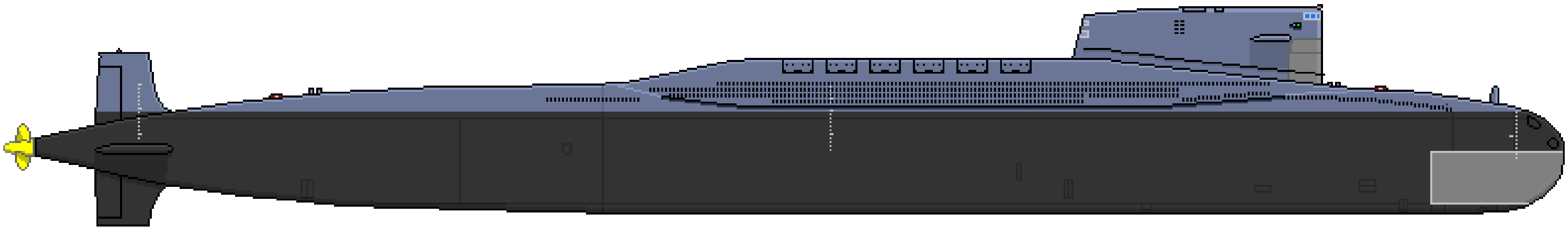


Source: sinodefenceforum.com

Chinese strategic missile subs (SSBN)

Class	# in Class	Length	Beam	Displacement (tons)	Reactor	Shaft hp	Max speed (kts)	Years delivered	Years in service
Type 092 Xia-class	1	120 m (393.7 ft)	10.0 m (32.8 ft)	xxxx (surf), 8,000 (sub)	1 x PWR 58 MWt	11,000 (est)	22 kts	1981	1987 - present
Type 094 Jin-class	5	135 m (442.9 ft)	12.5 m (41.0 ft)	xxxxx (surf), 11,500 (sub)	1 x PWR 175 MWt (est)	33,500 (est)	26 kts	2007 - present	2010 - present
Type 096 Tang-class	Not known	Not known	Not known	Not known	Not known	Not known	Not known	Not known	

Type 092 Xia-class SSBN



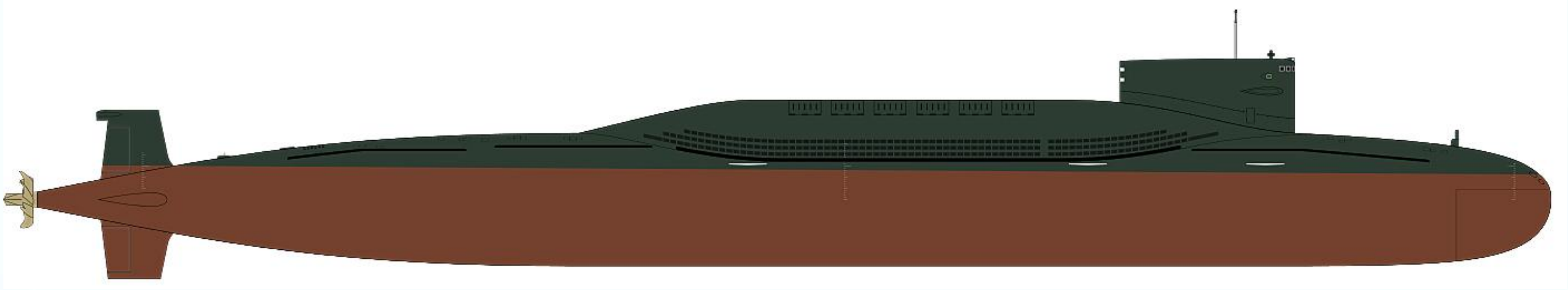
Source: adapted from shipbucket.com

- China's 1st-generation SSBN; derived from Type 091 SSN with an extended hull.
- 1 boat in the class. There have been rumors of a second Type 092 that may have been lost in a 1985 accident.
- Propulsion: 1 PWR rated @ about 58 MWt; 2 x steam turbines delivering about 11,000 hp (8.2 MW) to a single propeller
  - Believed to be same powerplant as on Type 091 SSN
- Armament: 12 x JL-1A SLBMs; 6 x 533 mm bow torpedo tubes
- Operational matters:
  - Completed in 1981; spent 6 years fitting out and testing the JL-1 SLBM; entered service in 1987
  - *Xia* made its world-wide debut on 23 Apr 2009, celebrating the 60th anniversary of PLA Navy's founding.
  - Reportedly never completed a single deterrent patrol
  - U.S. Defense Intelligence Agency (DIA) lists *Xia* as "not operational"

Type 092 Xia-class SSBN

Source (above): tommytoy.typepad.com

Type 094 Jin-class SSBN



Source: en.wikipedia.org

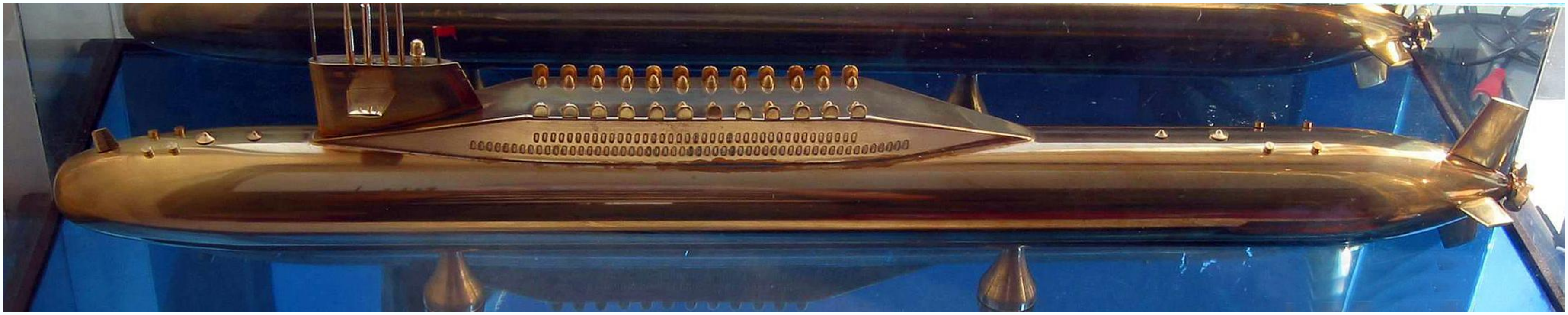
- China's 2nd-generation SSBN; 5 boats in the class; replaces Type 092.
- Propulsion: 1 x PWR rated @ about 175 MWt; secondary steam plant delivering about 33,500 hp (25 MW) to a single propeller
- Armament: 12 x JL-2 SLBMs; 6 x 533 mm bow torpedo tubes
- Operational matters:
  - 1st unit construction started in 2001; 1st spotted in 2006; 1st unit operational 2010
  - 1st successful test launch of a JL-2 SLBM from a Type 094 in 2009
  - 1st operational patrols expected to start in 2015, will provide China with a credible second-strike capability.
  - Type 094 is reportedly noisier than a Russian Delta III SSBN developed in the 1970s.

Type 094 Jin-class SSBN

Source: en.wikipedia.org

Source: khakispecs.com

Type-096 Tang-class SSBN



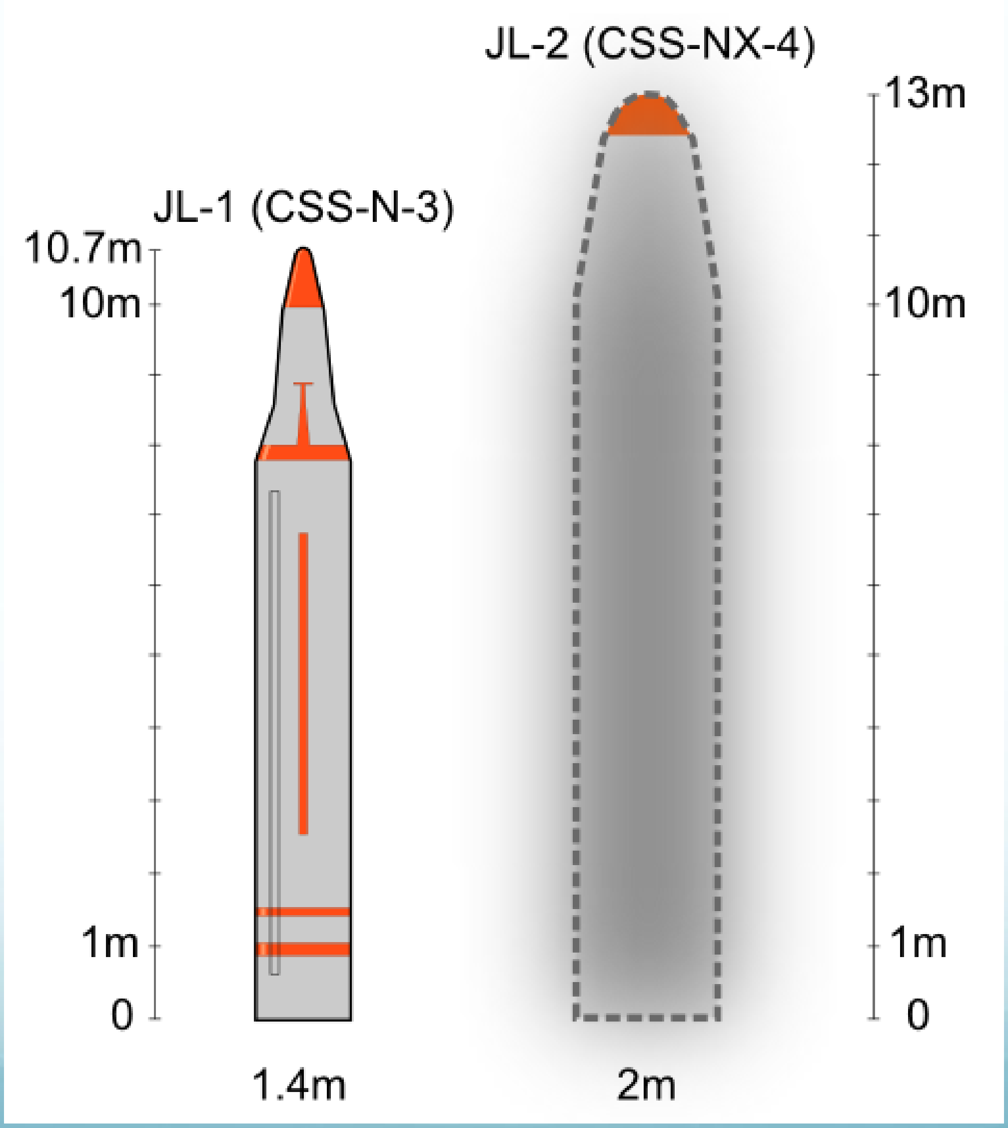
Source: en.wikipedia.org

- China's 3rd-generation SSBN
- Propulsion: 1 x PWR and secondary steam plant driving a single shaft and propeller / pump-jet
- Armament:
  - Up to 24 x JL-2 or JL-3 SLBMs
  - 533 mm bow torpedo tubes
- Operational matters:
  - Construction of this class was reported in the Western press in mid-2013.
  - The first boat could be completed in the 2015 – 16 timeframe.

Comparison of Chinese submarine-launched ballistic missiles

SLBM	Years in service	Weight	Length	Diameter	# of stages	Range /Guidance	Warhead
JL-1 (CSS-NX-3)	Initial Operational Capability (IOC) 1986	14,664 kg (32,328 lb)	10.7 m (35.1 ft)	1.4 m (4.6 ft)	2	2,150 km (2,150 mi) / Inertial	Nuclear, 1 @ 250 kT; 700 m CEP
JL-2 (CSS-NX-4)	2015 IOC on Type 094	20,000 kg (44,000 lb)	13.0 m (42.7 ft)	2.0 m (6.6 ft)	2 or 3	8,000 km (4,970 mi) (est) / stellar inertial + GPS	Nuclear, 1 @ 250 kT – 1 MT or 3 – 8 MIRV @ 20, 90, or 150 kT; 300 m CEP ----- Possible conventional anti-satellite warhead
JL-3	Under development in 2015	Not known	Not known	Not known	2 or 3	11,000 km (6,835 mi)	Nuclear

Comparison of Chinese submarine-launched ballistic missiles



Source
en.wikipedia.org

Example operating areas for Chinese SSBN deterrent patrols

Type 094 Jun-class SSBN with JL-2 missiles

Source: fas.org

Speculative view of a Type 041 test sub for the JL-2 SLBM

China naval nuclear power current trends

China current trends

- New build
  - Construction of improved Type 093 SSNs is continuing, with two new variants unveiled in 2015: Type 093G and Type 093T multi-mission subs.
  - Construction status of new Type 095 multi-mission SSN is not known, but is likely in progress.
  - Construction status of new Type 096 SSBN is not known, but is likely in progress.
- Phase-out / replacement
  - 1st-generation Type 092 SSBN will likely be retired or relegated to non-operational use.
- Refurbishment / modifications
  - Type 094 SSBN fleet will be upgraded to handle the new JL-3 when it enters service
- Operations
  - SSBN deterrent patrols should become regular occurrences
  - Use of SSNs in area denial roles during future conflicts in the South China Sea should be expected.
- New weapons system development
  - JL-3 SLBM development in progress. Longer range than JL-2.
  - There is speculation that a JL-2 with a conventional anti-satellite warhead is being developed.

China current trends

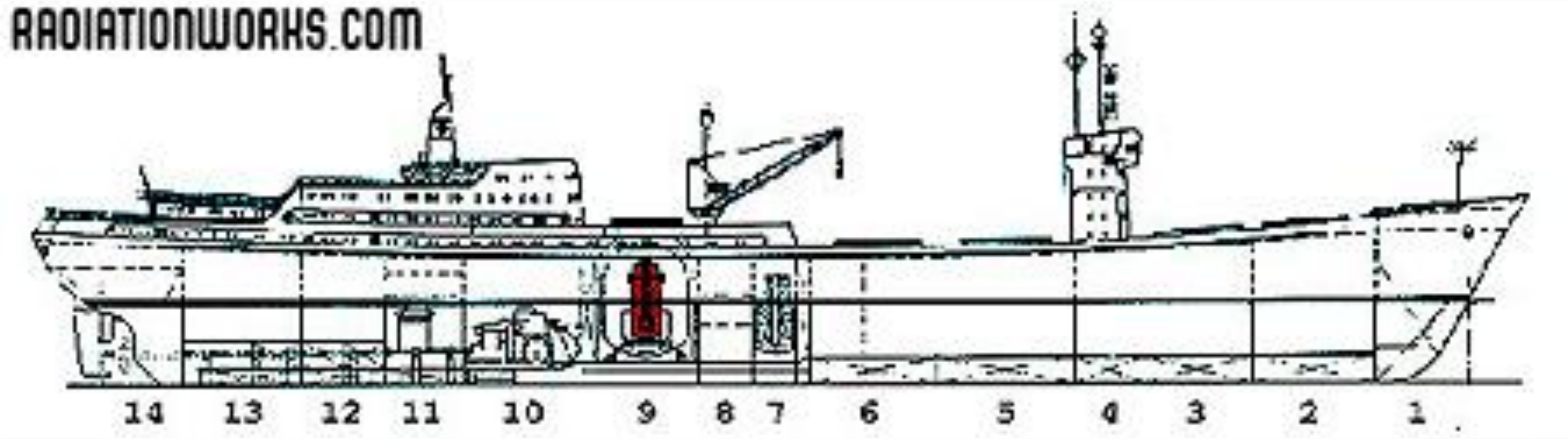
- New submarine development
  - In June 2015, a Chinese official announced completion of the development of the Type 098 fourth-generation SSBN
- New marine reactor development
  - China is likely developing one or more new reactor for the new SSBNs and SSNs now being developed.
  - China has been rumored to be developing a high-temperature gas-cooled reactor for use in a naval propulsion system. Status of this work is not known.
- Final disposition of retired nuclear vessels
  - China continues to operate all of it's nuclear vessels. None have been decommissioned.
  - However, the 1st-generation Han SSNs and Xia SSBNs should be reaching the end of their useful lives within the next decade.
- Technical support to other nations
  - It is not known if China is supporting North Korea (DPRK) in their development of an SLBM-firing conventional submarine.

Germany

Civilian nuclear prototype
bulk ore carrier / research vessel

Otto Hahn

Germany's prototype civilian bulk ore carrier + research vessel



- Launched in 1964; initial criticality 1968; commissioned 11 Oct 1969.
- Length OA: 172 m; beam 23.4 m; full load displacement: 25,790 tons
- Reactor: 38 MWt integral PWR (reactor & steam generator share common vessel)
  - B&W CNSG I, Manufactured by Deutsche B&W and Internationale Atomreaktorbau GmbH
  - Fuel: UO_2 pellets, 3.5% and 6.6% enrichment in Zr-4 fuel rods.
  - Core life: 900 full-power days (34,200 MW- days); refueled in 1972.
  - Located amidship, inside a steel containment vessel
- Propulsion: Steam turbine driving a single shaft; speed: 15.7 kts

Otto Hahn

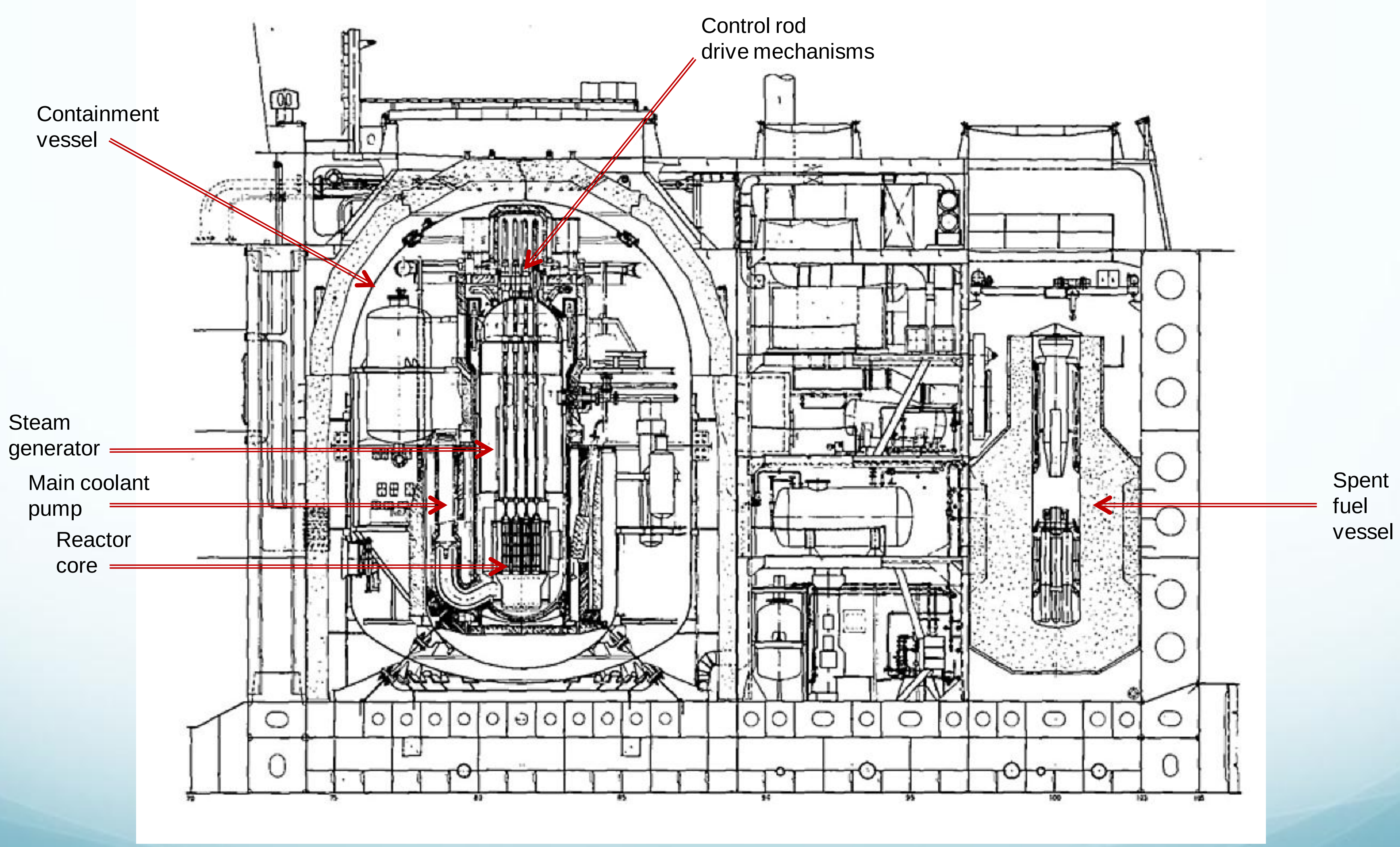
Germany's prototype civilian bulk ore carrier + research vessel

Source: www.shipspotting.com

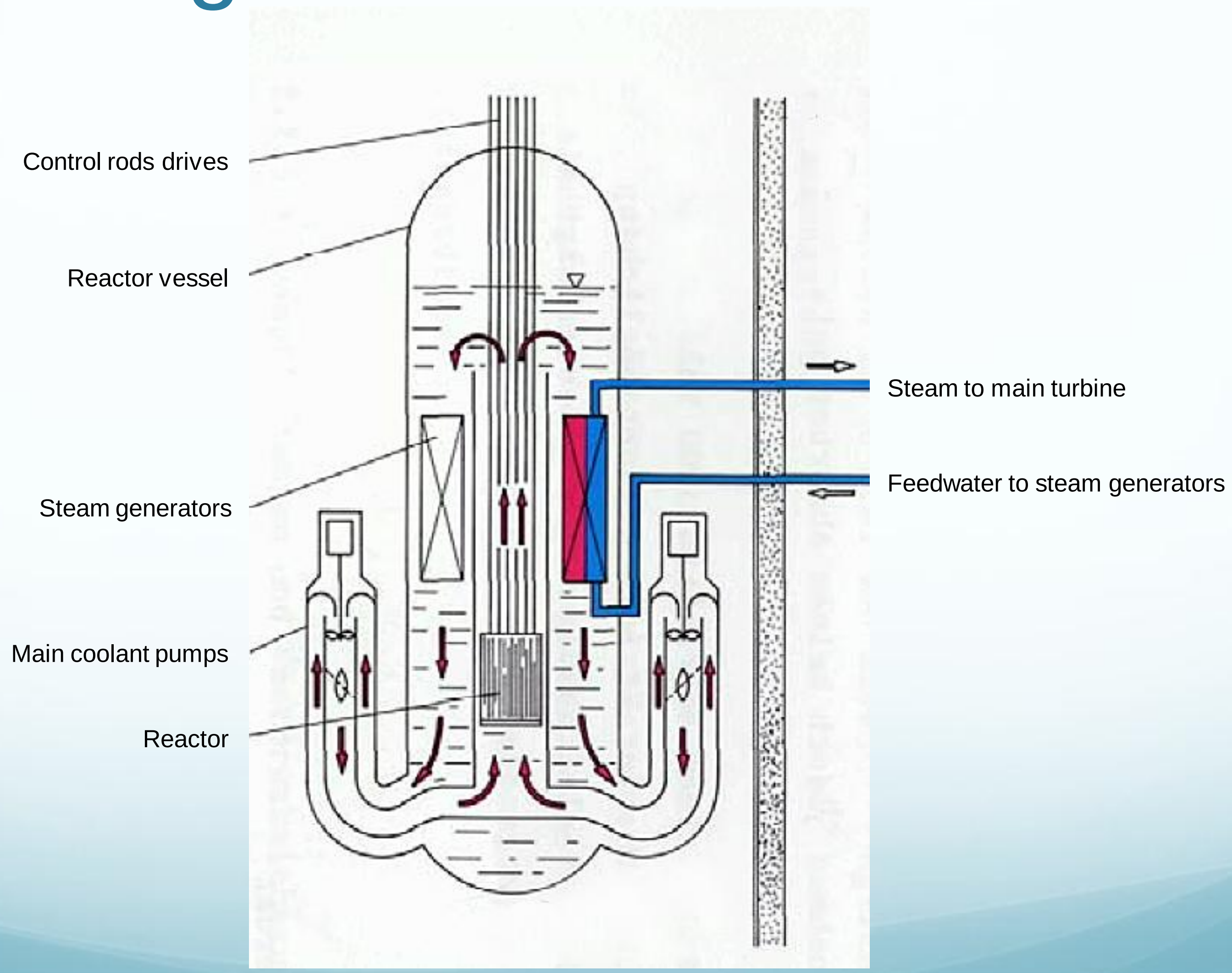
Otto Hahn reactor control room

- Operation:
  - Intended primarily as a research vessel. Accommodated 36 scientists + 63 crew.
  - 1970: 1st port of call: Casablanca
  - 1972: 1st refueling after cruising 250,000 miles
  - 1970 - 79: cruised a total of 650,000 miles on nuclear power, visiting 33 ports in 22 countries. Access to some ports was limited
  - 1979: Nuclear propulsion plant removed & replaced with a diesel powerplant. Ship re-commissioned in 1983 and continued operating until scrapped in 2009.

Otto Hahn CNSG I reactor layout



Otto Hahn CNSG I integral PWR schematic

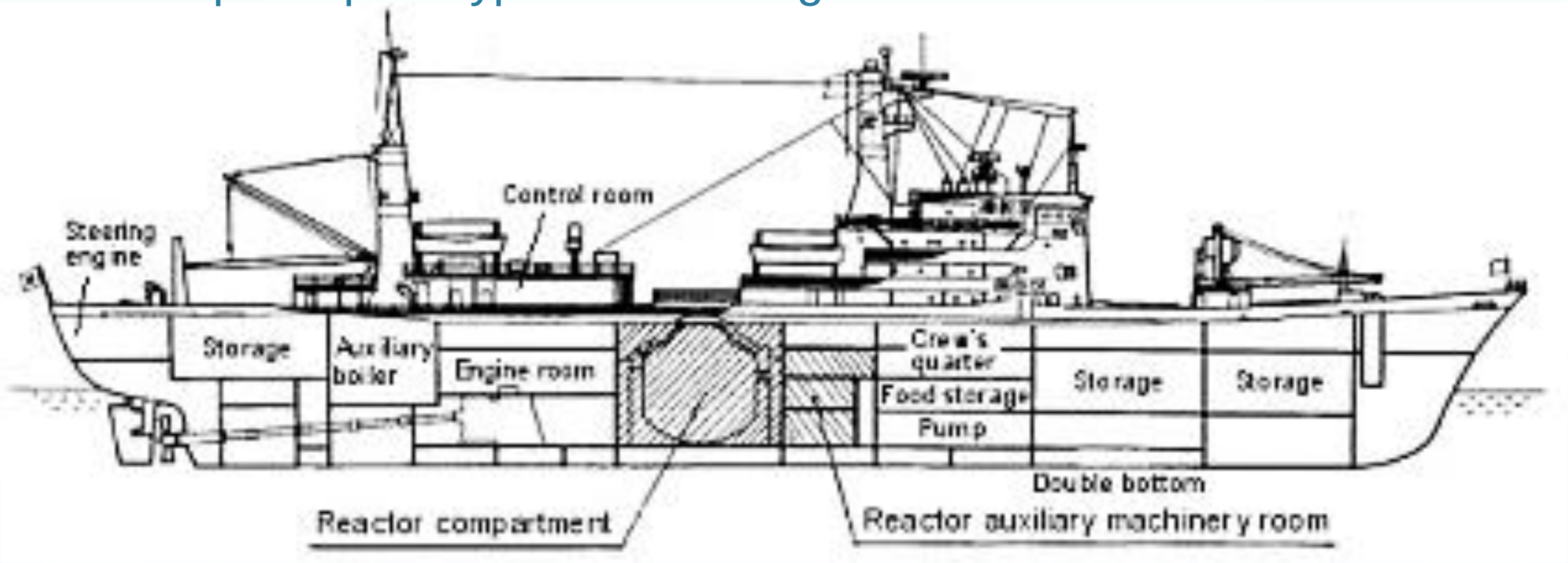


Japan

Civilian nuclear prototype
cargo vessel / research vessel

Mutsu

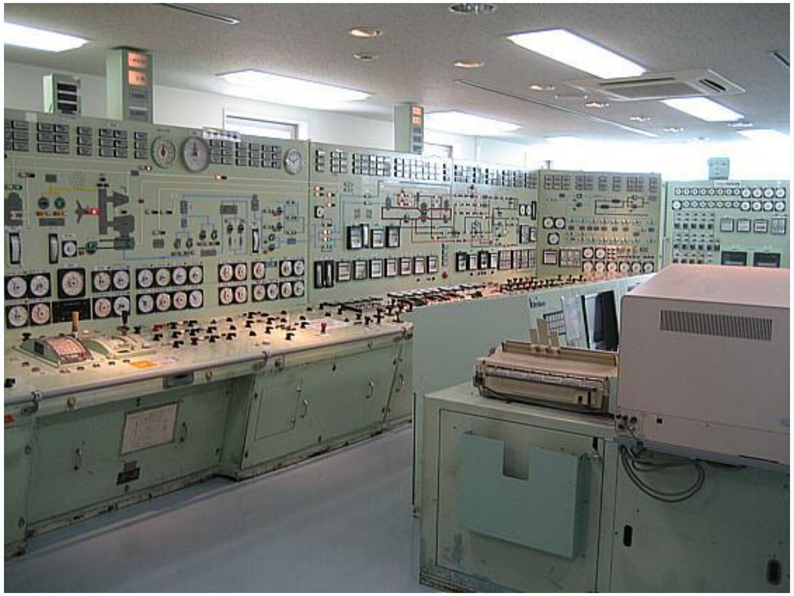
Japan's prototype civilian cargo vessel + research vessel



- Launched 12 Jun 1969
- Length OA: 130 m; beam 19 m; full load displacement: 10,400 tons
- Reactor: 2 x loop, 35 MWt PWR
  - Designed by Mitsubishi Atomic Power Industries
  - Fuel: UO_2 pellets; two enrichments: 3.24% & 4.44%; stainless steel rods in 11 x 11 fuel elements
  - Core life: 13,500 Megawatt-days (MWd)
  - Located amidship, inside a steel containment vessel
- Propulsion: Steam turbine, 10,000 hp, driving a single shaft; speed: 16.5 kts

Mutsu

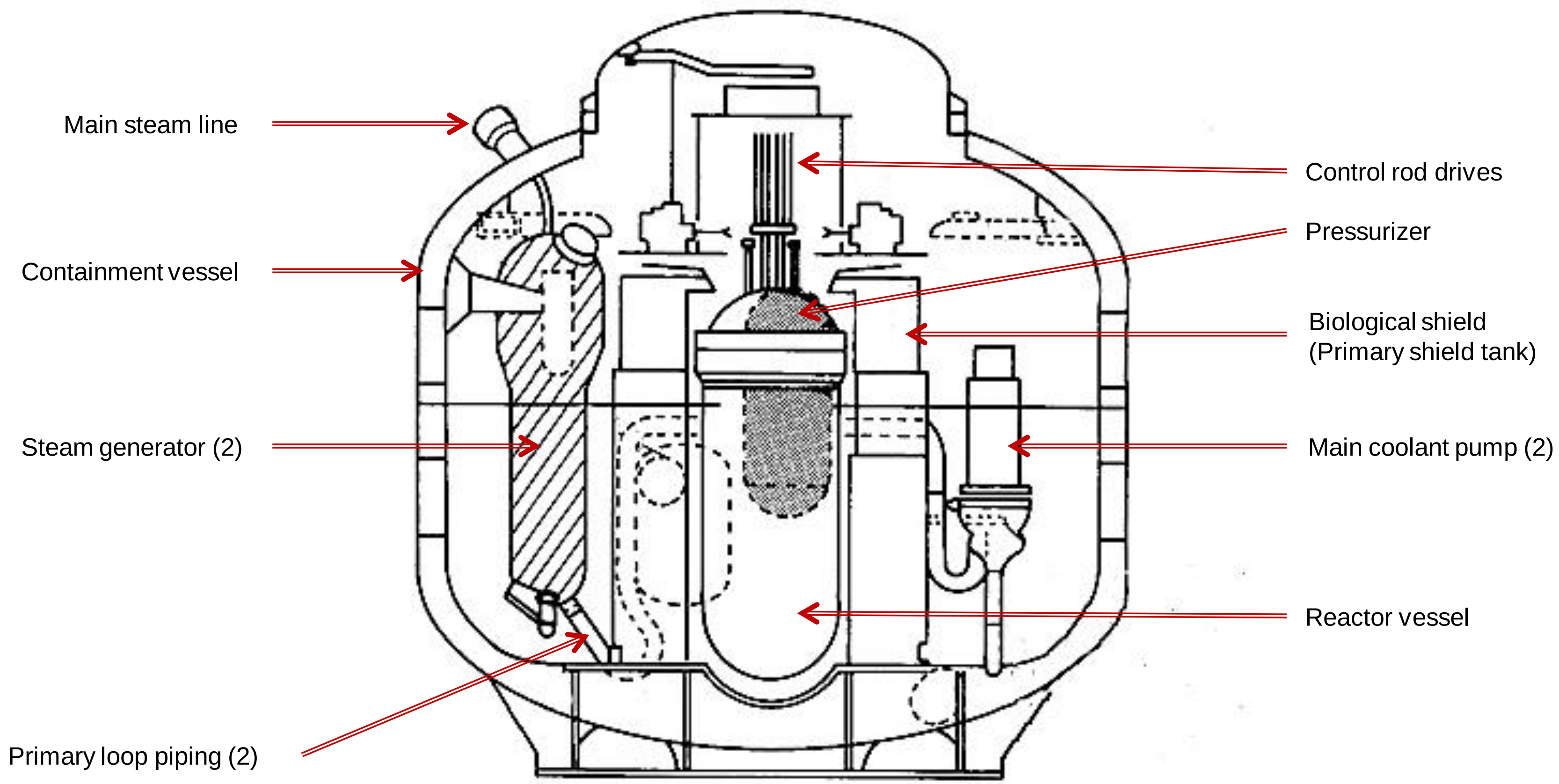
Japan's prototype civilian cargo vessel + research vessel



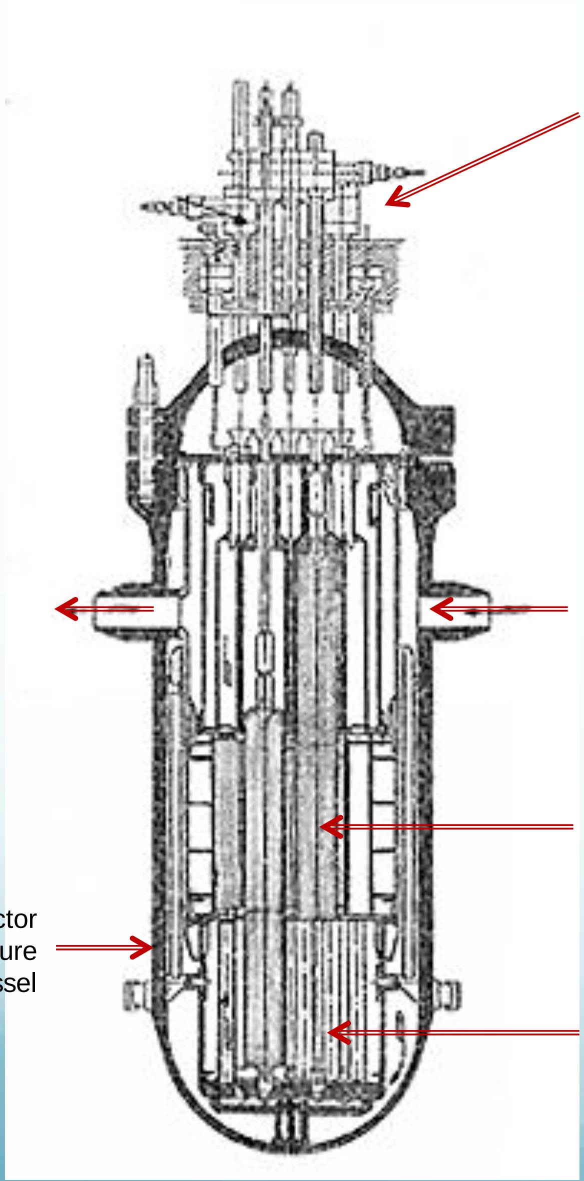
Mutsu reactor control room

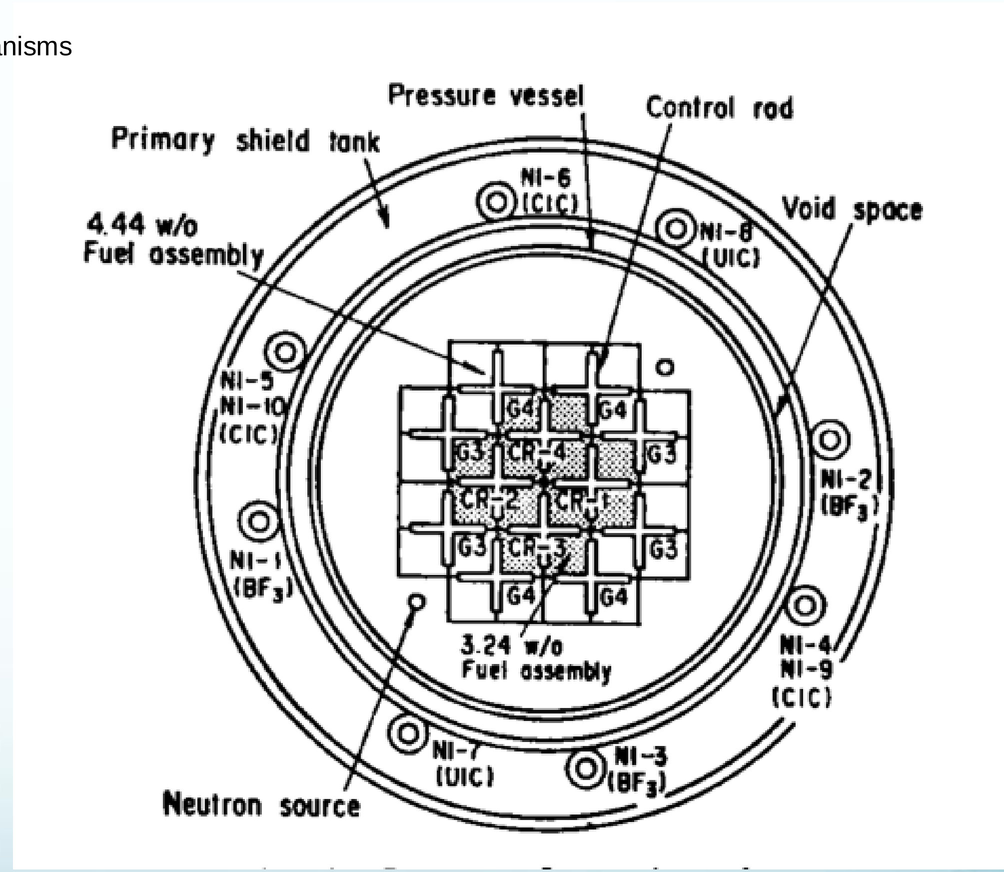
- Operation:
  - 1 Sep 1974: Towed to sea for first reactor test. Shielding design defect led to significant radiation streaming observed after initial criticality and operation at only 1.4% power. Reactor shutdown. Ship remained at sea for 50 days awaiting permission to return to port.
  - 1978 – 1982: In shipyard for modifications
  - February 1991: Ship completed; start of first voyage on nuclear power
  - 1992: Decommissioning after cruising 51,000 miles on nuclear power; reactor removed in 1993
  - 1996: "Re-born" as non-nuclear research vessel Mairi for Japan Marine Science Technology Center

Mutsu reactor compartment layout



Mutsu reactor vessel & core layouts





Mutsu reactor core cross-section

India

Naval nuclear submarines

India’s current nuclear vessel fleet

mid-2015

- India’s Navy operates a mixed fleet of conventional and nuclear submarines. The nuclear submarine fleet is comprised of the following classes:
  - One indigenous Arihant-class SSBN, with more being constructed
  - One leased Improved Akula-class SSN (*Chakra II*), leased from Russia, with one or more additional leased nuclear subs planned
- India also operates a larger fleet of conventionally-powered submarines
- India does not operate any nuclear-powered naval or commercial surface vessels.

India’s naval nuclear propulsion infrastructure

- Bhabha Atomic Research Centre (BARC), near Mumbai on India’s west coast
  - Nuclear engineering design and support facilities
- PRP Centre, located near Kalpakkam on India’s east coast
  - Submarine prototype reactor and training center
- Major naval reactor component manufacturers
  - Reactor vessel: Heavy Engineering Corporation, Ranchi
  - Steam generators: Bharat Heavy Electricals Limited (BHEL)
  - Valves: Audco India, Chennai and others
- Hindustan Shipyard Limited (HSL), located in Visakhapatnam, on India’s east coast
  - Builder of the *Arihant*-class subs

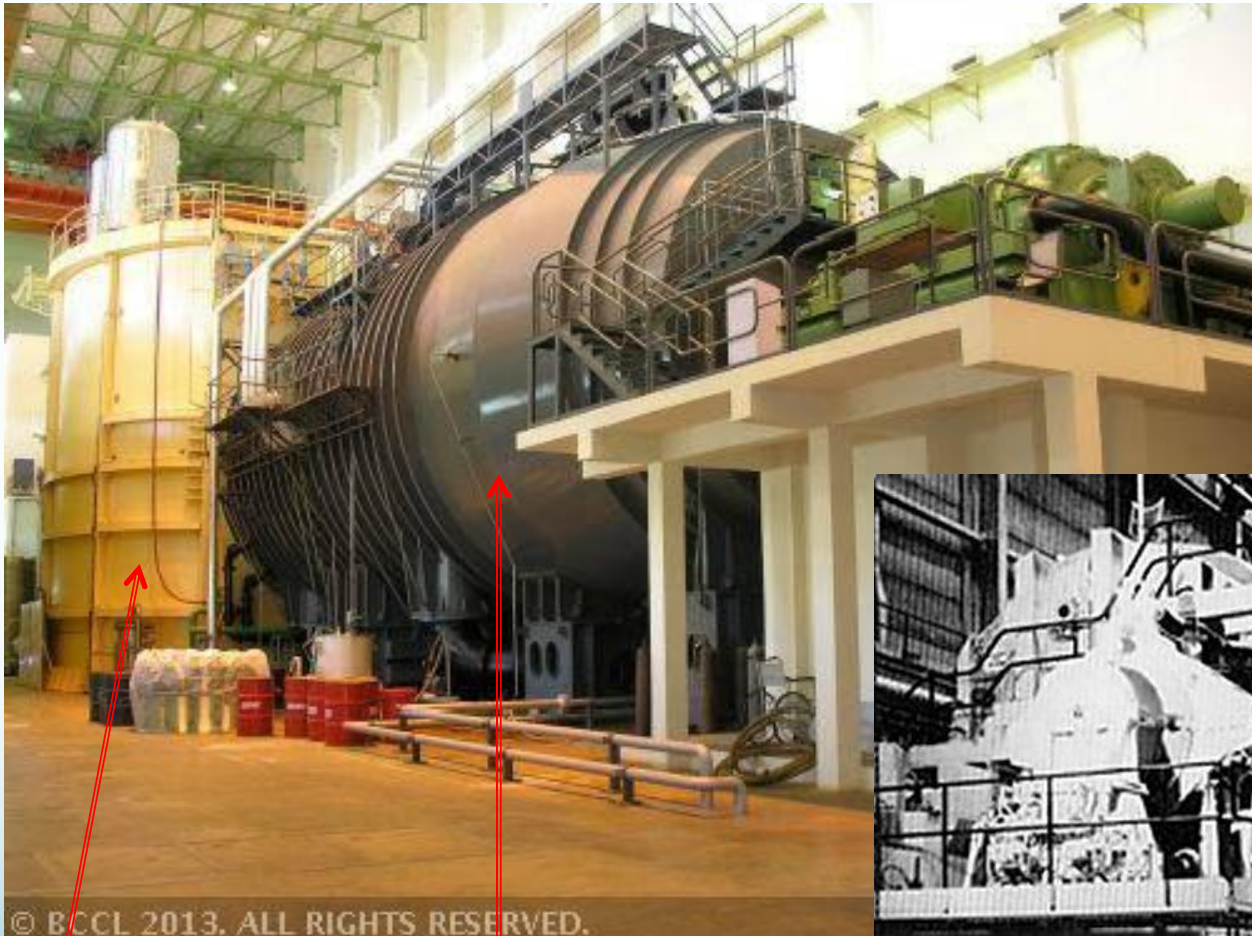
India’s naval nuclear propulsion infrastructure

- Enrichment:
  - India's uranium enrichment program is believed to be oriented primarily toward production of HEU for the nuclear submarine program.
  - A pilot-scale enrichment plant in the Bhabha Atomic Research Center (BARC) was reported to begin operations in 1985.
  - A larger centrifuge plant, officially known as the Rare Materials Project, reportedly has been operating at Rattehalli in southern India since 1990. The Rattehalli plant is being expanded.

India’s naval reactor prototype

- India Advanced Vessel Project (AVP) officially started in 1984 to develop an indigenous marine nuclear propulsion capability
- A prototype naval nuclear propulsion plant is located in Kalpakkam, which is also home of several other nuclear facilities.
  - The prototype was developed by the Bhabra Atomic Research Center (BARC), specifically by a group called PRP Centre
    - PRP originally stood for “Plutonium Reprocessing Project”
    - It has been suggested that India received considerable assistance from the Russians
  - The entire submarine propulsion plant with primary, secondary, electrical, propulsion systems and integrated control system was replicated in a land-based submarine hull.
    - Propulsion power (about 16,000 shaft horsepower, 11.9 MW) is absorbed by a dynamometer.
  - The prototype reactor is believed to be the same design as the Arihant submarine reactor:
    - Power rating: 82.5 MWt
    - Fuel: uranium metallic fuel, enriched to about 30% U-235
    - 13 fuel assemblies with each assembly having 348 fuel pins.
  - 11 Nov 2003: achieved initial criticality
  - 22 Sep 2006: declared operational and is used for both engineering development and training.

India's naval reactor prototype



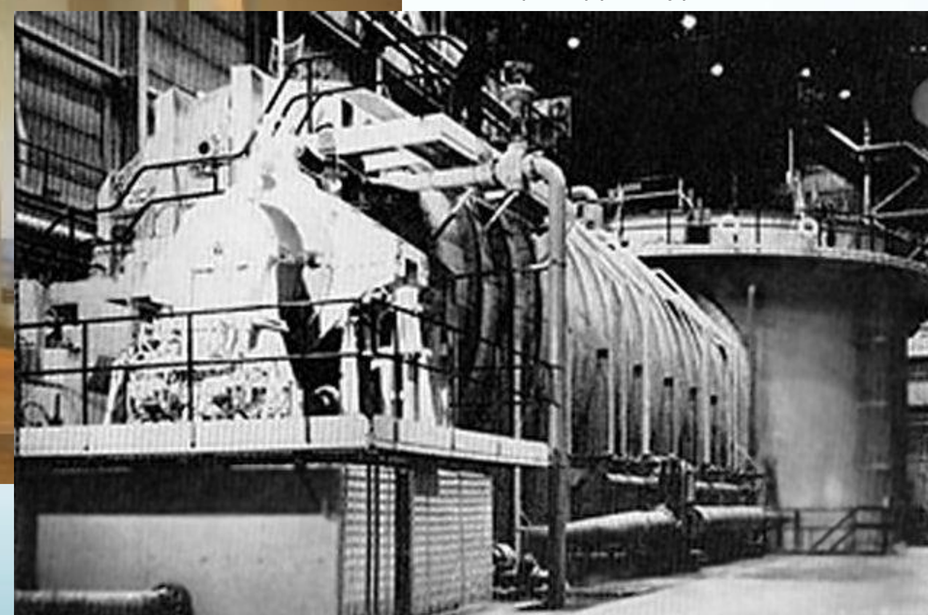
Left:
Indian naval marine reactor
Prototype, circa 2009

Dynamometer to absorb propulsion power

Reactor & primary coolant system in a hull section inside a shield water tank

Auxiliary systems and propulsion plant in unshielded hull section

Below: Very similar looking Westinghouse STR Mark 1 (S1W) prototype reactor, circa 1954

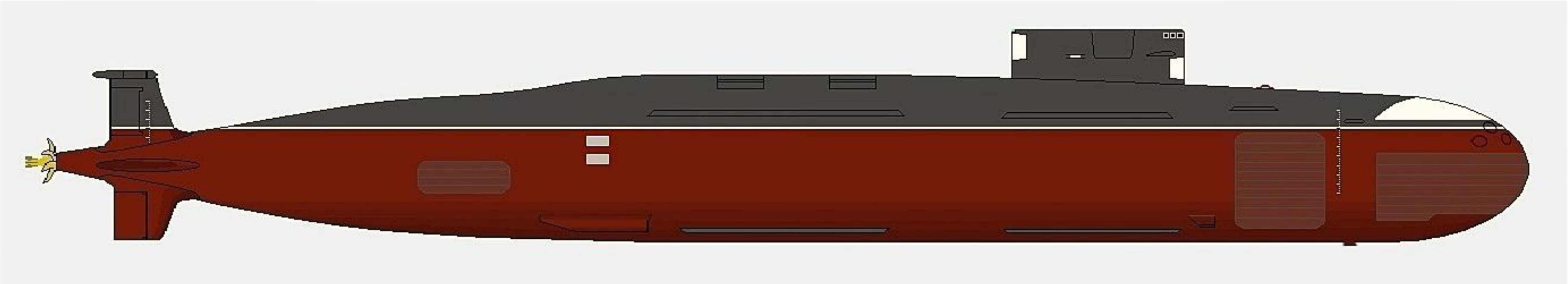


Source: Westinghouse

India’s leased Russian nuclear subs

- Leased Charlie I (*Chakra I*)
  - Former Russian designation was K-43
  - Leased by India from Russia 1988–1992, then returned to Russia.
  - Introduced Indian crews to nuclear submarine operations.
- Leased Akula II (*Chakra II*)
  - Former Russian designation K-152, *Nerpa;* longest and heaviest of the Akulas, likely to be among the quietest.
  - 10-year lease from Russia, 2011 – 2021
  - Modified by Russia for export and does not include some features on Russian counterparts:
    - No wake detection system (SOKS)
    - No counter-measure tubes above the torpedo tubes
    - 8 x 533mm tubes (no 650 mm tubes)
  - *Chakra II* is expected to be armed with the Russian 3M-54 Klub (Club) cruise missile, which is available in anti-ship and land-attack versions.
  - Officially inducted into the Indian Navy on 4 April 2012
- Second leased Akula II
  - In Dec 2014, India agreed to a 10-year lease for a second Akula II
  - The K-322, *Kashalot,* will be customized at the Amur shipyard in eastern Russia.
  - Modernization and testing of the submarine and training of the Indian crew will take three years.
  - *Kashalot* is expected to be transferred to the Indian Navy in 2018
- Possible future lease of a Yasen-class multi-purpose SSN
  - In 2015, India and Russia apparently have discussed lease of a modified new construction Yasen.

Arihant-class SSBN



Source: adapted from defence.pk

- Jointly developed by the Indian Navy, Bhabha Atomic Research Centre (BARC), and Defense Research and Development Organization (DRDO).
- 3 – 5 boats in this class are expected. 2nd ship in class named *Aridhaman* should be launched in 2015 – 16 timeframe.
- Propulsion:
  - Arihant is powered by 1 x PWR rated at about 82.5 MWt; secondary steam plant delivering about 16,000 shaft horsepower (11.9 MW) to a single propeller.
  - Follow-on boats are expected to have a more powerful reactor, with a rating of about 100 MWt.

Arihant-class SSBN

- Weapons: 4 x “universal” (large) SLBM tubes amidships, each capable of carrying either 3 x K-15 missiles or 1 x K-4 or K-5 longer-range SLBM, also 6 x 533 mm bow torpedo tubes
- Key milestone dates:
  - 26 Jul 2009: Arihant launched
  - 10 Aug 2013: Initial criticality
  - 15 Dec 2014: Arihant sea trials began

Source: http://www.indiastrategic.in/topstories3628_Indias_First_Nuclear_Attack_Submarine_Arihant_begins_Sea_Trials.htm

Arihant-class SSBN

4 "universal" vertical
launch system (VLS)
missile tubes

Seawater
scoop for
main condenser
cooling

6 bow torpedo
tubes

Source: www.naval-technology.com

Comparison of Indian submarine-launched ballistic missiles

SLBM	Years in service	Weight	Length	Diameter	# of stages	Range / Guidance	Warhead
K-15 Sagarika	Last development test in Jan 2013; IOC probably in 2015	5,500 - 6,300 kg (12,100 – 13,860 lb)	10.8 m (35.4 ft)	0.74 m (2.42 ft)	2 solid	800 km (497 mi) / inertial + GPS + terrain contour matching	1 x nuclear, weighing 500–800 kg (1,100 – 1,760 lb)
K-4 Mk I *	1st submerged development test in Mar 2014; IOC probably in 2016	17,270 kg (38,000 lb)	10.0 m (32.8 ft)	1.3 m (4.25 ft)	2 or 3	3,500 km (2,175 mi)	Nuclear, 200 – 250 kT, weighing about 2,000 kg (4,400 lb),
K-4 Mk II *	In development phase		12.0 m (39.9 ft)	1.3 m (4.25 ft)	2 or 3	5,000 km (3110 mi)	Nuclear
K-5	In design phase in mid-2015	Not known	Not known	Not known	2 or 3	6,000 km (3728 mi)	Nuclear, weighing about 910 kg (2,000 lb)

* Reportedly K-4 is not a ballistic missile, but is capable of 3-D maneuvering flight within the upper atmosphere, enroute to the target

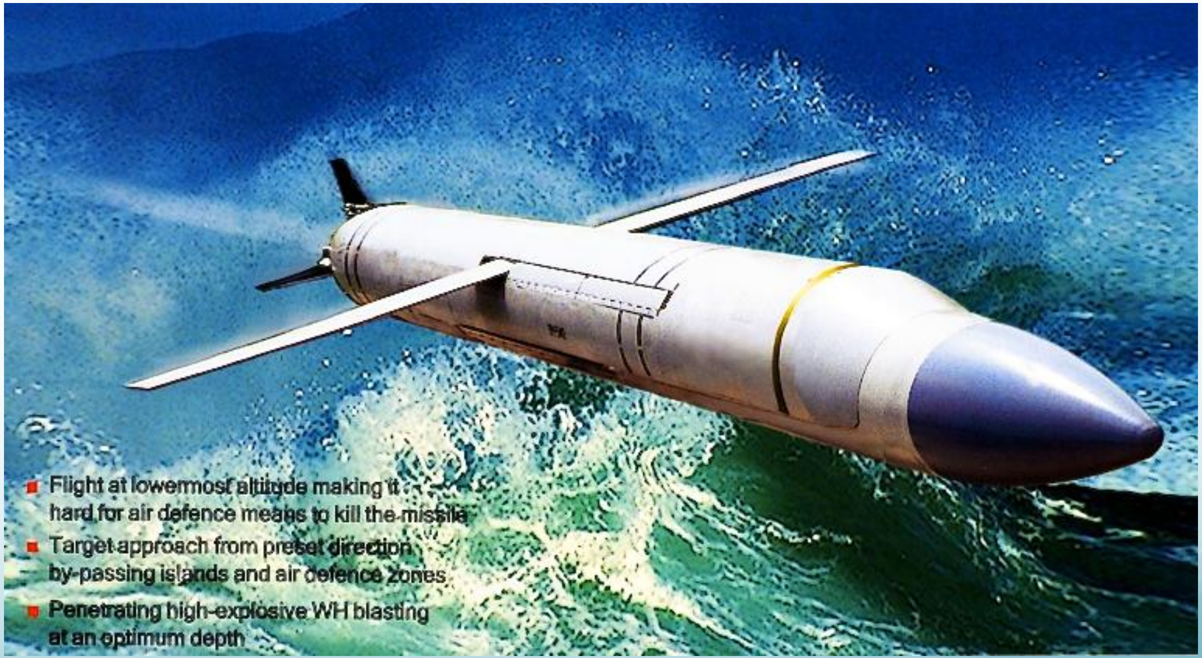
Comparison of Indian submarine-launched cruise missiles

Cruise missile	Years in service	Weight	Length	Diam (D) /Span (S)	Speed	Range	Guidance	Warhead
Anti-ship 3M-54 Club (SS-N-27 Sizzler)	Prior to 2015 on Kilo-class SS	1,780 kg (3,924 lb)	Club S: 6.2 m (20 ft)	D = 53 cm (21 in)	Subsonic cruise + M = 2.5 - 2.9 terminal "sprint"	220 km (137 mi)	Inertial + active radar homing	Conventional, 200 kg (440 lb) penetrating high-explosive warhead
Anti-ship BrahMos	2005 on a surface ship; 2016 on a submarine (expected)	3,000 kg (6,614 lb)	8.4 m (27.6 ft)	D = 0.6 m (2.0 ft)	M = 2.8 – 3.0	290 km (180 mi)	Inertial + GPS/GLONASS + terminal active radar	200 kg (440 lb) warhead capability; Conventional penetrating high-explosive warhead or nuclear
Land-attack Nirbhay	2017 on a submarine (expected)	1,500 kg (3,307 lb)	6.0 m (19.7 ft)	D = 0.5 m (1.6 ft)	M = 0.65	750 - 1,000 km (466 – 621 mi)	Inertial + GPS + terminal active radar	450 kg (990 lb) warhead capability; wide range of conventional warheads or nuclear

3M-54 Club / SS-N-24 Sizzler

Subsonic / supersonic anti-ship cruise missile

- Available from Russia in sub-, surface ship-, and air-launched versions
- Small rocket booster launches the weapon, then a turbojet engine powers the missile at subsonic speed until in the vicinity of the target. Then, a small, rocket-propelled “second stage” warhead separates from the subsonic airframe, accelerates to about Mach 2.5 - 2.9, and uses active radar to home in on the designated target.
- Can be launched from a standard 533 mm (21 in) torpedo tube at a launch depth 30 - 40 m (98 – 131 ft)
- Penetrating high-explosive warhead.
- Range about 220 km (137 mi).



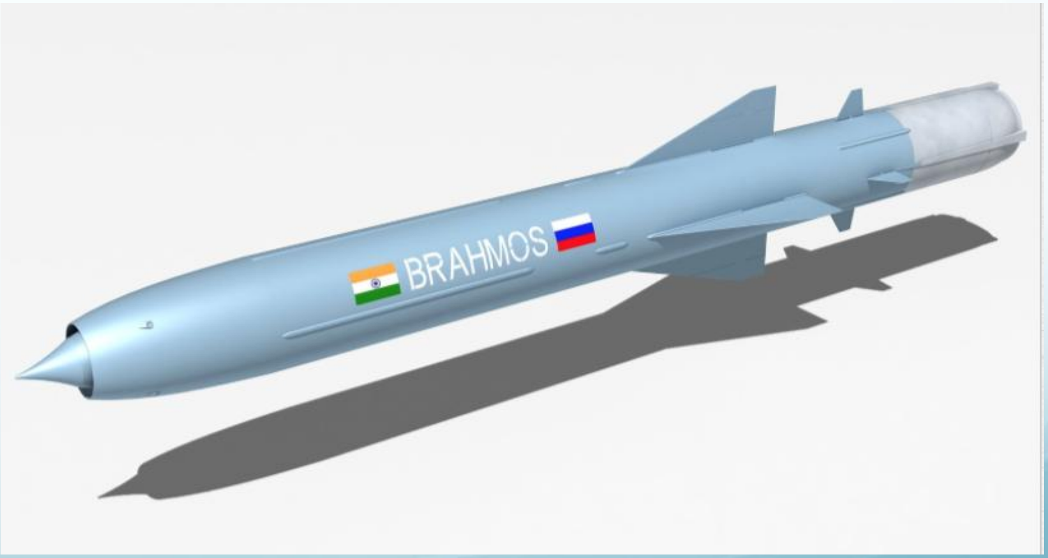
Source: http://www.ausairpower.net/APA-Rus-Cruise-Missile

BrahMos

Supersonic medium-range ramjet cruise missile

- Based on the Russian P-800 Oniks cruise missile
- BrahMos was developed under a Russian – Indian joint-venture; intended as a “universal” cruise missile with ship-, submarine-, land-, and air-launched versions
  - Missile is launched with a rocket booster and then flies to the target at Mach 2.8 – 3.0 powered by a ramjet engine.
- Capable of being launched vertically from a sub at depth of 40 – 50 meters (131 – 164 ft)
- As of mid-2015, the ship- and land-launched have been deployed. Development of the air- and submarine-launched versions is continuing.
  - 1st submerged launch (from a platform) occurred in March 2013.
  - After clearing the water, a protective nose cap is ejected and the missile turns toward the target, which may be up to 290 km (180 mi) away.

Source: http://www.brahmos.com/



Source: http://www.stlfinder.com/model/brahmos-pj10-missile

Nirbhay

Subsonic long-range cruise missile

- India's first indigenously produced cruise missile; being developed in ship-, submarine-, land-, and air-launched versions
- Nirbhay appears similar to the U.S. Tomahawk and the Russian Club 3M-14 / SS-N-27.
- Nirbhay can be launched from a standard 533 mm (21 in) torpedo tube.
- Range: 750 - 1,000 km (466 – 621 mi), with loiter capability en-route; Speed: Mach 0.9
- As of mid-2015, development testing was in progress:
  - 1st test flight was in Dec 2012.
  - In 2014, Nirbhay demonstrated the ability to fly a complex course (15 waypoints) and strike the intended target after flying for more than an hour.
  - 1st operational deployment is expected in 2017.

Source: http://missilethreat.com/missiles/nirbhay/

Source: http://www.rediff.com/news/report

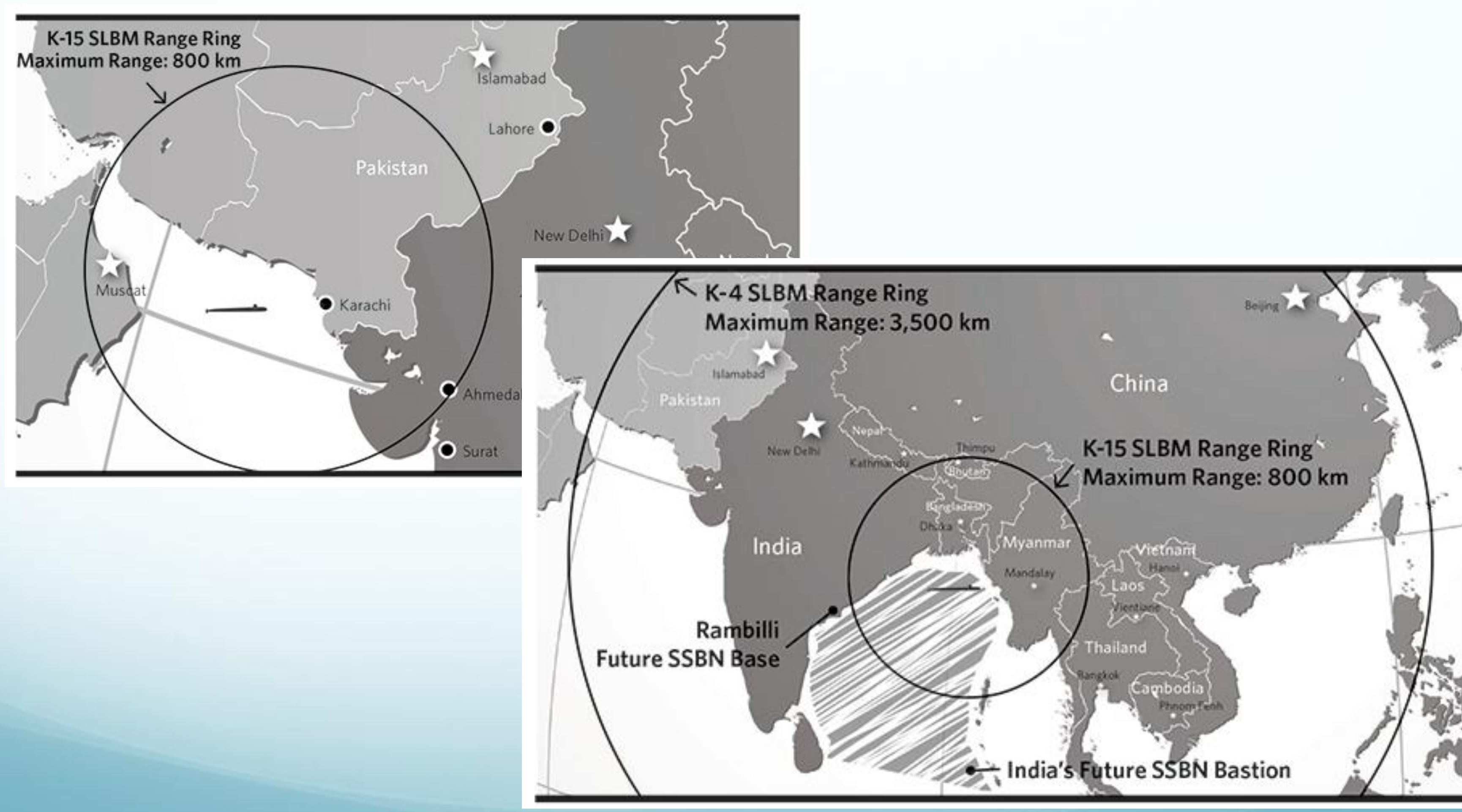
Naval Base *INS Varsha*

- This naval base is now being developed at Rambilli, on the east coast of India, about 50 km from Visakhapatnam
  - Designed to support a fleet of 8-12 *Arihant*-class nuclear submarines, the Indian Navy's first indigenous aircraft carrier, *INS Vikrant*, and other naval vessels.
  - The submarines will be housed in underground pens,
  - The depth of water in the Bay of Bengal at *INS Varsha* will allow submarines to enter and leave the base without being detected by satellites.
  - A nearby facility of the Bhabha Atomic Research Centre (BARC) will provide nuclear engineering support facilities and crew accommodation.

- Visakhapatnam is the headquarters of the Indian Navy's Eastern Naval Command
  - Also, Hindustan Shipyard Limited (HSL), in Visakhapatnam, can support submarine maintenance & repair

Example operating areas for Indian SSBN deterrent patrols

Arihant-class SSBN with K-15 and K-4 missiles



Source: http://carnegieendowment.org/2015/03/09/murky-waters-naval-nuclear-dynamics-in-indian-ocean

India current trends

- New build
  - Construction of the 2nd Arihant-class SSBN is in progress and a fleet of 3 - 5 Arihant-class SSBNs is expected.
- Additional leases
  - A 2nd Improved-Akula sub has been leased from Russia and is expected to join the fleet in 2018. Preliminary discussions with Russia have been held on the subject of also leasing a current-generation Yasen-class multi-purpose SSN.
- Operations
  - When completed, Naval Base *INS Varsha* will support nuclear fleet operations from the east coast of India and permit easy access of Arihant SSBNs to patrol areas that can target both China and Pakistan with longer range K-4 missiles.
- New weapons system development
  - The long-range K-4 submarine launched ballistic missiles is under development, with an initial operating capability expected in 2016. Even longer range K-4 Mk II and K-5 SLBMs are planned.
- New submarine development
  - Details on new nuclear submarine development are not known.
- New marine reactor development
  - The 2nd and later Arihant-class SSBNs are expected to have a more powerful 100 MWt PWR than the lead-ship.

Other Nations With an Interest in Marine Nuclear Power Technology

Brazil, Italy, Canada, Australia, North Korea, Israel, Pakistan, Iran

Brazil

Rapidly developing infrastructure to support indigenous naval nuclear submarines

Brazil's nuclear submarine timeline

- Brazil will likely become become the first Non-Proliferation Treaty (NPT) non-nuclear-weapon state to acquire an indigenous nuclear-powered submarine capability.

- 2008: Brazil's submarine force is a key part of the country's national armaments and defense strategy released in December.
  - Strategy defines the plan to protect Brazil's 8,500 km (5,282 mile) coast
  - Brazil currently operates a small fleet of five conventionally-powered subs built in Germany by Howaldtswerke-Deutsche Werft (HDW)

- 2008: Agreement signed in December between the governments of Brazil and France aimed at preparing the Submarine Development Program for the Navy of Brazil (PROSUB). This agreement provides for:
  - Four new conventionally powered submarines, derived from the French *Scorpene*, to be designated the SBR, plus
  - One nuclear powered submarine, to be designated the SNBR (or SN-Br)

- 2009: the Brazilian Navy (*Marinha do Brazil*) contracted with French shipbuilder DCNS (*Direction des Constructions Navales*) for submarine technology transfer & construction assistance, as well as design and construction of a new shipyard and naval base for the submarines at Itaguai.

Brazil's nuclear submarine timeline

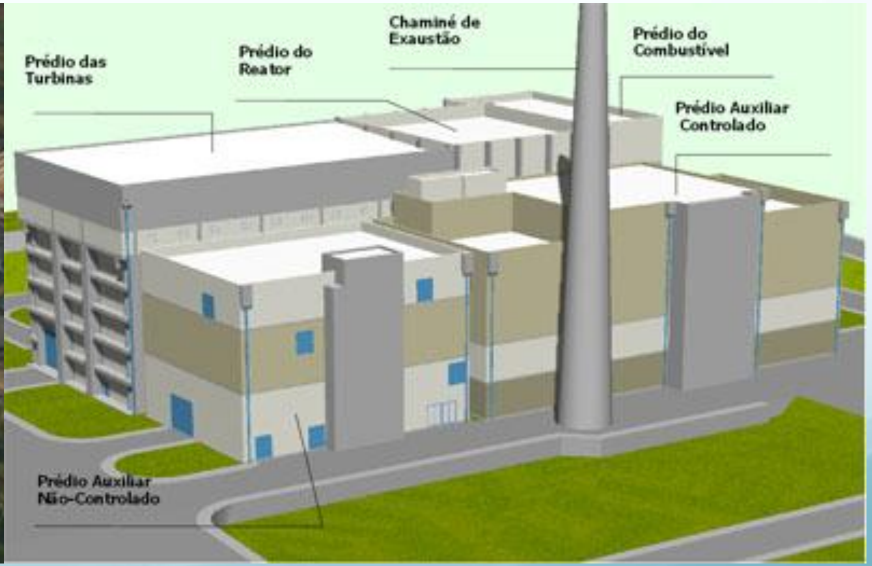
- 2010: Joint Plan for Marine Equipment of Brazil (*O Plano de Articulação e Equipamento da Marinha do Brasil - PAEMB*) provides a long-range plan for acquisition of 15 conventional subs (SBR) and 6 nuclear subs (SNBR) by 2034.
- 2012: the government set up Blue Amazon Defense Technologies (*Amazonia Azul*) to develop nuclear submarines using the Brazilian indigenous PWR with low-enriched uranium fuel (<20%)
- 2013: In March, President Dilma Rousseff inaugurated the factory that will make submarine metal hull structures:
  - Four conventional SBRs to be delivered to the Navy in 2017, and
  - One SNBR to be delivered to the Navy in 2023
- 2014. In December, President Dilma Rousseff inaugurated the main building of the construction shipyard in Itaguai.
  - Two submarines can be built in parallel in this building.

Brazil's naval nuclear propulsion infrastructure

- Centro gico da Marinha em o Paulo (CTMSP)
  - Develops the nuclear program for Brazil's Navy (*Marinha do Brazil*), including technological, industrial and operational processes of nuclear facilities applicable to naval propulsion.
  - This effort consists of two main projects:
    - Fuel Cycle Project:
      - Goal is to empower Brazil's Navy to design, deploy, commission, operate and maintain nuclear facilities applicable to naval propulsion
    - Infrastructure Project:
      - Provide all support facilities for the development of above nuclear projects
- Brazil Navy's Aramar Experimental Center (*Centro Experimental de Aramar,* CEA) near São Paulo, includes:
  - Isotopic Enrichment Laboratory; a pilot-scale centrifuge enrichment plant to enrich to < 20% U-235
  - A centrifuge manufacturing plant
  - A uranium purification facility
  - An experimental pressurized-water reactor (PWR)
  - A uranium conversion plant to convert yellowcake into uranium hexafluoride (UF6) for use in the enrichment process at the site
  - Laboratorio de Geracao Nucleo-Eletrica – LABGENE (Nuclear-Electric Generation Laboratory) for the submarine prototype reactor is being developed at Aramar

Brazil's naval nuclear propulsion infrastructure

- Laboratorio de Geracao Nucleo-Eletrica – LABGENE (Nuclear-Electric Generation Laboratory) at Aramar
  - Facility consisting of 11 main buildings will be used to validate design conditions & test operating conditions for a naval nuclear propulsion plant.
    - Multi-purpose thermodynamic laboratory (LABTERMO), comprised of mock-ups, experimental test benches (i.e., for control rods drives mechanism tests) and test circuits (i.e., experimental thermo-hydraulic circuit operating at about 2200 psig)
    - Buildings that will house the naval reactor prototype, shown below.



Source, both graphics: www.mar.mil.br/ctmsp

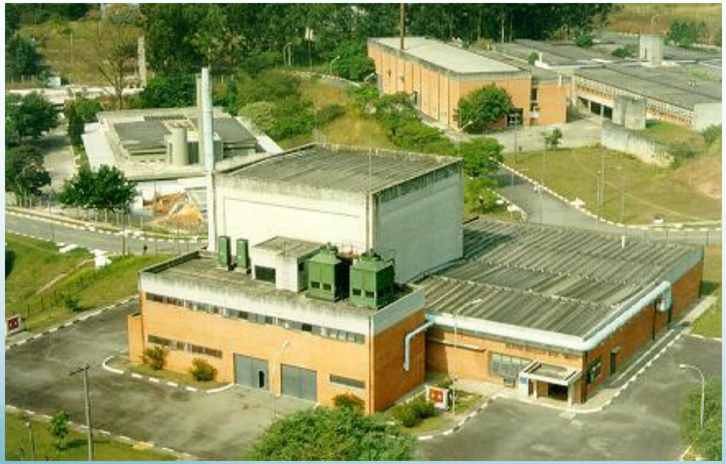
Brazil's naval nuclear propulsion infrastructure

- Instituto de Pesquisas Energéticas e Nucleares (IPEN)
  (Institute of Nuclear and Energy Research, near São Paulo)

IPEN/MB-01: zero-power (100 w) open pool-type critical facility

Developed in 1988 by IPEN researchers in partnership with the Brazilian Navy.

An experimental program was carried out to validate the neutronic parameters of the Brazilian naval reactor core and to validate calculational methodologies and related nuclear data libraries.



IPEN/MB-01 Source: www.mar.mil.br/ctmsp

IEA-R1: 5 MW swimming pool-type research reactor

Moderated and cooled by light water with graphite and beryllium reflectors

Commissioned in 1957

Nuclear Fuel Irradiation Circuit is used to determine naval reactor fuel rod behavior under irradiation.

IEA-R1 Source: IAEA

Brazil's naval nuclear propulsion infrastructure

- Resende Nuclear Fuel Factory, between Rio and São Paulo
  - An industrial-scale centrifuge enrichment plant was built based on the pilot plant technology developed at Aramar.
    - Centrifuges manufactured by Brazil's Navy (at Aramar)
    - Operation of the Resende enrichment plant commenced in 2009.
    - The planned 2131-R naval reactor does not require uranium enriched to > 20%
  - A reconversion plant to make UO_2 powder
  - The Components and Assembly Unit produces fuel pellets, fuel rods, and fuel elements for Brazilian reactors.
- Sociedade de Proposito Especifico (SPE) will build Brazil's nuclear submarines at the new shipyard being built at Itaguai
  - Consortium consists of Brazil's Odebrecht (50%), France's DCNS (49%) and the Brazilian Navy (1%)

Submarine base & shipyard at Itaguai

Conceptual arrangement of Brazil's Itaguai submarine base and shipyard

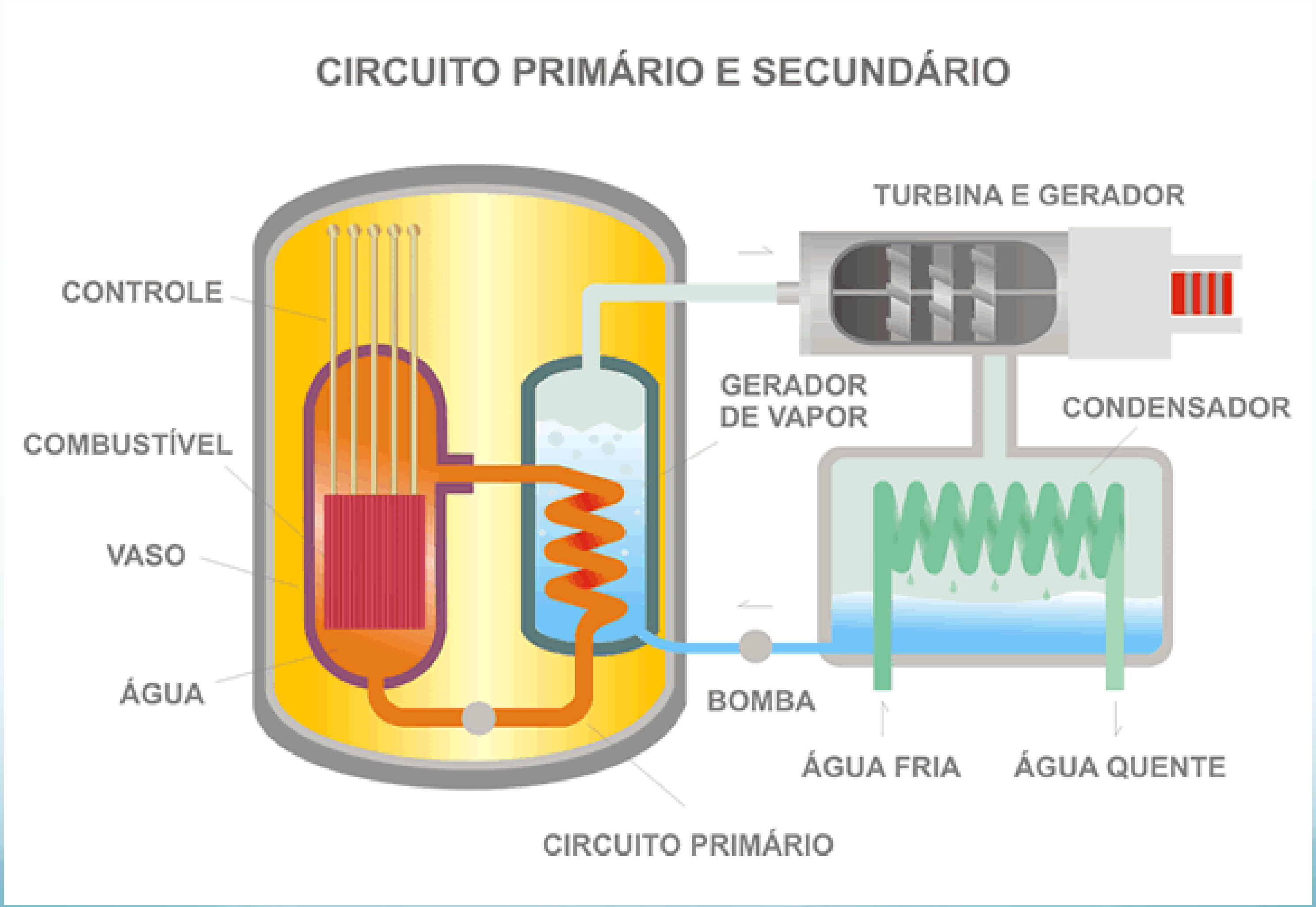
Source: www.defesanet.com.br

Main building of the construction shipyard, inaugurated Dec 2014; big enough to assemble two subs in parallel

Source: www.sinodefenceforum.com

RENAP-11 naval PWR prototype

(Reactor Naval de Potência (PWR) de 11 Megawatts)

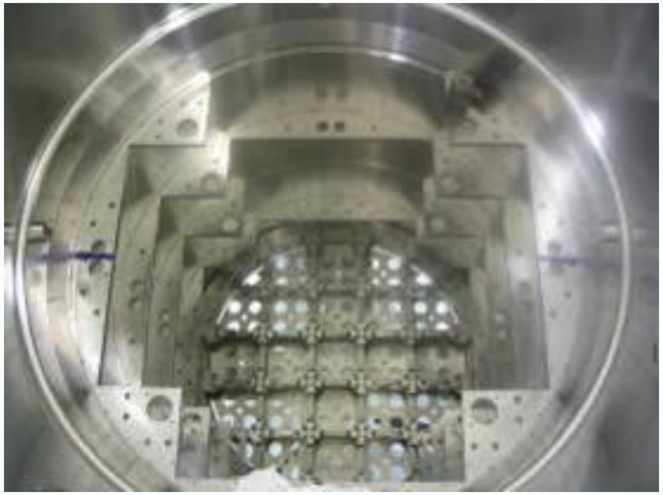


Source: www.zona-militar.com

RENAP-11 naval PWR prototype

(Reactor Naval de Potência (PWR) de 11 Megawatts)

- 2-loop PWR rated, believed to be rated at 11 MWt
- Core comprised of 21 fuel elements (based on reactor grid plate in photo at right)
- Reactor systems are enclosed by a steel containment, surrounded by a water tank for shielding and, if needed, passive cooling.



Source: www.zona-militar.com

- Main components of the secondary circuit include turbo-generators, main condensers, condensate pumps & feedwater pumps.
- Most of the main equipment has been manufactured, delivered and is in storage awaiting further progress on building construction.
- Completion of the prototype reactor facility and commissioning the submarine prototype reactor seems possible in the 2016 – 2017 timeframe.
- The prototype reactor facility is licensed by *Comissão Nacional de Energia Nuclear* (CNEN), Directorate of Radiation Protection and Safety (DRS)

Brazil's 2131-R naval PWR

Models displayed at LAAD 2013 exhibition, Rio de Janeiro

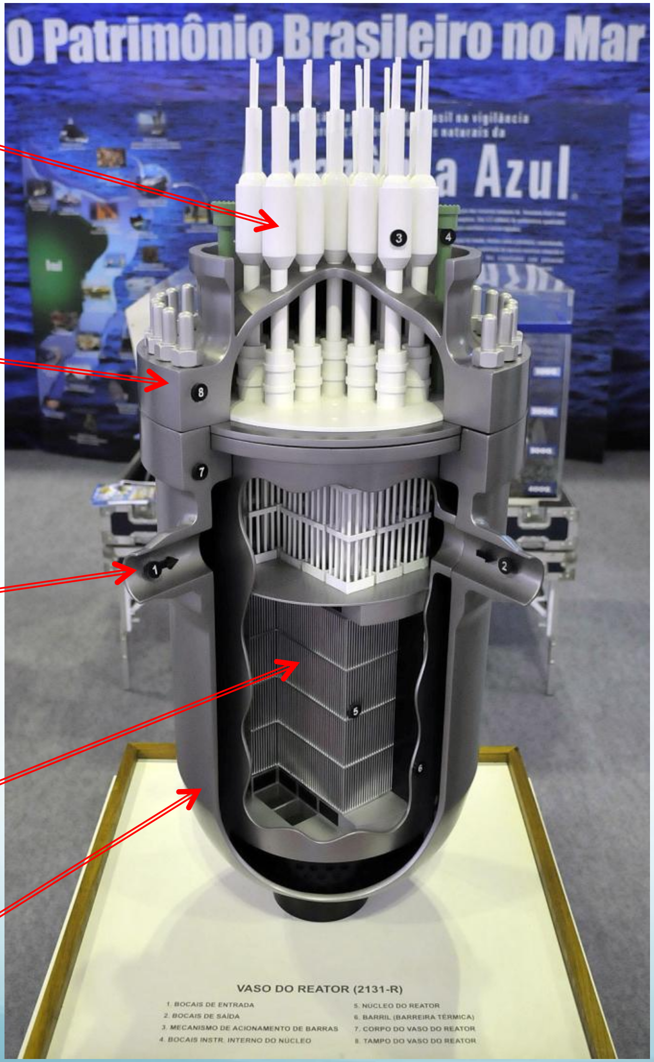
Control rod drive mechanisms

Reactor vessel head

Primary coolant loop piping nozzle (typ. of 4)

Reactor core

Reactor vessel



48 MWt

21 x 21 fuel element

Individual fuel rods

Source: www.zona-militar.com

Brazil's nuclear sub - SNBR

Model displayed at LAAD 2013 exhibition, Rio de Janeiro.

Source: www.shephardmedia.com

Two submarine versions were revealed at LAAD 2013:

- One version with 8 x 533 mm bow torpedo tubes
- A second version with 6 x bow vertical launch system (VLS) tubes and 2 x 533 mm bow torpedo tubes

Brazil's nuclear sub - SNBR

Model displayed at LAAD 2015 exhibition, Rio de Janeiro

Source: www.esdpa.org

SNBR key design parameters:
Length: 100 m (328 ft); hull diameter 9.8m (32.2 ft)
Displacement: 4,000 tons submerge

Brazil current trends

- New build
  - Construction on the 1st indigenous nuclear submarine has not yet started.
  - The industrial consortium is in place and the new submarine construction facility at the shipyard at Itaguai has been completed.
  - Progress on executing the new-build submarine program likely will be affected by Brazil's current weak economy, which could result in a stretch-out of submarine procurement.
- Operations
  - Only conventional submarine operations until delivery of the first indigenous nuclear submarine, expected no sooner than 2023.
- New weapons system development
  - No indigenous weapons expected. Brazil's submarine force currently operates the U.S. Mark 48 heavyweight torpedo and the French SM-39 Exocet submarine-launched anti-ship cruise missile.
- New submarine development
  - Development of the 1st indigenous submarine, the SNBR, is in progress.
- New marine reactor development
  - The RENAP-11 naval reactor prototype being built at the Brazil Navy's Aramar Experimental Center is not likely to be completed before 2016 – 17.
  - The first indigenous submarine reactor is expected to be the 48 MWt 2131-R naval PWR as displayed in model form at the LAAD 2013 & 2015 exhibitions

Italy

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

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 U.S., 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 U.S. 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 U.S. 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

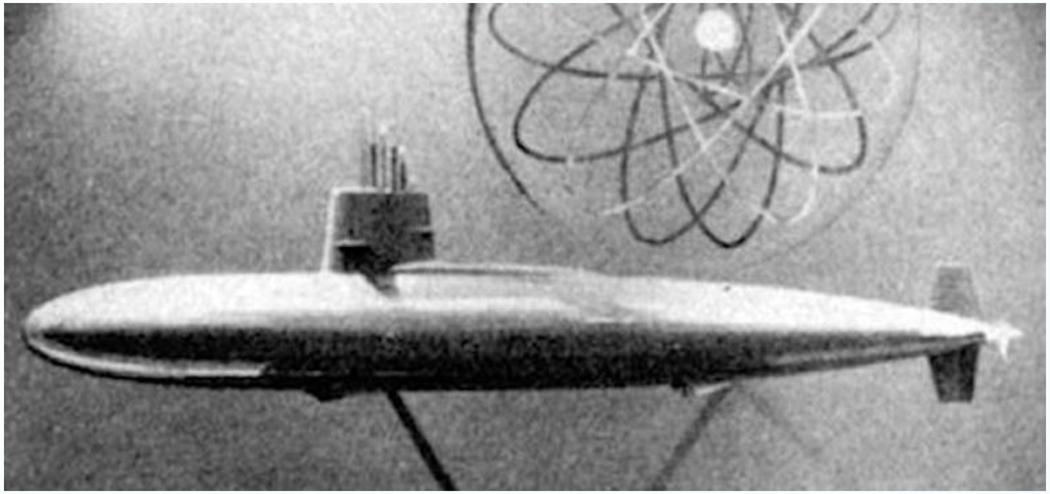
Timeline for the Italian naval nuclear program

- 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 U.S. 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 U.S. 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.
- U.S. refused to supply the reactor. The *Marconi* SSN project was cancelled in 1963-1964.

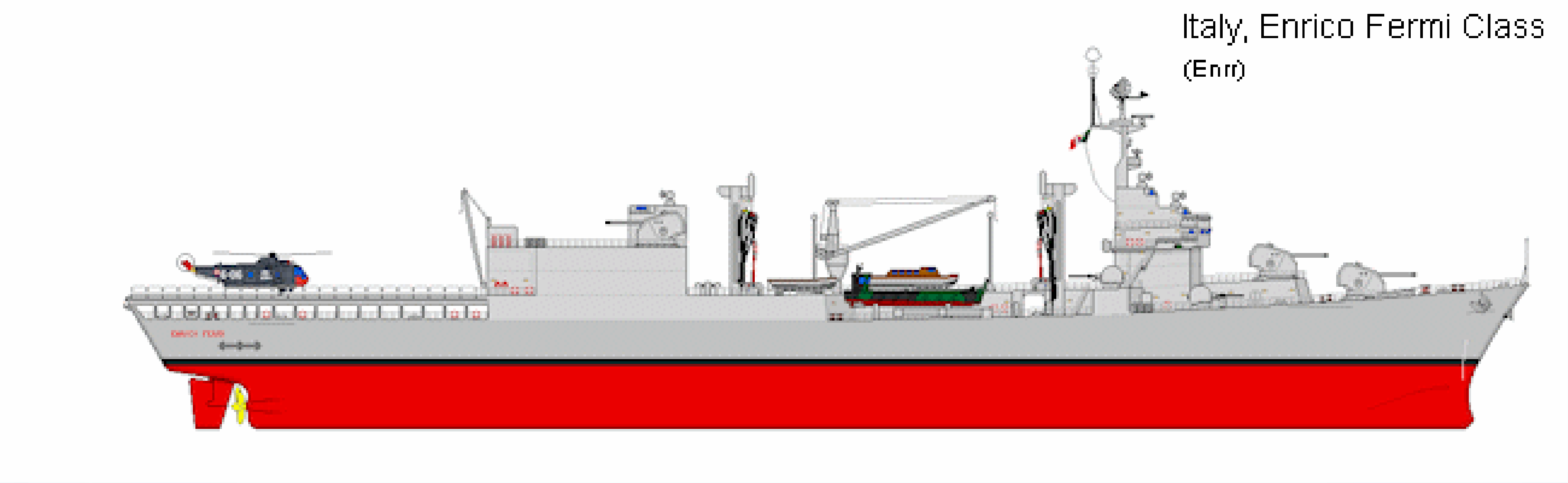
Comparison of *Guglielmo Marconi* and *USS Skipjack*

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.

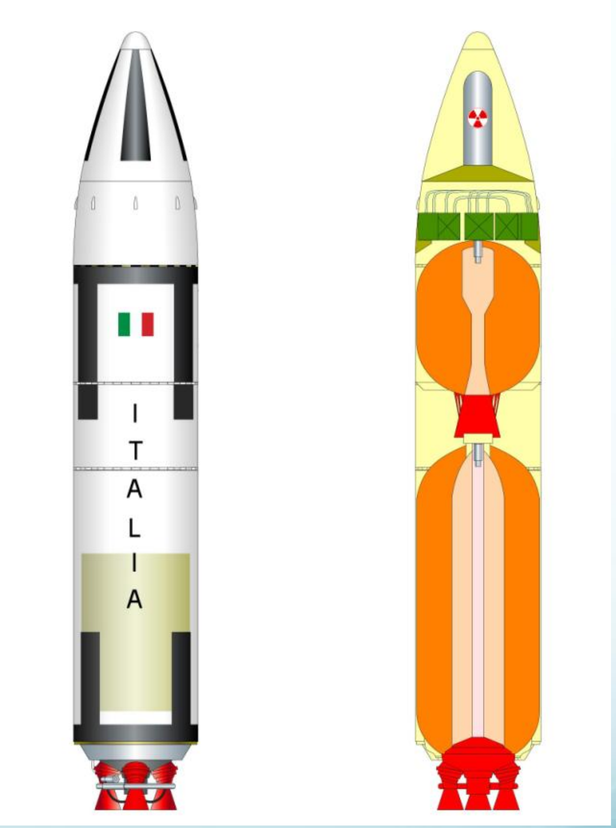
Alfa

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 it's 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 U.S. pressure Italy signed the Nuclear Non-proliferation Treaty as a non-nuclear state on 2 May 1975.



Source: Wikipedia, Giuseppe De Chiara 1968

Canada

Former interest in a
Coast Guard heavy nuclear icebreaker,
Naval nuclear submarines, and the
SAGA-N commercial nuclear submarine

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 U.S. 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" Defence White Paper* 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 marine vessel studies

- The Canadian government studied, but did not proceed with, the acquisition of any of the following nuclear marine vessels:
  - 1970 – 1980s: A nuclear powered polar icebreaker for the Canadian Coast Guard, to support economic development in the Canadian Arctic
  - 1987: 10 - 12 nuclear submarines (SSNs) for the Canadian Navy, as announced in the Government's *Defence White Paper.*
    - The UK or France were the candidate suppliers.
  - Late-1980s: "Nuclear battery", 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 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 icebreaker, with acquisition in the 1990s.
- In 1976, the Cabinet funded the design of a Class 10 nuclear 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: U.S., 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, who offered to transfer the needed marine nuclear technology to Canada.
- The project was cancelled in the early 1980s for several reasons, including:
  - 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
  - Commercial exploitation of Canada’s Arctic resources was occurring slower than expected, and thereby weakening the business case for the Class 10 icebreaker.

Nuclear submarine fleet plans

- In 1987, the Canadian "*Defence White Paper*" recommended the purchase of 10 to 12 French *Rubis* or UK *Trafalger*-class nuclear-powered submarines, with the goal of building up a three-ocean Navy to assert Canadian sovereignty over Arctic waters.
  - 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 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 to Canada.
- The plan to purchase nuclear submarines was finally abandoned in April 1989.
- 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 in 2015.
  - Unreliability has made these subs largely unusable.

SAGA-N

Commercial nuclear-powered mini-submarine

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

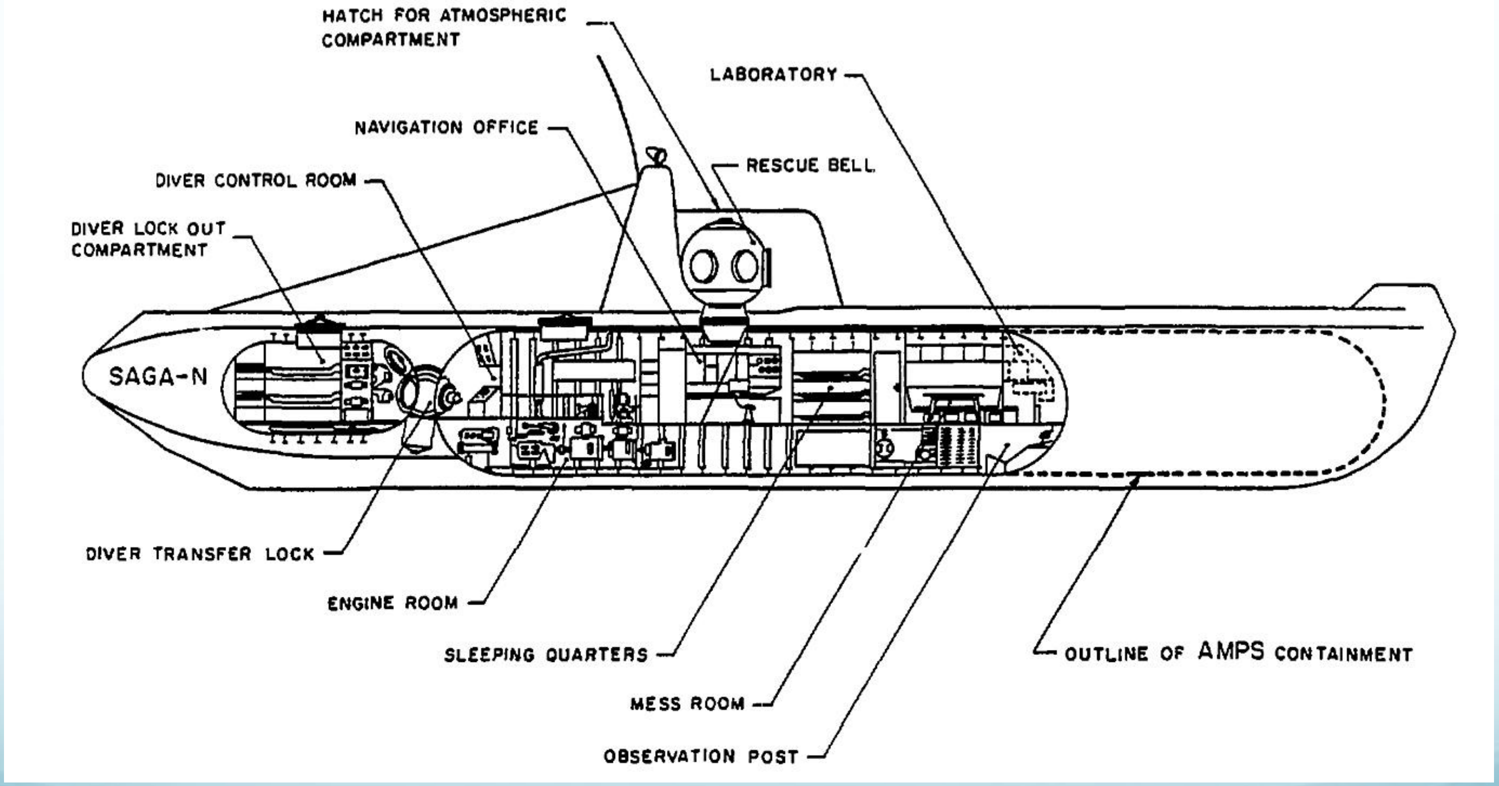
Source: http://www.anciencomex.com/

- 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 nucleat 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 and other work site operations to 600 m, both at submerged ranges to 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.



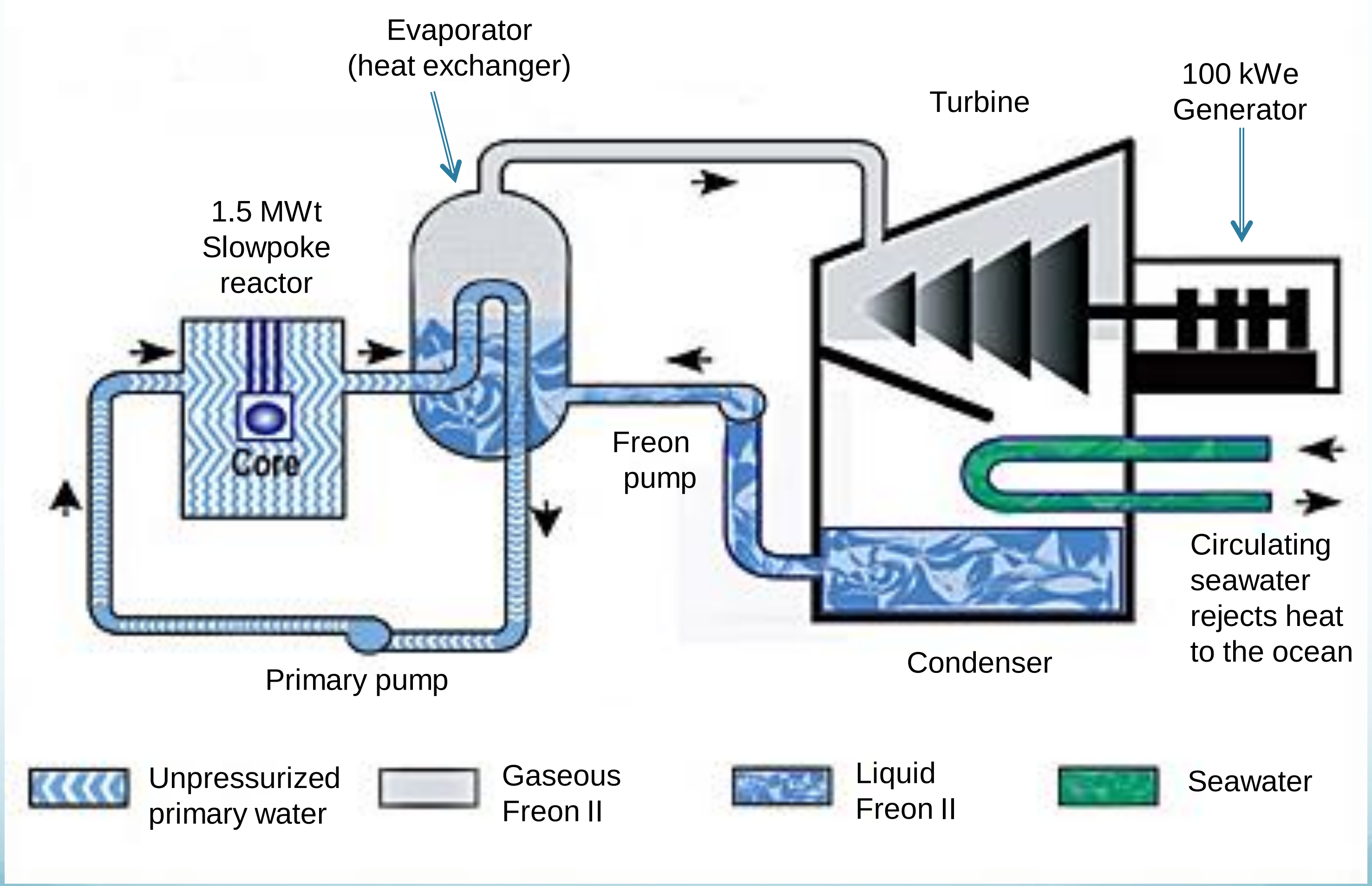
Source: SAGA-N, a nuclear-powered submarine vehicle for commercial operation, Hewitt, J.S.; Wilkins, P.; Kastner, G.A., Proceedings of the Canadian Nuclear Society sixth annual conference, 1985

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).

Australia

Modernization of the submarine force

- Royal Australian Navy submarine force is based in Western Australia with a small fleet of 6 x Collins-class diesel-electric subs.
  - These boats entered service between 1996 and 2003 and will begin to reach the end of their useful life in 2026

- SEA-1000 (Future Submarine Program) study is evaluating Australia's options for a next-generation sub.
  - Preference seems to be for a conventionally-powered sub with air-independent propulsion (AIP)
  - Nuclear propulsion seems to be an unlikely alternative because of a lack of an indigenous nuclear industry, lack of marine nuclear regulatory infrastructure, and adverse public opposition
  - French firm DCNS is proposing a technical transfer program similar to the program being implemented now in Brazil for the in-country construction of conventional and nuclear-powered subs
  - A winning design is expected to be announced before 2016.

North Korea

Conventionally-powered submarine force

- North Korea currently operates a small fleet of conventionally-powered submarines, believed to include the following:
  - 4 former Soviet Whiskey-class diesel-electric subs (early Cold War-vintage)
  - 22 Soviet-designed Romeo-class (Chinese Type 033) diesel-electric subs
    - Seven imported from China, the others locally assembled from Chinese-supplied parts
  - Up to 40 Sang-O class coastal subs displacing 325 tons submerged
  - 10 midget submarines of the Yono class
- While North Korea has a program to develop nuclear-armed submarine launched ballistic missiles (SLBMs), it appears that their current focus is on installing these missiles on conventionally-powered submarines.

North Korea

Refurbished former Russian Golf II-class SSB

- By 1990, all Russian diesel-powered Golf-class ballistic missile submarines were decommissioned.
  - These subs were capable of launching three R-21 liquid-propellant SLBMs.
  - Ten decommissioned Golf II submarines were sold to North Korea in 1993 – 94, to be dismantled under Russian military observation.
- On 1 Nov 2014, North Korea launched a refurbished Golf II sub, either for active service or as a testbed to support development of submarine launched ballistic missiles (SLBMs) for a similar indigenous sub.
  - First reported in October 2014 by the U.S.- Korea Institute at the Johns Hopkins School of Advanced International Studies in the U.S.
- On-going tests conducted on land and sea are supporting development of a modern submarine missile launching capability.

Missile launch from a missile tube in the sail of a submerged Golf II submarine

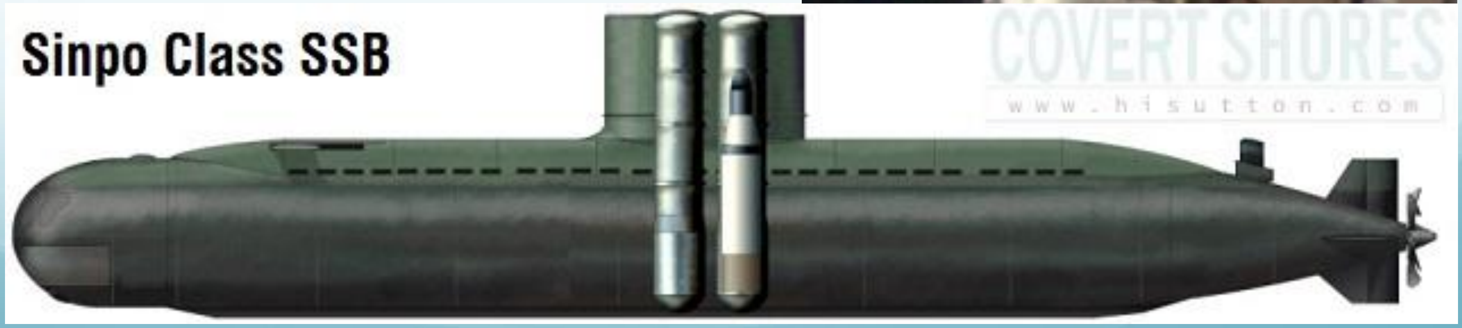
Source: FAS.org

North Korea

Sinpo-class indigenous SSB

Source: 38north.org

- North Korea is developing a new class of ballistic missile submarines based on the design of the Soviet-era Golf-II class submarine.
  - It is not known if this sub is intended as a testbed or as an operational unit.
- Preliminary evidence points to a conventionally-powered sub about 65-68 m (213 – 223 ft) long, with two missile launch tubes in a 10 m (32.8 ft) long sail.
- The commercial satellite photo shows the suspected submarine at the Sinpo South Shipyard in December 2014.
- A speculative view of the missile tube installation in the sub is shown below.



Israel

Modern conventionally-powered submarine force

- Israel's submarine force currently consists of three Type 800 Dolphin-class submarines and two Dolphin II submarines manufactured in Germany at the ThyssenKrupp’s Howaldtswerke (HDW) shipyard in Kiel.
  - The first three boats are diesel-electric Type 800 Dolphin subs built in the 1990s
    - Basic parameters: Length: 57.3 meters (188 ft); displacement: 1,565 tons surfaced, 1,720 tons submerged
  - 4th & 5th boats, the INS Tannin, and INS Rahav, are more advanced Dolphin II class submarines, capable of remaining submerged for long periods (weeks) using “air independent propulsion” (AIP) technology, which allows the engines of diesel-electric submarines to run without atmospheric oxygen
    - Basic parameters: Length: 68.6 meters (225 ft); displacement: 2,050 tons surfaced, 2,400 tons submerged
  - March 2012: Israel and Germany signed a contract a third Dolphin II submarine that will be delivered in the 2015 – 16 timeframe at a cost of about 600 million Euro.

Israel

Modern conventionally-powered submarine force

- Armament:
  - Ten torpedo tubes: 4 x 650 mm (25.6 in)diameter and 6 x 533 mm (21 in) diameter tubes for a variety of weapons, including DM-2A4 Seehake wire-guided torpedoes, UGM-84C Harpoon anti-ship cruise missiles and Triton anti-helicopter missiles.
  - Also likely to carry Israel’s indigenous Popeye Turbo cruise missile, which is believed to have a range of up to 1,500 km (932 mi) and carry a 200 kg (441 lb) payload.
- Operational matters:
  - Israeli subs have operated in the Persian Gulf
  - 2011: Israel invested about $27 million in a comprehensive structural overhaul and upgrade of the three Dolphin I submarines at a shipyard in Haifa, including 650 mm (25.6 in) torpedo tubes and larger fuel tanks.

Israel

Dolphin II-class AIP submarine IHS Tannin prior to delivery

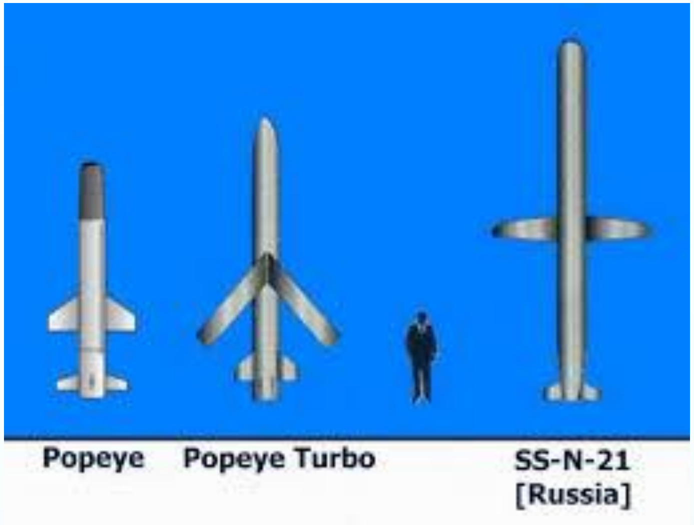
Source, all photos: http://intercepts.defensenews.com/2014/08/

Popeye

Indigenous subsonic cruise missile family

- 2000: Israel's request for U.S. Tomahawk cruise missiles was rejected by the Clinton administration on the grounds that the sale would violate the Missile Technology Control Regime (MTCR) restriction on missiles with ranges > 300 km (185 mi).
- Israel's Navy operates shorter-range U.S. Harpoon cruise missiles with anti-ship and land-attack capabilities.

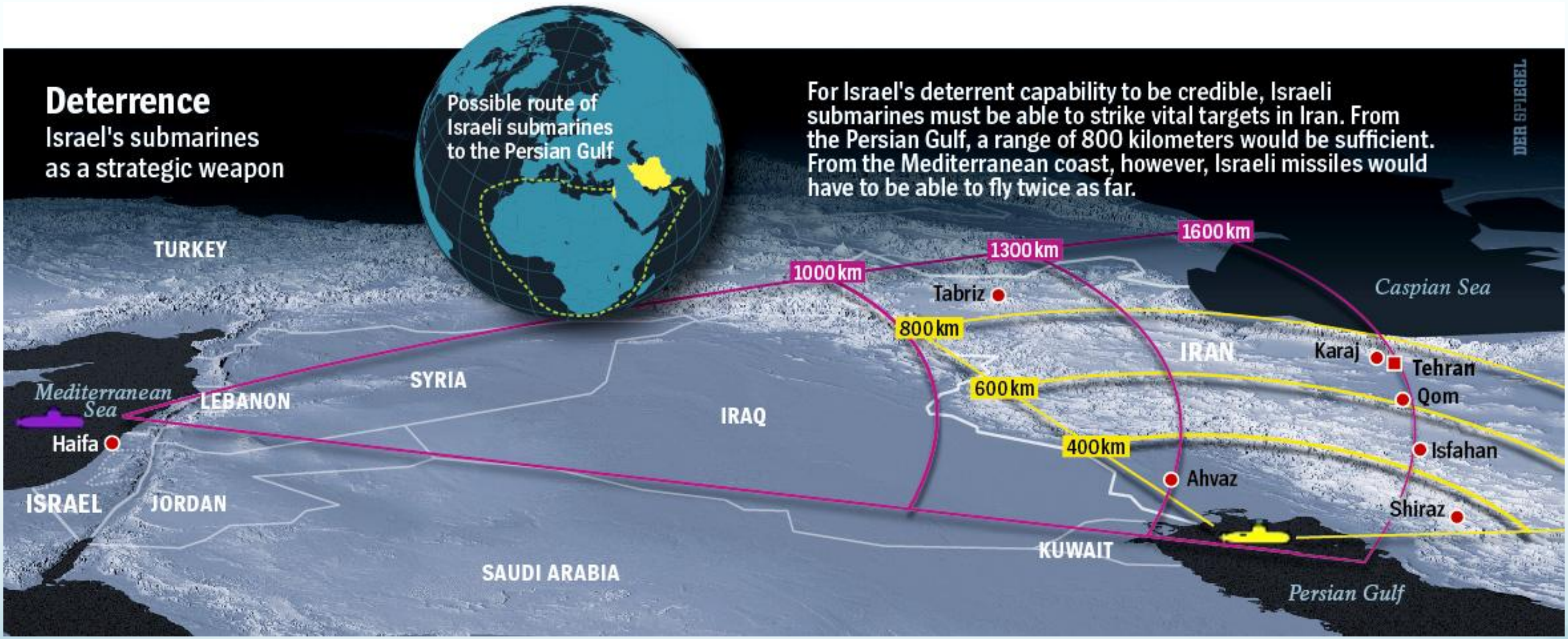
Source: http://fas.org/nuke/guide/israel/missile/popeye-t.htm



- Popeye cruise missiles are produced in several versions (ship-, submarine-, and air-launched) and are sold to several nations, including the U.S.
- 2002: 1^{st} long-range (1,500 km) test flight of a variant of the indigenous Popeye Turbo submarine-launched cruise missile (SLCM) occurred in the Indian Ocean.
- The long-range Popeye Turbo SLCM has the capability to serve as a strategic second-strike nuclear deterrent weapon.

Israel

Deterrence capability with a long-range submarine-launched cruise missile



Source: http://www.supervideo.com/dolphin.htm

Pakistan

Aging conventionally-powered submarine force

- Pakistan has a long-standing goal of acquiring a sea-based nuclear deterrent as part of its maritime strategy.
- Pakistan's Navy currently operates five French Agosta submarines (two older Agosta-70 boats & three modern Agosta-90B). The two 40 years old Agosta-70 boats are in need of replacement.
- On 31 March 2015, *Daily Pakistan Global* reported that Pakistan Navy officials informed the National Assembly's standing committee for defense on plans for new submarine purchases:
  - France refused to sell six air independent propulsion (AIP)-equipped Scorpène submarines to Pakistan, citing technology transfer issues. However, France is selling Scorpène to India.
  - Pakistan announced plans to buy eight new Chinese submarines that likely will be based of the Type 39B Yuan SSK with AIP.
- An October 2013 article in *The Diplomat* by Haris Khan, a senior analyst at PakDef Military Consortium, reported that the Pakistan Atomic Energy Commission (PAEC) has a project known as KPC-3, "to design and manufacture a miniaturized nuclear power plant for a submarine."
- PAEC and National Engineering and Scientific Commission (NESCOM) have been working on a miniaturized plutonium warhead, which could be used on a naval version of Pakistan's indigenous Babur land attack cruise missile (similar to the U.S. Tomahawk).
  - The naval version of Babur can be launched from a standard 533 mm torpedo tube.

Babur (Hatf VII)

Indigenous subsonic cruise missile family

- Basic design features are comparable to a U.S. BGM-109 Tomahawk cruise missile.
- Turbojet or turbofan powered; speed about 550 mph (885 kph); range about 621 miles (1,000 km); can be armed with conventional or nuclear warheads.
- Ground-, ship- and submarine-launched versions. Can be launched from a 533 mm (21 in) standard torpedo tube.

Source: http://www.terminalx.org

Iran

Conventionally-powered submarine force but possible aspirations for nuclear-powered submarines

- Iran's submarine force currently consists of three Russian-designed Kilo-class (4,000 ton) diesel-electric subs and several small (400 ton) and midget (150 ton) conventionally-powered subs.
  - The Kilo-class and small/midget submarines create a balance between littoral defensive operations and offensive operations further from the Persian Gulf.
  - The Kilo subs have been in service for about 20 years.
- Iran has a plan to develop one or more indigenous conventionally-powered submarine types.
- In June 2012, an Iranian official asserted that scientists were "at the initial phases of manufacturing atomic submarines.”
  - Senior Iranian naval officers have said that they plan to use fuel enriched to 45 - 56% U-235.
  - Outside analysts stressed that manufacturing a nuclear reactor for use in submarines would be beyond Iran's current capabilities, suggesting that the announcement may have been meant as leverage in negotiations with the West.