Marine Nuclear Power: 1939 – 2018

Part 2B: United States - Surface Ships

Peter Lobner

July 2018

Foreword

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

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

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

Foreword

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

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

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

Best regards,

Peter Lobner
July 2018

Marine Nuclear Power: 1939 – 2018
Part 2B: United States Surface Ships

Table of Contents

Marine Nuclear Power: 1939 – 2018

Refer to Part 2A, *United States - Submarines*, for the following content related to US marine nuclear power:

- Timeline for development of marine nuclear power in the US
- US current nuclear vessel fleet
- US naval nuclear infrastructure
- Use of highly-enriched uranium (HEU) in US naval reactors
- US submarine reactors and reactor prototype facilities
- US Navy nuclear-powered submarines
  - Nuclear-powered fast attack submarines (SSN)
  - Nuclear-powered strategic ballistic missile submarines (SSBN)
  - Nuclear-powered guided missile submarines (SSGN)
  - Nuclear-powered special operations submarines

US naval surface ship reactors & prototype facilities

US naval reactor designation scheme

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

US naval surface ship reactors

Reactor	Estimated Reactor Power (MWt)	Estimated Propulsion Power per Reactor (shp)	Initial ops	Application
CVR	390	75,000	Not built	• Proposed land-based prototype PWR for a single propulsion train rated at about 75,000 shp. • Authorized in 1952 & cancelled in 1953. • Became the basis for the design of the 1st full-scale US commercial nuclear power plant at Shippingport, PA.
C1W	200	40,000	1961	• 2 x C1W used only on *USS Long Beach* (CGN-9), yielding 80,000 shp total propulsion power. • Reportedly derived from A1W.
D1G, D2G	148	30,000	1962	• D1G prototype, West Milton, NY. • 2 x D2G used on *USS Bainbridge* (CGN-25), *USS Truxtun* (CGN-35) and all California (CGN-36) and Virginia (CGN-38)-class CGNs, yielding 60,000 shp total propulsion power.
D1G-2	150	30,000	1976	• Not used in any surface ship, in spite of its “D” designation. • Used as the original core in the S6G nuclear plant on 31 x 688 Flight I Los Angeles-class SSNs. One mid-life refueling required at the mid-point of sub’s 30 year service life.
D1W	300	60,000 – 70,000	Not built	• Originally conceived as a low-cost, simple, lightweight, single-reactor propulsion plant for a destroyer. • Project approved in 1960, but redirected in 1962 to a more powerful two-reactor design for large surface ships. • Planned to be the APHNAS submarine propulsion plant (1971).

US naval surface ship reactors

Reactor	Estimated Reactor Power (MWt)	Estimated Propulsion Power per Reactor (shp)	Initial ops	Application
D2W	165	30,000 – 35,000 (33,500 for 688 SSNs)	1985	• Used as the mid-life refueling core for the 2 x D2G propulsion plants on California-class (CGN-36) CGNs. • Likely reactor choice, 2 x D2W, for the CGN-42 and CSGN cruisers, which were not built. • Used as the mid-life refueling core in the S6G submarine propulsion plant for 20 x 688 Flight I SSNs. • Used as the original core in the S6G submarine propulsion plant for 8 x 688 Flight II and 23 x 688i Los Angeles-class SSNs. Life-of-the-boat core for the sub's extended 33 year service life.
A1W, A2W	165	35,000	1958	• 2 x A1W at the prototype at NRF Idaho (A1W-A & A1W-B) • 8 x A2W on *USS Enterprise* (CVN-65), yielding a total reactor power output of about 1,320 MWt and propulsion power of 280,000 shp
A3W	300	70,000	Not built	• 4 x A3W intended for *USS John F Kennedy* (CVN-67), yielding a total reactor power output of about 1,200 MWt and propulsion power of 280,000 shp • CVN-67 keel laid in 1964, but design was changed and completed as a conventionally-powered CV. A3W was not built.

US naval surface ship reactors

Reactor	Estimated Reactor Power (MWt)	Estimated Propulsion Power per Reactor (shp)	Initial ops	Application
A4W	550	130,000	1975	• Evolved from the D1W reactor design. • ¼ core was tested in the A1W-B prototype • 2 x A4W on each Nimitz-class CVN yielding a total reactor power output of about 1,100 MWt and propulsion power of 260,000 shp. • One mid-life refueling required for a 50 year CVN service life. Core life is about 25 years.
A1G	550	130,000	Not known	This is the General Electric replacement core for the A4W.
A1B	> 550	130,000	2017	• 2 x A1B on each Ford-class CVN, yielding a total reactor power output of >1,100 MWt and propulsion power of 260,000 shp. The nuclear plants on Ford-class CVNs support almost twice the electric power generating capacity as on Nimitz-class CVNs. • Core life is about 25 years. One mid-life refueling required for a 50 year CVN service life. • A1B core has 25% more energy than the A4W core.

Westinghouse CVR

Large ship reactor (LSR) / carrier vessel reactor (CVR)

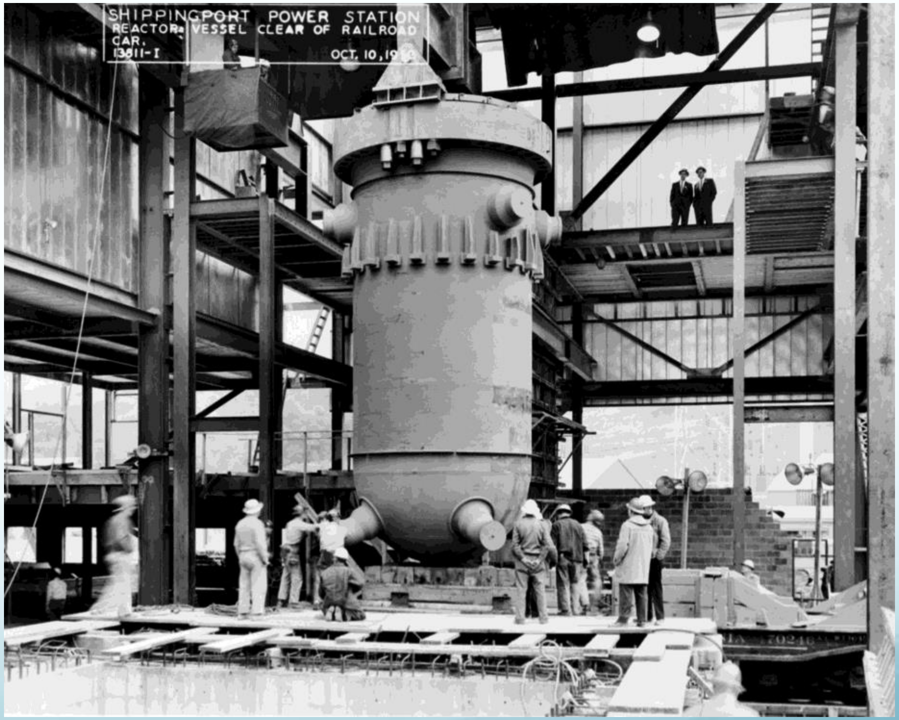
- "This project, known as the CVR, was instituted on the basis of a military requirement set up by the Joint Chiefs of Staff. That requirement stated that the CVR was to be a shore-based prototype of a single shaft for a large naval vessel such as an aircraft carrier, and to be used after completion to produce power and plutonium." *
  - CVR was a light-water cooled and moderated pressurized water reactor (PWR) design with an expected propulsion output of 75,000 shp (56 MW). Reactor power would have been about 390 MWt.
- CVR was authorized in 1952.
- April 1953: The CVR was eliminated from the FY 1954 defense budget.
- "Cancellation of the aircraft carrier reactor resulted in a letter appeal from the (Atomic Energy) Commission to the President (Eisenhower) and a special appearance before the Joint Committee (of Congress). As a result, a completely civilian version of the aircraft carrier reactor was put back in the fiscal 1954 budget….." *
  - The AEC transferred the entire development team to the new civilian project, while maintaining Naval Reactors is a leadership role.
- In their testimony before Congress, the AEC noted, "We are convinced that substantial delays would result if an attempt were made to develop some other reactor system for this first civilian powerplant." *

* Source: Hearings Before the Joint Committee on Atomic Energy, 86th Congress, 1st Session, 11 & 15 Apr 1959

Westinghouse Shippingport

An analog for what CVR might have been

- The CVR prototype design and development work done by Naval Reactors and its industrial team became the starting point for the realigned civilian project to build a PWR as the first US full-scale commercial nuclear power plant, which would become the Shippingport Atomic Power Station operated by Duquesne Light Co.
- Shippingport reactor design and construction was managed by Naval Reactors and built by the former CVR prime contractor, Westinghouse. Babcock & Wilcox (today BWTX) manufactured the reactor vessel and other large components.
- The rapid startup of Shippingport construction is an indication of the advanced state of design and development of the original CVR prototype.
    - September 1954: Ground broken (this was only 17 months after CVR was eliminated from the Defense budget).
    - The plant was built in 32 months at a cost of $72.5 M.
    - 2 December 1957: Initial criticality
    - 23 December 1957: The plant was connected to the grid for the first time and operated at full power (231 MWt) delivering 60 MWe to the grid.



Shippingport reactor vessel. Source: Library of Congress, Prints and Photography Division, Digital ID hhh.pa1658

Westinghouse Shippingport

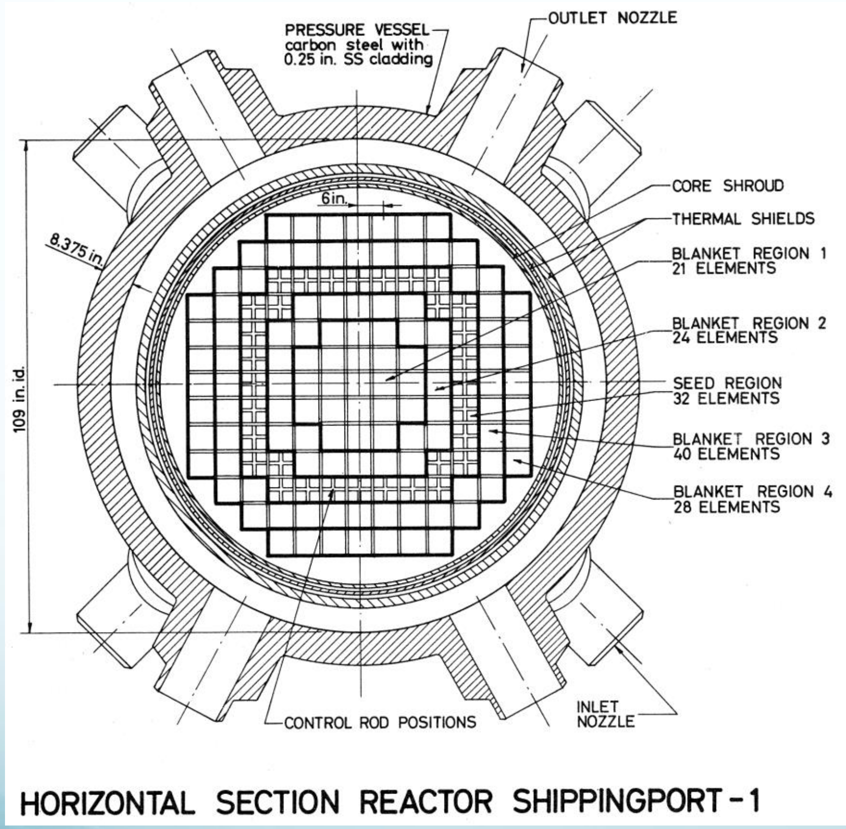
An analog for what CVR might have been

- One of the main purposes of this plant was to develop and test new technologies to reduce the cost of future nuclear power plants, not to optimize current technology and deliver maximum efficiency from this plant.
- The first two reactor cores were "seed-and-blanket" designs, with an annular HEU (93% enriched) "seed" region surrounded inside and outside by a natural uranium "blanket." This core design is attributed to Alvin Radkowsky, NR Chief Scientist.
- Core 1 operated from December 1957 to February 1964 with three refuelings of the seed region.
  - The HEU annular seed region was comprised of 32 fuel elements with Zircaloy-2 clad, plate-type, metallic alloy fuel containing 198 pounds (90 kg) of U-235. Reactor control was provided by 32 cruciform hafnium control rods, one in each fuel element.
  - The blanket regions were comprised of 113 blanket elements containing 17.6 tons (16,000 kg) of natural uranium in the form of UO_2 pellets clad in Zircalloy-2 tubes.
  - During operation, fissionable plutonium was produced in the blanket, yielding about 50% of the core power.
- Core 2 was an advanced seed-and-blanket design that operated from April 1965 to February 1974 with one seed refueling.
  - The HEU annular seed region was comprised of 20 fuel elements with Zircaloy-2 clad, plate-type, metallic alloy fuel containing 741 lb (336 kg) of U-235. Reactor control was provided by 20 cruciform hafnium control rods, one in each fuel element.
  - The blanket regions were comprised of 77 blanket elements with natural uranium in the form of Zircaloy-2 clad, plate-type, metallic alloy fuel containing 23.4 tons (21,200 kg) of natural uranium.
- Thereafter, Shippingport operated with a different core design for the Department of Energy (DOE, then known as ERDA) light water breeder reactor program before being decommissioned in December 1989.

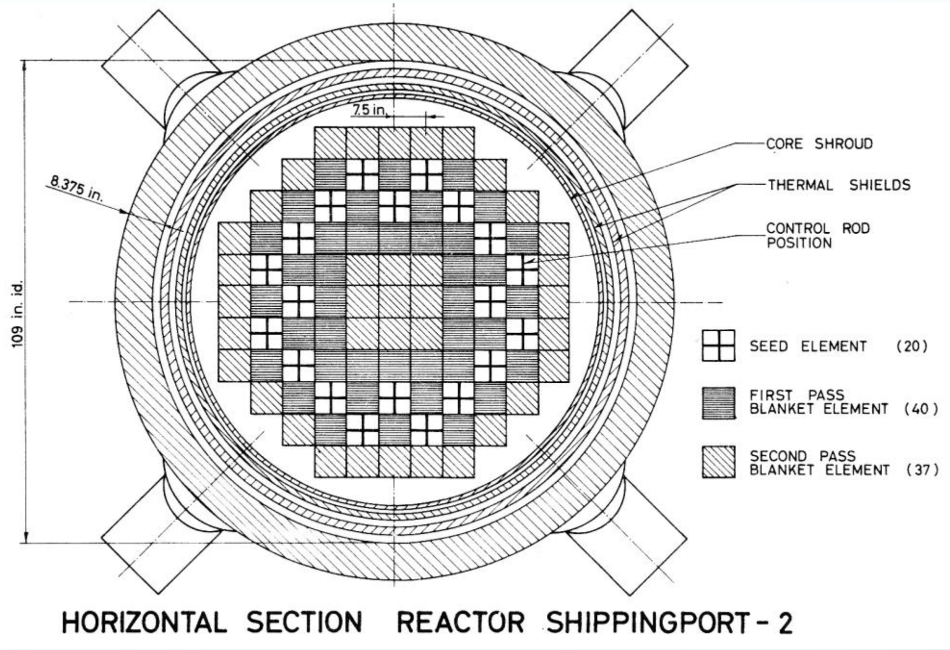
Westinghouse Shippingport

An analog for what CVR might have been

Core 1



Core 2



Source: "Directory of Nuclear Reactors, Vol. IV, Power Reactors," International Atomic Energy Agency (IAEA), Vienna, 1962

Westinghouse Shippingport

An analog for what CVR might have been

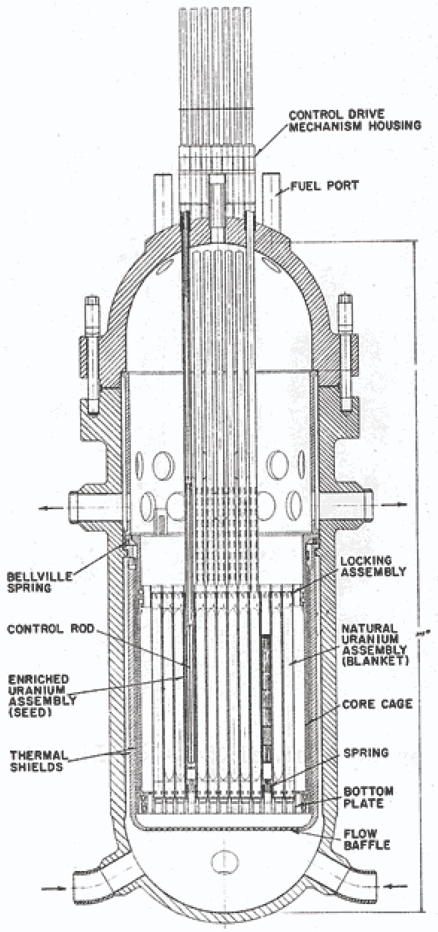


Fig. III-3 -- Longitudinal section of reactor vessel

MG 508/ PA STATE ARCHIVES

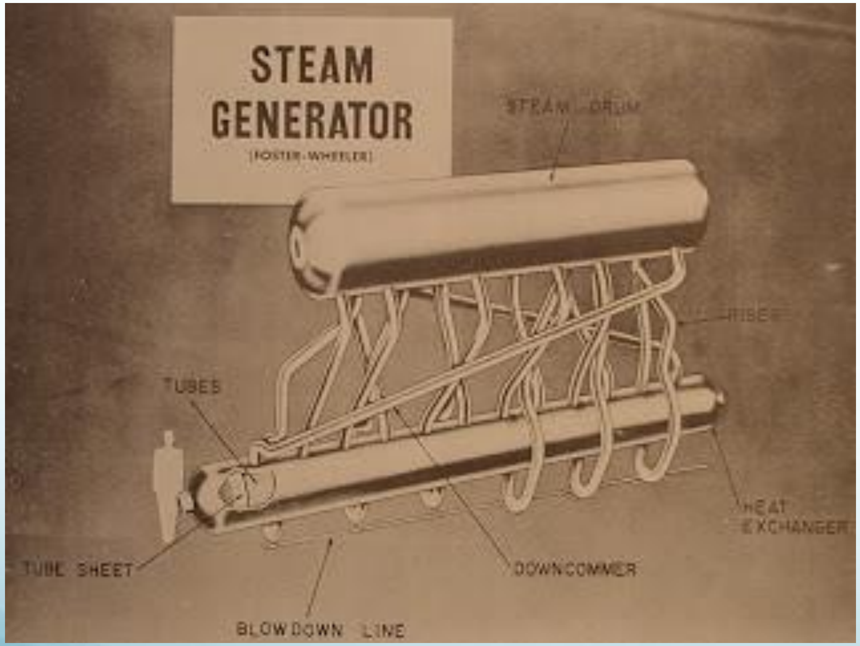
Source: Pennsylvania State Archives

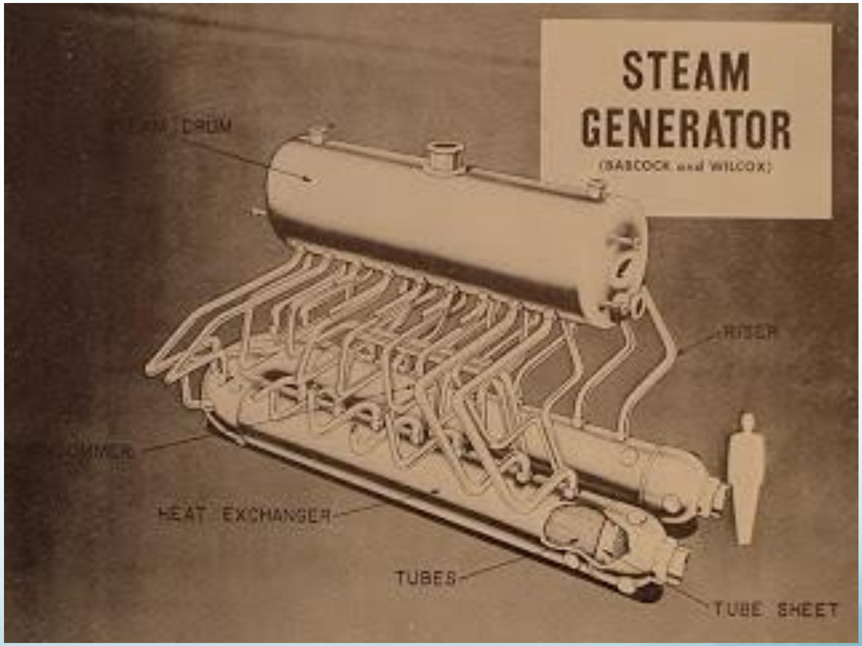
- In the Shippingport reactor vessel layout diagram, note the hot leg (outlet) nozzles are above the level of the reactor core, near the vessel mid-plane, and the cold leg (return) nozzles are at the bottom of the reactor vessel. In later PWR vessel designs, the cold leg nozzles universally have been moved up, above the level of the reactor core (i.e., to prevent draining the reactor vessel if there were a break in primary system loop piping below the level of the core).
- At full power (with 3 of 4 primary loops operating), Core 1 was rated at 231 MWt and the plant had a net electrical output of 60 MWe.
  - In comparison, the A1W / A2W reactors developed later for the *USS Enterprise* were rated at about 170 MWt. These were much more compact reactors fueled entirely by HEU.
- At full power, Core 2 was rated at 505 MWt. The steam generators were sized to handle the greater thermal output, but the secondary system was limited by the 100 MWe capacity of the turbine generators. To handle the greater heat load, a steam bypass line was added to route surplus steam (equivalent to an added 50 MWe) through a separate air-cooled condenser.
  - In comparison, the A4W reactor developed later for the Nimitz-class aircraft carriers are rated at about 550 MWt.

Westinghouse Shippingport

An analog for what CVR might have been

- Shippingport was a 4-loop PWR with two different horizontal steam generator designs. Both had a separate heat exchanger and steam drum connected by a network of slender steam riser tubes that delivered saturated steam to the steam drum. Another set of slender downcomer tubes returned condensed saturated water to the heat exchanger.
  - Two steam generators were from Foster Wheeler (left) and two were for Babcock & Wilcox (right).
  - This gave Naval Reactors the opportunity to evaluate the actual performance of competing designs to help optimize the steam generator design in future naval propulsion plants.





Source: Shippingport Atomic Power Station press package via Atomic Power Review, http://atomicpowerreview.blogspot.com/2012/03/steam-generators-design-and-details.html

Westinghouse C1W

- 1st nuclear propulsion plant designed for use on a cruiser.
  - A product of NR's Large Ship Reactor (LSR) program.
- Originally planned for use in a four-reactor nuclear propulsion plant capable of producing the same propulsion power as a Des Moines-class heavy cruiser: 120,000 shp.
  - The nuclear cruiser propulsion requirement later was reduced to 80,000 shp.
- Applications:
  - There was no C1W prototype. The C1W design was very similar to the A1W / A2W reactor, for which there was a prototype at NRF, Idaho.
    - C1W was scaled to deliver 40,000 shp per reactor vs. 30,000 shp per A1W / A2W reactor.
  - The only use of C1W was on the *USS Long Beach* (CGN-9).
    - The propulsion system consisted of 2 x C1W reactors each rated @ 200 MWt (est.); 2 x steam turbines driving 2 x shafts; delivering a total propulsion power of 80,000 hp (60 MW).
    - *Long Beach's* reactors were refueled twice. Cores 1 & 2 operated for an average of 9.5 years; Core 3 operated for almost 14 years.

General Electric D1G, D2G

High Power Reactor

- The D1G propulsion plant originally was designed for large guided missile “destroyer-leader” class ships (DLGN), which later were reclassified as guided missile cruisers (CGN).
- Applications:
  - The D1G prototype was constructed in the “Horton Sphere” steel containment building previously used for the S2G prototype submarine reactor at the Kenneth A. Kesselring Site in West Milton, NY.
    - 1962: operation started
    - The D1G prototype was refueled with the D1G-2 core
    - March 1996: D1G permanently shut down. Reactor pressure vessel removed in 2002.
  - The D2G was used to power *USS Bainbridge* (CGN-25), *USS Truxtun* (CGN-35), the two California (CGN-36)-class cruisers, and the four Virginia (CGN-38)-class cruisers.
    - The propulsion system consisted of 2 x D2G reactors each rated @ 148 MWt; 2 x steam turbines driving 2 x shafts; total propulsion power 60,000 hp (45 MW).
    - The D2G reactor compartment measured 31 ft. (9.4 m) in diameter x 37 ft. (11.3 m) in length; weighed 1,400 tons.
    - *USS Bainbridge* refueled three times and *USS Truxtun* refueled twice; each time with longer-life cores: 1st cores: 5 – 6.5 years; last cores: 13 years.
    - In the early 1990s, the two California-class CGNs were refueled with more powerful D2W cores during their mid-life overhaul. D2G core 1 life was 16 years.
    - In 1993 the Navy cancelled mid-life refueling overhauls for the four Virginia-class CGNs, which were retired early along with the two California (CGN-36) cruisers.

General Electric D1G-2

- The D1G-2 reactor core is a variant of the surface ship D1G / D2G reactor that was adapted for use in the S6G submarine reactor plant. D1G-2 was not used in any surface ship.
- Applications:
  - The D1G-2 core was the second core tested at the D1G prototype.
  - The D1G-2 was the original core in 31 x Flight I SSN-688 Los Angeles-class SSNs (this was the first "batch" of this class of subs).
    - The propulsion system consisted of 1 x D1G-2 reactor rated @ 150 MWt; 2 x steam turbines driving a single shaft; total propulsion power 30,000 hp (22 MW) (est.).
    - The SSN-688 submarine reactor compartment for the S6G reactor plant has an outside diameter of 33 feet (10.1 meters), a length of 42 feet (12.8 meters) and a weight of about 1,680 tons.
    - 1998 – 2001: 11 x Flight I boats were decommissioned early after their mid-life reactor refuelings were cancelled. These boats had an average of 13 years of life remaining on their 30 year service life. The remaining 20 x Flight I boats were refueled with more powerful D2W cores.

Westinghouse D1W

- Originally conceived as a low-cost, simple, lightweight, single-reactor propulsion plant for a destroyer-class vessel (i.e., ships smaller than the 8,000 ton guideline generally adopted by the Navy for nuclear-powered surface ships).
  - 8,000 – 9,000 ton conventionally-powered Kidd and Spruance-class destroyer propulsion plants delivered 80,000 shp to two screws.
  - 4,000 – 5,500 ton conventionally-powered Charles F. Adams and Farragut-class destroyer propulsion plants delivered 70,000 - 85,000 shp to two screws.
- The single-reactor, small-ship project was approved in 1960.
  - 1961 studies by Bettis, with assistance from Electric Boat, failed to show significant advantages over a two-reactor design in terms of space and weight. The high center of gravity of the reactor plant created a disadvantage for a small ship.
- The project was redirected in 1962 to a larger reactor and a two-reactor propulsion plant designed for larger surface ships.
  - This D1W design was intended to replace a pair of D2G reactors and deliver about 60,000 - 70,000 shp propulsion power. To deliver this output, the reactor would have been rated at about 300 MWt.
  - The project continued into 1964, when it was discussed by Bettis as a possible propulsion plant for an aircraft carrier smaller in size than *USS Forrestal* (CV-59), which was similar in size to a modern Nimitz-class CVN.

Westinghouse D2W

- The D2W reactor core originally was developed as a more powerful replacement for the D1G / D2G reactor core.
- Applications:
  - There was no D2W prototype.
  - The D2W was the mid-life refueling core for the two California (CGN-36) class cruisers, which were refueled in the early 1990s.
    - The 2 x D2G power plants in each cruiser were refueled with a D2W reactor core rated @ 165 MWt. This was expected to give these CGNs an additional 18 - 20 years of service life. These CGNs were retired in 1999, just 5 and 6.5 years after refueling.
  - The D2W likely would have been the mid-life refueling core for the four Virginia (CGN-38)-class cruisers, but their mid-life refuelings were cancelled in 1993. The CGNs were retired between 1994 – 98.
  - The D2W likely would have been the reactor for the planned CGSN Strike Cruiser (cancelled in 1976) and the CGN-42 (cancelled in 1979).
  - D2W was the original core in the S6G submarine power plant used in 8 x 688 Flight II and 23 x 688i (improved) Los Angeles-class SSNs.
    - The S6G submarine propulsion plant consisted of 1 x D2W reactor rated @ 165 MWt; 2 x steam turbines driving 1 x shaft; total propulsion power 33,500 hp (25 MW) (est.).
    - D2W is intended as a life-of-the-boat core for this submarine's extended 33 year service life (originally 30 years).
  - D2W also was the replacement core for the mid-life refueling for 20 x 688 Flight I SSNs (in place of their original D1G-2 core).

Westinghouse A1W, A2W

Large Ship Reactor (LSR)

- 1st nuclear reactor designed for use on an aircraft carrier.
- Applications:
  - The A1W reactor prototype was built at the Naval Reactors Facility (NRF) at the Idaho National Lab (INL)
    - The prototype consists of 2 x A1W reactors (A1W-A & A1W-B) operating as a pair; with their secondary systems supplying steam to 1 x main turbine, driving a single shaft.
      - A dump condensers simulate the transient steam demand during aircraft catapult launches. This was a surplus ESSEX-class main condenser installed adjacent to A1W
    - Early 1956: Start of construction
    - Oct 1958: A1W 1st reactor initial criticality
    - Jul 1959: A1W 2nd reactor initial criticality
    - mid-Sep 1959: full-power operation achieved with both reactors
    - Early 1970s: A1W-B core replaced by ¼ of an A4W core destined for the Nimitz-class aircraft carriers
    - 26 Jan 1994: A1W prototype permanently shut down. About 14,500 students were trained at A1W.
  - The *USS Enterprise* (CVN-65) propulsion system consisted of 8 x A2W reactors each rated @ 170 MWt (est.); supplying 4 x steam turbines driving 4 x shafts; total propulsion power 280,000 hp (210 MW).
    - The secondary system also supplied steam for the ship's turbine generators and catapults.
    - Cores 1 & 2 operated for an average of 3 years; Cores 3 & 4 operated for an average of 18.9 years

Westinghouse A3W

- A1W core 3 provided data that formed the technical basis for the design of a larger reactor and a 4-reactor CVN propulsion plant.
- This new reactor, the A3W, was intended for use on the *USS John F. Kennedy*, which originally was designed as a nuclear-powered aircraft carrier (CVN-67).
- Application:
  - The original CVN-67 propulsion system was to consist of 4 x A3W reactors each rated @ 300 MWt (est.); 4 x steam turbines driving 4 x shafts; total propulsion power 280,000 hp (210 MW).
    - The secondary system also would have supplied steam for the ship's turbine generators and catapults for launching aircraft
    - Core design life is about 23 years.
  - This design was rejected by Secretary of Defense McNamara in 1964.
- The *Kennedy* was redesigned for conventional propulsion and was completed in 1967 as CVA-67. It was the last conventionally-powered aircraft carrier procured by the US Navy.

Westinghouse A4W

- This reactor was developed for, and is used on all 10 of the Nimitz-class aircraft carriers.
- Applications:
  - There was no separate A4W reactor prototype.
    - Early 1970s: At the A1W prototype at the Naval Reactors Facility (NRF) on Idaho National Lab (INL), the A1W-B core was replaced by ¼ of an A4W core.
    - 26 Jan 1994: A1W prototype permanently shut down
  - The Nimitz propulsion system consists of 2 x A4W reactors each rated @ 550 MWt (est.); 4 x steam turbines driving 4 x shafts; total propulsion power is 260,000 hp (194 MW).
    - The secondary system also supplies steam for:
      - 8 X turbine generators with a combined rating of 64 MWe
      - Catapults for launching aircraft
    - The carriers are designed for an service life of 50 years with one mid-life refueling, so core life is about 25 years.
- General Electric provides a replacement core known as A1G.

Bechtel A1B

- This reactor was developed for the Gerald R. Ford-class aircraft carriers.
  - The reactor power rating of the A1B is not known, but is expected to be a greater than the 550 MWt A4W.
  - The ship propulsion system is expected to be generally similar to that of the Nimitz-class carriers: 2 x large PWRs driving 4 x main steam turbines, which deliver about 260,000 shp (194 MW) propulsion power to 4 x main shafts & propellers.
  - The secondary steam system no longer supplies steam to the catapults.
  - One major change is that the reactor plants will be delivering a substantially greater electric power generating capacity to support the shift to electromagnetic catapults and electro-mechanical arresting gear, and to power future high-energy weapons.
    - Nimitz-class CVNs have 64 MWe electric generating capacity. Ford-class CVNs are expected to have 104 MWe generating capacity.
  - In the 2004 NR Congressional Budget proposal, the Navy reported to Congress that:
    - "The CVNX reactor (now A1B) will provide greater than 25 percent more energy than the reactors in Nimitz-class ships."
    - " CVNX…will require just half the number of sailors to operate and will be easier to maintain."
- Applications:
  - There is no separate A1B reactor prototype.
  - The Ford-class carriers are designed for an operating life of 50 years and are expected to require one mid-life refueling. Core life is likely to be 23 - 25 years.

Summary of the refueling cycles of US nuclear surface ships

Ship type	Ship class	Representative ships (1)	Ship years in service (2)	Reactor type	Core #	Avg. core life (years)	Notes
CVN	Enterprise	Enterprise	1961 - 2012	8 x A2W	Core 1 Core 2 Core 3 Core 4	3 4 19.7 18.3	Ship service life 51 yr.
CGN	Long Beach	Long Beach	1961 - 1994	2 x C1W	Core 1 Core 2 Core 3	9.5 9.5 13	
CGN	Bainbridge	Bainbridge	1962 - 1996	2 x D2W	Core 1 Core 2 Core 3 Core 4	5 5 6 11	
CGN	Truxtun	Truxtun	1967 - 1995	2 x D2W	Core 1 Core 2 Core 3	6.5 7 11	
CGN	California	California & South Carolina	1974 - 1999	2 x D2W 2 x D2W / D2G	Core 1 Core 2	16.2 5.6	Core 2 was D2G instead of D2W. These CGNs were retired early. D2G expected core life was about 20 yr.

Notes:
(1) Refueling overhaul dates could be determined for the identified "representative" ships.
(2) Years in service apply to the named representative ships, not to the class of ship.

Summary of the refueling cycles of US nuclear surface ships

Ship type	Ship class	Representative ships [1]	Ship years in service [2]	Reactor type	Core #	Avg. core life (years)	Notes
CVN	Nimitz	Nimitz, Eisenhower, Vinson, T. Roosevelt & Lincoln	1975 - present	2 x A4W	Core 1 Core 2	23 23	Est. Core 2 life at 50 yr. ship service life with 4 yr. mid-life RCOH. Core 2 may be an A1G core.
CGN	Virginia	Virginia, Texas, Mississippi & Arkansas	1976-1998	2 x D2G	Core 1	17.5	These CGNs were retired early after Core 1 was expended. There was no Core 2.
CVN	Gerald R. Ford	Gerald R. Ford	2017 - present	A1B	Core 1 Core 2	23 23	Est. Core 1 & 2 life for a 50 yr. ship svc life with a 4 yr. mid-life RCOH.

US Navy nuclear-powered surface ships

Evolution of the US nuclear-powered surface fleet

- **Aug 1955:** Chief of Naval Operations, Admiral Arleigh Burke, authorized studies to determine the feasibility of installing a nuclear propulsion plant in a guided missile destroyer-leader (DLG) hull (smaller than a contemporary cruiser). Key findings were:
  - The smallest hull would be 540 feet long, with a displacement of 8,500 tons to achieve a 30 knot top speed.
  - A nuclear-powered ship cost $20 – 30 million more in 1955 dollars than a ship with a conventional power plant delivering the same shaft horsepower and with the same weapons suite and top speed.
  - The nuclear-powered ship had a heavier propulsion plant with a higher center of gravity. The hull required greater beam to house the propulsion machinery and provide adequate stability.
- **Dec 1957:** Keel was laid for the 1st nuclear-powered surface warship, the guided missile cruiser (CGN) *USS Long Beach* (CGN-9).
- **Feb 1958:** Keel was laid for the 1st nuclear-powered aircraft carrier (CVN) *USS Enterprise* (CVN-65). Two more conventionally-powered aircraft carriers would be built (CVA-66 & -67) before the Navy committed to a nuclear CVN fleet.

Evolution of the US nuclear-powered surface fleet

- **1961:** The *USS Long Beach* (CGN-9), was commissioned 9 Sep 1961, just 2-1/2 months before the *USS Enterprise* (CVN-65) was commissioned on 25 Nov 1961.
- **1962:** *USS Bainbridge*, originally classified as a "destroyer leader" (sized between a destroyer and a cruiser), was commissioned on 6 Oct 1962 as DLGN-25.
- **1964:** The benefits of an all-nuclear-powered strike force were demonstrated with *Operation Sea Orbit*, in which the all-nuclear Task Force One, comprised of *USS Enterprise* (CVN-65), *USS Long Beach* (CGN-9), and *USS Bainbridge* (DLGN-25, later CGN-25), circumnavigated the globe in 65 days without refueling or replenishment.
- **1964:** Keel was laid for aircraft carrier *USS John F. Kennedy*, which originally was planned to be a nuclear-powered carrier, but revised after construction started to be the last conventionally-powered US aircraft carrier, CVA-67.
- **1968:** Keel laid for CVN-68, *USS Nimitz*, 1st of a 10-ship class
- **1970:** Keel laid for CGN-36, *USS California*, 1st of a two-ship class
- **1972:** Keel laid for CGN-38, *USS Virginia*, 1st of a four-ship class

Evolution of the US nuclear-powered surface fleet

- **1974:** The DoD Authorization Act for FY1975 made it a matter of US policy that all future large combatants intended to serve with strike forces should be nuclear powered, unless the President specifically waived that condition.
- **Early to mid-1970s:** The Navy designed a modified Virginia-class CGN with the new Aegis combat system, to be known as CGN-42, and a larger nuclear-powered Aegis "strike cruiser" (CSGN).
- **1975:** *USS Nimitz* commissioned.
- **1975:** As reported by Congressional Research Service, "procurement of nuclear-powered cruisers was halted after FY1975 largely due to a desire to constrain the procurement costs of future cruisers."
  - The Secretary of Defense had made the assessment that, "the military value of an all-nuclear-powered Aegis ship program does not warrant the increased costs or, alternatively, the reduced force levels." CGN-42 and CSGN were were not procured.
  - The first conventionally-powered Ticonderoga-class Aegis cruisers were procured in FY1978, with a total of 27 joining the fleet through 1994.

Evolution of the US nuclear-powered surface fleet

- **1980:** The last of nine nuclear-powered cruisers was commissioned.
- **Early 1990s:** Due to budget cutbacks and obsolescence of the combat systems on the nuclear-powered cruisers (relative to the newer Aegis cruisers), the Navy decided to cancel mid-life refueling for the four Virginia-class CGNs and decommission all CGNs at the end of their current reactor operating cycles.
- **1999:** The last CGN was decommissioned. The US nuclear-powered surface fleet was comprised only of aircraft carriers.

Virginia-class *USS Texas* (CGN-39) leads one of its successors, the conventionally-powered Aegis cruiser *USS Princeton* (CG-59). Source: http://www.navalanalyses.com/

Evolution of the US nuclear-powered surface fleet

- **2005:** Naval Reactors Quick Look Analysis
  - This analysis developed preliminary life-cycle cost estimates (procurement cost + life-cycle operating and support cost + post-retirement disposal cost) for two classes of ships:
    - A surface combatant similar to past CGNs
    - A large-deck (LHA-type) amphibious assault ship
  - The analysis then determined the break-even fossil fuel price needed to equalize the life-cycle cost of a nuclear-powered vessel and its conventionally-powered counterpart. The break-even crude oil prices were:
    - $178 per barrel for a surface combatant
    - $70 per barrel for a large-deck (LHA-type) amphibious assault ship
  - The analysis did not quantify the mobility-related operational advantages of nuclear propulsion for a surface ship.
  - The analysis was based on a 40-year ship life, which is roughly consistent with the expected service life of an amphibious assault ship, but five years longer than the 35-year life the Navy had been planning for its cruisers and destroyers.

- **2007:** With the retirement of the conventionally-powered *USS John F. Kennedy* (CV-67) on 23 March 2007, the Navy had an all-nuclear-powered fleet of 10 aircraft carriers: *USS Enterprise* + nine Nimitz-class carriers, with one more under construction.

Evolution of the US nuclear-powered surface fleet

- **2006:** Navy Alternative Propulsion Study
  - More detailed study; superseded the 2005 NR Quick Look Analysis
  - Confirmed that the procurement costs of nuclear vessels were significantly higher than for their conventionally-powered counterparts
    - For a small surface combatant, the procurement-cost increase was about $600 million.
    - For a medium-size combatant (defined as a 21,000 - 26,000 metric ton vessel with a 30 - 31 MWe combat system similar to CG(X)), the increase was in the $600 - $700 million range
    - For a large-deck amphibious ship, the increase was about $800 million
  - Although nuclear-powered ships have higher procurement costs (which include the cost of the first reactor core(s)) than conventionally-powered ships, they have lower operating and support costs when fuel costs are taken into account.
  - At a crude oil cost of $74.15 per barrel (which was a representative 2006 market price), the life-cycle cost premium of nuclear power was:
    - 17% to 37% for a small surface combatant
    - 0% to 10% for a medium sized surface combatant
    - 7% to 8% for an amphibious ship
  - The study concluded that a nuclear-powered medium-size surface combatant was the most likely of the three ship types studied to prove economical, depending on the operating tempo that the ship actually experienced during its service life.

Evolution of the US nuclear-powered surface fleet

- **2008:** Section 1012 of the FY2008 Defense Authorization Act (again) made it US policy to construct major combatant ships of the Navy with integrated nuclear power systems, unless the Secretary of Defense submits a notification to Congress that the inclusion of an integrated nuclear power system in a given class of ship is not in the national interest.
  - Ships included were, ".. cruisers and other large surface combatants, as well as submarines and aircraft carriers,…."
- **2009:** The last of 10 Nimitz-class CVNs (*USS George H.W. Bush*, CVN-77) was commissioned. The keel was laid for the first next-generation Ford-class CVN.
- **2010:** The Congressional Research Service published, *"Navy Nuclear-Powered Surface Ships: Background, Issues, and Options for Congress,"* reported:
  - The procurement cost of the initial nuclear fuel core is included in the total procurement cost of the ship, which is funded in the Navy's shipbuilding budget.
  - In constant FY2007 dollars, the initial fuel core for a Virginia-class SSN cost about $170 million.
  - The initial fuel cores for a Nimitz-class aircraft carrier, which has two reactors, have a combined cost of about $660 million.

Evolution of the US nuclear-powered surface fleet

- **2010:** The Navy studied nuclear power as a design option for a new cruiser design, CG(X), but cancelled CG(X) in favor of procuring smaller, conventionally-powered surface combatants: Arleigh Burke (DDG-51) Flight III-class Aegis destroyers.
- **2012:** *USS Enterprise* (CVN-65) retired, reducing the US carrier force to 10, which is below the Congressionally-mandated fleet of 11 CVNs.
- **2016:** In December, the Navy released a new force-level goal for achieving and maintaining a fleet of 355 ships, including 12 aircraft carriers (one more than the currently-mandated fleet of 11 carriers). No other new nuclear-powered naval surface vessels are planned.
- **2017:** The US carrier force was restored to 11 CVNs when the *USS Gerald R. Ford* (CVN-78) was commissioned in July 2017. However, the *Ford* is not expected to be ready for operational deployment until 2020.
- **2017:** A RAND report, *"Future Aircraft Carrier Options,"* prepared for the Chief of Naval Operations, is the latest in a long history of studies that have examined options for the Navy's carrier fleet. This RAND report offered four options: two nuclear-powered and two conventionally-powered.

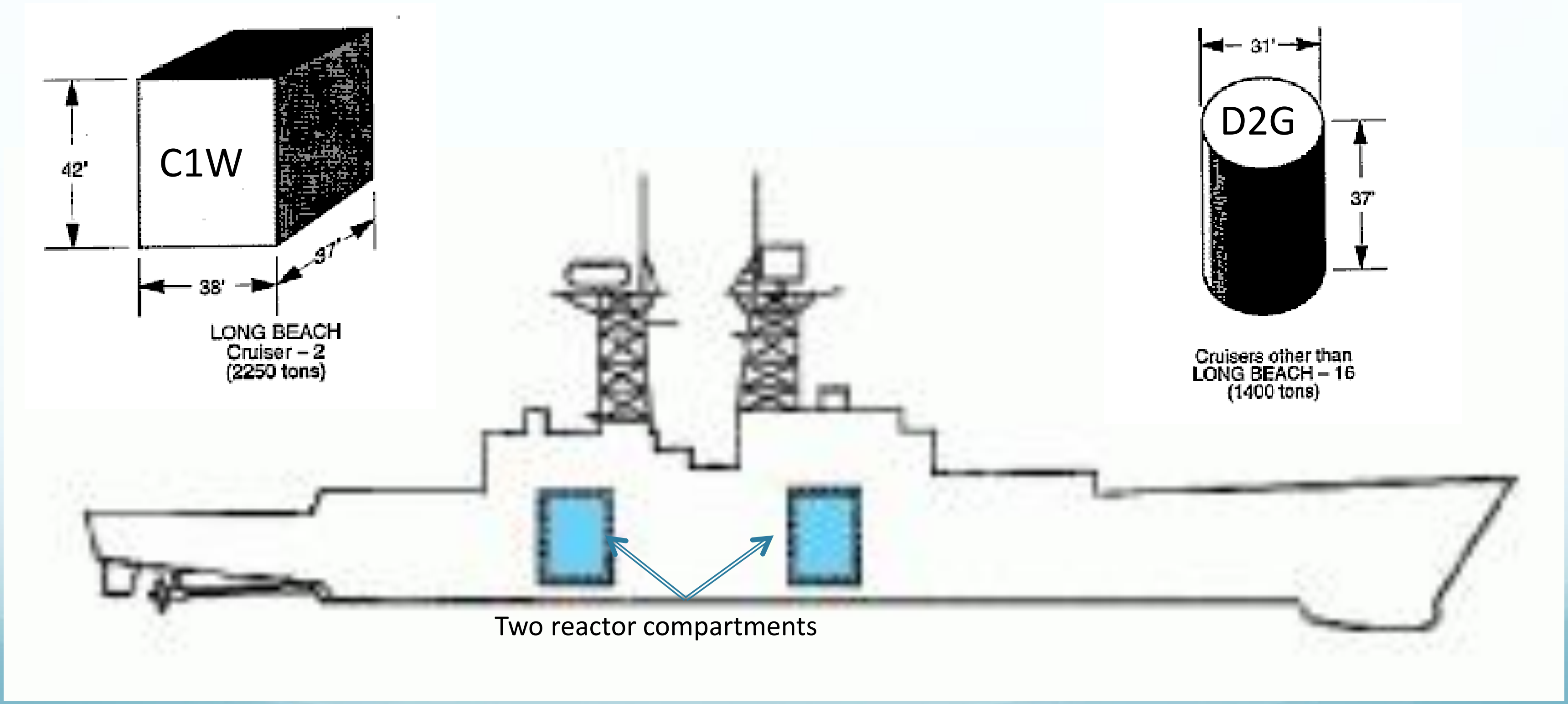
Nuclear-powered guided missile cruisers (CGN)

Nuclear-powered cruisers

- The US nuclear-powered guided missile cruisers were large, multi-purpose ships that provided anti-aircraft / missile defense and anti-submarine defense for carrier strike groups.
- For this class of ship, the primary benefit of nuclear power is independence from the need to refuel, enabling high-speed deployment over long distances, ability to commence combat operations immediately upon arrival in the theater of operations, and long on-station time.
- Nine CGNs were commissioned over two decades between 1961 and 1980.
- In addition to conventional armament, these cruiser carried various nuclear-armed tactical weapons:
  - RIM-2D Terrier BT-3A(N) anti-air missile with a 1 kT W45 warhead (retired 1990)
  - RIM-8B & -8D Talos anti-air missile with a 2 - 5 kT W30 warhead (retired 1979)
  - RUR-5 ASROC anti-submarine missile with a 10 kT W44 nuclear depth charge (retired 1989)
- All of these tactical nuclear weapons had been removed from the CGNs before the GHW Bush Presidential Nuclear Initiative, dated 27 September 1991, required all tactical nuclear weapons to be removed from Navy ships.
- All CGNs were retired between 1994 to 1998.

CGN reactor compartments

- US cruiser has two reactors in separate, shielded reactor compartments located fore-and-aft in the hull. Approximate dimensions and weights are shown in the diagrams below.
- In contrast to an aircraft carrier, the nuclear propulsion plant of a cruiser was a greater fraction of the total vessel displacement as well as construction and operating costs.



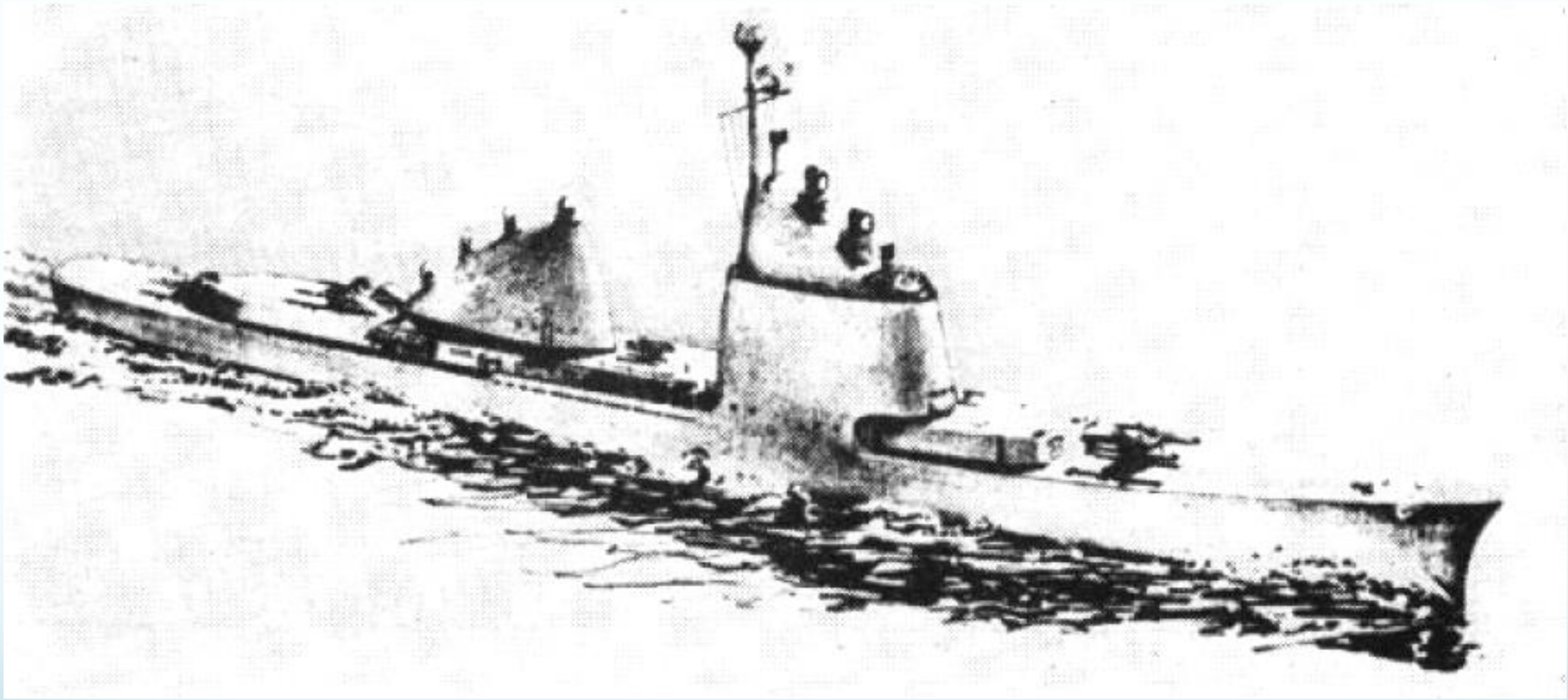
Source: adapted from http://fas.org

Nuclear-powered cruisers

Class	# in Class	Length	Beam	Displacement (tons)	Reactor	Shaft hp	Max speed (kts)	Years delivered	Years in service
Long Beach (CGN-9)	1	219.7 m (721 ft)	22.3 m (73 ft)	17,100	2 x C1W	80,000	30	1961	1961 - 95
Bainbridge (CGN-25)	1	172.2 m (565 ft)	17.6 m (57.7 ft)	8,580	2 x D2G	60,000	34	1962	1962 - 96
Truxtun (CGN-35)	1	171.9 m (564 ft)	17.7 m (58 ft)	8,800	2 x D2G	60,000	31	1967	1967 - 95
California (CGN-36)	2	181.8 m (596 ft)	18.6 m (61 ft)	10,530	2 x D2G (Core 1) 2 x D2W (Core 2)	60,000	30+	1974-75	1974 - 99
Virginia (CGN-38)	4	178.3 m (585 ft)	19.2 m (63 ft)	11,300	2 x D2G	60,000	30+	1976-80	1976 - 98
CGN-42	0	Similar to CGN-38	Similar to CGN-38	12,100	2 x D2W	70,000	30+	Cancelled 1979	
CSGN	0	216 m (709 ft)	23 m (76 ft)	17,200	2 x D2W	70,000	30+	Cancelled 1976	
CGSN Mark II	0	Similar to CGSN	Similar to CGSN	18,000 (est)	2 x D2W	70,000	30+	Cancelled 1976	
CGN(X)	0	Similar to DDG-1000: 182.9 m (600 ft)	Similar to DDG-1000: 24.6 m (80.7 ft)	> 15,000 (est)	1 x A1B	130,000	30+	Cancelled 2010	

Nuclear-powered cruiser

1956 concept drawing

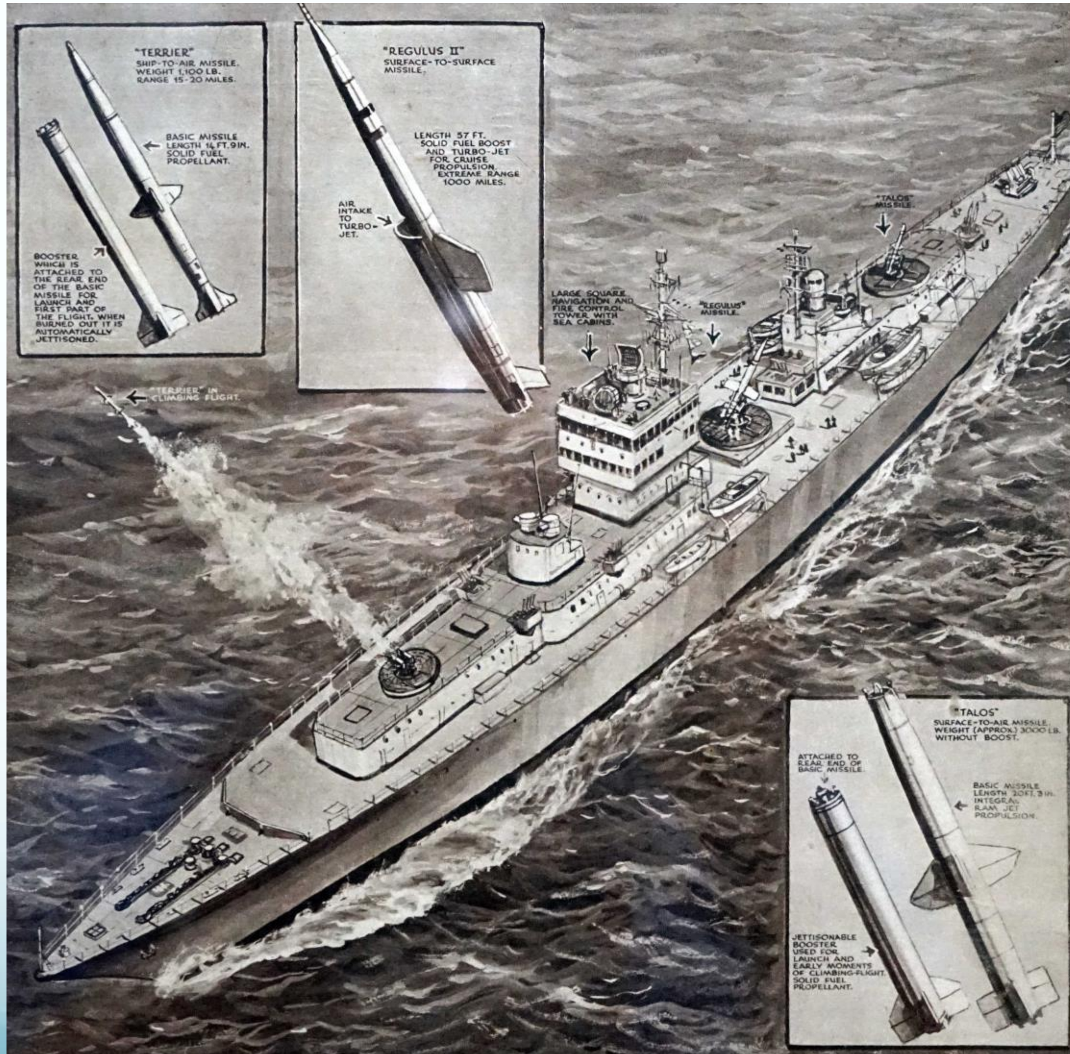


Concept for a nuclear-powered guided missile cruiser, designed to be equally effective against sea, air, land or underwater (SALU) targets. Funding was included in the Navy's FY 1957 new construction program.

Source: 58th edition of Jane's Fighting Ships / US Navy *All Hands* magazine, June 1956, p. 35.

USS Long Beach (CGN-9)

1958 concept drawing

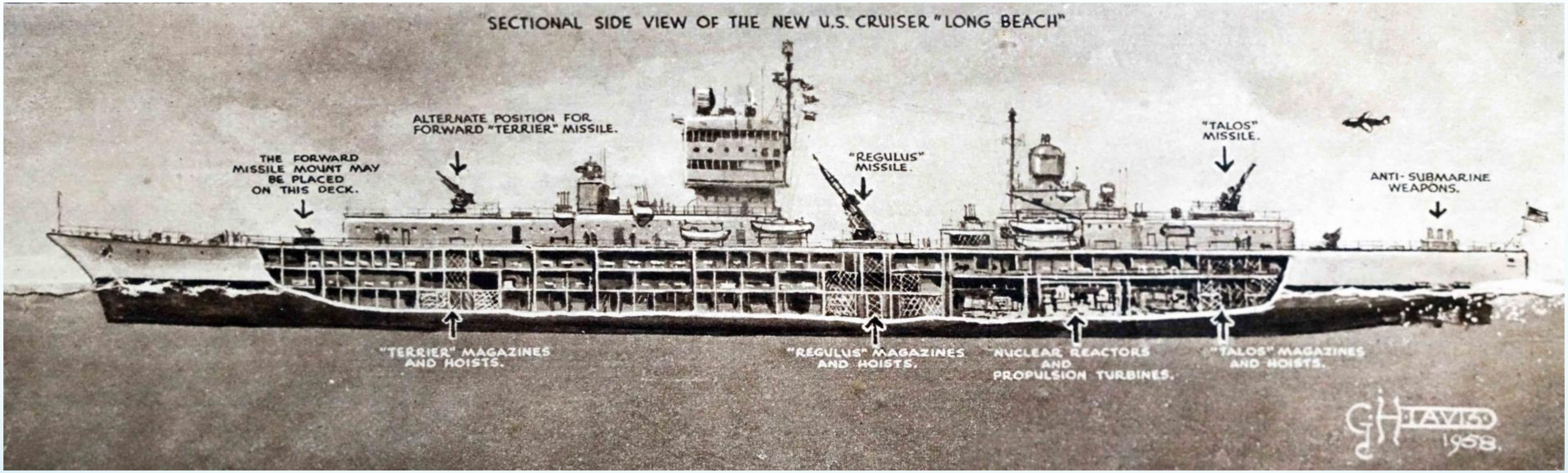


Source: The Illustrated London News, 7 July 1958, drawing by G.H. Davis

- One twin-arm launcher for Terrier medium-range anti-aircraft missiles forward.
- One launcher for Regulus II land-attack cruise missiles amidships.
- One twin-arm launcher for Talos long-range anti-aircraft missiles aft.
- No deck guns.

USS Long Beach (CGN-9)

1958 concept drawing



Source: The Illustrated London News, 7 July 1958, drawing by G.H. Davis

USS Long Beach (CGN-9)

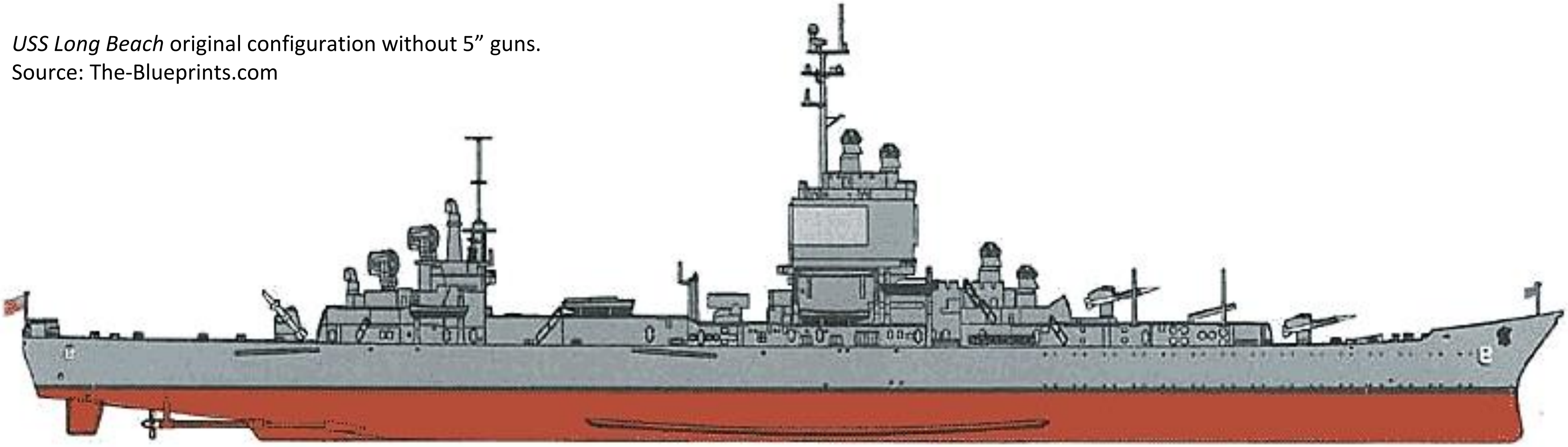
1960 concept drawing

Source: Sperry Gyroscope Company / Aviation Week & Space Technology magazine, 15 Feb 1960

USS Long Beach (CGN-9)

1st nuclear-powered cruiser & 1st US nuclear-powered surface ship

USS Long Beach original configuration without 5" guns.
Source: The-Blueprints.com



- Built by Bethlehem Steel, Quincy, MA. Keel laid in Dec 1957; 1st underway on nuclear power 5 July 1961; commissioned 9 September 1961.
- *Long Beach* originally was designed as an all-missile, anti-air / anti-submarine cruiser. Space on the midship deck behind the bridge superstructure originally was reserved for launching Regulus cruise missiles, and later for eight Polaris missile launch tubes. Neither was implemented. After witnessing a failed Terrier missile demonstration by *USS Dewey* (DLG-14), President Kennedy personally ordered that all missile cruiser be equipped with guns. During a 1962 – 63 alteration, *Long Beach* received 2 x 5 inch/38 WW-II vintage single gun mounts amidships.
- A second CGN in this class, costing $187 M, was planned, but was cancelled in 1957.

USS Long Beach (CGN-9)

- Propulsion: 2 x C1W reactors each rated @ 200 MWt (est.); 2 x steam turbines driving 2 x shafts; total propulsion power 80,000 hp (60 MW).
  - *USS Long Beach* was refueled twice. C1W Cores 1 & 2 operated for an average of 9.5 years; Cores 3 operated for almost 14 years.
- Original Armament:
  - 2 x twin-arm launchers forward for medium-range RIM-2D Terrier anti-air missiles.
  - 1 x twin-arm launcher aft for long-range RIM-8 Talos anti-aircraft missiles. This Talos launcher and its fire control system were removed in 1979.
  - 1 x eight-cell box-launcher amidships for RUR-5 ASROC (Anti-Submarine ROCket)
  - 2 x 5 inch/38 gun mounts were added amidships.
- Updated Armament:
  - *Long Beach* was converted to operate with RIM-67A SM-1ER missiles. Later, under the New Threat Upgrade (NTU) program, further modifications were made to enable use of the SM-2ER missiles.
  - In 1977, the capability was added to handle helicopters landing on the fantail.
  - In 1978, two Harpoon anti-ship cruise missile 4-cell launchers were added aft.
  - In 1980, 2 x Phalanx 20 mm close-in weapon systems (anti-aircraft / anti-cruise missile) were installed aft.
  - In 1985, two BGM-109 Tomahawk land-attack cruise missile 4-cell Armored Box Launchers were installed aft in the former location of the Talos launcher.

USS Long Beach (CGN-9)

- Operation:
  - 1964: As a member of Task Force One, *USS Long Beach* conducted *Operation Sea Orbit, which was* a 65-day around-the-world cruise, from 31 July – 3 October 1964, with *USS Enterprise* (CVN-65) and *USS Bainbridge* (DLGN-25, later CGN-25).
  - May 1968: *USS Long Beach* was deployed off the coast of Vietnam, where it engaged North Vietnamese MiGs with its Talos missiles battery at a range of over 60 miles (96.6 km). This was the first occasion in which a ship destroyed hostile aircraft with guided missiles.
  - 1974: The Navy's FY1974 budget included $800 million to refit *USS Long Beach* with the Aegis Combat System so it could serve as a "proof-of concept" ship for the Strike Cruiser CSGN.
    - In 1978, the Navy the construction cost of the first conventionally-powered Ticonderoga-class Aegis cruiser would be $940 million.
    - The Aegis refit proposal for *USS Long Beach* was cancelled in 1976.
  - July 1986: *USS Long Beach* was part of the first battleship battle group to deploy to the Western Pacific since the Korean War, led by the battleship *USS New Jersey* (BB-62).
  - *USS Long Beach* was deactivated 2 July 1996 after a service life of 35 years.

USS Long Beach (CGN-9)

Late-in-life configuration

Above: USS Long Beach beam view.
Source: US Navy photo

Left: *USS Long Beach & USS La Jolla* in San Diego Bay. Source: www.reddit.com/r/WarshipPorn/comments

USS Long Beach (CGN-9)

FY 1974 proposed conversion to an Aegis Combat System CGN

- The Navy's FY1974 budget included $800 M to refit *USS Long Beach* with the Aegis Combat System so it could serve as a proof-of concept ship for the proposed CGSN Strike Cruiser.
- In 1976, Congress denied the Navy's request for funding to build CSGN-1 and also cancelled the conversion of *USS Long Beach*.

USS Long Beach as it might have appeared after refit with Aegis Combat System.
Source: US Navy / Washington Navy Yard

USS Bainbridge (CGN-25)

Source: www.militaryart.com

- The design of *USS Bainbridge* (CGN-25) was based on the conventionally-powered Leahy-class guided missile frigate (DLG-16 / CG-16).
  - Built by Bethlehem Steel, Quincy, MA. Keel was laid on 5 May 1959 and the ship was commissioned on 6 October 1962.
  - Originally classified as a guided missile “destroyer leader” (DLGN) and re-classified as a guided missile cruiser (CGN) in 1975.
- Propulsion: 2 x D2G reactors, each rated @ 148 MWt; 2 x steam turbines delivering a total of 60,000 hp (45 MW) to 2 x shafts.

USS Bainbridge (CGN-25)

- Operational matters:
  - 31 Jul – 3 Oct 1964: As a member of the all-nuclear Task Force One, *USS Bainbridge* participated in *Operation Sea Orbit,* along with *USS Enterprise* (CVN-65) and *USS Long Beach* (CGN-9), and circumnavigated the globe in 65 days without refueling or replenishment.
  - *USS Bainbridge* was refueled three times:
    - Core 1 was designed for a life of about 5,000 equivalent full power hours (EFPH). The first refueling was conducted in 1967 – 68, after about five years of operation on Core 1 and 180,000 nautical miles steamed.
    - The second refueling occurred during the Jun 1974 – Sep 76 overhaul after about five years of operation on Core 2. *Bainbridge* returned to the fleet in Apr 1977 and operated on Core 3 for about six years.
    - The third refueling occurred during the 1983 – 85 overhaul, after which Core 4 operated for about 11 years.
  - *USS Bainbridge* was decommissioned in Sep 1996 after a service life of 34 years.
  - Bainbridge construction cost was $168 million, which was about $60 million more than the original estimate.

USS Bainbridge (CGN-25)

Armament, bow:
- 1 × twin-rail launcher, originally for RIM-2 Terrier, later for RIM-67A Standard Missile extended range (ER);
- 1 x 8-cell ASROC anti-submarine missile launcher with no reloads

Armament, midships:
- 2 x 20mm Phalanx close-in weapons system (CIWS);
- 2 x triple-mount torpedo tubes for Mark 46 ASW torpedo

Armament, stern:
- 1 × twin-rail launcher, originally for RIM-2 Terrier, later for RIM-67A Standard Missile (ER);
- 2 x 4-cell Mark 141 Harpoon anti-ship missile launchers;
- Helicopter landing pad at stern, but no helicopter hanger.

Source, both photos: http://destroyerhistory.org/coldwar/nuclearclasses/

USS Truxtun (CGN-35)

- The *USS Truxtun* (CGN-35) design was based on the *Bainbridge* hull form with a weapon system similar to a conventionally-powered Belknap-class guided missile frigate (CG-26). In comparison to *Belknap, Truxtun* had a 3 feet (0.91 m) greater beam, a 2-foot (0.61 m) deeper draft, and a displacement almost 1,200 tons greater.
  - Built by New York Shipbuilding, Camden, NJ. Keel was laid on 17 June 1963 and the ship was commissioned on 27 May 1967.
  - Originally classified as a guided missile "destroyer leader," (DLGN) and re-classified as a guided missile cruiser (CGN) in 1975.

USS Truxtun (CGN-35)

- Propulsion: 2 x D2G reactors, each rated @ 148 MWt; 2 x steam turbines delivering a total of 60,000 hp (45 MW) to 2 x shafts.
- Operational matters:
  - *Truxtun* had the large SQS-26 bow sonar dome, as found also on the Belknap-class frigates, and originally was intended to operate with the remotely-operated, torpedo-armed Drone Anti-Submarine Helicopters (DASH). Truxtun's helicopter facilities were redesigned to operate instead with the Kaman SH-2 Seasprite manned ASW helicopter.
  - *Truxtun* did not receive the New Threat Upgrade Combat System that was installed on California and Virginia-class CGNs in the early 1990s. Instead, Truxtun received only a modest weapons system upgrade that included installation of 2 x 20mm Phalanx close-in weapons systems (CIWS) on the foredeck.
  - *Truxtun* was refueled twice:
    - The first refueling was conducted during an 18-month overhaul from Jan 1974 – Jun 1975, after about 6.5 years of operation on Core 1.
    - The second refueling occurred during the Sep 1982 – Jul 1984 overhaul after about 7 years of operation on Core 2. *Truxtun* operated on Core 3 for about 11 years.
  - Truxtun was decommissioned on 11 Sep 1995 after a service life of 28 years.

DASH helo. Source: https://foxtrotalpha.jalopnik.com/

USS Truxtun (CGN-35)

Armament, bow:

- 1 x 5 inch/54 Mark 42 naval gun
- 2 x 20mm Phalanx close-in weapons system (CIWS).

Armament, midships:

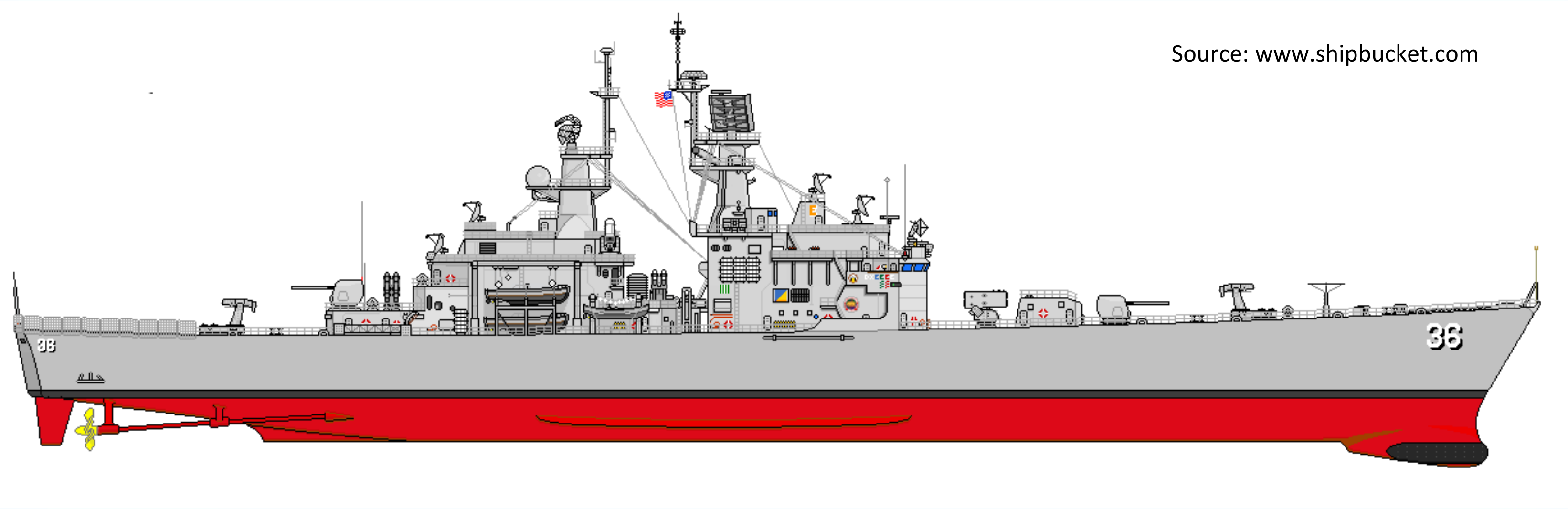
- 2 sets of 2 fixed ASW torpedo tubes built into the aft deckhouse for Mark 46 torpedoes
- 2 x 4-cell Mark 141 Harpoon anti-ship missile launchers

Armament, stern:

- Helo pad and hanger for one SH-2 Seasprite (LAMPS) helicopter
- 1 × twin-rail Mark 10 launcher for RIM-67A Standard Missile extended range (ER) and ASROC anti-sub missiles

Source, both photos: https://commons.wikimedia.org/

California (CGN-36)-class cruisers



- Two ships in this class; both built by Newport News Shipbuilding. They were delivered to the fleet in 1974 & 1975.
- These were larger cruisers than *Bainbridge / Truxtun*, with more comprehensive anti-air and anti-sub capabilities.
- Propulsion:
  - Originally 2 x D2G reactors, each rated @ 148 MWt; 2 x steam turbines delivering a total of 60,000 hp (45 MW) to 2 x shafts. Operating life for both ships on core 1 was 16 years
  - During their mid-life refueling in the early 1990s, the original D2G reactor cores were replace by more powerful 165 MWt D2W reactor cores that were intended to give these CGNs an additional 18 - 20 years of service life.

California (CGN-36)-class cruisers

Armament, bow:
- 1 × single-rail Mk 13 launcher for RIM-66D Standard Missile (MR);
- 1 x Mk 45 5-inch/54 gun;
- 1 x 8-cell ASROC anti-submarine missile launcher (deleted during mid-life OH)

Armament, midships:
- 2 x 20mm Phalanx close-in weapons system (CIWS);
- 2 x twin-mount torpedo tubes for Mk 46 ASW torpedoes

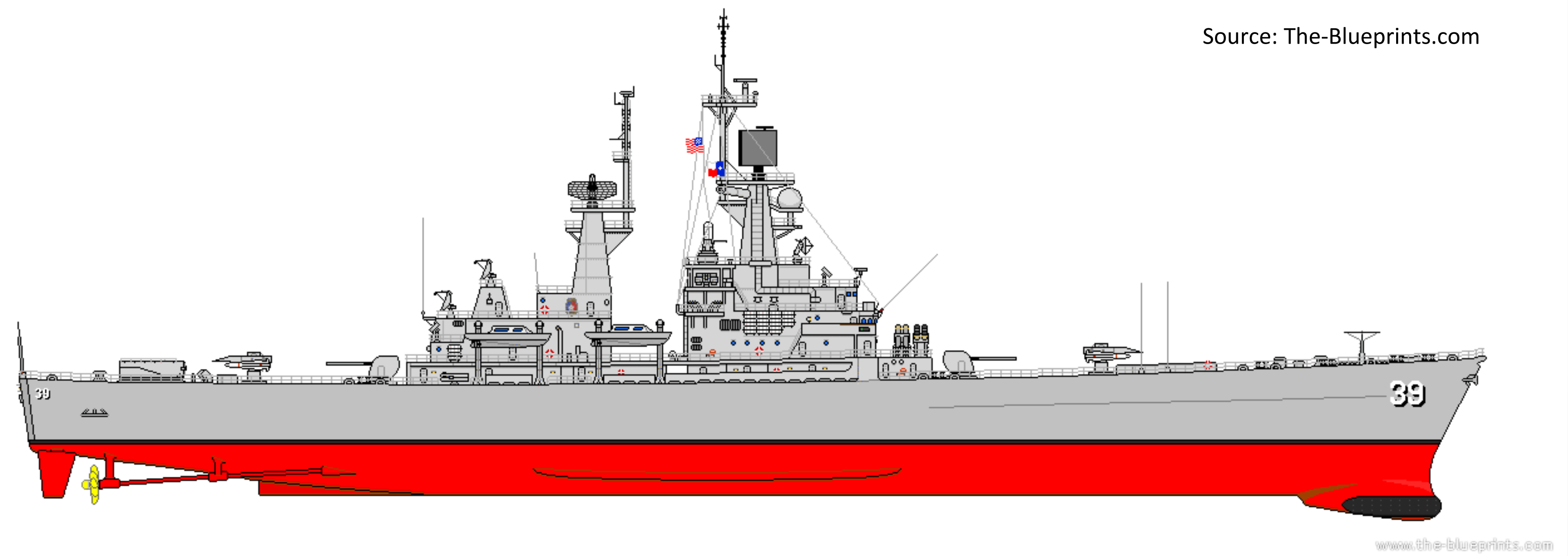
Armament, stern:
- 1 × single-rail Mk 13 launcher for RIM-66D Standard Missile (MR);
- 1 x Mk 45 5-inch/54 gun
- 2 × 4-cell Mk 141 Harpoon anti-ship missile launchers
- Helicopter landing pad at stern, but no helo hanger

USS California (CGN-36). Source: http://destroyerhistory.org/coldwar/nuclearclasses/

California (CGN-36)-class cruisers

- Operational matters:
  - The mid-life refueling overhaul included installation of the New Threat Upgrade Combat System, which improved the cruiser's anti-air capabilities (now able to handle the RIM-66 Standard Missile SM-2MR). However, the bow sonar was deactivated and the 8-cell ASROC box launcher on the foredeck was removed.
    - Apr 1990 – Jan 1993: *USS California,* overhaul & refueling cost $425 million.
    - Mar 1991 – Mar 1994: *USS South Carolina*
    - Both ships operated for about 16.2 years on D2G Core 1.
  - In 1998, the annual operating cost of a California-class cruiser was estimated to be about $38.8 million (cost of crew, operation and maintenance). In comparison, the the annual operating cost for a typical conventionally-powered CG-47 Ticonderoga-class Aegis cruiser was estimated to be about $29.5 million annually.
    - California-class cruiser crew size was about 600, including costly nuclear-trained crew. In comparison, CG-47 Ticonderoga-class cruisers require fewer than 400 crew.
  - The 1998 cost study also noted that California-class cruisers lacked significant war fighting capabilities found on the newer CG-47 Aegis cruisers.
    - No Aegis Combat System (radars, fire control system, etc.)
    - Not capable of handling the more advanced anti-air missiles used on Aegis cruisers: RIM-161 Standard Missile 3
    - No helicopter hangars; no modern ASW sonar or stand-off ASW weapons
  - The Navy determined that an overhaul to remedy the above deficiencies was not cost-effective. Both CGN-36 class cruisers were decommissioned in Jul 1999 after a service life of 24 – 25 years. Operating life on D2W Core 2 was only 5.3 – 6.5 years.

Virginia (CGN-38)-class cruisers



- The Navy originally planned to procure 12 ships of the CGN-38 Virginia-class.
  - Their main mission was as air-defense ships for Carrier Strike Groups. In addition, they had capabilities as ASW ships and as surface warfare ships, including gun and missile bombardment of shore targets. They also could serve as a flagship for a fleet commander.
  - After four units (CGN-38 to -41) had been ordered between 1971 and early 1975, further orders were suspended while consideration was given to a Modified Virginia design (CGN-42) and a Strike Cruiser (CSGN), both fitted with the Aegis Combat System.
  - The four Virginia-class CGNs were built by Newport News Shipbuilding. They were generally comparable in size and capabilities to the CGN-36 California-class cruisers.
- Propulsion: 2 x D2G reactors, each rated @ 148 MWt; 2 x steam turbines delivering a total of 60,000 hp (45 MW) to 2 x shafts.

Virginia (CGN-38)-class cruisers

Armament, stern:
- 1 × twin-rail Mark 26 rapid-fire launcher for RIM-66D Standard missile (MR) & RUR-5 ASROC anti-submarine missile
- 1 x Mark 45 5-inch/54 gun
- 2 x 4-cell Tomahawk armored box launchers on the stern
- Helicopter landing pad at stern with below-deck helo hanger for 2 x SH-2 Seasprite (LAMPS) helicopters.

Armament, bow:
- 1 × twin-rail Mark 26 rapid-fire launcher for RIM-66D Standard missile (MR) & RUR-5 ASROC anti-submarine missile
- 1 x Mark 45 5-inch/54 gun
- 2 × 4-cell Mk 141 Harpoon anti-ship missile launchers

Armament, midships:
- 2 x 20mm Phalanx close-in weapons system (CIWS)
- 2 x triple-mount torpedo for Mark 46 ASW torpedo

Source, two photos: http://www.navalanalyses.com/

Virginia (CGN-38)-class cruisers

- In 1993, the Navy cancelled the mid-life refueling overhauls for all Virginia-class CGNs. All would be retired early.
- The 1996 *Navy Visibility and Management of Operating and Support Costs (VAMOSC)* study determined the annual operating cost of a Virginia-class cruiser was $40 million, compared to $28 million for a conventionally-powered CG-47 Ticonderoga-class cruiser, or $20 million for a DDG-51 Arleigh Burke-class destroyer, both of which carried the modern Aegis Combat System.
- When the four Virginia-class CGNs were retired between 1994 – 1998, the ship's service life, and the operating life on D2G reactor Core 1 was only 15.8 - 19 years (17.7 years average).

Comparison of Virginia-class CGN & *USS Long Beach* (CGN-9).
Source: http://www.modelwarships.com/

California & Virginia-class cruisers

A 1981 family portrait of all six CGNs

All six California- and Virginia-class nuclear-powered cruisers in a 1981 exercise, from left to right: *USS Texas* (CGN 39), *USS California* (CGN 36), *USS South Carolina* (CGN 37), *USS Virginia* (CGN 38), *USS Arkansas* (CGN 41), and bringing up the rear, *USS Mississippi* (CGN 40). Source: US Navy.

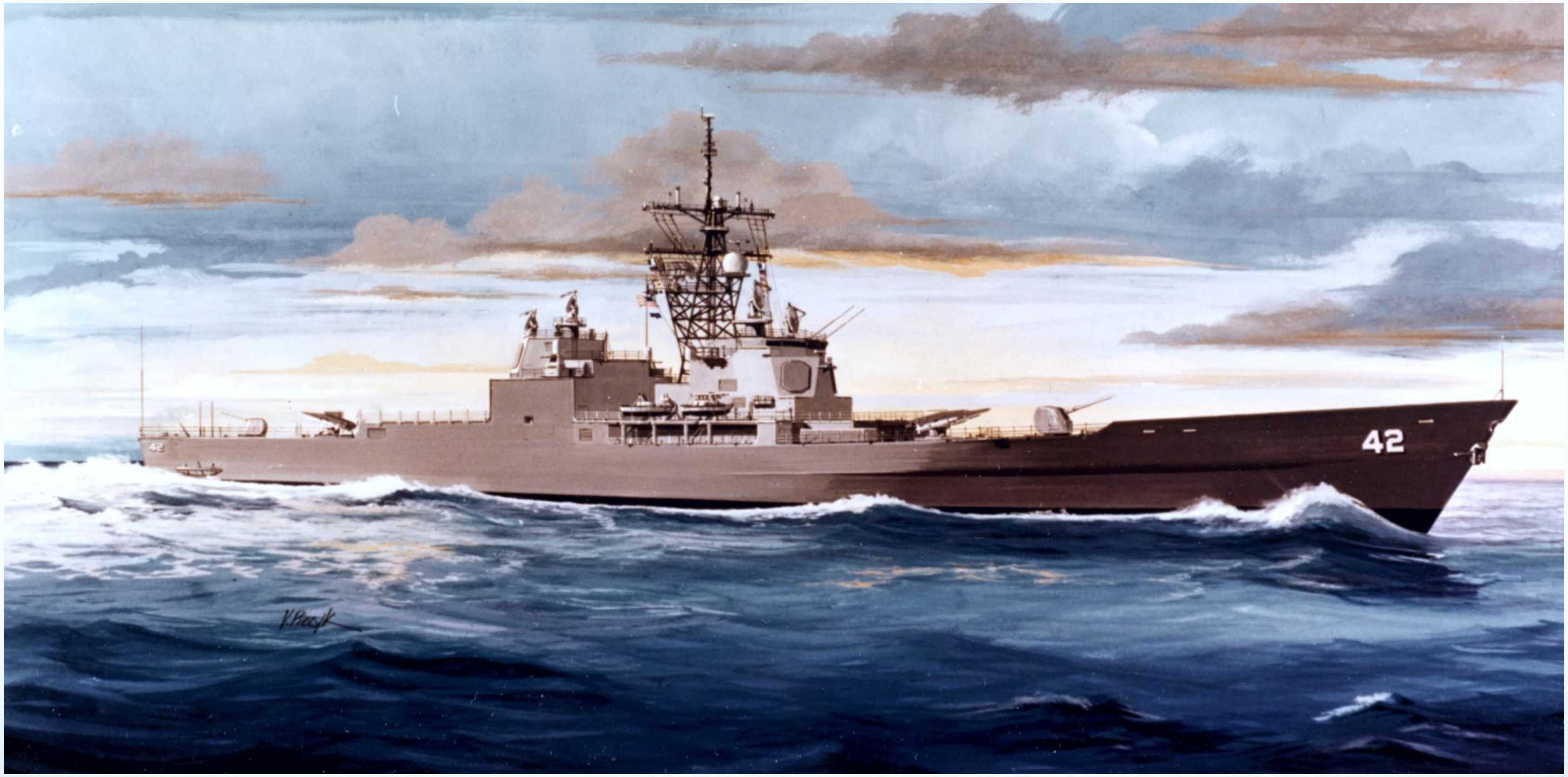
California & Virginia-class cruisers

A 1981 family portrait of all six CGNs

Source: US Navy

CGN-42

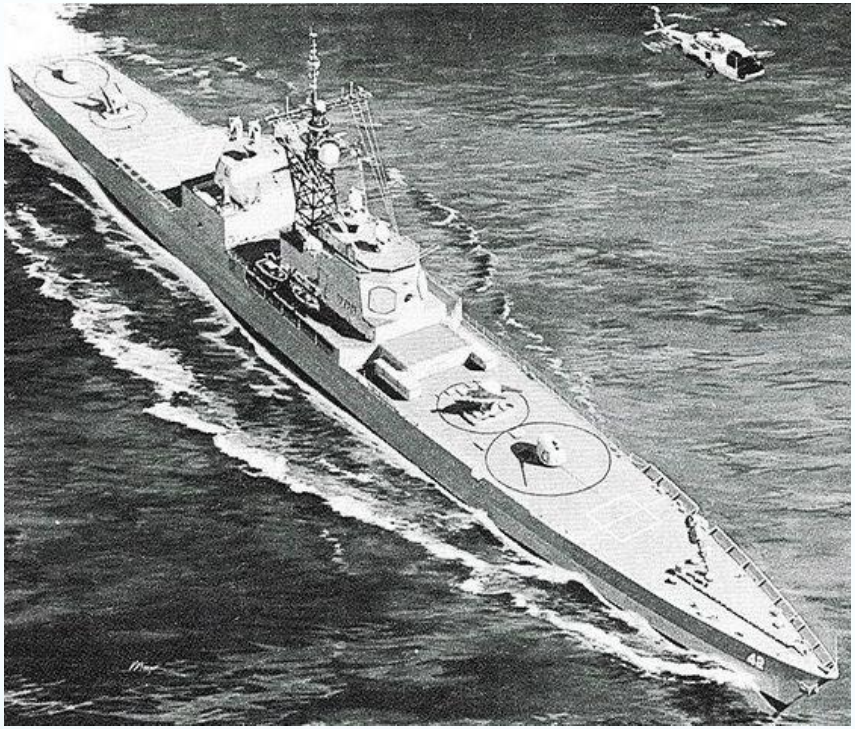
A redesigned Virginia-class CGN with the Aegis Combat System



CGN-42 artist's concept by V. Piecyk. Source: https://commons.wikimedia.org/

- CGN-42 was a 12,100-ton derivative of the Virginia-class (CGN-38) hull with the addition of the Aegis Combat System.
- Propulsion: 2 x D2W reactors delivering a total of about 70,000 shp to two screws.

CGN-42

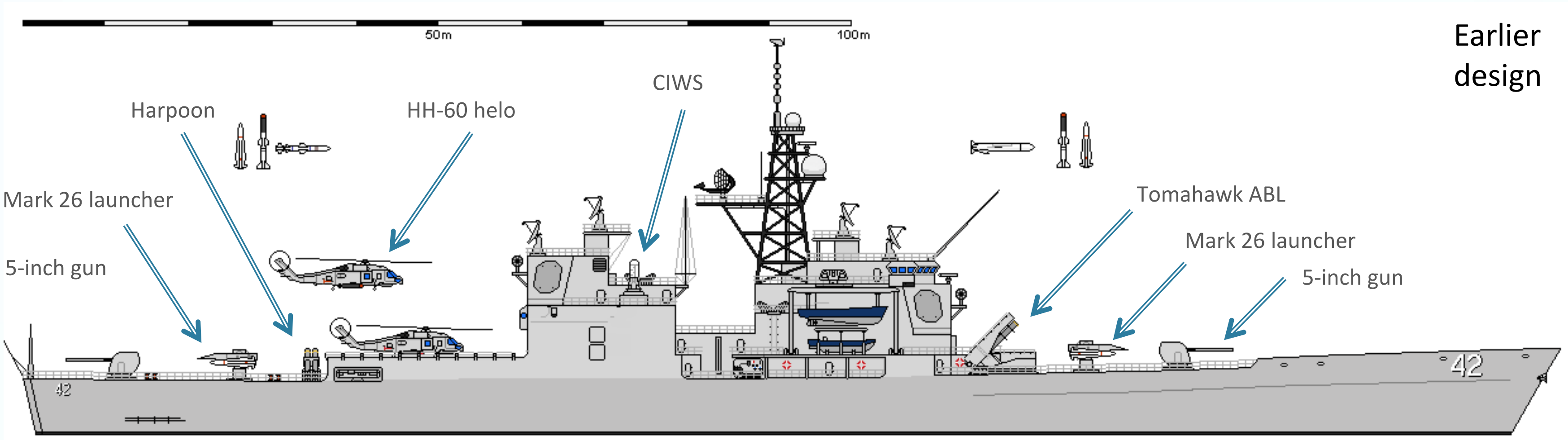


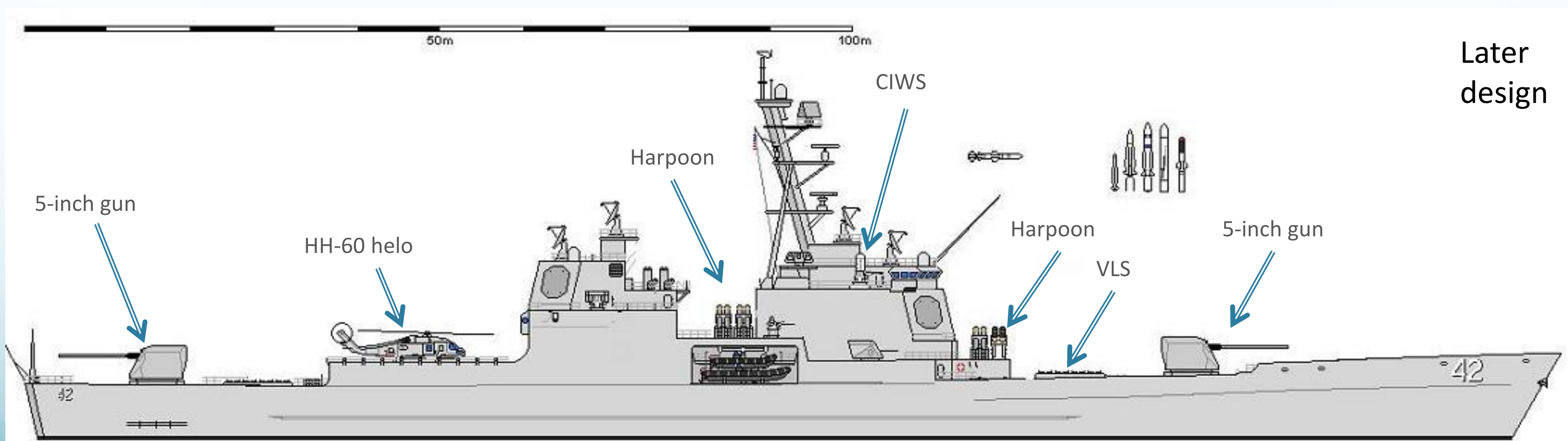
Source: http://www.mdc.idv.tw/mdc/navy/usanavy/E-Aegis-ship.htm

- Armament, bow:
  - 1 x Mark 45 5-inch gun
  - 1 × twin-rail Mark 26 launcher for RIM-66D Standard missile (MR) & RUR-5 ASROC anti-sub missile, replaced later by VLS
  - 2 x 4-cell Tomahawk armored box launchers
  - Harpoon anti-ship launchers (later design)
- Armament, midships:
  - 2 x 20mm Phalanx close-in weapons system (CIWS)
  - Likely, 2 x triple-mount torpedo for Mark 46 ASW torpedo
- Armament, stern:
  - Helicopter landing pad and hanger for SH-2 or HH-60 helicopters.
  - 1 × twin-rail Mark 26 rapid-fire launcher, replaced later by VLS
  - 1 x Mark 45 5-inch gun
  - Harpoon anti-ship launchers (earlier design)

- The CGN design evolved during the late-1970s, with the final version deleting the Mark 26 rail launchers in favor of the Vertical Launch System (VLS), then being planned for Ticonderoga-class cruisers, starting with CG-52.
- The Navy's FY1978 budget included engineering and advance procurement of nuclear components for CGN-42.
- In 1979, CGN-42 was cancelled.

CGN-42 design evolution





Source, top: Adapted from https://www.the-blueprints.com/ (MihoshiK)
Source, bottom: Adapted from http://www.shipmodels.info/mws_forum/

CGN-42 comparison with CGN-38 and CG-47

Two nuclear-powered cruisers compared: an original CGN-38 Virginia-class cruiser, which does not have the Aegis Combat System (right), and the proposed CGN-42 Aegis cruiser (left), which was derived from the Virginia-class CGN design.

Two Aegis cruisers compared: the proposed CGN-42 (right) and a conventionally-powered CG-47 Ticonderoga-class cruiser (left).

Source, both graphics: http://www.mdc.idv.tw/mdc/navy/usanavy/E-Aegis-ship.htm

Strike Cruiser CSGN

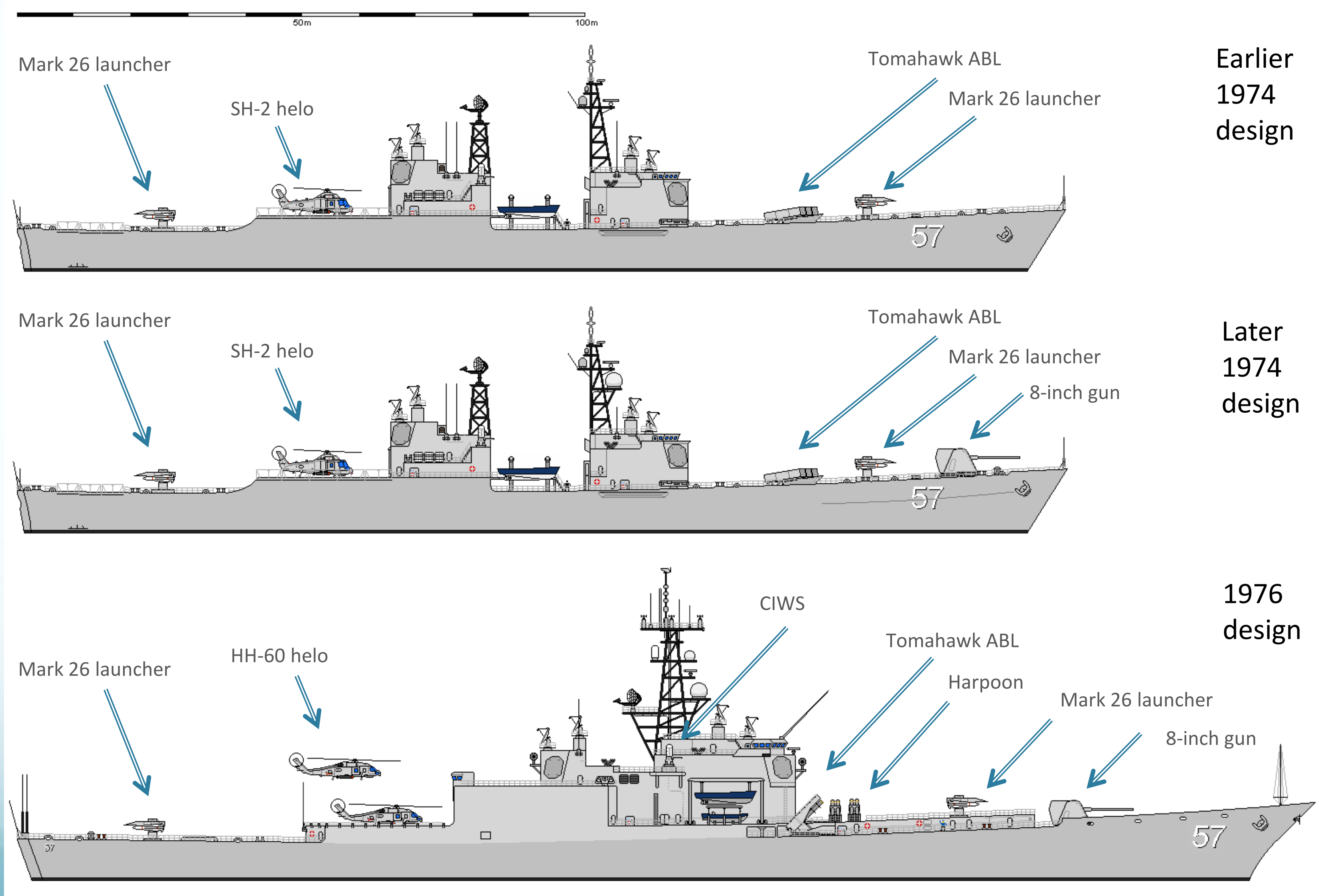
CSGN 1974 concept. Source: http://www5e.biglobe.ne.jp/~vandy-1/csgn.htm

- Unlike CGN-42, the CSGN was an all-new, larger design of a heavily-armed, nuclear-powered Aegis cruiser. With a displacement of about 17,200 tons, and a length of 216 m (709 ft), CSGNs were significantly larger than Virginia-class CGNs and Ticonderoga-class CGs.
- Originally planned as a class of 12 strike cruisers. This was later trimmed to eight ships in the FY1975 budget.
- Propulsion: Likely 2 x D2W reactors, delivering a total of about 70,000 shp to two screws.
- The Navy's FY1974 budget included $800 million to refit *USS Long Beach* (CGN-9) with the Aegis Combat System so it could serve as a "proof-of concept" ship for the CSGN.

Strike Cruiser CSGN

- The CSGN design evolved significantly between 1974 – 1976, ultimately becoming a much larger vessel than the 1974 concept. Among the concepts considered was a hybrid aircraft-carrying version known as CSGN Mark II.
- CGSN Armament (1976 proposal):
    - 2 x Mark 26 launchers for RIM-66 Standard Missile SM-2 anti-air missiles and ASROC anti-submarine missiles, each launcher with a magazine of 64 missiles.
    - 2 or 4 x Mark 141 quad launchers for RGM-64 Harpoon anti-ship missiles
    - 2 x Mark 143 quad Armored Box Launchers for BGM-109 Tomahawk land attack missiles (TLAM)
    - 1 x Mark 71 8-inch gun
    - 2 x Mark 15 Phalanx close-in weapons system (CIWS)
    - 2 x triple torpedo tubes for Mark 46 anti-submarine torpedoes
    - 1 or 2 x SH-2F or HH-60 helicopters
- In 1976, Congress denied the Navy's request for funding to build CSGN-1 and also cancelled the Aegis conversion of *USS Long Beach*, effectively killing the CSGN program.

CSGN design evolution



Source: Adapted from https://www.the-blueprints.com/ (MihoshiK)

Strike Cruiser CSGN and CGN-42 comparison

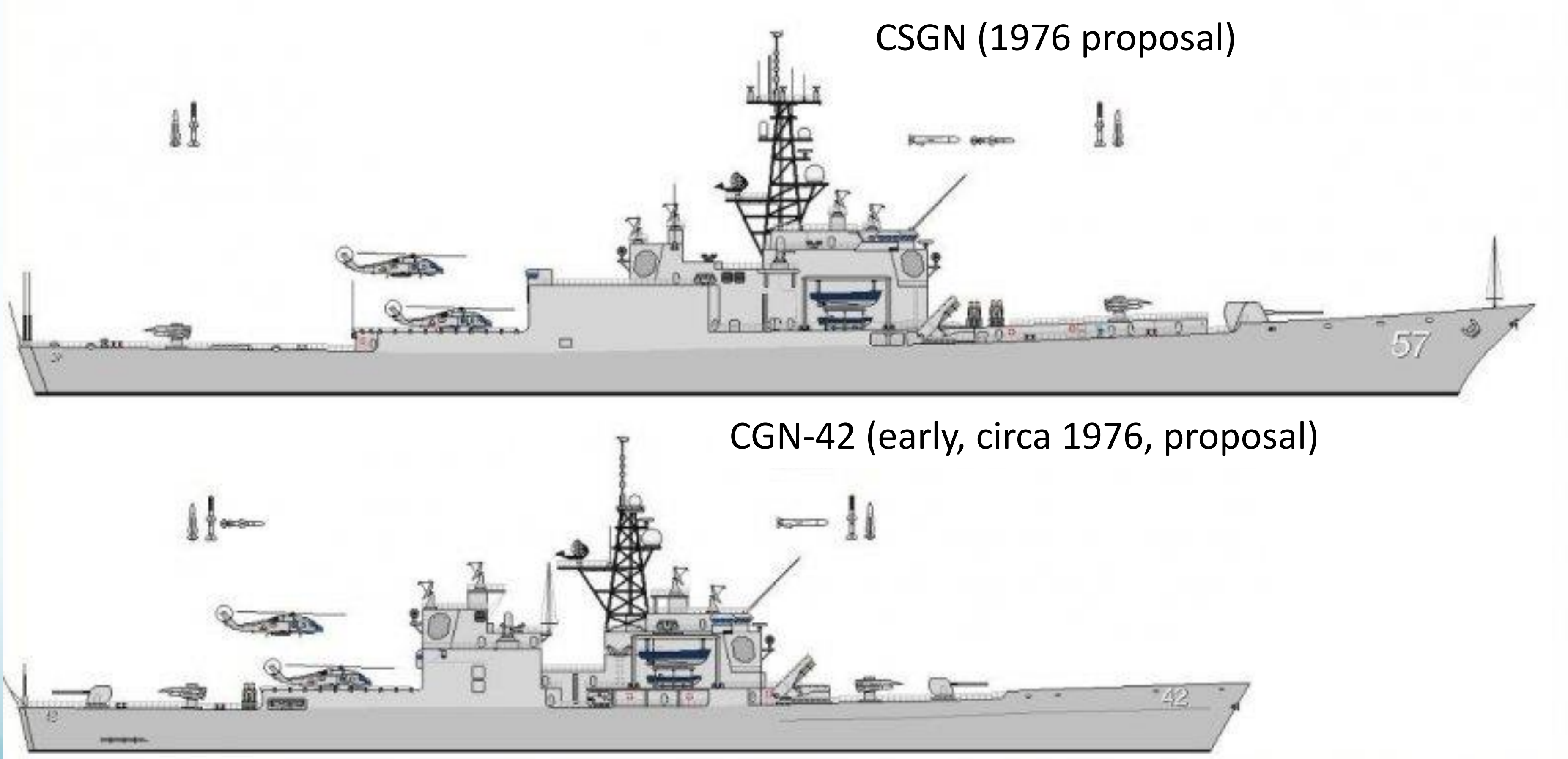
CSGN

- New hull design plus the Aegis Combat System
- 17,200-ton
- Likely propulsion: 2 x D2W reactors delivering a total of about 70,000 shp
- CSGN was estimated to have a unit procurement cost in the range of $1.8 – 2.1 billion; about double that of a CG-47 conventionally-powered Aegis cruiser.
  - CSGN procurement cost included the cost of the 1st reactor cores, which would last about 20 years.
- In 1976, the Senate Armed Services Committee completely deleted the Navy's request to fund the nuclear-powered strike cruiser.

CGN-42

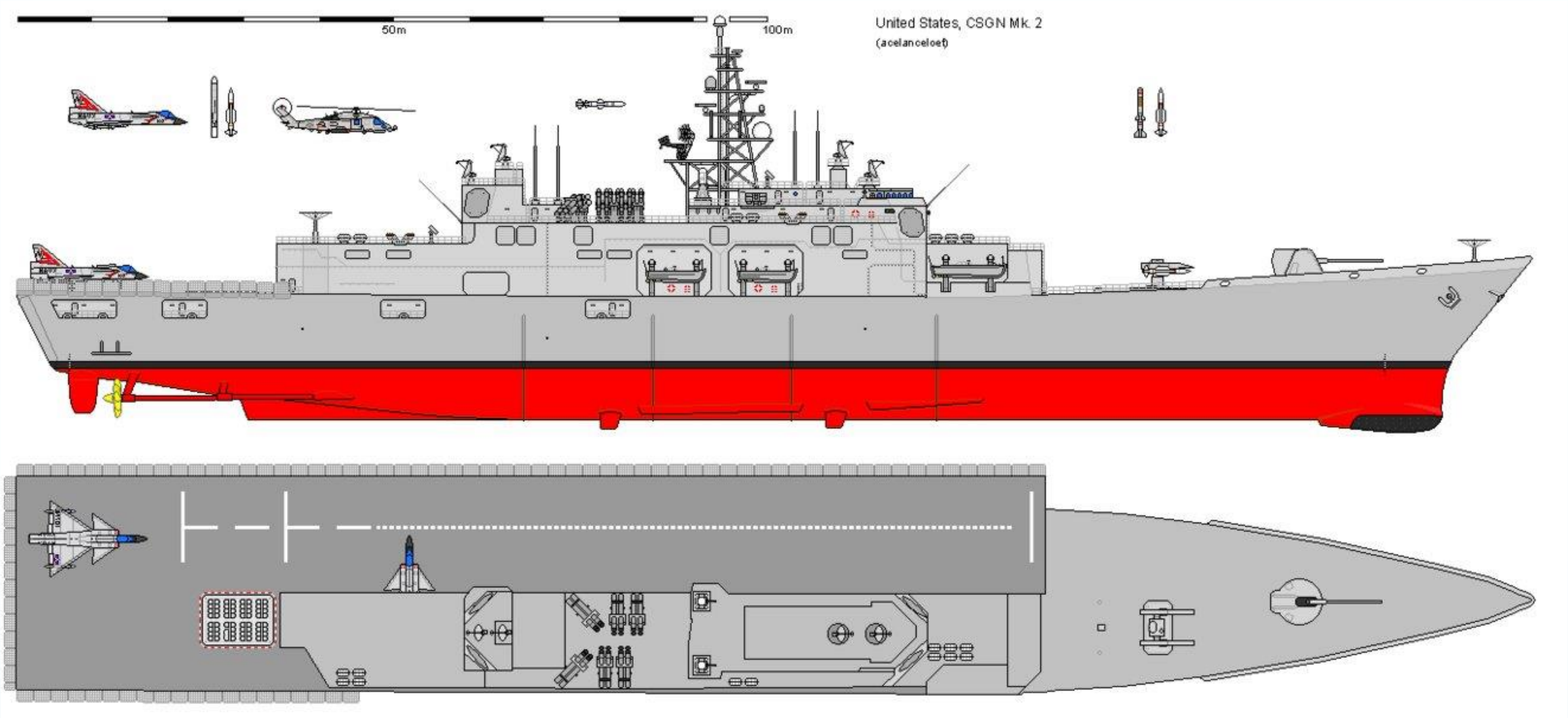
- A derivative of the Virginia-class (CGN-38) hull plus the addition of the Aegis Combat System
- 12,100-ton
- 2 x D2W reactors delivering a total of about 70,000 shp
- CGN-42 was estimated to have a unit procurement cost of about $1.34 billion (1981 dollars); 30% - 50% greater than a CG-47 conventionally-powered Aegis cruiser.
  - CGN-42 procurement cost included the cost of the 1st reactor cores, which would last about 20 years.
- Funding for engineering and advanced procurement continued into 1978.
- In 1979, CGN-42 was cancelled.

Strike Cruiser CSGN and CGN-42 comparison



Source: Adapted from https://www.the-blueprints.com/ (MihoshiK)

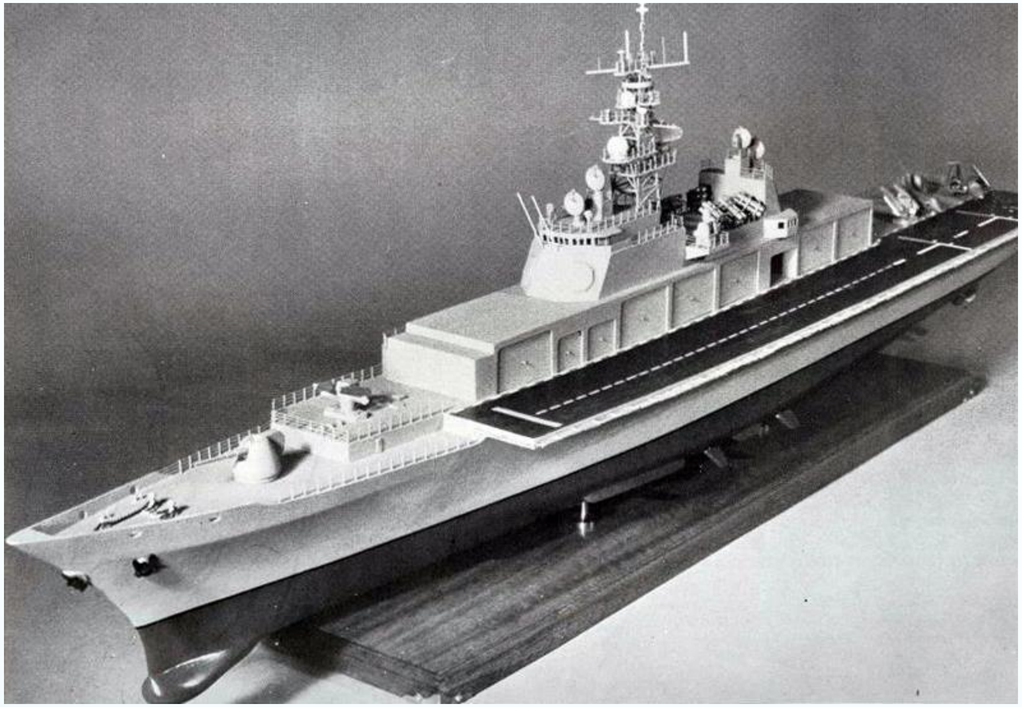
Strike Cruiser CSGN Mark II



CSGN Mark II concept circa 1975. Source: https://acelanceloet.deviantart.com/art/CSGN-Mk2-202807096

- The CSGN Mark II concept from the mid-1970s used the basic hull, Aegis Combat System and nuclear propulsion plant of the CSGN, rearranged the defensive and strike armament, and added a flight deck and hangers to support operations with embarked fixed-wing, short/vertical takeoff & landing aircraft and helicopters.
- CSGN Mark II likely could have served as the flagship of a Surface Action Group.

Strike Cruiser CSGN Mark II

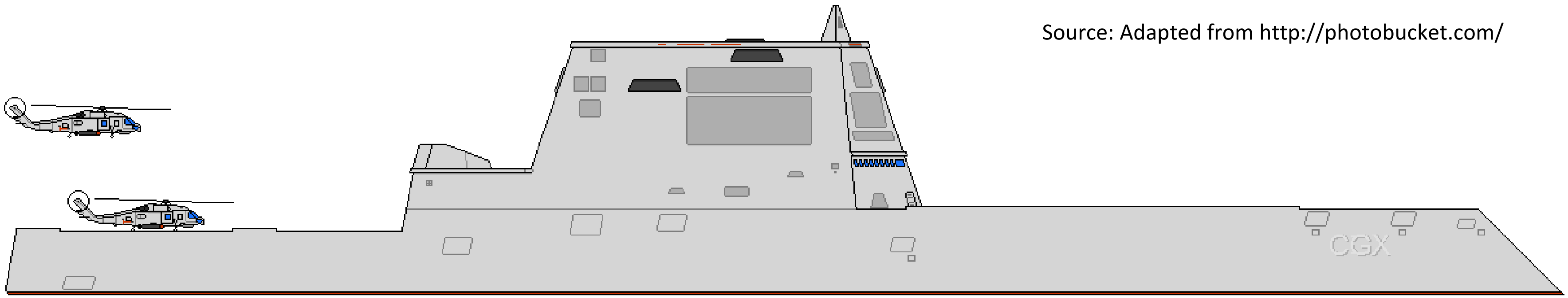


CSGN concept. Source: https://www.secretprojects.co.uk/forum/
originally from N. Polmar, "*Ships and Aircraft of the US Fleet*," (13th Edition)

- Armament:
  - 1 x Mark 71 8-inch gun
  - 1 x Mark 26 launcher for RIM-66 Standard Missile SM-2 anti-air missiles and ASROC anti-sub missiles
  - 2 x 2 x Mark 15 Phalanx close-in weapons system (CIWS), amidships
  - 6 x Mark 141 quad launchers for RGM-64 Harpoon anti-ship missiles, amidships
  - Vertical Launch System (VLS, possibly 64-cell) aft of the superstructure; capable of handling a variety of weapons, including the BGM-109 Tomahawk
  - Accommodations for up to 18 Harrier VTOL fighters and helicopters, including hangers on the main deck.

- The large number of anti-surface weapons (Harpoon, Tomahawk & 8-inch gun) likely reflect the ship's role as part of a Surface Action Group.
- The embarked aircraft could be used for long-range search and target acquisition and to attack surface targets with various aircraft-delivered weapons.
- CSGG Mark II was terminated in 1976, along with the rest of the CSGN program, when Congress denied the Navy's request for funding.

CG(X) next-generation cruiser



Source: Adapted from http://photobucket.com/

- CG(X) was a product of the Navy's *Surface Combatant for the 21st Century (SC–21)* program, which developed concepts for a destroyer called DD–21 (which became the DDG-1000 Zumwalt-class) and a cruiser called CG–21, which evolved into CG(X).
- The CG(X) program was announced in 2001, with a requirement for 19 ships under the Navy's plan for a 313-ship fleet in 2005. Both conventionally-powered and nuclear-powered version were considered.
- CG(X) was intended to be the replacement for the CG-47 Ticonderoga-class Aegis cruisers, with planned procurement starting in 2017. The 22 VLS versions of the Ticonderoga-class cruiser were scheduled to retire between 2021 and 2029 after a service life of 35 years.
- To reduce development costs, CG(X) was expected to share the DDG-1000 hull and major mechanical system designs.
- CG(X) likely would have used a version of the DDG-1000 electric propulsion system:
  - 2 x 34.6 MW (46,000 shp) Advanced Induction Motors delivering a total of 92,000 shp to two shafts (some sources cite 78 MW, 105,000 shp propulsion power).

CG(X) next-generation cruiser

- The Navy considered a nuclear-powered version: CGN(X)
  - In its FY 2009 Congressional Budget Justification, Naval Reactors reported: "FY 2008 Congressional direction requires major combatant vessels to be designed and constructed with integrated nuclear power systems, unless the Secretary of Defense submits a notification to Congress that states the inclusion of an integrated nuclear power system in such a vessel is not in the national interest. The preferred approach for a nuclear powered cruiser would be to modify a single next-generation aircraft carrier propulsion plant (such as that planned for installation in the new Gerald R. Ford class of carriers)."
    - A single A1B reactor plant, which is rated at > 550 MWt, is designed to drive two main propulsion turbines and deliver about 130,000 shp to two screws.
    - In comparison, a CG-47 Ticonderoga-class cruiser and a DDG-51 Arleigh Burke destroyer both are propelled by 4 x General Electric LM-2500 gas turbines, with a total propulsion power of 90,000 – 105,000 shp to two screws.
  - The A1B operating life in aircraft carrier service is about 25 years. Much better performance would be expected when propelling a CGN(X), which has one-fifth the displacement of a CVN (about 20,000 tons vs. 100,000 tons).
  - A nuclear-powered CGN(X) was estimated to cost 32 - 37% more than a conventionally powered CG(X).
- CG(X) would have had the powerful Air and Missile Defense Radar (AMDR):
  - The Navy reported the power requirement of the CG(X) combat system, including the AMDR radar, to be 30 - 31 MWe, compared with about 5 MWe for the CG-47 version of the Aegis Combat System.

CG(X) next-generation cruiser

- Other than for propulsion, CG(X) was to have a total electric power-generating capacity of about 80 MWe, which would provide 49 – 50 MWe for other ship systems, including future advanced energy weapons. There was concern that this electrical system did not have enough capacity to support the combat system and the rest of the ship's systems.
- The CG(X) program was cancelled in 2010.
  - Instead of CG(X), the Navy funded procurement of additional conventionally-powered DDG-51 Flight III (Arleigh Burke-class) destroyers in the FY2011 budget.

CG(X) would have looked like an enlarged Zumwalt-class (DDG-1000) guided missile destroyer

DDG-1000. Source: https://en.wikipedia.org/wiki/CG(X)

- The Navy has initiated an overhaul program to extend the service lives of the 22 active Ticonderoga-class cruisers to 40 years. This will extend their retirement dates to between 2026 and 2034.
- The Navy has no active program to procure replacement guided missile cruisers.

Nuclear-powered guided missile cruiser (CGN) tactical weapons

CGN tactical weapons

Above: RIM-2 Terrier BT-3

RIM-8 Talos.
Source, two photos: US Navy

- RIM-2 Terrier BT-3 (beam riding, tail control, Series 3) medium-range anti-aircraft missile
  - Two-stage rocket-propelled missile with beam riding + semi-active radar homing (SARH) terminal guidance.
  - RIM-2C Terrier entered service in 1958, armed with a 218 lb (99 kg) high-explosive controlled fragmentation warhead.
  - RIM-2D Terrier BT-3A(N) entered service in 1962, armed with a 1 kT W45 nuclear warhead. Terrier's W45 nuclear warhead was retired and removed from the Navy's fleet in 1990.
  - Speed: Mach 3.0; Range: 17.7 nautical miles (32 km); ceiling, > 80,100 ft (24,400 meters).
  - RIM-2 was deployed on CGNs *Long Beach, Bainbridge & Truxtun*.
  - The Terrier was replaced by the RIM-67 Standard Missile Extended Range (ER).
- RIM-8 Talos long-range anti-aircraft missile
  - Two stage missile with a rocket booster and a ramjet-powered second stage with beam riding + SARH terminal guidance.
  - IOC was in 1958.
  - Armed with a conventional high-explosive warhead (-8A) or continuous-rod warhead (-8C), or a 2 - 5 kT W30 nuclear warhead (-8B and -8D) with SARH terminal guidance deleted.
  - The -8A / -8B versions had a range of about 50 nautical miles (92.6 km). The improved -8C / -8D versions had double that range; ceiling > 80,100 ft (24,400 meters).
  - *USS Long Beach* (CGN-9) was the only CGN armed with Talos. *Long Beach* was commissioned in 1961. Its Talos launcher and fire control system were removed in 1979.
  - The last Talos missile systems were retired in 1979.

CGN tactical weapons

- RIM-67A Standard Missile (SM) Extended Range (ER) (aka SM-1ER & SM-2ER)
  - Two-stage rocket-propelled anti-air missile with semi-active radar homing. The SM-2 version added inertial guidance and also could be used as an anti-ship missile.
  - Developed to replace the RIM-8 Talos and the RIM-2 Terrier.
  - Armed with a high explosive 137 lb (62 kg) continuous rod (later blast fragmentation) warhead.
  - There was a plan to build a nuclear armed Standard Missile armed with a W81 nuclear warhead as a replacement for the earlier Nuclear Terrier missile (RIM-2D). The Navy rescinded the requirement for this nuclear-armed missile in the 1980s, and the project was canceled.

RIM-67A (SM-1ER) launch. Source: US Navy

  - Speed: Mach 3.5; Range: 65 – 100 naut. miles (120 – 185 km); ceiling: > 80,100 ft (24,400 m).
  - RIM-67 missiles fit the existing RIM-2 magazines and rail launchers on earlier US guided missile cruisers and was backfit on many of these ships, including CGNs *Long Beach, Bainbridge & Truxtun*.
    - These CGNs were converted to operate with RIM-67A SM-1ER missiles.
    - Under the New Threat Upgrade (NTU) program, further modifications were made to enable these CGNs to operate with SM-2ER missiles.
    - Later Standard Missile models, which were developed for ships with the Aegis combat system, were incompatible with US CGNs without a costly, major overhaul to install the complete Aegis system.

CGN tactical weapons

- RIM-24C Tartar medium-range anti-aircraft missile
  - The Tartar was a RIM-2C Terrier without the booster stage, intended to engage airborne targets at closer range with beam riding + semi-active radar homing (SARH) terminal guidance.
  - Armed with a 130 lb (59 kg) continuous rod warhead.
  - Speed: Mach 1.8; range: 17.5 nautical miles (32.4 km); ceiling 65,000 ft (20,000 m).
  - Entered service in 1962. It was original equipment on all California-class and Virginia-class CGNs.
  - The RIM-24C version was the product of the Tartar Reliability Improvement Program (TRIP).

RIM-66 Standard MR/SM-2 missiles on a Mark 26 launcher. RIM-24 Tartar looked similar. Source: US Navy

- RIM-66 Standard Missile (SM) Medium Range (MR) (aka SM-1MR & SM-2MR)
  - The RIM-66 was developed to replace the RIM-2 Terrier and the RIM-24C Tartar.
    - It used the same fuselage as the earlier RIM-24 Tartar missile and was compatible with with existing rail launchers and magazines aboard the CGNs and other ships in the fleet.
    - This missile is a RIM-67 upper stage without the booster stage.
  - The RIM-67 uses semi-active radar homing. The SM-2 version added inertial guidance and command mid-course guidance, which allowed the SM-2 version to be used as an anti-ship missile.
  - Speed: Mach 3.5; range: 40 – 90 nautical miles (74 – 167 km); ceiling > 80,100 ft (24,400 m).
  - All California-class and Virginia-class CGNs were modernized to handle the RIM-66A SM-1MR missiles. Under the New Threat Upgrade (NTU) program, further modifications were made to enable these CGNs to operate with SM-2MR missiles.

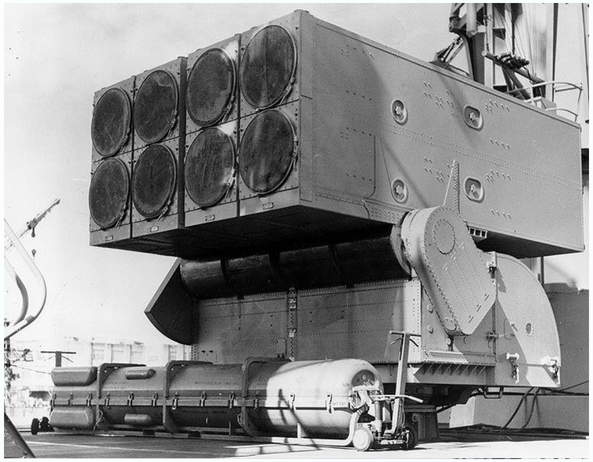
CGN tactical weapons

- Mark 46 Anti-Submarine Torpedo
  - Mark 46 is a lightweight active or passive/active homing torpedo. IOC was in 1965.
  - It can be launched by itself from surface ships, fixed-wing aircraft and helicopters. It is the torpedo component of the RUR-5 ASROC anti-submarine missile system deployed on surface ships. It also was the torpedo component of the Mark 60 CAPTOR mine.
  - This is a small torpedo: diameter 12.75 in (324 mm); length 8.5 ft (2.6 m); weight: 508 lb (231 kg) with a 96.8 lb (44 kg) high explosive (PBXN-103) warhead.
  - Maximum speed: > 40 knots; range: 12,000 yards (11 km); depth: > 1,200 ft (365 m).
  - 2-speed Otto fuel II combustion engine.

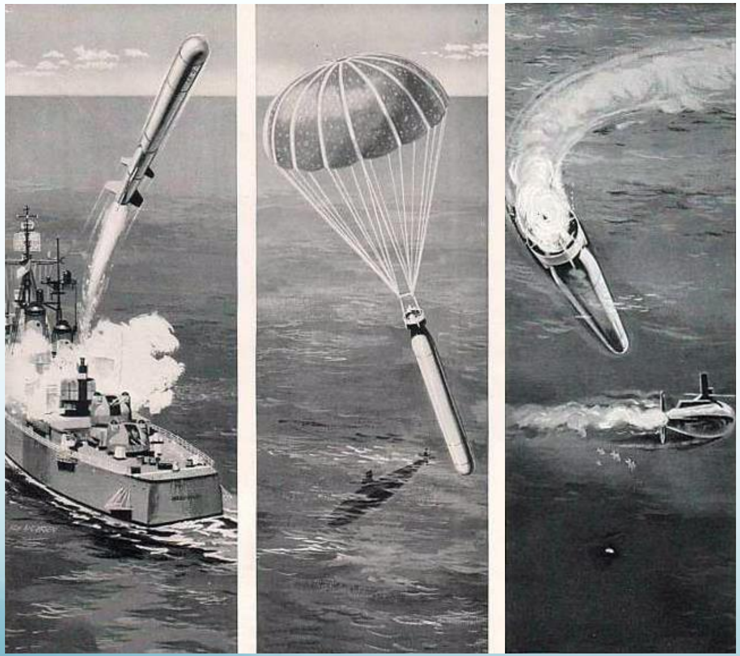
Mark 46 torpedo handling and launch from a deck-mounted triple launcher. Source, Top: http://www.seaforces.org/
Bottom: https://commons.wikimedia.org/

CGN tactical weapons

- RUR-5 ASROC (Anti-Submarine ROCket)
  - Designed as a quick-reaction, standoff anti-submarine weapon. IOC was in 1961.
  - ASROC originally was armed with either a Mark 46 homing torpedo with a high-explosive warhead or a 10 kT W44 nuclear depth charge.
  - Deployed in an 8-cell box launchers and also as individual rounds launched from a rail launcher.
  - The W44 warhead separates from its rocket booster, sinks to a predetermined depth after impact and detonates near the target.



RUR-5 ASROC box launcher. Source: US Navy



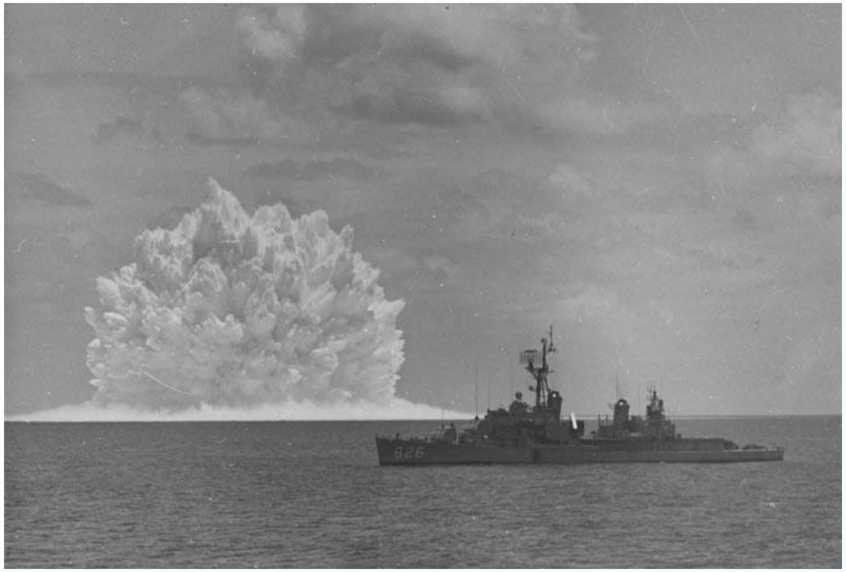
ASROC mission profile. Source: Honeywell Military Products

- The Mark 46 torpedo warhead separates from its rocket booster and deploys a parachute to permit water entry at a low speed. Water entry activates the torpedo, which is guided to the target by active or passive/active homing.
- The ASROC missile dimensions, including the dark 46 torpedo: length: 14.75 ft (4.5 m); diameter: 16.6 in (420 mm); weight: 1,073 lb (487 kg).
- Range: 12 miles (19 km)
- The ASROC W44 nuclear warhead was retired and removed from the Navy's fleet in 1989.

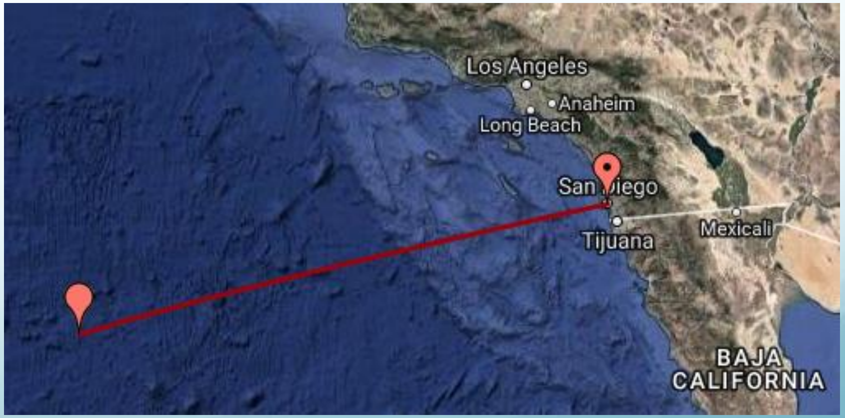
Operation Dominic, test *Swordfish*

Operational test of a W44 nuclear-armed ASROC

- A live-fire test of a nuclear-armed ASROC was conducted on 11 May 1962 by Joint Task Group 8.9, which was led by aircraft carrier *USS Yorktown* (CV-10), was comprised of 19 ships, two submarines and 55 naval aircraft.
- *USS Monticello* (LSD-35) set the instrumentation array for the test, one destroyer (*USS Bausell,* DD-845) was positioned 2,200 yards from the blast to monitor surface effects and the crew was evacuated, and the *USS Razorback* (SS-394) monitored underwater effects from a distance of 4,600 yards.
- The nuclear-armed ASROC was fired from the destroyer *USS Agerholm* (DD-826) at a target about 2.5 miles (4.0 km) away.
- The test occurred 426 miles (685 km) west of San Diego, CA at: 31° 14.7’ N, 124° 12.7’W.
- The blast was rated at < 20 kT.



USS Agerholm in the foreground. Source: Navsource.org



Swordfish test site. Source: Google maps

CGN tactical weapons

- BGM-109 Tomahawk land-attack missile (TLAM)
  - To improve their offensive strike capability, several US Navy surface warships were updated to carry the BGM-109C or D TLAM cruise missile housed in deck-mounted Armored Box Launchers (ABL), each containing four cruise missiles
    - The updated ships included the CGNs *USS Long Beach* and the four Virginia class cruisers.
  - The ABL is fixed to the deck. The top of the launcher is raised to launch a TLAM.
  - The BGM-109C has a range of about 900 nautical miles (1,700 km) with a 1,000 lb (454 kg) unitary high-explosive warhead; the BGM-109D has a range of about 700 nautical miles (1,300 km) with a submunitions warhead. Both are subsonic missiles, flying at a speed of about 550 mph (890 kph) at low altitudes.
  - The ABL cannot be reloaded at sea.

2 x Mark 143 TLAM armored box launchers (ABL) on CGN-40, *USS Mississippi.* Source: https://commons.wikimedia.org

Source: https://www.military.com/daily-news/

CGN tactical weapons

- RGM-84 Harpoon anti-ship cruise missile
  - The Harpoon anti-ship cruise missile IOC was in 1977.
  - To improve their anti-ship offensive and defensive capability against enemy surface ships, many US Navy surface warships were updated to carry the RGM-84 housed in simple, fixed deck-mounted Mark 141 launchers, each containing four missiles.
  - All US CGNs received 2 x Mark 141 launchers.

Mark 141 Harpoon launcher

Harpoon launch from Mark 141.
Source, both photos: http://www.seaforces.org/

- The small solid-fuel rocket booster detaches after launch and the missile's turbojet continues the flight to the target at very low altitude. The flight to the target is controlled by a radar altimeter and active radar terminal homing.
- Harpoon missile dimensions, including booster: length: 15 ft (4.6 m); diameter: 13.5 in (340 mm); weight: 1,523 lb (691 kg).
- Range is > 67 nautical miles (124 km) at a speed of Mach 0.71 (537 mph, 864 kph).
- Warhead is 488 lb (221 kg) of high explosives.

CGN tactical weapons

- 5 inch (127 mm) Deck Gun
  - All CGNs except *USS Bainbridge* (CGN-25) have one or two 5 inch guns for engaging surface threats.
  - Gun range is about 13.1 nautical miles (24.1 km).

5 inch Mark 45 gun. Source: http://slideplayer.com/slide/5148624/

CIWS. Source: https://commons.wikimedia.org/

- Phalanx Close-In Weapons System (CIWS)
  - CIWS is an integrated, automated, radar- and FLIR (forward-looking infra-red)-directed M61 Vulcan 20 mm, 6-barrel Gatling cannon system that is used to defend against close-in aerial threats, including cruise missiles, that have not been defeated by the ship's other missile systems.
  - A complete CIWS module weighs 12,500 – 13,600 lb (5,700 – 6,200 kg)
  - IOC was in 1980.
  - Maximum range is about 2.2 mi (3.5 km).

CGN tactical weapons

- Kaman SH-2 Seasprite anti-submarine warfare (ASW) helicopter
  - Developed in the early 1970s under the Light Airborne Multi-Purpose System (LAMPS) helicopter program to provide the Navy's fleet with a manned helicopter capable of supporting a non-aviation vessel and serve as its tactical ASW arm.
    - The compact size of the SH-2 allowed it to operate from flight decks that were too small for the majority of the Navy's helicopters.
    - The SH-2 also performed anti-surface ship, search and rescue (SAR), mine hunting and plane guard missions.
  - *USS Truxtun* (CGN-35) had a flight deck and hanger facilities for one SH-2.
  - The four Virginia-class CGNs originally had a stern flight deck and below-deck hanger facilities for one SH-2. This helicopter capability was deleted later in favor of installing two Tomahawk cruise missile box launchers on the former flight deck.
  - SH-2 was equipped with surveillance radar, magnetic anomaly detector, sonobuoys and various other sensors.
  - Crew of 3 for the ASW role.
  - Powered by 2 x gas-turbine engines, 136 mph (220 kph) cruise speed.
  - Range with two external fuel tanks: 550 miles (885 km)
  - Armament: 1 or 2 x Mark 46 or Mark 50 homing torpedoes for the ASW role; 1 or 2 Maverick missiles for the anti-ship role; various machine-guns.

SG-2F Seasprite.
Source: https://commons.wikimedia.org/

Nuclear-powered aircraft carriers (CVN)

Advantages of nuclear-powered aircraft carriers

- Independence from the need to refuel, enabling high-speed deployment over long distances and long on-station time.
  - Demonstrated convincingly in 1964 by the all-nuclear Task Force One during Operation Sea Orbit.
  - However, today this benefit is constrained by the need for the CVN to deploy with a Carrier Strike Group (CSG) that consists of all conventionally-powered vessels that need to be refueled during a long transit and while on station.
- No ship's exhaust gas interfering with flight operations and causing corrosion problems for the ship and aircraft.
- Greater storage capacity for aviation fuel and weapons to support air operations between replenishments.
  - However, during sustained operations, regular replenishment of aviation fuel and ordnance is still required.

	USS Constellation (CVA-64)	USS Nimitz (CVN-68)
Endurance	12,000 mi @ 20 kts	unlimited
Aviation fuel	6,500 tons	9,180 tons
Aviation ordnance	1,800 tons	2,970 tons

Post WW-II evolution of aircraft carrier operations

- **1945 - 1946:** At the end of WW-II, the Navy's carrier fleet was dominated by Essex-class carriers, 18 of which were completed during WW-II, and 7 more were completed after the war. The first of the larger Midway-class carriers (then classified as CVB), was not delivered until after the war. All of these were straight-deck carriers designed for conventional warfare with propeller-driven aircraft.
  - Navy leadership, particularly Admiral Marc Mitscher, Deputy Chief of Naval Operations (Air), and James V. Forrestal, Secretary of the Navy, wanted a larger carrier that could handle long-range naval bombers capable of delivering nuclear weapons.
  - A key goal was to break the monopoly held on such weapons and missions by the Army Air Force.
  - In September 1945, the Chief of Naval Operations established the Special Weapons Division of the Office of the CNO, with the task of preparing the Navy to deploy nuclear weapons.
- **1946:** A McDonnell FH-1 Phantom made the first jet landing aboard a US aircraft carrier, the Midway-class *USS Franklin D. Roosevelt* (CVB-42), on 21 July 1946. On 3 Dec 1945, British pilot Capt. Eric "Winkle" Brown, flying a de Havilland Sea Vampire, had accomplished the first-ever jet landing on, and takeoff from, the carrier *HMS Ocean*. These events marked the start of naval aviation's jet age.

FH-1 Phantom, originally designated FD-1. Source: http://www.wikiwand.com/en/McDonnell_FH_Phantom

Post WW-II evolution of aircraft carrier operations

- **1946 - 1947:** The "CVB Improvement Program 1" for the three Midway-class carriers was approved on 19 Nov 1946 and completed by September 1948.
  - Upgraded the ship's capabilities to launch & recover jet aircraft and the AJ-1 heavy attack aircraft.
  - Added Special Aircraft Service Stores (SASS) areas where nuclear weapons components would be stored and the weapons would be assembled.
- **1947:** The National Security Act of 1947 restructured the US military, creating a civilian Secretary of Defense (James Forrestal), the Joint Chiefs of Staff, and the National Military Establishment comprised of three military departments: Air Force, Navy and Army. The Act also defined basic roles for each service.
  - The Navy's aviation roles and organizations were preserved:
    - The Navy included "…naval combat and service forces and such aviation as may be organic therein……Naval aviation shall consist of combat and service and training forces, and shall include land-based naval aviation, air transport essential for naval operations, all air weapons and air techniques involved in the operations and activities of the United States Navy, and the entire remainder of the aeronautical organization of the United States Navy, together with the personnel necessary therefor………The Navy shall develop aircraft, weapons, tactics, technique, organization, and equipment of naval combat and service elements; matters of joint concern as to these functions shall be coordinated between the Army, the Air Force, and the Navy."
  - The USAF role was was broadly defined, and would require later clarification.
    - "In general the United States Air Force shall include aviation forces both combat and service not otherwise assigned. It shall be organized, trained, and equipped primarily for prompt and sustained offensive and defensive air operations. The Air Force shall be responsible for the preparation of the air forces necessary for the effective prosecution of war except as otherwise assigned…."

Post WW-II evolution of aircraft carrier operations

- **1948:** *Key West Agreement* clarified the division of aviation assets and roles among the Army, Navy, and the newly created Air Force. This policy paper drafted by Secretary of Defense James Forrestal, was formally titled, *"Function of the Armed Forces and the Joint Chiefs of Staff."* The *Key West Agreement* was enacted by President Harry S. Truman via Executive Order 9950, dated 21 Apr 1948.
  - The Air Force got control of all strategic air assets and the strategic bombardment mission, as well as most tactical and logistics aviation functions.
  - The Army retained limited aviation assets for reconnaissance and medical evacuation purposes.
  - The Navy would retain its own combat air arm primarily for tactical missions ("…to conduct air operations as necessary for the accomplishment of objectives in a naval campaign…"), but would not function as a separate strategic air force.
  - The *Key West Agreement* did not address missiles.
- **1948:** The first fully operational jet carrier squadron, VF-17A, deployed on the light carrier *USS Saipan* (CVL-48) with FH-1 Phantoms on 5 May 1948.
- **1948:** The Navy's Bureau of Aeronautics (BuAer) issued a Request for Proposal on 16 August 1948 to selected aircraft manufacturers for a long range, heavy attack airplane, with details provided in Outline Specification OS-111.
  - The mission was to conduct a high-altitude bombing attack with a 10,000 lb (4,536 kg) nuclear bomb load to a point no less than 1,700 nm (3,148 km) from the takeoff point.
  - Maximum aircraft weight was set at 100,000 lb (45,360 kg); the aircraft was to be designed for catapult launch (plus JATO if needed).

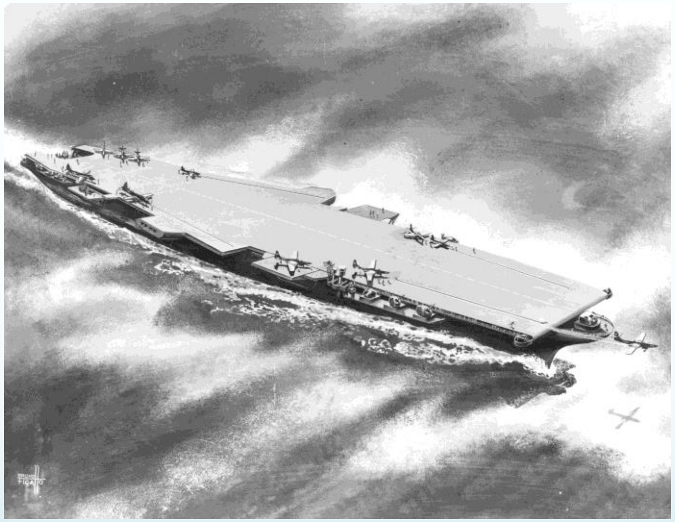
Post WW-II evolution of aircraft carrier operations

- **1948:** *Newport Agreement*, dated 21 Aug 1948, clarified inter-service nuclear warfare roles:
  - Established that the Air Force would have interim operational control of nuclear weapons, but that "each service, in the fields of its primary missions, must have exclusive responsibility for planning and programming and the necessary authority."
  - The Navy gained access to nuclear weapons and a portion of strategic operations planning while the Air Force gained primary oversight of the nuclear weapons development program.
- **1948:** The first Navy heavy attack squadron, VC-5, commissioned on 9 September 1948, established an interim, long-range nuclear attack capability from Midway-class carriers. VC-5 trained to fly the Lockheed P2V-3C Neptune on one-way nuclear attack missions with 10,000 pound (4,536 kg) Mark 1 ("Little Boy") bombs and not return to the carrier.

P2V-3C jet-assisted takeoff (JATO) from Midway-class carrier. Source, both photos: http://www.tailsthroughtime.com/2015/08/

Post WW-II evolution of aircraft carrier operations

- **1949:** On 18 April 1949, Secretary of Defense Louis A. Johnson cancelled construction of the Navy's first post-war "supercarrier," the radical flush-deck *USS United States* (CVA-58), in favor of the Air Force B-36 strategic bomber. This led to the "revolt of the admirals."
  - CVA-58 could handle various missions, but primarily was designed to undertake long-range nuclear attack missions with heavy bombers (up to 100,000 lb, 45,356 kg) that could accommodate a large nuclear weapon and escort fighters. It was not intended for conducting multiple strikes..



US Navy CVA-58 concept drawing by Bruno Figallo, circa 1948. Note that there is no "island" superstructure. There are four catapults, two of which are angled out near the mid-section.
Source: https://en.wikipedia.org/

- **1949:** After cancellation of CVA-58, the ambitious Navy plans for carrier-borne, long-range, heavy attack aircraft defined in BuAer Outline Specification OS-111 were scaled back

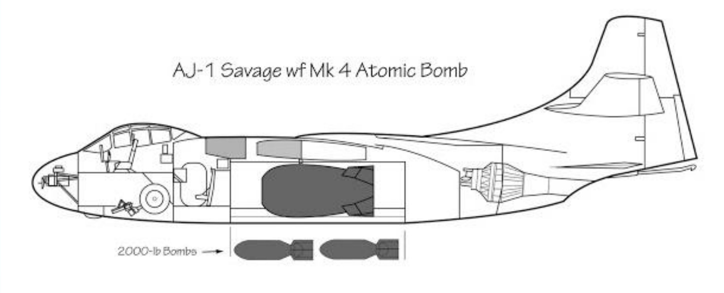
Post WW-II evolution of aircraft carrier operations

- **Late 1940s – mid-1950s:** The Navy initiated Ship Characteristics Board (SCB) Program 27 to significantly upgrade the operational capabilities of WW II-vintage, straight-deck Essex-class carriers. SCB-27A conversion included:
  - Strengthening the straight-deck flight deck and adding steam catapults to enable use of heavier aircraft (up to 52,000 pounds, 23,587 kg, which was the expected weight of the AJ-1 Savage.)
  - Establishing SASS areas where nuclear weapons components would be stored and the weapons would be assembled. Special weapons elevators were designed to handle "a package 15 feet long weighing 16,000 lbs," (4.57 meters x 7,257 kg).
  - Removing much of the WW-II era gun armament to minimize overall weight gain.

  The lead Essex-conversion ship, *USS Oriskany* (CV-34), was commissioned after SCB-27A conversion in September 1950. The last SCB-27C conversion was completed in 1955.
- **1950 – 1953:** The Korean War demonstrated the the lack of preparedness of the US to fight this war at its outset, and the importance of aircraft carriers and tactical jet aircraft in the prosecution of this war.
- **Early 1950s:** Smaller nuclear bombs that could be carried by light- and medium-attack aircraft were becoming operational, including:
  - Mark 7: 1,680 lb (762 kg), IOC 1952
  - Mark 8: 3,280 lb (1,490 kg), IOC 1952
  - Mark 12: 1,200 lb (540 kg), IOC 1954

Post WW-II evolution of aircraft carrier operations

- **1950:** The North American Aviation AJ-1 Savage heavy-attack bomber was the first operational carrier-based aircraft that was designed for the nuclear attack mission. It was propeller-driven, with a small, supplementary turbojet engine in the tail. It was designed for weapons up to the 60 inch (1.52 m) diameter of a Mk-IV implosion bomb (similar to the Mk-III "Fat Man"). Maximum range was about 1,505 nautical miles (2,787 km), but considerably shorter with a full bomb load. The AJ-1 began operating on Midway-class carriers in April 1950, replacing the P2V-3C.



Source: Tommy H. Thomason / tailspintopics.blogspot.com

Initially, Midway-class carriers (after CVB Improvement 1) were the only carriers able to carry nuclear weapons and also launch and recover the AJ-1. Later, SCB-27A Essex-class carriers were able to operate with the AJ-1.

Midway-class ships didn't participate in the Korean War because they were deployed in the Atlantic and Mediterranean Sea on nuclear deterrent patrols. Some AJ-1 aircraft were forward-deployed to a land base in Morocco while their nuclear weapons were stored aboard the carriers. The AJ-1s would deploy to the carrier to conduct nuclear training exercises.

Post WW-II evolution of aircraft carrier operations

- **1951:** *USS Forrestal* (CVA-59) was ordered 2-1/2 years after cancellation of CVA-58. *Forrestal* would be the lead ship for the first class of modern US “supercarriers” designed to handle large jet aircraft and nuclear weapons. Before completion, major design changes were made to *Forrestal*, most important of which were the implementation of the angled flight deck and the steam catapult, both of which were invented in the UK.
- **1952:** The *USS Antietam* (CV-36) was modified and, from Sep – Dec 1952, conducted the first-ever angled flight deck tests with full arrested landings.
- **1952:** The Navy deployed a nuclear-armed version of the AD Skyraider attack airplane, the single-seat AD-4B, which was equipped to carry a single Mark 8 nuclear bomb; 193 were built.

  - Attack squadron VC-35 received AD-4Bs and, in June 1952, deployed to Korea on *USS Essex* (CV-9), which had received SCB-27A modifications to store and assemble nuclear weapons. In the war zone, the AD-4Bs were based in Japan while their nuclear weapons remained aboard the *Essex*.
  - Attack squadron VC-33 deployed with their AD-4Bs on Midway-class carriers operating in the Atlantic and Mediterranean.

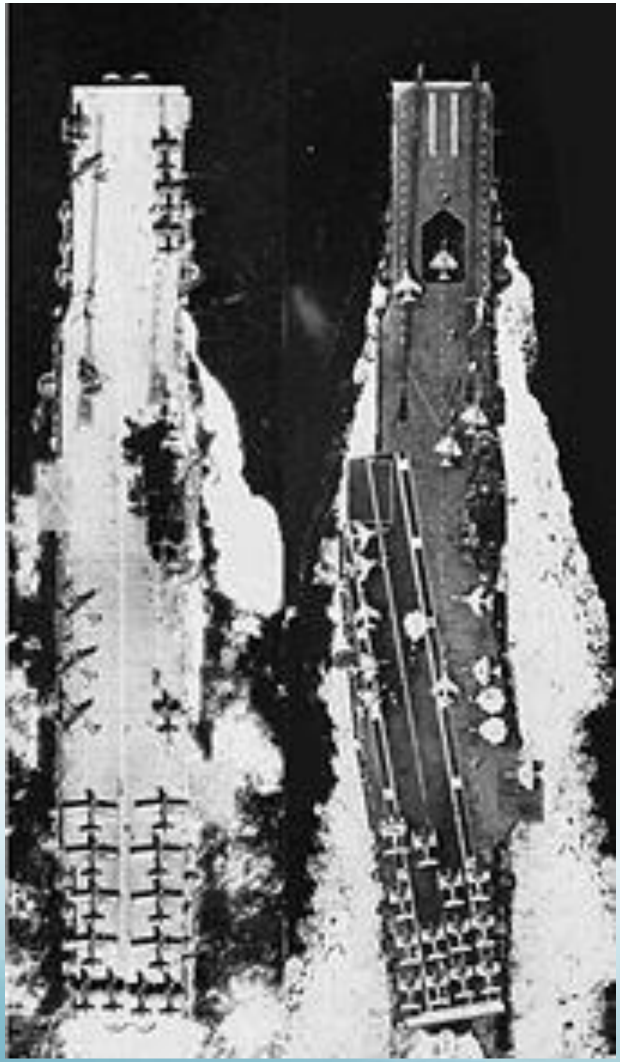
AD-4B at Fallon NAS, NV. Source: https://abpic.co.uk/pictures/view/1165873

Post WW-II evolution of aircraft carrier operations

- **1952:** First shipboard launch of a Chance Vought Regulus I cruise missile was from the aircraft carrier *USS Princeton* (CV-37) in November 1952.
- **1954:** The *Key West Agreement* was updated and codified as DoD Directive 5100.1, "*Functions of the Armed Forces and the Joint Chiefs of Staff*," dated 16 Mar 1954.
- **Mid-1950s:** Ten aircraft carriers were configured to carry and launch nuclear-armed Regulus I missiles and/or to employ their jet aircraft as part of the Regulus Assault Mission (RAM) concept to provide mid-course guidance for Regulus I missiles launched from other ships.
  - The aircraft carriers *USS Randolph* (CV-15) and *USS Hancock* (CV-19) are known to have deployed with 3 - 4 Regulus I missiles.
  - A wheeled cart was used to launch Regulus I missiles via the steam catapult.
  - Regulus I, with W5 or W27 nuclear warheads, were in service only about two years on carriers.

Above: Regulus I launch from *USS Hancock* (CV-19) circa 1955. Below: Launch from *USS Princeton* (CV-37) circa 1954. Source, both photos: https://commons.wikimedia.org/

Post WW-II evolution of aircraft carrier operations



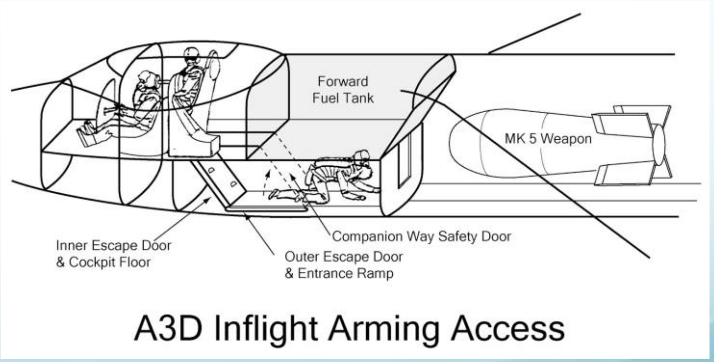
- **Mid-1950s:** The Navy initiated SCB Program 125 to apply additional design changes to the Essex-class carriers, including the addition of an angled flight deck, which greatly improved flight operations with heavy aircraft.
  - SCB-125 work began in 1952 and the last carrier was re-commissioned in 1959.
- **Mid-1950s:** Under SCB Program 110, the Navy modified the three Midway-class aircraft carriers in much the same way the Essex-class carriers were modified under SCB-27C and SCB-125, including addition of an angled flight deck capable of handling heavy aircraft up to 75,000 lb (34,000 kg).
  - SCB-110 work on the lead ship, *USS Franklin D. Roosevelt* (CVA-42*)* began in 1954 and was completed in 1956. Conversion of the other two Midway-class carriers was completed by 1960.
  - SCB-110 was necessary to handle the all-jet A3D Skywarrior heavy attack aircraft.

USS Intrepid after SCB-27C (left) and SCB-125 (right). Source: https://en.wikipedia.org/

Post WW-II evolution of aircraft carrier operations

- **1955:** The *USS Forrestal* (CV-59) was commissioned on 1 October 1955.
  - The as-delivered design featured a large angled flight deck and four steam catapults capable of handling heavy aircraft (up to 70,000 lb, 31,751 kg), a traditional island superstructure, a large hanger deck, facilities for nuclear weapons storage, handling and assembly, and a powerful propulsion system (260,000 shp) enabling a top speed of about 33 knots. *Forrestal* gave the Navy a viable nuclear attack capability.
  - *Forrestal* became the model for later US aircraft carriers, including the nuclear-powered *USS Enterprise* and the Nimitz-class carriers.
- **1956:** The 70,000 lb (31,751 kg) jet-powered, carrier-based Douglas A3D Skywarrior bomber entered service in 1956, replacing the AJ-1 Savage in the heavy nuclear attack role. The A3D evolved from an earlier Douglas OS-111 design.
  - Range: about 2,100 miles (3,380 km); cruise speed about 520 mph (837 kph).
  - The bomb bay was sized for a 60 inch (1.52 meter) diameter Mark 5 nuclear bomb and provided access to the bomb bay from the cockpit so the weapon could be armed in flight after takeoff.

Source: US Navy photo.

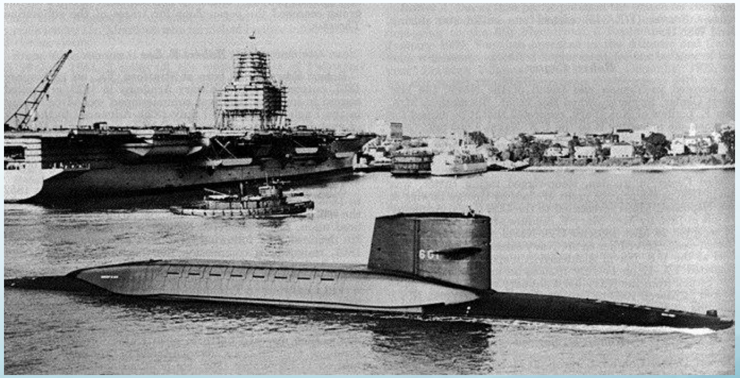


Source: Tommy H. Thomason, "*Strike from the Sea – US Navy Attack Aircraft from Skyraider to Super Hornet, 1948 – Present,*" Specialty Press, p.78, 2009

Post WW-II evolution of aircraft carrier operations

- **1958:** The keel was laid for the Navy's first nuclear-powered aircraft carrier, *USS Enterprise* (CVN-65), on 4 Feb 1958. Its basic design was similar to the preceding Forrestal and Kitty Hawk-class conventionally-powered carriers.
- **By 1960:** The Navy had a fleet of updated and new aircraft carriers qualified to deploy with conventional and nuclear weapons, including:
  - 6 x Essex-class carriers with SCB 27C plus some additional SCB-27A carriers
  - 3 x Midway-class carriers
  - 4 x Forrestal-class

  The Navy had a fleet of nuclear-capable, carrier-based jet attack aircraft, and were rapidly developing their successors. The aircraft fleet in 1960 included:
  - Heavy attack: A3D Skywarrior
  - Light attack: AD Skyraider, F2H Banshee, F9F-8 Cougar, A4D Skyhawk, FJ-4 Fury
- **1960:** Introduction of the Fleet Ballistic Missile (FBM) submarine challenged the carrier's role as the Navy's premier nuclear attack platform. The *USS George Washington* (SSBN-598) departed on the first Polaris nuclear deterrent patrol in November 1960.



USS Enterprise (CVN-65) & FBM sub *USS Robert E Lee* (SSBN-601).
Source: navsource.com

Post WW-II evolution of aircraft carrier operations

- **1960-1973:** The US involvement in the Vietnam War included extensive use of aircraft carriers deployed off the coast with a wide variety of fighters and light- and medium-attack aircraft using conventional weapons.
  - On 2 December 1965, *USS Enterprise* (CVN-65) became the first nuclear-powered ship to engage in combat when she launched aircraft against targets in South Vietnam.
  - During the period of the Vietnam War, the former heavy attack A3D aircraft (re-designated A-3) were converted to other roles that benefited from its large size, including aerial tanker and intelligence gathering. Its successor, the supersonic North American Aviation A3J (A-5) served only a short period in the early 1960s as a heavy attack aircraft before being converted into the high-performance RA-5C reconnaissance aircraft.
  - By the mid-1960s, the role of the heavy nuclear attack bomber no longer existed in the Navy. However, nuclear weapon size continued to decrease, thereby enabling medium-attack Grumman A-6 and light-attack Vought A-7 aircraft to conduct nuclear strike missions with bombs such as B43 (2,125 lb, 935 kg), B57 (500 lb, 227 kg) & B61 (700 lb, 320 kg).
- **1975:** *USS Nimitz* (CVN-68), the lead ship for the 10 CVN Nimitz-class of nuclear-powered aircraft carriers, was commissioned on 3 May 1975.
  - Nimitz was an evolutionary design that externally resembled the *USS Enterprise* and the conventionally-powered Forrestal- and Kitty Hawk-class CVAs. *Nimitz* matched the 260,000 – 280,000 propulsion power and 30+ knots speed of its predecessors.
  - A major improvement was the great simplification of the nuclear propulsion plant, which had only two large reactors in place of the eight smaller reactors on *Enterprise*.

Post WW-II evolution of aircraft carrier operations

- **1986:** The Initial Operating Capability (IOC) of the UGM-109A Tomahawk Land Attack Missile - Nuclear (TLAM-N) on submarines further challenged the nuclear attack role of aircraft carriers. The UGM-109C provided a conventional land-attack capability that could augment or replace some of the attack capabilities of the carrier's manned attack aircraft.
- **By 1991:** During the period form the end of the Vietnam War to the end of the Cold War, the US aircraft carrier fleet continued to demonstrate its value in supporting conventional, regional military conflicts, particularly in Lebanon, Libya and most notably in the 1990 – 1991 Gulf War. At the time of the dissolution of the Soviet Union on 26 Dec 1991, the US naval nuclear attack role had largely shifted from aircraft carriers to nuclear-powered submarines.
- **1991:** The GHW Bush Presidential Nuclear Initiative, dated 27 Sep 1991, ordered all tactical nuclear weapons (missiles, free-fall bombs) removed from Navy ships.
    - This Initiative affected aircraft carriers, other surface combatants, and submarines.
    - About 40 years after the first nuclear weapons were deployed on US aircraft carriers, Carrier Strike Groups no longer were armed with offensive or defensive nuclear weapons.
    - The Navy's strategic ballistic missile submarine (SSBN) fleet and their submarine launched ballistic missiles (SLBMs) were unaffected by this Initiative. The Navy's SSBN fleet remains as one leg of the US strategic nuclear triad, along with USAF nuclear bombers and ICBMs.

Post WW-II evolution of aircraft carrier operations

- **1998:** GAO reported on the cost-effectiveness of conventionally-powered and nuclear-powered aircraft carriers (GAO/NSIAD-98-1). At the time of the study, the Navy operated a mixed fleet of 12 carriers, with 4 conventionally-powered CVAs and 8 nuclear-powered CVNs. Key findings were:
  - CVAs and CVNs both have been effective in fulfilling US forward presence, crisis response, and war-fighting requirements and share many characteristics and capabilities (i.e., same air wings, same mission requirements).
    - Unified Commanders consider the quality of presence of the two carriers types to be the same.
    - CVA maintenance requirements are not as stringent and complex as those of a CVN, making CVAs more available for deployment and other fleet operations than CVNs.
    - CVNs perform better than CVAs on long transits and had fewer logistics requirements in the theater of operation. GAO judged that these differences were operationally not that significant.
  - Life-cycle costs for CVAs and CVNs (for a 50-year service life) were estimated at $14.1 billion and $22.2 billion (in FY 1997 dollars), respectively. GAO estimated the life-cycle premium per CVN to be about $8 billion, which was significantly higher than a Navy study, which estimated a $4 billion premium.
    - Mid-life modernization of a CVN was estimated to be almost three times as expensive as for a CVA: about $2.4 billion versus $866 million (in fiscal year 1997 dollars).
- **2006 – 2008:** Four former Ohio-class SSBNs converted to SSGNs re-entered service, each armed with up to 154 conventionally-armed Tomahawk land-attack cruise missiles. These SSGNs can conduct high-volume, sustained attacks and and can replace manned attack aircraft in high-risk missions.

Post WW-II evolution of aircraft carrier operations

- **2007:** With the retirement of the *USS John F. Kennedy* (CVA-67) on 23 March 2007, the Navy had an all nuclear-powered CVN fleet.
- **2012:** *The USS Enterprise* (CVN-65) was retired on 1 December 2012 and then brought to Newport News Shipbuilding for inactivation, which started in 2013. *Enterprise* is the first CVN that will be processed through the Navy's Nuclear Ship & Submarine Recycling Program (NSSRP). Eight reactor plants and the large size of the ship create challenges that NSSRP has not encountered previously.
- **2013:** The first successful automated takeoffs and landings by an unmanned, autonomous aircraft on an aircraft carrier at sea were conducted, opening a new era in naval aviation.
  - 14 May 2013: A Northrop X-47B prototype made the first autonomous takeoff from the *USS George H.W. Bush* (CVN 77).
  - 10 July 2013. The Northrop X-47B made multiple autonomous landings on, and launches from *Bush.*

Northrop X-47B prototype on *USS George H.W. Bush.*
Source: US Navy photos / https://www.popsci.com/

Post WW-II evolution of aircraft carrier operations

- **2017:** The lead ship in the next generation of US aircraft carriers, the *USS Gerald R. Ford* (CVN-78) was commissioned on 22 July 2017, bringing the CVN fleet back up to its authorized level of 11 CVNs. While *Ford* is a further evolution of the Nimitz-class design, it includes some first-of-a-kind technical changes, including the electromagnetic catapults and arresting gear. If these changes are successfully implemented, *Ford* will greatly change future carrier operations.

- **2017:** The stealthy F-35C Lightning II Joint Strike Fighter made its first successful landings and launches from the *USS Abraham Lincoln* (CVN-72) in September. First deployment is not expected until 2021. The F-35C will be the first stealth fighter deployed on an aircraft carrier. This will be a significant advance for naval aviation.

F-35C. Source: Lockheed Martin / https://www.navytimes.com/

The current US aircraft carrier operational cycle

- With the current fleet of 11 CVNs, the Navy's operational goal is to have at least six carriers deployed (or able to deploy) within 30 days, and a seventh carrier deployed (or able to deploy) within 90 days.
  - For the first time in several years, the Navy had seven CVNs simultaneously deployed in November 2017. Three were on operational deployments in the Western Pacific and four were conducting training operations or workups prior to their upcoming operational deployments.
- Beginning in FY 2015, the Optimized Fleet Response Plan (O-FRP) calls for operating Carrier Strike Groups to a 36-month training and deployment cycle (4 months longer than the previous cycle). All required maintenance, training, evaluations, plus a single eight-month overseas deployment, are scheduled throughout this 36-month cycle in order to reduce costs while increasing overall fleet readiness.
  - Streamlines inspection and evaluation processes while maintaining a surge capacity for emergency deployments.
  - The ultimate objective is to reduce time at sea while increasing in-port time from 49% to 68%.
- Norfolk Naval Shipyard and Puget Sound Naval Shipyard are the two public shipyards that perform depot-level maintenance for aircraft carriers, including the 6-month planned incremental availability (PIA) and 15-month docking planned incremental availability (DPIA).
- One 46 - 48 month (about 4 year) mid-life refueling + complex overhaul (RCOH) typically takes place about 25 years into a CVN's service life. Newport News Shipbuilding is the only shipyard qualified to perform a RCOH.

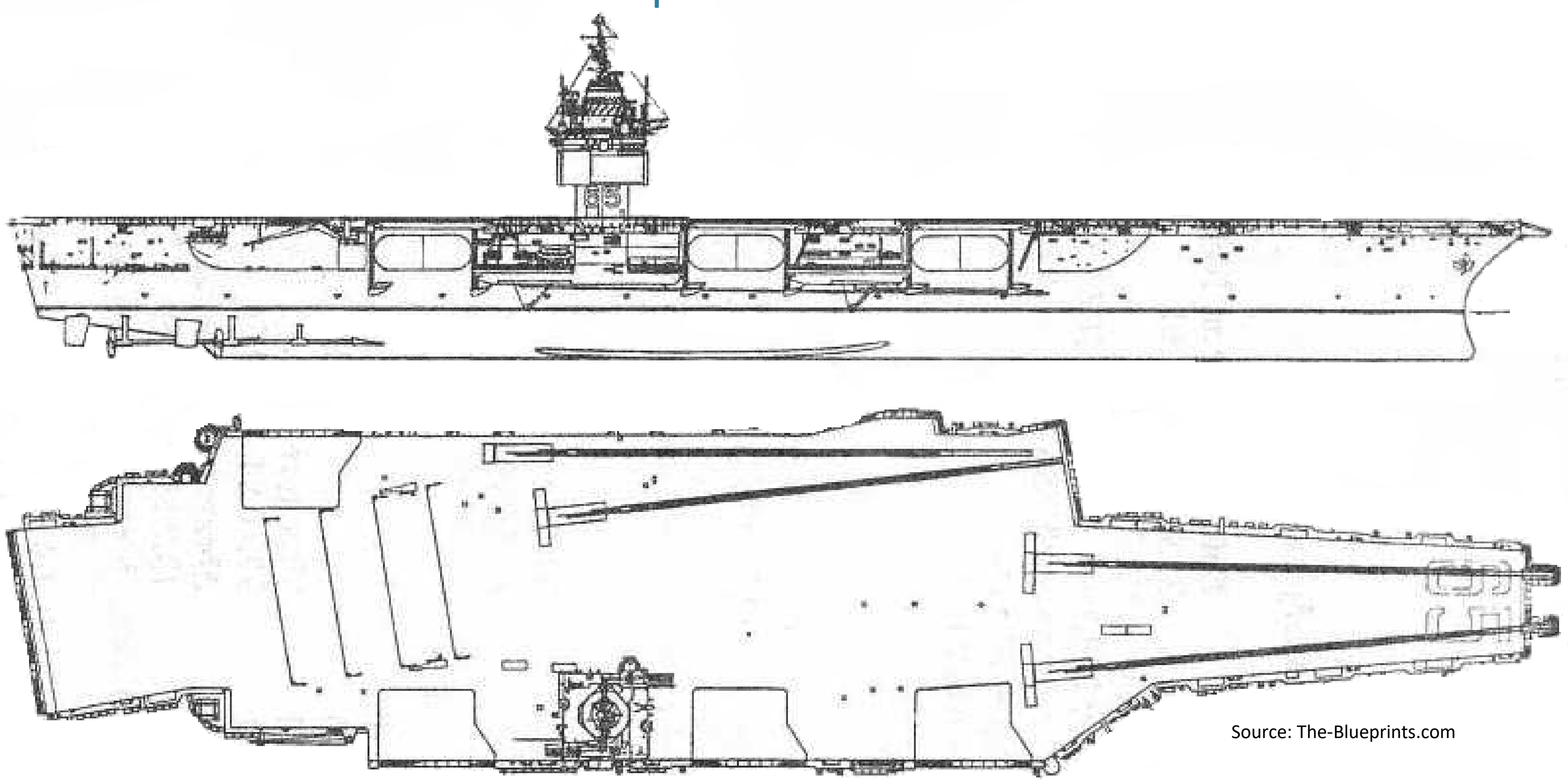
Nuclear-powered aircraft carriers

Class	# in Class	Length	Beam	Displacement (tons)	Reactor	Shaft (hp)	Max speed (kts)	Years delivered	Years in service
Enterprise (CVN-65)	1	342.3 m (1,123 ft)	40.5 m (132.8 ft) (waterline) 78.4 m (257.2 ft)(max)	94,781	8 x A2W	280,000	33.6	1962	1962 - 2012
John F. Kennedy (originally CVN-67, completed as CV-67)	1	321 m (1,052 ft)	40 m (130 ft) (waterline) 76.8 m (252 ft) (max)	82,655	4 x A3W (original plan); Oil-fired steam plant (as delivered)	260,000	30+	1968, delivered as non-nuclear CV-67	1968 - 2007
Nimitz (CVN-68)	10	332.8 m (1,092 ft)	40.8 m (134 ft) (waterline) 76.8 m (252 ft) (max)	101,600 – 106,300	2 x A4W	260,000	30+	1975 - 2009	1975 - present
Ford (CVN-78)	11* (plan)	337.1 m (1,106 ft)	40.8 m (134 ft) (waterline) 78.0 m (256 ft) (max)	100,000	2 x A1B	260,000	30+	2017	2017 - present

- The current congressional mandate is for a fleet of 11 CVNs. This is reflected in the Navy's 2014 Force Structure Assessment (FSA) for a 305-ship fleet. The updated December 2016 FSA for a 355-ship fleet projects the need for 12 CVNs. Congress has not yet authorized this increase.

USS Enterprise (CVN-65)

1st nuclear-powered aircraft carrier



Source: The-Blueprints.com

- Keel laid 4 Feb 1958 at Newport News Shipbuilding; commissioned 25 Nov 1961; in service 12 Jan 1962.
- Propulsion: 8 x A2W reactors each rated @ 150 MWt (est.); 1,200 MWt total; 4 x steam turbines driving 4 x shafts; total propulsion power 280,000 shp (210 MW). Two reactor plants were dedicated to each of the four propulsion trains. The secondary steam system also supplied steam for the aircraft catapults.

USS Enterprise (CVN-65)

- Operational matters
  - Original service life was 20 years, and subsequently was extended to 52 years.
  - 1st deployment occurred during the 1962 Cuban missile crisis.
  - 1st nuclear ship to engage in combat: 2 December 1965, providing air support for ground operations in Vietnam.
  - 1979 - 81: Original bridge superstructure rebuilt; planar SCANFAR radars removed and replaced with more modern air search radars.
  - Enterprise's reactors were refueled three times as part of refueling and complex overhauls (RCOH). Cores 1 & 2 operated for an average of 3 years; Cores 3 & 4 operated for an average of 18.9 years.
  - *Enterprise* was retired on 1 Dec 2012 after 51 years of service and decommissioned on 3 Feb 2017.

CVN-65 with original superstructure & SCANFAR. Source: US Navy

CVN-65 revised superstructure, circa 1990. Source: tapatalk.com

Operation Sea Orbit

31 July – 3 October 1964

Task Force One. Note the planar SCANFAR radars on the bridge superstructures of the *USS Enterprise* and *USS Long Beach*. Source: US Navy

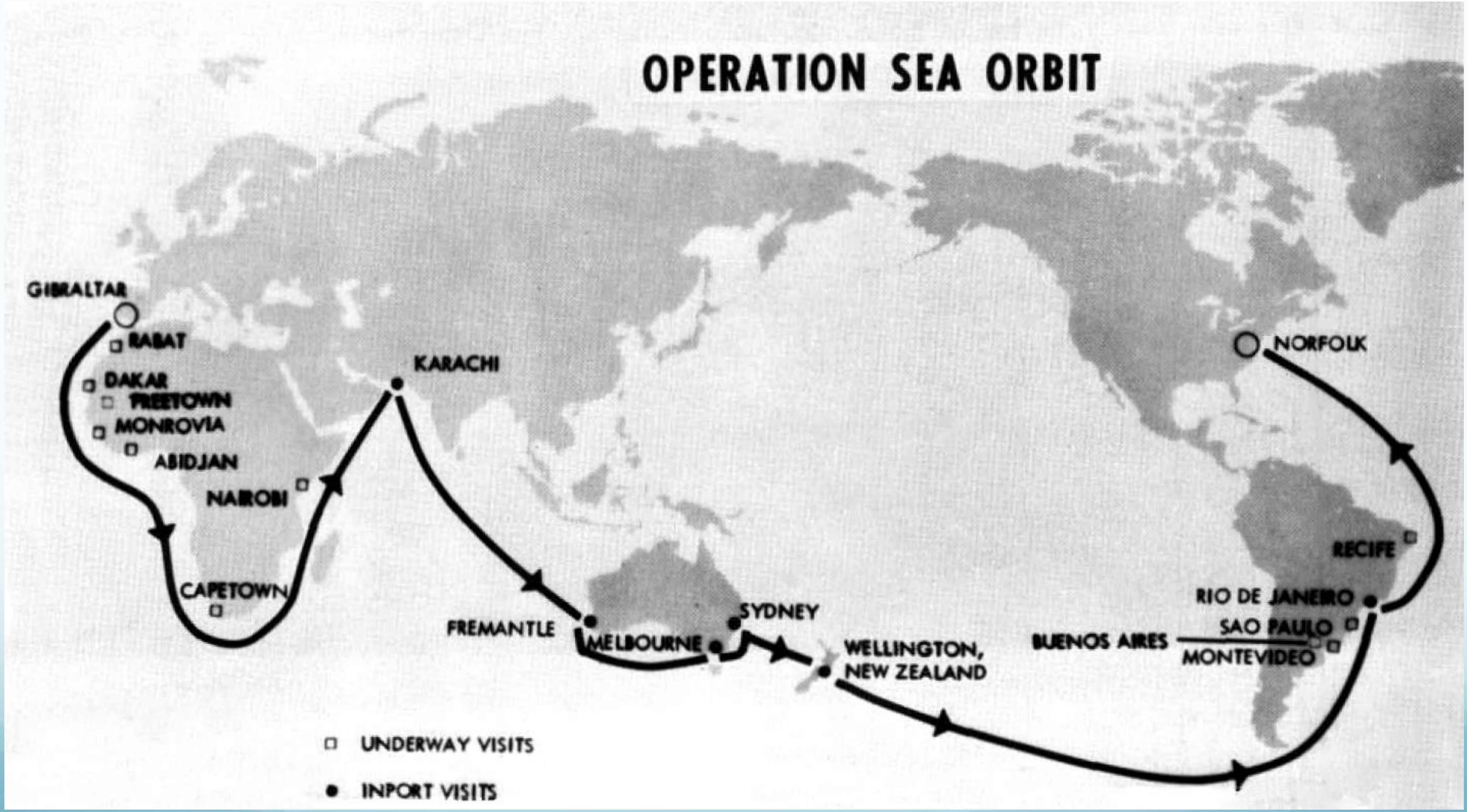
On 31 July 1964 the all-nuclear Task Force One (TF1), comprised of US Navy warships *USS Enterprise* (CVN-65), *USS Long Beach* (CGN-9), and USS *Bainbridge* (DLGN-25, later CGN-25), commenced a global cruise, *Operation Sea Orbit*, circumnavigating the globe without refueling or replenishment.

Task Force One spent 65 days deployed, with 57 of them at sea, and steamed 30,216 nautical miles (48,628 km). Average speed while underway was about 22 kts.

Rear Admiral Strean noted that the flexibility of operating a force of nuclear powered vessels meant that TF1 "could have been diverted to any other maritime area of the world without logistical considerations and could have been ready for immediate operations upon arrival."

Operation Sea Orbit

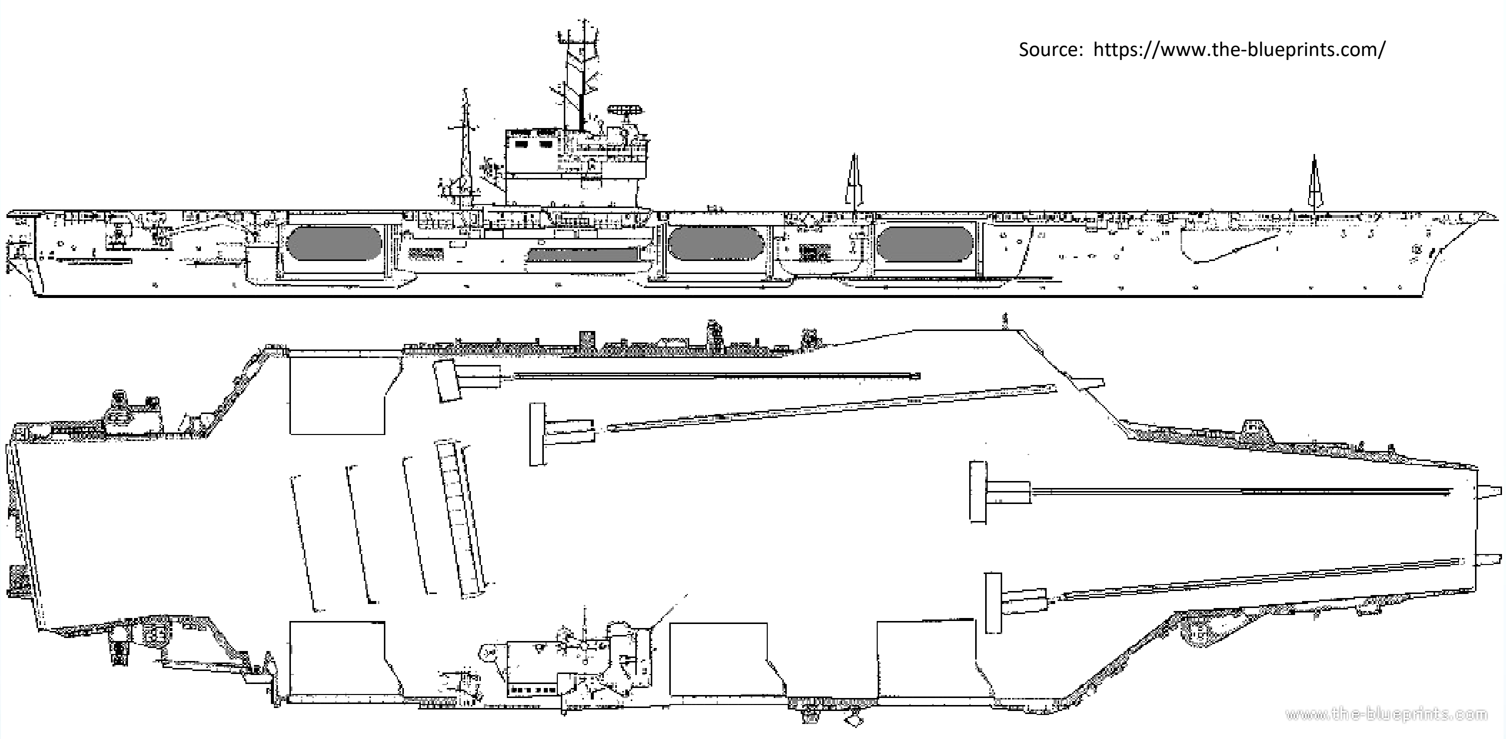
31 July – 3 October 1964



Source: US Navy

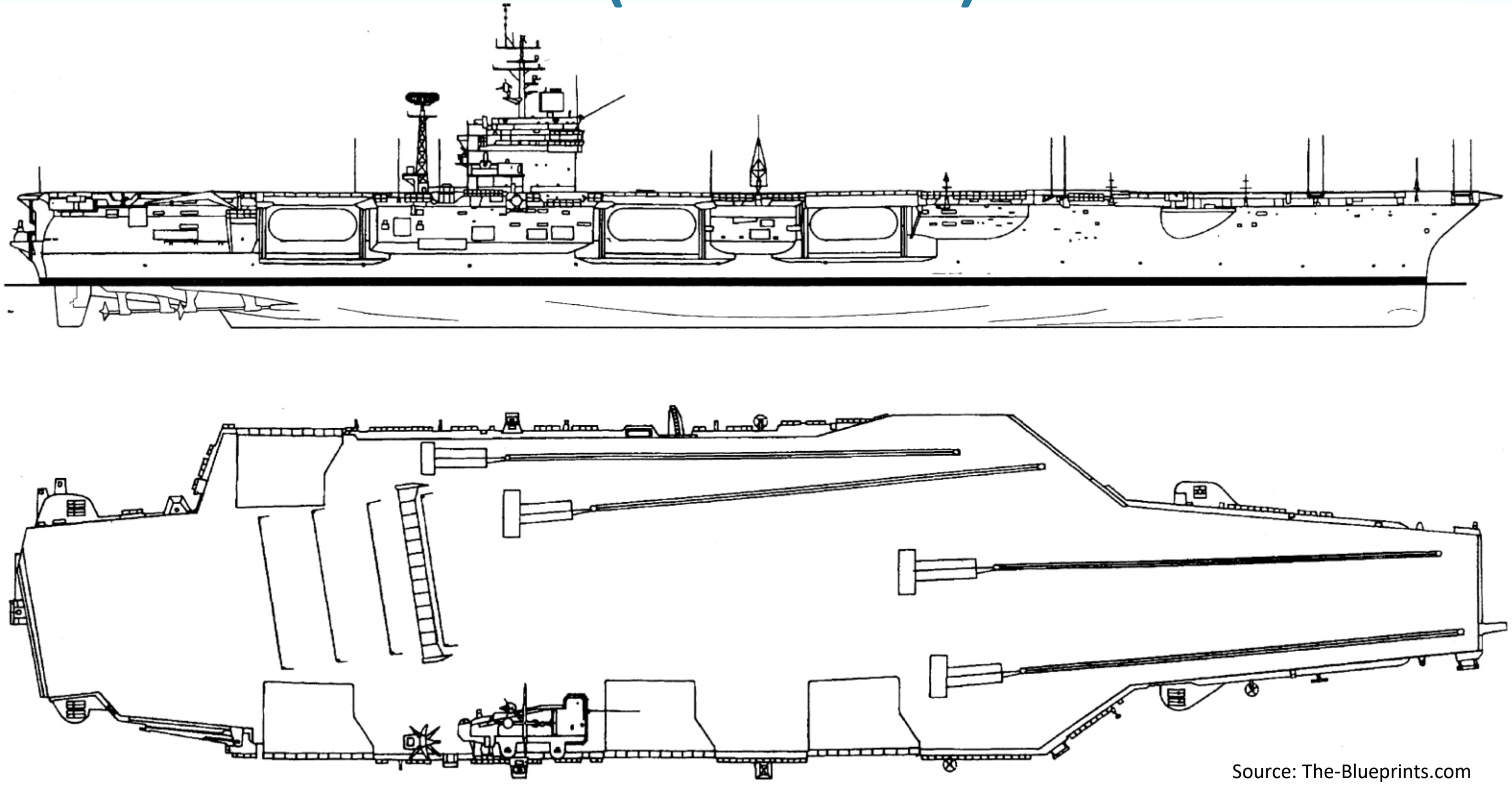
USS John F. Kennedy

Almost CVN-67



- Originally, *USS John F. Kennedy* was intended to be a nuclear-powered modification of the Kitty Hawk-class of carriers and was to be designated CVN-67. However, it was converted to a conventional propulsion plant after construction began at Newport News Shipbuilding in 1964 and was completed as CV-67. It was the last conventionally-powered carrier built for the Navy.
- CVN-67 planned nuclear propulsion: 4 x A3W PWRs, each rated @ about 300 MWt; 1,200 MWt total; with 4 x steam turbines driving 4 x shafts; total propulsion power 280,000 shp (210 MW). The secondary steam plants also supply steam for the aircraft catapults.
- CV-67 has been decommissioned. The name *USS John F. Kennedy* will will be assigned to the second Ford-class nuclear-powered carrier, CVN-79.

Nimitz (CVN-68)-class



Source: The-Blueprints.com

- Ten Nimitz-class aircraft carriers were built by Newport News Shipbuilding and were commissioned between 1975 - 2009.
- Propulsion & electric power: 2 x A4W PWRs, each rated @ 550 MWt; 1,100 MWt total. The General Electric A1G is a replacement reactor core for the A4W.
  - 4 x steam turbines driving 4 x shafts; total propulsion power 260,000 hp (194 MW).
  - The secondary steam plants also supply steam for the aircraft catapults.
  - 8 x steam turbine-generators producing 8 MWe each, for a total electrical generating capacity of 64 MWe.

Nimitz (CVN-68)-class

- Armament:
  - Embarked air wing: typically 70 - 75 fixed-wing and rotary-wing aircraft (max. of about 90)
  - The CVNs, themselves, have only modest close-in anti-air armament (varies from ship to ship): Sea Sparrow, Rolling Airframe Missile (RAM), Phalanx 20 mm Close-In Weapon System (CIWS).
  - CVNs depend on other ships in the carrier strike group as their primary means of anti-air/missile, anti-surface & anti-submarine defense.
- Operational matters:
  - The construction cost of the earlier Nimitz-class ships was about $4.5 billion each. Almost 30 years later, the construction cost for the last ship (*USS George H. W. Bush*), which was commissioned in 2009, was about $6.2 billion.
  - In November 2013, the Congressional Budget Office reported that Nimitz-class carriers can sustain 95 strike sorties per day and, with each aircraft carrying four 2,000-pound bombs, deliver three-quarters of a million pounds of bombs each day.
  - Operating life is planned to be 50 years, with one 46 - 48 month (about 4 year) mid-life refueling + complex overhaul (RCOH) that typically takes place after 25 years of service.
    - About 35% of all maintenance and modernization work the carrier will ever get in its service life takes place during the four-year RCOH.
    - As of early-2018, the RCOH has been completed on five ships (CVN-68 to -72). The RCOH for *USS George Washington* (CVN-73) started in August 2017, one year later that originally planned. The contract price for the CVN-73 RCOH is $2.8 B. The RCOH for CVN-74 to -77 should occur between 2020 and 2034.
    - Only one aircraft carrier is out of service for a refueling overhaul at a time.
  - The first Nimitz-class carrier (*USS Nimitz*) will reach the end of its service life in 2025, and the last (*USS George H W Bush*) in 2059.
    - Nimitz-class carriers will reach their 50 year service life at 3 – 4 year intervals during this period.

USS Nimitz (CVN-68)

Source: US Navy

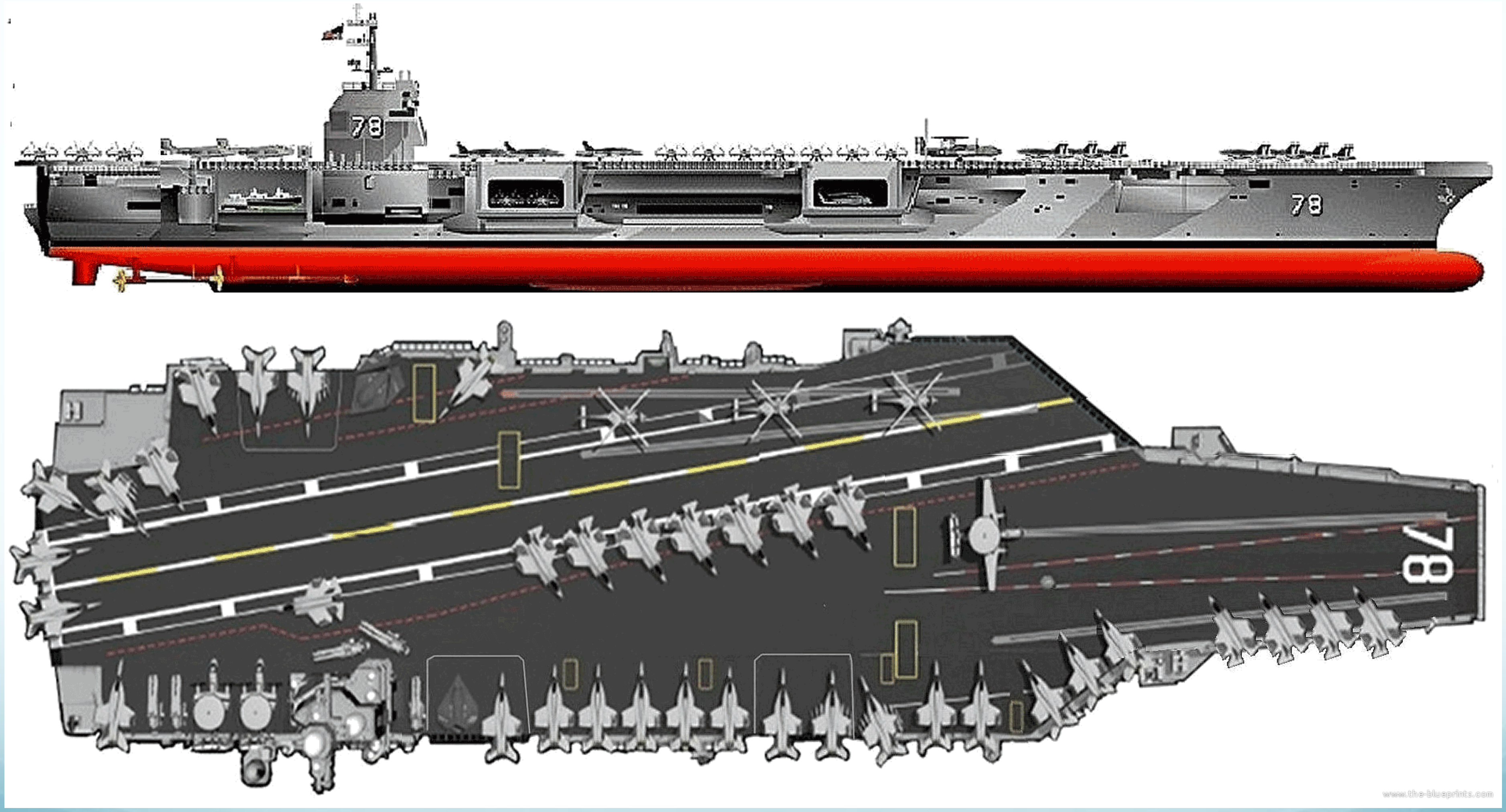
Three Nimitz-class carriers

USS Nimitz (CVN-68), *USS Theodore Roosevelt* (CVN-71) & *USS Ronald Reagan* (CVN-76) in joint exercise off South Korea, November 2017. Source: US Navy

Gerald R. Ford (CVN-78)-class

- This is the first new class of US aircraft carriers since construction of the last Nimitz-class carrier (*USS George H.W. Bush,* CVN-77) was completed in 2006.
- The first Ford-class carrier replaces the *USS Enterprise (CVN-65)*, which retired in 2012, to restore the Navy to its Congressionally-mandated fleet of 11 carriers.
  - Follow-on Ford-class carriers are intended to replace the 10 Nimitz-class aircraft carriers on a one-for-one basis.
- Propulsion and electric power: 2 x A1B Bechtel PWRs
  - Reactor power rating is not known, but is expected to be greater than the 550 MWt A4W reactors used in Nimitz-class carriers.
  - 4 x steam turbines driving 4 x shafts; total propulsion power 260,000 hp (194 MW); same as Nimitz-class
  - Electric power generating capacity of about 104 MWe from 4 x 26 MWe generators; almost twice the 64 MWe generating capacity of Nimitz-class CVNs.
    - Primary generation voltage is 13,800 volts vs. 4,160 volts on Nimitz-class CVNs.
    - New large electrical loads: ElectroMAgnetic Launch System (EMALS) and the Advanced Arresting Gear (AAG) system replace steam catapults and hydraulic arresting gear on Nimitz-class CVNs.

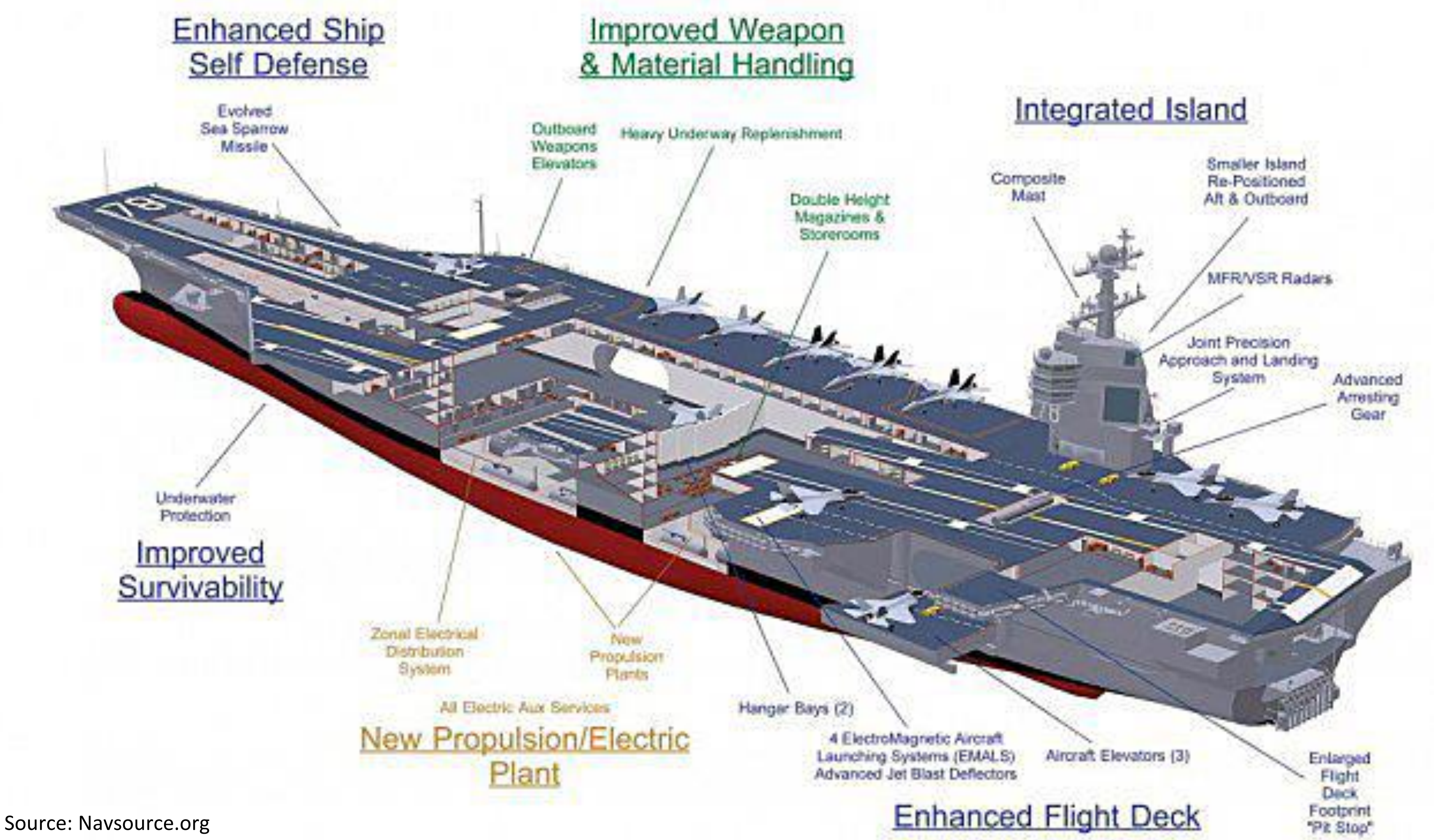
Gerald R. Ford (CVN-78)-class



Source: https://www.the-blueprints.com/blueprints/ships/

Gerald R. Ford (CVN-78)-class

Overview of design changes and system improvements

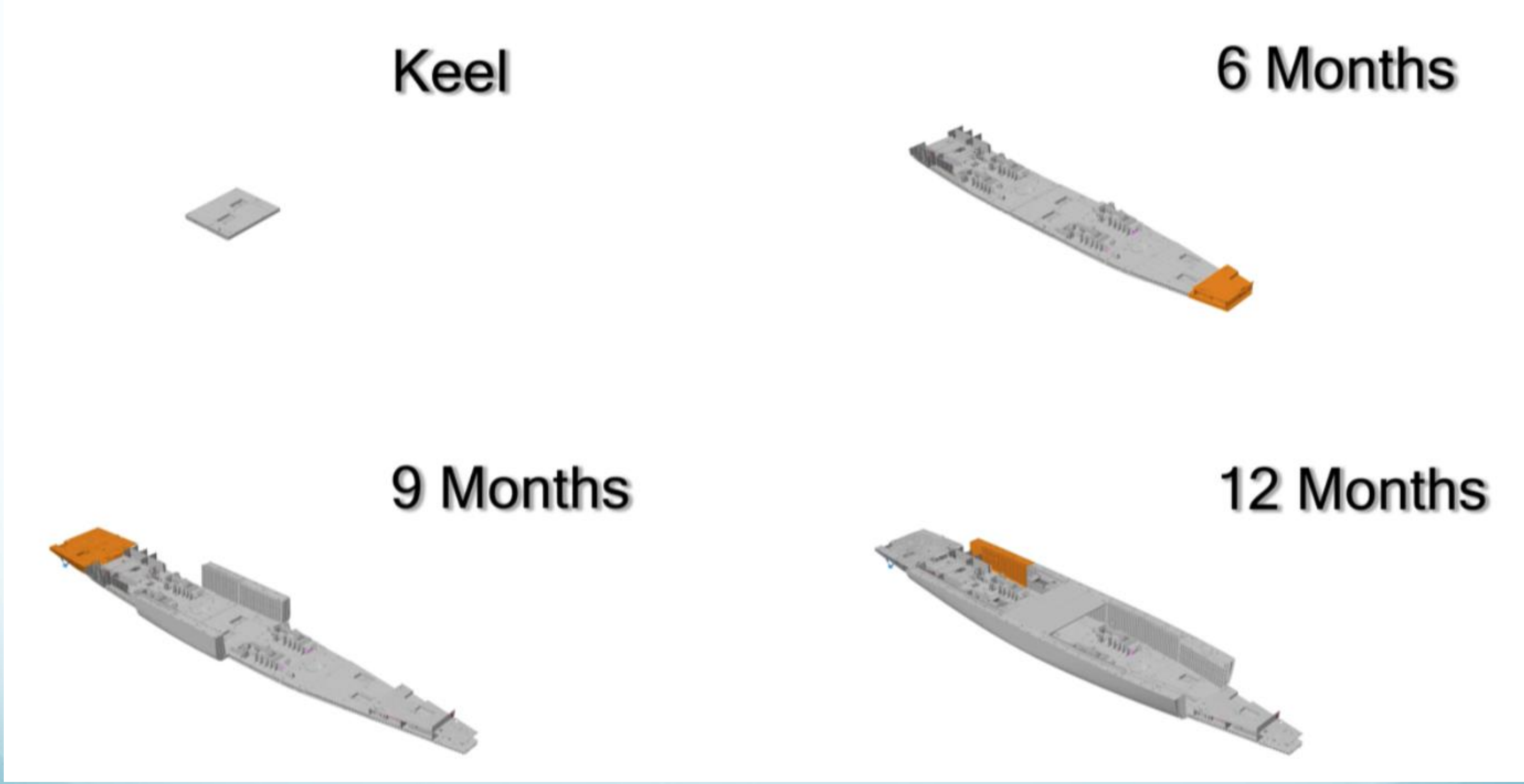


Source: Navsource.org

Gerald R. Ford (CVN-78)-class

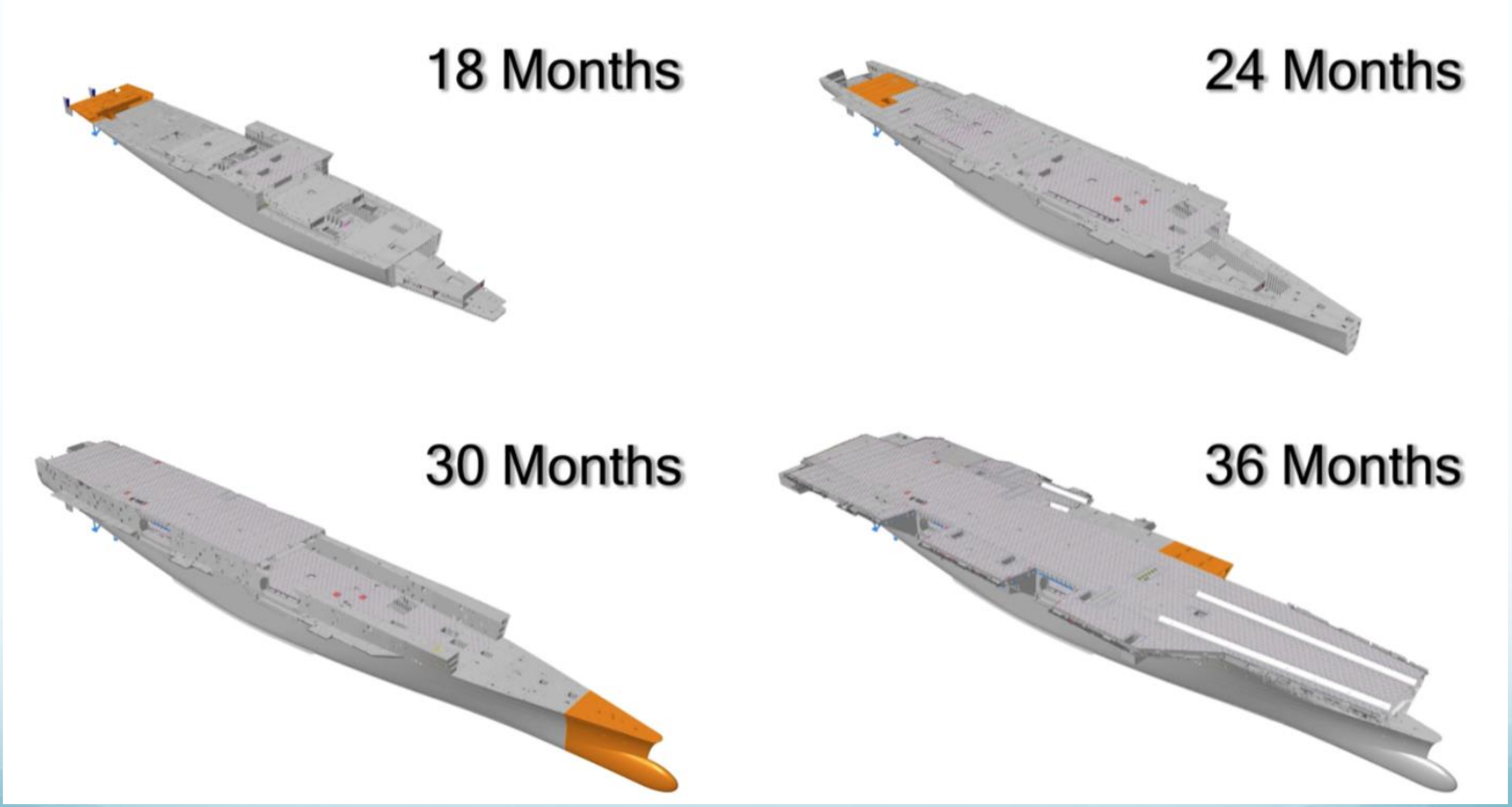
- Operational matters:
  - 13 November 2009: Keel laid for lead ship, *USS Gerald R. Ford* (CVN-78)
  - 22 July 2017: *USS Gerald R. Ford* commissioned. The Navy's FY2016 estimate of the ship's procurement cost was about $12.9 billion.
  - 28 July 2017: First aircraft launch (an F/A-18F) using the electrically-powered ElectroMAgnetic Launch System (EMALS) and recovery using the Advanced Arresting Gear (AAG) system from an aircraft carrier.
  - First deployment of *USS Ford* may not occur until 2020 to allow time to complete operational testing, including shock tests (live munitions exploded in the water close to the ship).
- Procuring the replacement fleet:
  - 2nd ship in class, *USS John F. Kennedy* (CVN-79), keel was laid on 22 August 2015. The Congressionally mandated price cap is $11.5 B. *Kennedy* is scheduled to replace *USS Nimitz (CVN-68),* which is scheduled to retire in 2025.
  - 3rd ship in class, *USS Enterprise* (CVN-80), is scheduled to be procured in FY2018.
  - The next ship, CVN-81, will be procured in FY2023 and following ships will be procured at 3 – 4 year intervals until the *USS George H.W. Bush* (CVN-77) is replaced after 50 years of service in 2059.

Building *USS Gerald R. Ford*



Source: Composite of 4 screenshots from a Newport News Shipbuilding video at http://nns.huntingtoningalls.com/

Building *USS Gerald R. Ford*



Source: Composite of 4 screenshots from a Newport News Shipbuilding video at http://nns.huntingtoningalls.com/

Building *USS Gerald R. Ford*

Source: Screenshot from a Newport News Shipbuilding video at http://nns.huntingtoningalls.com/

Commissioning. 22 July 2017.
Source: http://metro.co.uk/2017/07/23/

USS Gerald R. Ford (CVN-78)

Source: US Navy

Carrier strike group (CSG) & carrier air wing composition

Carrier Strike Group (CSG) composition

Above: Ticonderoga-class CG. Source: US Navy
Below: Arleigh Burke DDG. Source: en.wikipedia.org

- Other than its embarked air wings, a CVN is lightly armed and not able to put up a strong defense against attack. The CVN was designed to operate in a Carrier Strike Group with other heavily-armed ships that are responsible for defending against air, missile, surface and underwater threats.
- Carrier strike group elements vary, but typically include:
  - The nuclear-powered aircraft carrier with its embarked carrier air wing,
  - At least one Ticonderoga (CG-47)-class guided missile cruiser, which has the Aegis combat system,
  - A destroyer squadron with at least two Arleigh Burke (DDG-51)-class guided missile destroyers, which also have the Aegis combat system,
  - A combined ammunition, oiler & supply ship, such as a Supply-class T-AOE, or a combination of smaller logistics ships.
  - Fast attack nuclear submarines (SSNs) may join the CSG in the theater of operation.

Carrier Strike Group (CSG) composition

USS George Washington (CVN-73) Carrier Strike Group in 2003, includes three Ticonderoga-class Aegis guided missile cruisers, three Arleigh Burke-class Aegis destroyers, an Oliver Hazard Perry-class guided-missile frigate, and a Supply-class fast combat support ship (T-AOE). Source: US Navy photo.

Carrier Strike Group (CSG) composition

Three carrier strike groups operating together in international waters in the Western Pacific, November 2017. The *USS Ronald Reagan* (CVN 76), *USS Theodore Roosevelt* (CVN 71) and *USS Nimitz* (CVN 68) Strike Groups transit the Western Pacific with ships from the Japanese Maritime Self-Defense Force. Source: US Navy photo Mass Communications Specialist 3rd Class Anthony J. Rivera.

Replenishment at sea

- A 49,600 ton Supply-class fast combat support ship (T-AOE) travels with a carrier strike group to refuel, rearm & restock ships in the battle group.
- T-AOEs have a maximum speed of 25 knots and are the only Navy resupply ships able to keep up with a carrier strike group.

Source: http://www.defense.gov/Photos

Source: http://cimsec.org

- In 2014, the Navy was considering retiring the four T-AOEs and replacing carrier strike group service with 20 knot oilers and dry cargo ships.
- There is no comparable single vessel planned to replace the Supply-class T-AOEs.
- In early-2018, two Supply-class T-AOEs were in active service (*Supply & Arctic*) and two were inactive, in reserve.

Carrier air wing composition

- Each nuclear-powered aircraft carrier deploys with an embarked air wing typically composed of 70 - 75 fixed-wing and rotary-wing aircraft (up to a maximum of about 90) organized in several squadrons as follows:
  - Four strike fighter (VFA) squadrons with a total of more than 40 F/A-18 Hornets and/or Super Hornets, soon to be supplemented by F-35C Lightning II.
    - The first operational squadron is expected to transition to the F-35C in January 2018, leading to an Initial Operating Capability (IOC) by early 2019 and first operational deployment aboard an aircraft carrier in 2020.
  - One electronic attack (VAG) squadron with 5 EA-18G Growlers.
  - One carrier airborne early warning (VAW) squadron with 4 or 5 turboprop E-2 Hawkeyes (E-2C or E-2D).
  - One helicopter sea combat (HSC) squadron with 8 MH-60S Seahawks to carry out missions such as vertical replenishment, combat search and rescue (SAR), special warfare support, and airborne mine countermeasures.
  - One helicopter maritime strike squadron (HSM) with 11 MH-60R Seahawks, 3 to 5 of which are based on other ships in the carrier strike group, to carry out missions such as anti-submarine warfare (ASW), anti-surface warfare, naval gunfire support (NGFS), surveillance and communications relay. The also can perform SAR, logistics support, personnel transfer and vertical replenishment.
  - One fleet logistics support (VRC) squadron detachment with 2 turboprop C-2A Greyhound cargo planes.

Carrier air wing composition

F/A-18E Superhornet
Source, both photos: US Navy

EA-18G Growler
Sources: Ralph Duenas/Airliners.net (above);
Boeing (below)

Carrier air wing composition

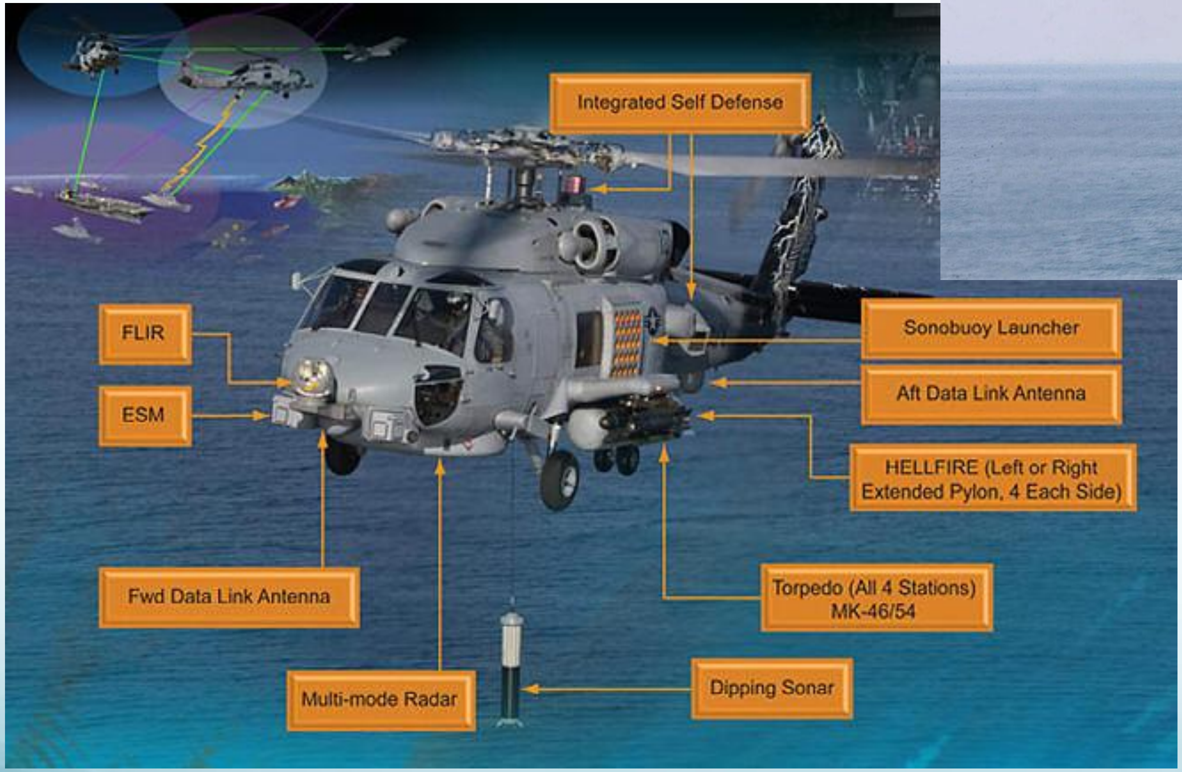
E-2C Hawkeye
Sources: US Navy photos, by Ltjg John A. Ivancic (above), by Mass Communication Specialist Seaman Jamaal Liddell (below)

C-2A Greyhound
Sources: http://aerosimulation.com (above); https://www.cybermodeler.com/aircraft/e-2/ (below)

Carrier air wing composition

Both versions of the MH-60 Seahawk helicopter can be reconfigured for various missions. If the ASW mission package is removed from the MH-60R, it takes several hours to reinstall and reconfigure the helicopter for ASW duty.

MH-60S Seahawk
Source: US Navy photo by Photographer's Mate 1st Class Marvin Harris



MH-60R Seahawk
Sources: US Navy

Land-based patrol aircraft support carrier strike groups

- The carrier air wing has no ASW / maritime patrol fixed-wing aircraft. The last S-3 Viking patrol aircraft were retired in January 2009.
- The ASW mission package for the multi-mission MH-60R helicopters is not always be installed. Conversion of a helicopter to the ASW role, including installation of the dipping sonar, takes several hours.
- Today, the carrier strike group is dependent on the ASW / maritime patrol capabilities of the strike group destroyers, cruisers and submarines, supplemented by two types of long-range, land-based, fixed-wing patrol aircraft: the older P-3 Orion and the newer P-8 Poseidon.

P-3 Orion. Source: Royal Air Force Museum

P-4 Poseidon. Source: http://www.businessinsider.com

Anti-access/area denial (A2/AD) challenges to CSG operations

- Anti-access/area denial (A2/AD) challenges can be raised even by small nations armed with modern, long-range, precision-guided anti-ship cruise and ballistic missiles, quiet conventional submarines, and layered anti-aircraft defenses. The proliferation of these types of weapons systems is redefining the role of the Carrier Strike Group in international conflicts.
- Long-range anti-ship weapons that can be launched from a variety of platforms (i.e., land, aircraft, surface ship and submarine) give many nations the ability to raise an A2/AD threat that could force CSGs to operate further from their intended target. For example:
  - Subsonic and supersonic anti-ship cruise missiles: A full salvo of cruise missiles from a single Russian Oscar-class SSGN may overwhelm the defense capabilities of a carrier strike group. Russia is modernizing the Oscar-class SSGNs to carry up to 72 x 3M55 (P-800) Oniks and/or 3M54 Kalibr supersonic anti-ship cruise missiles.
  - Hypersonic anti-ship cruise missiles: Russia and India are developing this new class of cruise missiles capable of flying and maneuvering at hypersonic speeds. The Russian 3M22 Zircon / Tsircon and the Indian / Russian joint venture BrahMos II will fly at Mach 5 – 7 with a range of 300 km (186 miles) or more. The ability of the US Navy's Aegis Combat System to defend against this type of threat is not known.
  - Ballistic anti-ship missiles: Access to the South China Sea could become an issue for any US military vessels in a time of conflict, due to the presence of China's unique DF-21D anti-ship ballistic missiles with a range of 1,448 km (900 mi).

Anti-access/area denial (A2/AD) challenges to CSG operations

- CSG defenses inherently are limited by the number of cruisers and destroyers in the CSG and the array of weapons in their vertical launch systems (VLS).
  - Each Ticonderoga-class cruiser has 2 x 61 cell Mk-41 VLS launchers (122 missiles total)
  - Each Arleigh Burke Flight I destroyer has 90 Mk-41 VLS launchers. The Flight II DDGs have 96 launchers.
  - The VLS launchers handle a range of weaponry, only some of which are for anti-aircraft and anti-missile defense. Other weapons normally carried include Tomahawk cruise missiles and ASROC anti-submarine missile. The VLS launchers cannot be reloaded at sea.
  - The Navy was planning to retire 11 of the 22 Ticonderoga-class Aegis cruisers, which are key elements of CSG anti-air and anti-missile defense, with no plans for a replacement cruiser. In early 2017, Congress reached a compromise with the Navy to modernize all 11 cruisers over a period of about 6 years, with no more than 6 out of service at a time.
- An A2/AD threat could challenge the range of current carrier attack aircraft.
  - The Navy no longer operates long-range heavy attack aircraft. The limited range of current naval attack aircraft (Boeing F/A-18 variants and the new Lockheed F-35C) could compromise their combat effectiveness in a distant target zone and/or require in-flight refueling to complete the mission.
  - The Navy has no dedicated refueling aircraft. After the retirement of the Lockheed S-3 Viking in 1990, the Navy lost a capable refueling tanker. F/A-18 fighters can refuel each other using "buddy system" pods, but this takes a fighter out of service to provide refueling service to another fighter. A new naval refueling tanker is at least a decade away.
  - When needed at a larger scale, refueling services for naval fighters can be provided by the much larger US Air Force refueling tankers.

Anti-access/area denial (A2/AD) challenges to CSG operations

- The difficulty of penetrating modern, layered anti-air defense systems continues to increase.
  - Carrier air wings soon will be receiving the Lockheed F-35C Lightning II joint strike fighter, which will become the premier attack aircraft in an A2/AD environment. The stealth features of the F-35C should decrease detectability and improve survivability in an A2/AD environment
  - The Boeing EF-18G Growler provides electronic warfare support, which is of particular value when employing the less-stealthy F/A-18 attack aircraft.
  - The Navy is developing a variety of unmanned aerial systems (UAS) and doctrine for their use in combat. The next decade likely will see changes in the way carrier air wings are structured to take advantage of the new USA capabilities.
- Very quiet, modern non-nuclear submarines are proliferating, enabling many nations to mount a credible submarine threat to a CSG operating in littoral waters or in the open ocean.
  - The CSG typically includes one or two nuclear-powered attack submarines, which can defend against hostile submarines. However, it is a big ocean when the adversary has long-range anti-ship weapons.
  - The vertical launch ASROC (RUM-139) on the CSG cruisers and destroyers only has a range of 22 km (13.7 mi) and is not useful against a long-range submarine threat.

Naval nuclear vessel decommissioning and nuclear waste management

US Navy's Nuclear Ship & Submarine Recycling Program (NSSRP)

- Defueling usually is carried out at any of five ship repair facilities on the US West Coast.
  - Reusable ship's equipment also is removed at this time.
  - After fuel has been removed, the hulls are classified as low-level radioactive waste.
  - Spent fuel is shipped by rail to Naval Reactors Facility (NRF) at Idaho National Laboratory (INL) where the fuel is stored in special canisters.
- *USS Enterprise* (CVN-65) was an exception. It was brought to Newport News Shipbuilding (NNS), Newport News, VA in 2013 and defueled there.

Source: http://snakeriveralliance.org/nuclear-navys-final-port-of-call/

US Navy's Nuclear Ship & Submarine Recycling Program (NSSRP)

- After defueling, sub and cruiser hulls are towed to Puget Sound Naval Shipyard (PSNS) and placed in temporary "afloat storage."
- Submarine hulls are processed in Drydock 1, where the vessel is cut into 3 or 4 sections: bow, missile, reactor, stern.
  - Missile compartments of FBM subs are dismantled according to the provisions of the Strategic Arms Reductions Treaty.
  - The reactor compartment of each vessel is removed and sealed with welded steel bulkheads.
  - Until 1990, the forward and aft sections of the submarines were rejoined and placed in floating storage.
  - Since 1990, hazardous and toxic material in the remaining submarine sections are cleaned, usable equipment is recycled, and the balance is scrapped.
    - *USS Scamp* (SSN-588) was the first submarine to be scrapped in 1990.
  - By the mid-2017, 112 submarines and 9 cruisers have completed processing. In addition, there are 21 submarines in various stages of processing.

Four Lafayette class (SSBN-616) in the early stages of being scrapped at PSNS in 1993

Four subs in drydock at PSNS being recycled.
Source: http://barthworks.com/submarine/

Subs awaiting processing by NSSRP in 2015

11 x Los Angeles (688)-class Flight I subs, *USS Narwhal* (SSN-671), and NR-1 (on the floating platform) at PSNS.

Source: wikimapia.org/1823114/SRP-Fleet

Recycling the nuclear cruisers

USS Long Beach and the California- and Virginia-class CGNs

- NSSRP processed all nine of the US CGNs at PSNS between 1997 – 2012. Each had two reactors.
- Bainbridge & Truxtun were the first two CGNs to complete recycling in 1999.
- Long Beach was to last to complete recycling. Its hull was auctioned for scrap to Tacoma Metals on 12 July 2012 for about $900,000.

CGN	Recycle start date	Recycle completion date
Long Beach (CGN-9)	1 May 2009	13 Jul 2012
Bainbridge (CGN-25)	1 Oct 1997	30 Oct 1999
Truxtun (CGN-35)	1 Oct 1997	28 Apr 1999
California (CGN-36)	1 Oct 1998	12 May 2000
South Carolina (CGN-37)	1 Oct 2007	10 May 2010
Virginia (CGN-38)	1 Oct 1999	25 Sep 2002
Texas (CGN-39)	1 Oct 1999	30 Oct 2001
Mississippi (CGN-40)	1 Oct 2004	5 Dec 2006
Arkansas (CGN-41)	7 Jul 1998	1 Nov 1999

Source: adapted from https://en.wikipedia.org/wiki/Ship-Submarine_Recycling_Program

Source, above: http://ssn578.com/gallery/

Another view of Long Beach (bottom), Texas (with about 100 feet of stern removed so it could fit in a scrapping dock with another CGN) & Virginia (top).
Source, above: Shelton, https://o1c.net/Bottomguns/psns.htm

Recycling a nuclear aircraft carrier

USS Enterprise (CVN-65)

- The *USS Enterprise* is the first nuclear-powered aircraft carrier that will be recycled.
- In 2013, it was brought to Newport News Shipbuilding (NNS) in Virginia, where its eight A2W reactors were defueled and the ship was readied for the next phase of recycling.
- In 2014, the Navy expressed concerns that recycling *USS Enterprise* was such a large job that recycling it at PSNS would disrupt the shipyard's ability to recycle the many nuclear submarines scheduled for retirement in the next decades.
- February 2017: Naval Sea Systems Command cancelled plans for commercial recycling of non-nuclear parts of CVN-65, citing the need for more information to plan the disposal process.

USS Enterprise at NNS, October 2016. Source: The Virginian-Pilot

- April 2018: Huntington Ingalls Industries announced that inactivation of the *Enterprise* was complete.
- *Enterprise* will be towed to an interim location in the Hampton Roads, VA area for a period of "temporary storage" dockside until the Navy decides how to recycle of the vessel.

US Navy's Nuclear Ship & Submarine Recycling Program (NSSRP)

Above: Two sealed reactor compartment on barges at PSNS.
Source: Joel M. Huston, https://o1c.net/Bottomguns/psns.htm

- After removal from the vessel, the sealed reactor compartment is loaded on a barge at PSNS and shipped down the coast and along the Columbia River to the port of Benton, WA.
- There the hull section is transferred to a special multi-wheeled, high-load trailer and transported by road to the DOE Hanford Nuclear Reservation.

Sealed reactor compartment being shipped by barge. Source: State of Oregon

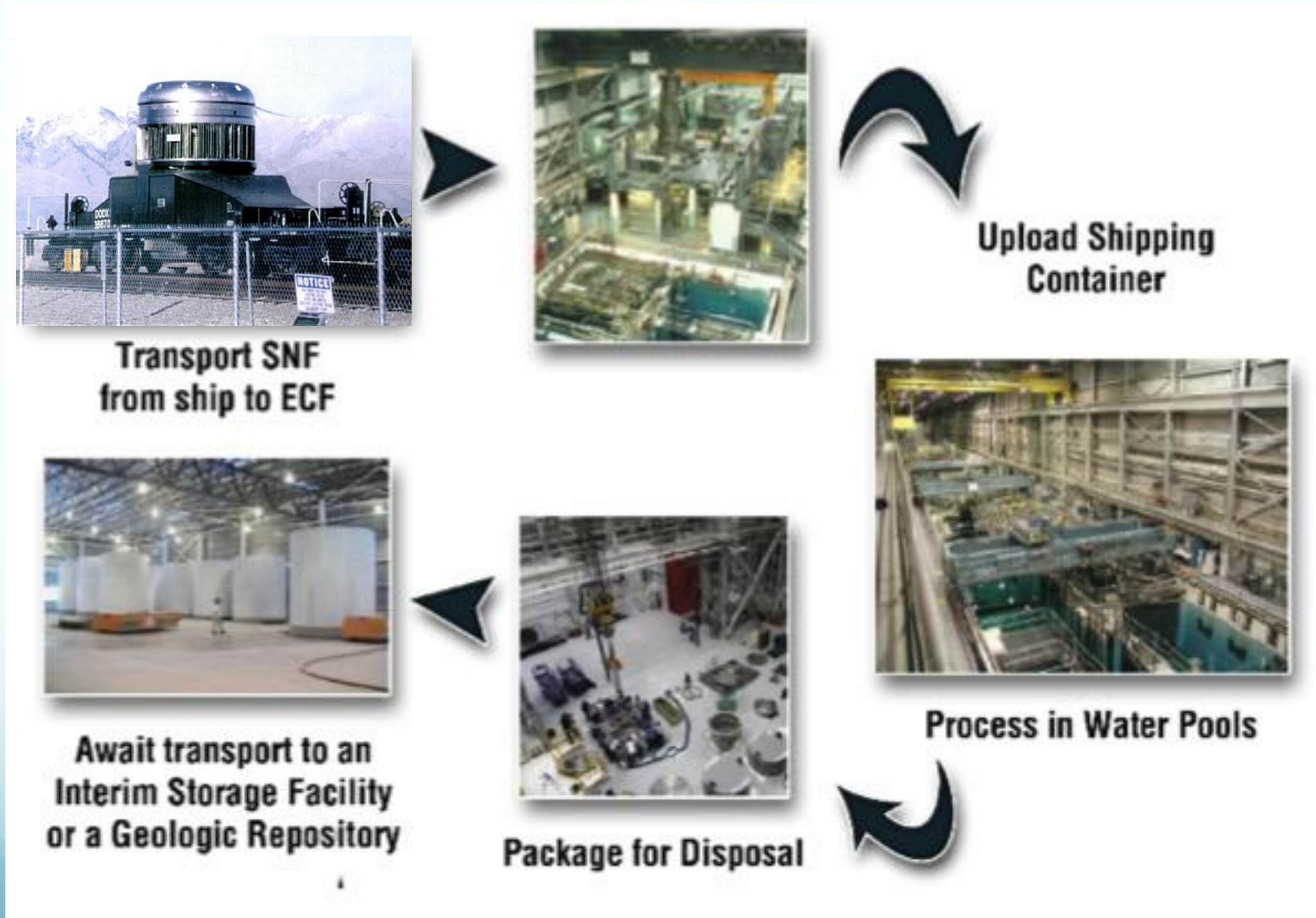
Sealed reactor compartment being moved to the storage pit at Hanford. Source: Guut Goot

US Navy's Nuclear Ship & Submarine Recycling Program (NSSRP)

- At the Hanford Nuclear Reservation, the sealed reactor compartments are kept in dry, open storage in engineered burial trenches that eventually will be covered (Trench 94, 200 Area East).
  - The sealed hull sections and burial trenches are designed for long-term safe storage
- Disposal of a submarine by this process is estimated to cost the Navy $25 – 50 million.

Source: Wikipedia

Spent fuel management at NRF



Source: adapted from http://www.ecfrecapitalization.us/handout2.pdf

US civilian nuclear marine vessels and reactors

US civilian nuclear marine vessels and reactors

- The US only produced one nuclear powered merchant vessel, the *NS Savannah*, and one floating nuclear power plant, *Sturgis*.
  - Both *NS Savannah* and *Sturgis* were retired by the mid-1970s after relatively short service lives.
- The Maritime Administration and Atomic Energy Commission (AEC) sponsored several industry studies of different advanced marine nuclear reactor designs in the 1950s and 1960s.
  - Only one, the Babcock & Wilcox Consolidated Nuclear Steam Generator I (CNSG I), was used in a civilian marine propulsion system, on the German vessel *Otto Hahn*.
  - Only one, the General Atomics EBOR, advanced to the prototype reactor construction stage. However, it was not completed.

US civilian nuclear marine vessels and reactors

- The US and worldwide market demand for civilian nuclear powered vessels never materialized. Reasons are many, including:
  - Early expectations for economically-competitive civilian nuclear vessels have not been demonstrated.
    - In practice, life-cycle costs for civilian nuclear vessels have been higher than their conventionally-powered counterparts. This alone may limit civilian nuclear vessels to high-value, specialty roles such as high-speed transports and ice breakers.
  - A complex and uncertain domestic and international regulatory environment increases the investment risk for nuclear vessels.
    - Many different jurisdictions and stakeholders complicate the marine nuclear licensing process and determination of potential nuclear accident liability.
    - There are greater port infrastructure requirements for nuclear vessels, including shore-side nuclear waste facilities and shore-side nuclear emergency planning.
    - Established maritime pay scales and labor rules may not adequately reflect special qualification requirements for nuclear engineering crew.
    - Public safety concerns.

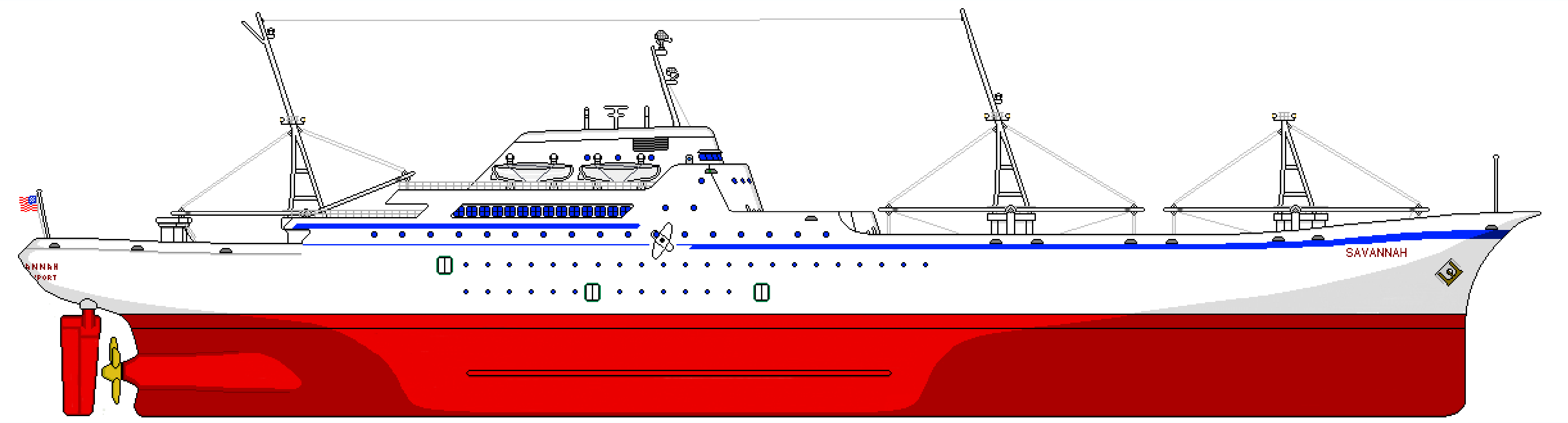
Operational & planned civilian marine vessels and their reactors

US civilian nuclear marine vessels

Class	# in Class	Length	Beam	Displacement (tons)	Reactor	Shaft hp	Max speed (kts)	Years delivered	Years in service
NS Savannah passenger + bulk cargo carrier	1	596 ft (181.7 m)	78 ft (23.8 m)	22,000	1 x 74 MWt B&W 2-loop PWR	22,000	22+	1962	1962 - 72
Sturgis floating nuclear power plant	1	441 ft (134.4 m)	56 ft (17.1 m)	14,500	1 x 45 MWt MH-1A single-loop PWR	0 shp; 10 MWe to shore facilities	O	1962	1968 – 75 at Panama Canal
USNS American Explorer oil tanker	1	595 ft (181 m)	80 ft (24 m)	14,980	1 x GE 630A gas-cooled reactor (original plan)	Not specified	20	1959, completed with conventional boilers	
MARAD PD108 bulk cargo carrier	0				1 reactor, type not specified			Concept only	Concept only

NS Savannah

US prototype civilian bulk cargo + passenger vessel



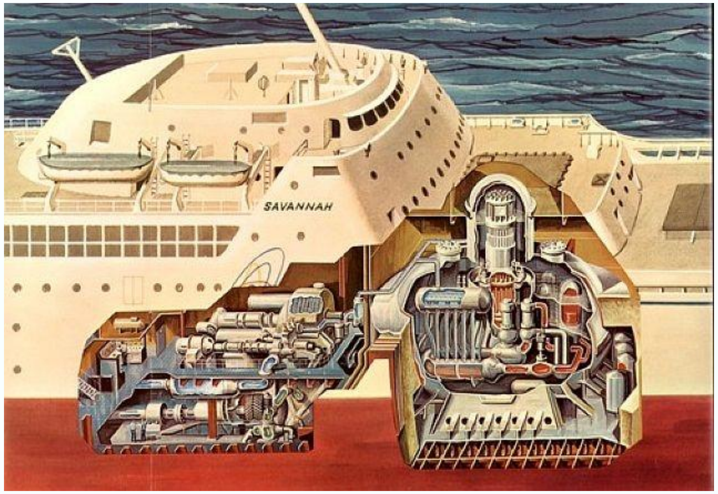
Source: Sailor82, http://www.shipbucket.com/drawings/7051

- In 1955, President Dwight Eisenhower proposed building a nuclear-powered merchant ship as a showcase for his "Atoms for Peace" initiative.
- In 1956, Congress authorized the construction of the first US nuclear-powered merchant ship, *NS Savannah,* as a joint project between the Maritime Administration of the Department of Commerce and the Atomic Energy Commission (AEC).
- Key dates:
  - Keel laid: Maritime Day, 22 May 1958 at New York Shipbuilding, Camden, NJ
  - Launched: 21 July 1959
  - Initial criticality: 21 Dec 1961
  - Delivered: March 1962 to the Maritime Administration

NS Savannah

US prototype civilian bulk cargo + passenger vessel

- Length: 596 ft (181.7 m); beam 78 ft (23.8 m); full load displacement: 22,000 tons
- Propulsion:
  - 74 MWt Babcock & Wilcox loop-type pressurized water reactor located amidships, inside a steel containment vessel.
  - 1 x main steam turbine delivering 22,000 shp to a single shaft; speed: 22+ kts.
  - Backup propulsion using 2 x diesel generators driving a 750 hp electric motor geared to the main shaft.



Source: http://www.nssavannah.net/gallery.php?PCat_ID=3

- Operational matters:
  - Originally designed to carry 60 passengers & 124 crew + 8,500 tons of bulk cargo
  - August 1962 – February 1963: Operated by State Marine Lines on initial passenger / cargo domestic voyages, starting on 20 Aug 1962.
  - May 1964 – March 1965: Operated by American Export-Isbrandtsen Lines on domestic & international passenger / cargo domestic voyages
  - August 1965: Leased to First Atomic Ship Transport (FAST), Inc. (part of the American Export-Isbrandtsen Line), passenger service discontinued, and ship used to transport cargo (up to 10,000 tons) between the US and Europe / Mediterranean thru 1971.
  - Between 1962 and 1971, *Savannah* cruised 450,000 miles (724,204 km) on nuclear power; visited 32 domestic ports and 45 international ports in 26 countries.

NS Savannah

US prototype civilian bulk cargo + passenger vessel

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

NS Savannah public areas

Above: Reception area
Below: Restaurant

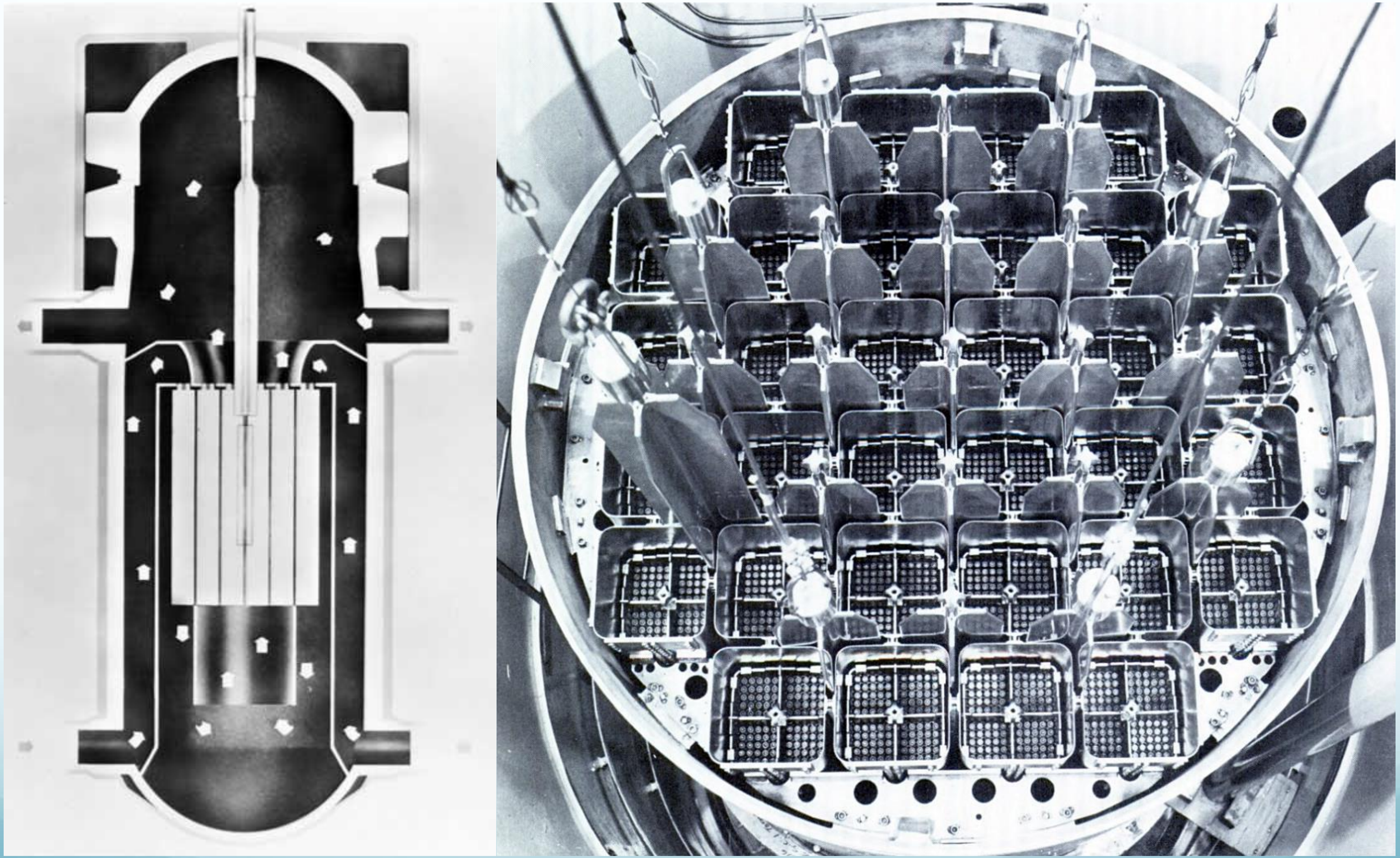
Gene Roddenberry was a passenger. Did he get the idea for the the Star Trek badge from this bar table?

Source: Author

NS Savannah reactor

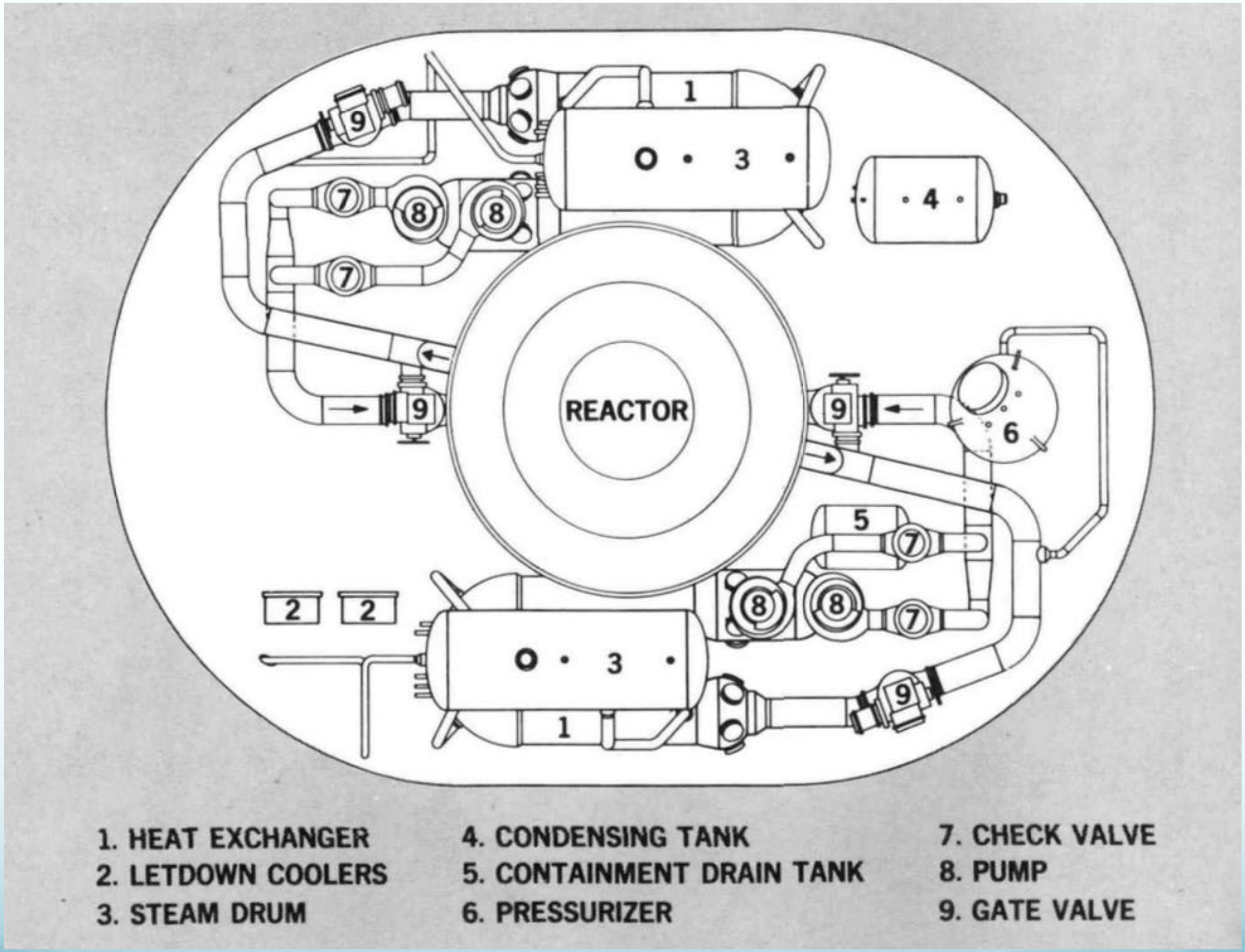
- 74 MWt, 2 x loop PWR designed by Babcock & Wilcox.
- Core: 164 fuel rods per fuel element; 32 fuel elements in a stainless steel reactor grid structure.
- Fuel: UO_2 pellets in stainless steel rods; two enrichment zones: 4.2% (innermost 16 fuel elements); 4.6% (outermost 16 fuel elements).
- Reactivity control: 21 cruciform control rods; boron-stainless steel jacketed in stainless steel plate.
- Core design life: 6 years (core 1)
- Refueling: By late 1968 when it returned to Galveston, TX for maintenance & refueling, Savannah had sailed 350,000 miles (563,270 km) on its 1st core. A complete 2nd core was available but was not needed. Refueling entailed replacing only four fuel elements and shuffling the remainder. The refueled core operated until 1971, by which time Savannah had cruised a total of 450,000 miles (724,204 km) before its retirement.

NS Savannah reactor



Source: http://www.maritime.org/tour/savannah

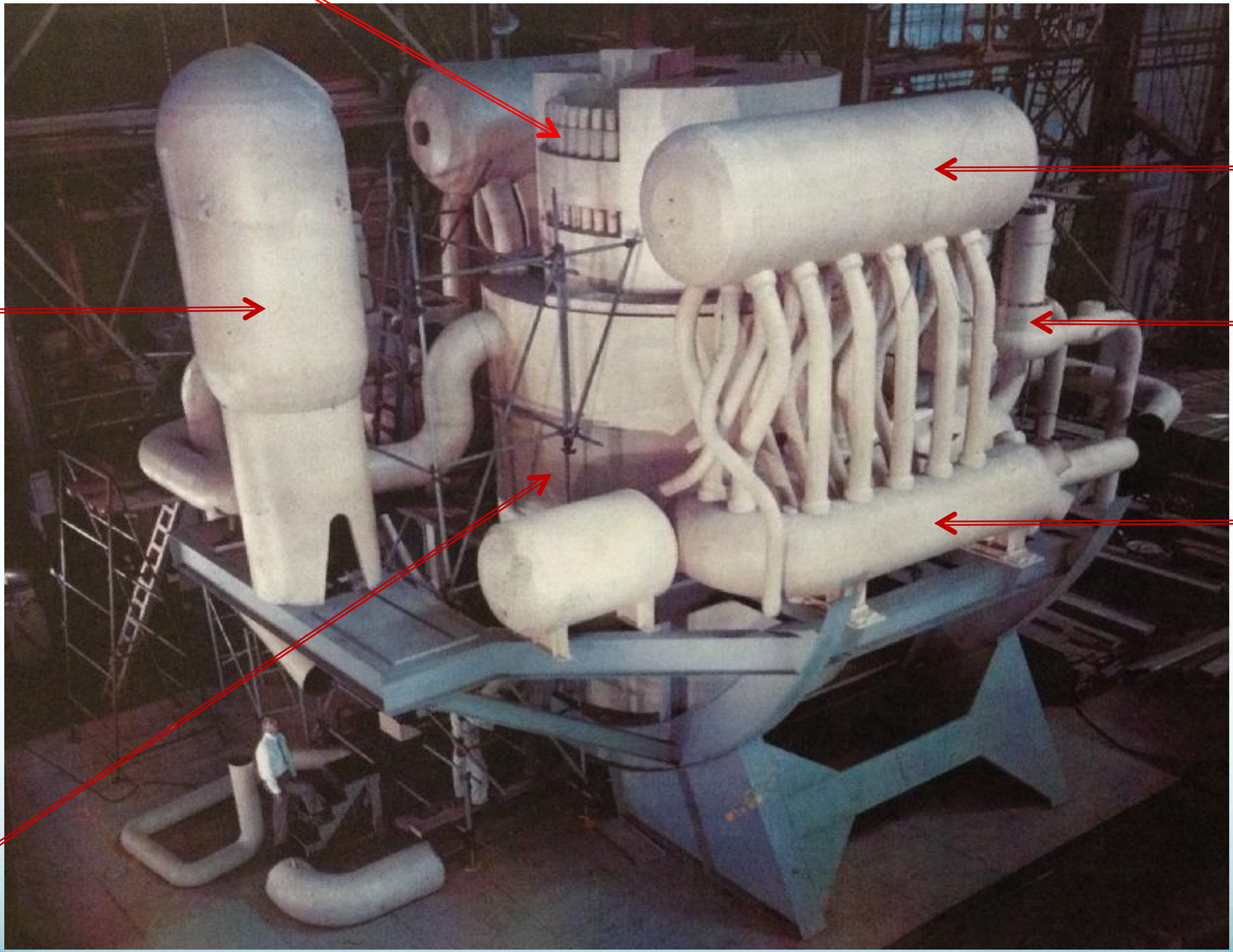
NS Savannah primary system



Source: US Atomic Energy Commission, *Nuclear Power and Merchant Shipping*, 1969

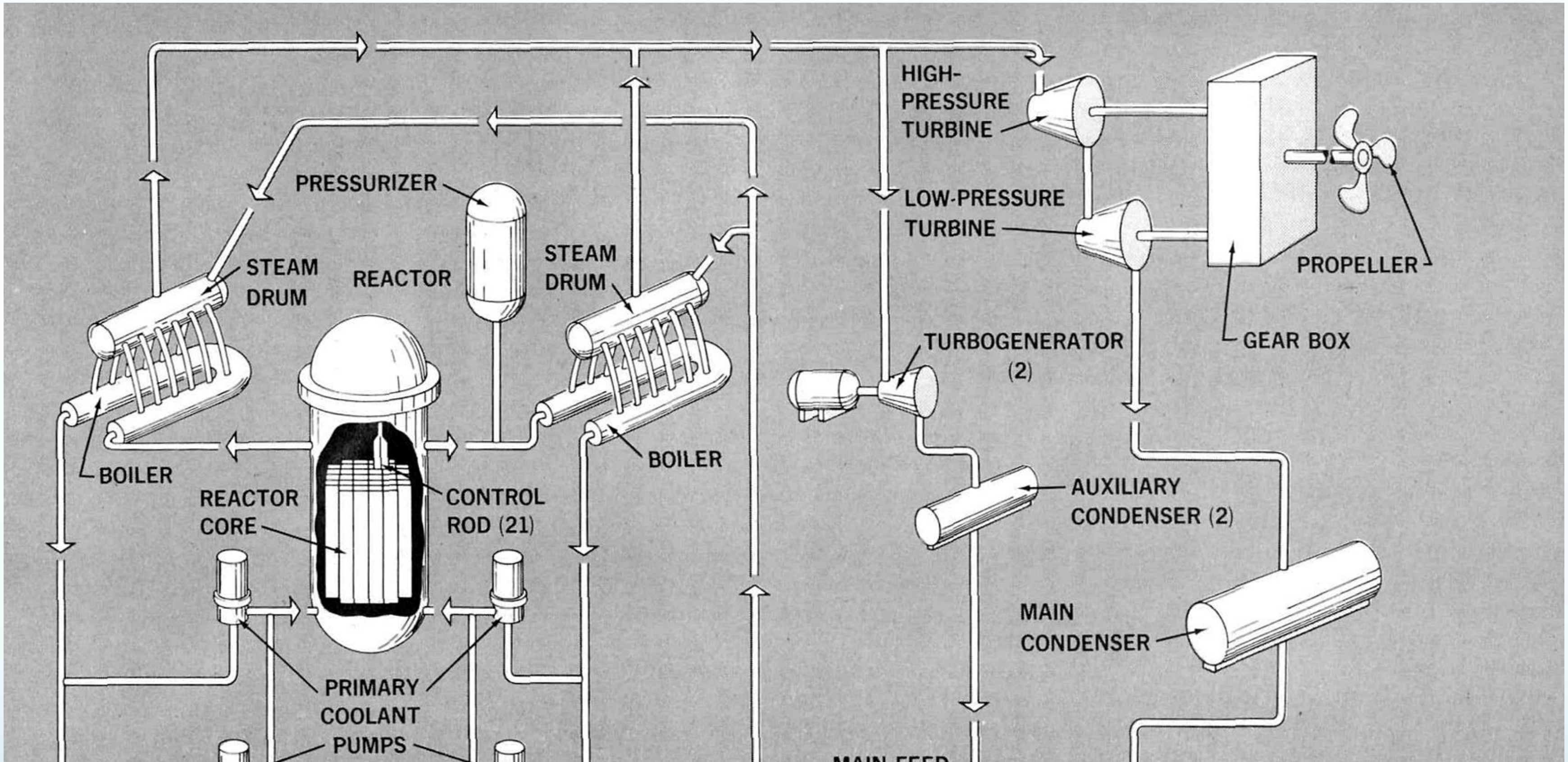
NS Savannah primary system

mockup



Source: adapted from http://ansnuclearcafe.org/2013/12/05/

NS Savannah propulsion plant



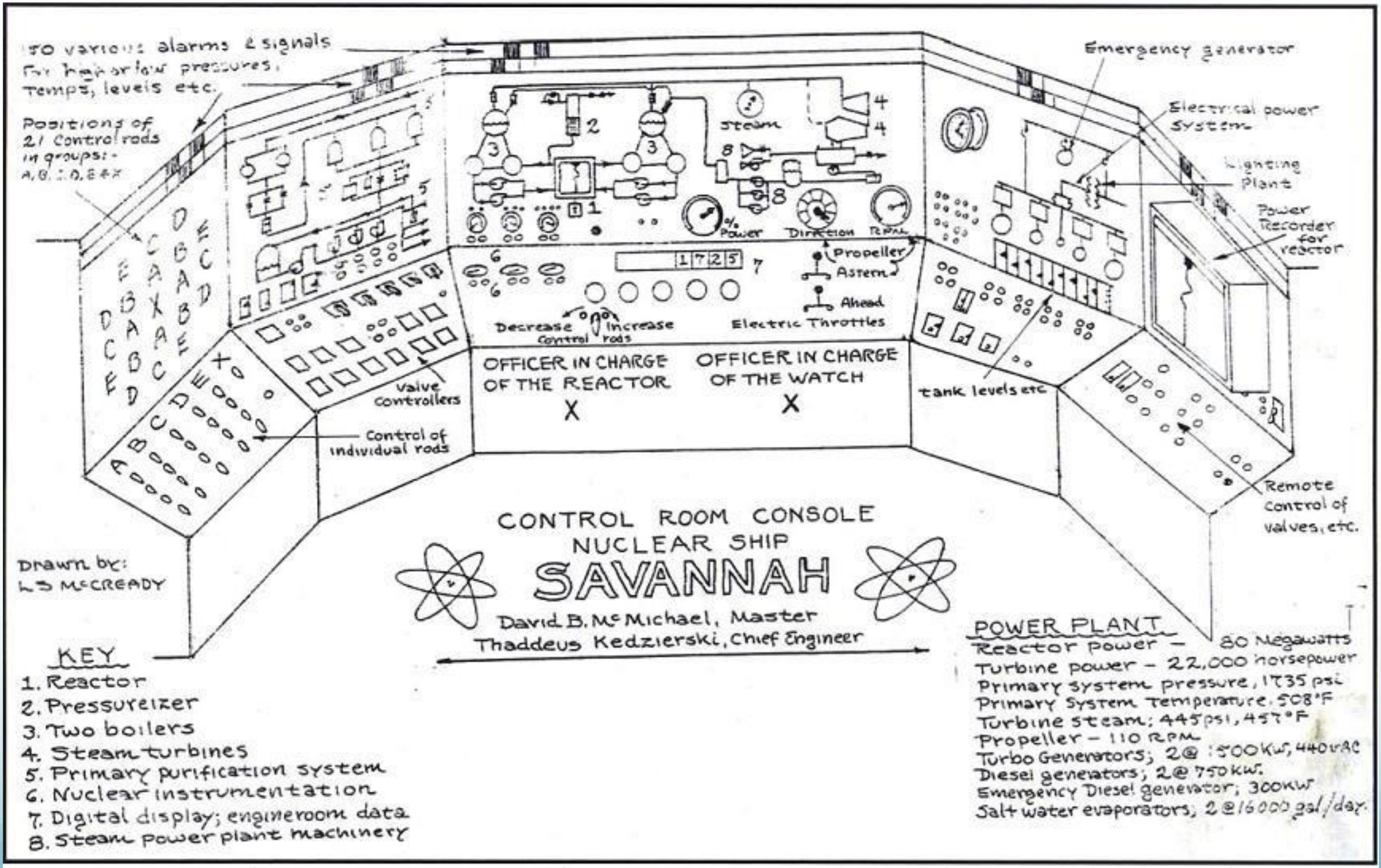
Basic parts of the propulsion system for a nuclear-powered ship, such as the NS Savannah. *Note the few parts and the simplicity of the design.*

Source: US Atomic Energy Commission, *Nuclear Power and Merchant Shipping*, 1965

NS Savannah reactor control room

Source: Author

NS Savannah reactor control room



Source: http://www.travelserver.net/travelpage/

NS Savannah

In retirement, 1972 to present

- 10 Jan 1972: Laid up in Savannah, GA.
- 1975: The reactor was de-fuelled in in Galveston. However, the Maritime Administration did not fund complete decommissioning and removal of other nuclear components. The complete NSSS remained in place.
- 1981 – 1994: On display at Patriots Point Naval & Maritime Museum in Charleston, then various movements for drydock repairs and storage.
- 1991: Designated a National Historic Landmark.
- Now dockside in Baltimore's inner harbor.
- Full funding for the final nuclear cleanup and decommissioning of *NS Savannah* was included in the budget for the US Maritime Administration, as part of the federal omnibus spending bill signed into law in March 2018. Decommissioning and final nuclear license termination are expected to be completed by 2031.
- The future fate has not been determined, however one option is to serve as a museum ship.
- For more information, visit: http://www.ns-savannah.org

NS Savannah

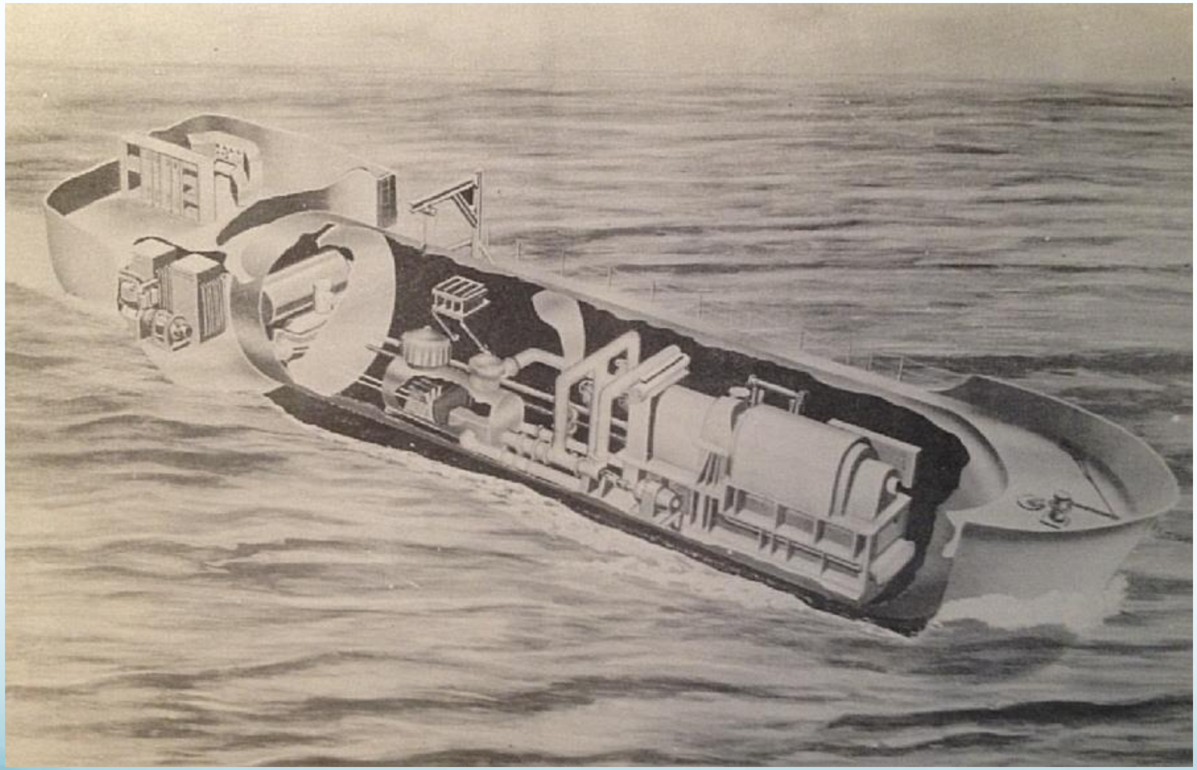
Canton Marine Terminal, Baltimore, MD

Source: Martin, Ottaway, van Hemmen & Dolan, Inc.

Source: Author, 2015

Floating nuclear power plant

- In the 1950s and 1960s, the Army Nuclear Power Program (ANPP) developed a range of small power reactors for use in a variety of applications, including power generation at remote sites.
- An early concept for deploying a small Army power reactor on a floating barge is shown in the following figure.

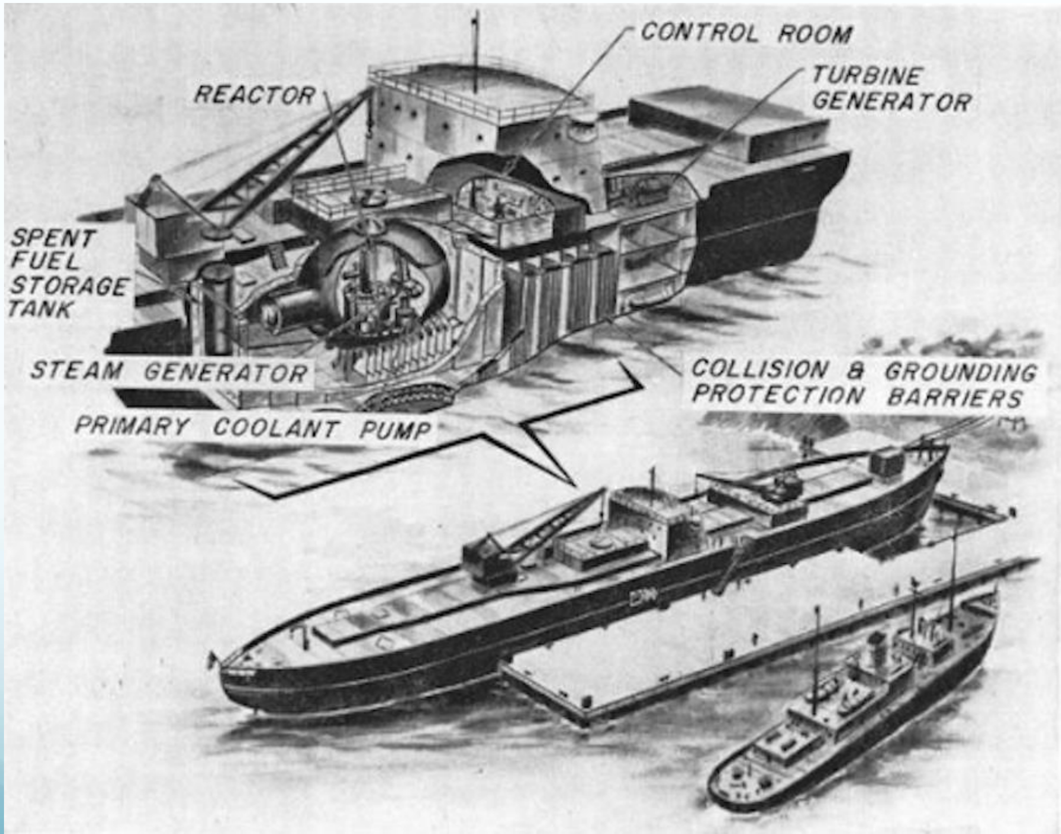


Source: US Army, *"Army Nuclear Power Program,"* 1958 and American Nuclear Society / Will Davis collection 17 Apr 2014

- The reactor and the primary system are housed in a small containment vessel within a larger protective volume that also contains the secondary system and generating equipment.
- The control room is shown near the stern.

Floating nuclear power plant

- In January 1963, the Army Corps of Engineers announced that it had awarded a $15.8 M contract to Martin Marietta's Nuclear Division (Baltimore, MD) to install a 10 MWe nuclear power plant on the Liberty ship *SS Walter F. Perry*, which would be modified as shown in the following diagram to house the reactor.



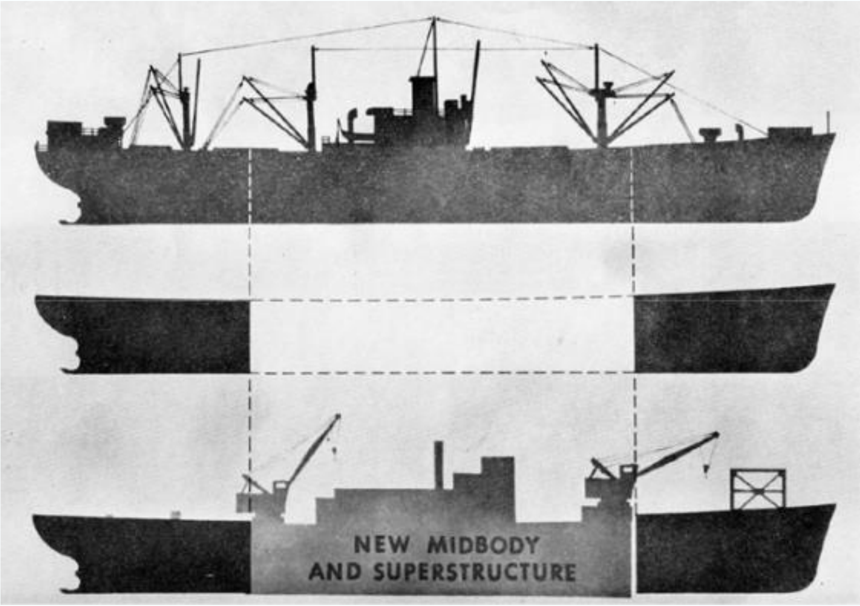
Sturgis 1963 concept. Source: Aviation Week & Space Technology, 28 Jan 1963

- The reactor and the primary system are housed in a small containment vessel.
- Collision and grounding protection barriers are installed to protect the reactor and equipment spaces.
- *SS Walter F. Perry* was never modified. Work shifted to the *Charles G. Cugle,* which became the first floating nuclear power plant, renamed *Sturgis.*

Sturgis

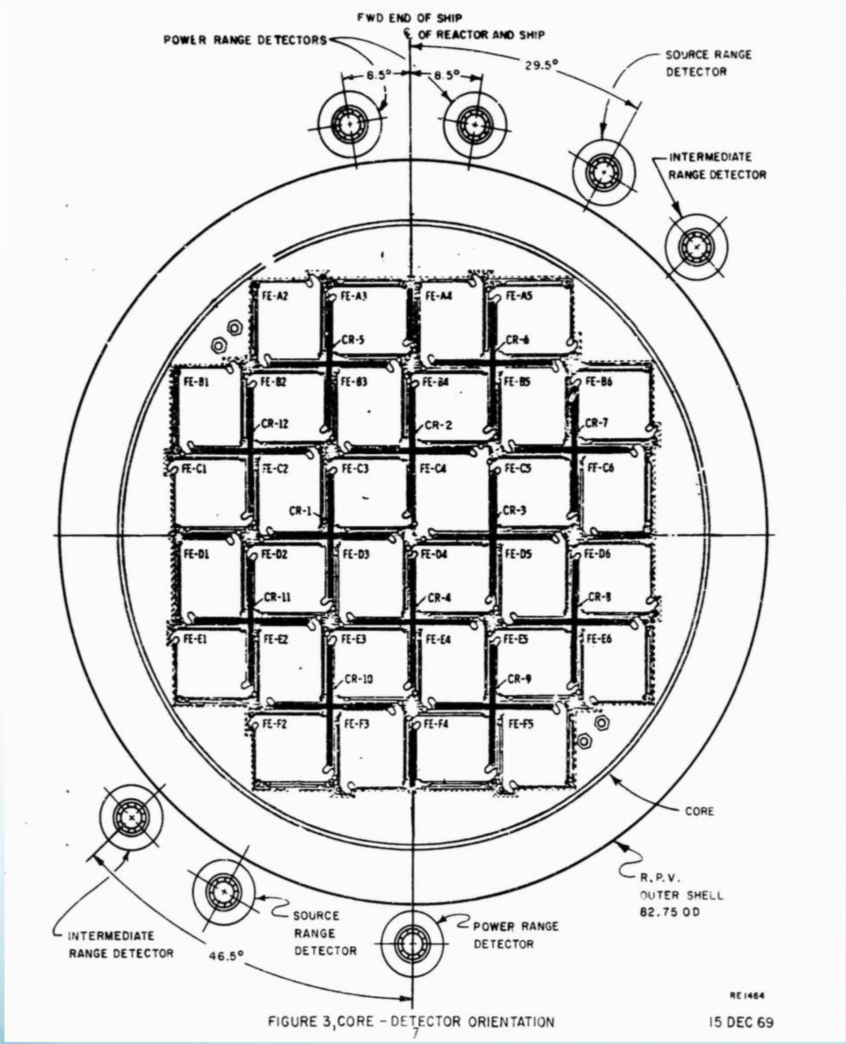
US floating nuclear power plant

- Built on the hull of WW II Liberty ship *Charles G. Cugle*, with a new mid-section inserted between the bow and stern to house the MH-1A reactor and associated systems.
  - Designed as a towed craft; it was intended to stay dockside, connected to the shore power infrastructure when the reactor was operating
  - The new mid-section included heavy radiation shielding and collision protection for the nuclear plant
  - Named for former Army Chief of Engineers, General Samuel D. Sturgis, Jr.
- Length OA: 441 ft (134.4 m); beam 56 ft (17.1 m); displacement: 14,500 tons (approx.).
- *Sturgis* arrived at Fort Belvoir, VA for installation of the reactor in April 1966; initial criticality was on 24 Jan 1967 followed by one year of testing.
- Operating staff were trained on an MH-1A analog simulator and on the Army's SM-1 reactor at Fort Belvoir.



Source: US Army Corps of Engineers

MH-1A reactor

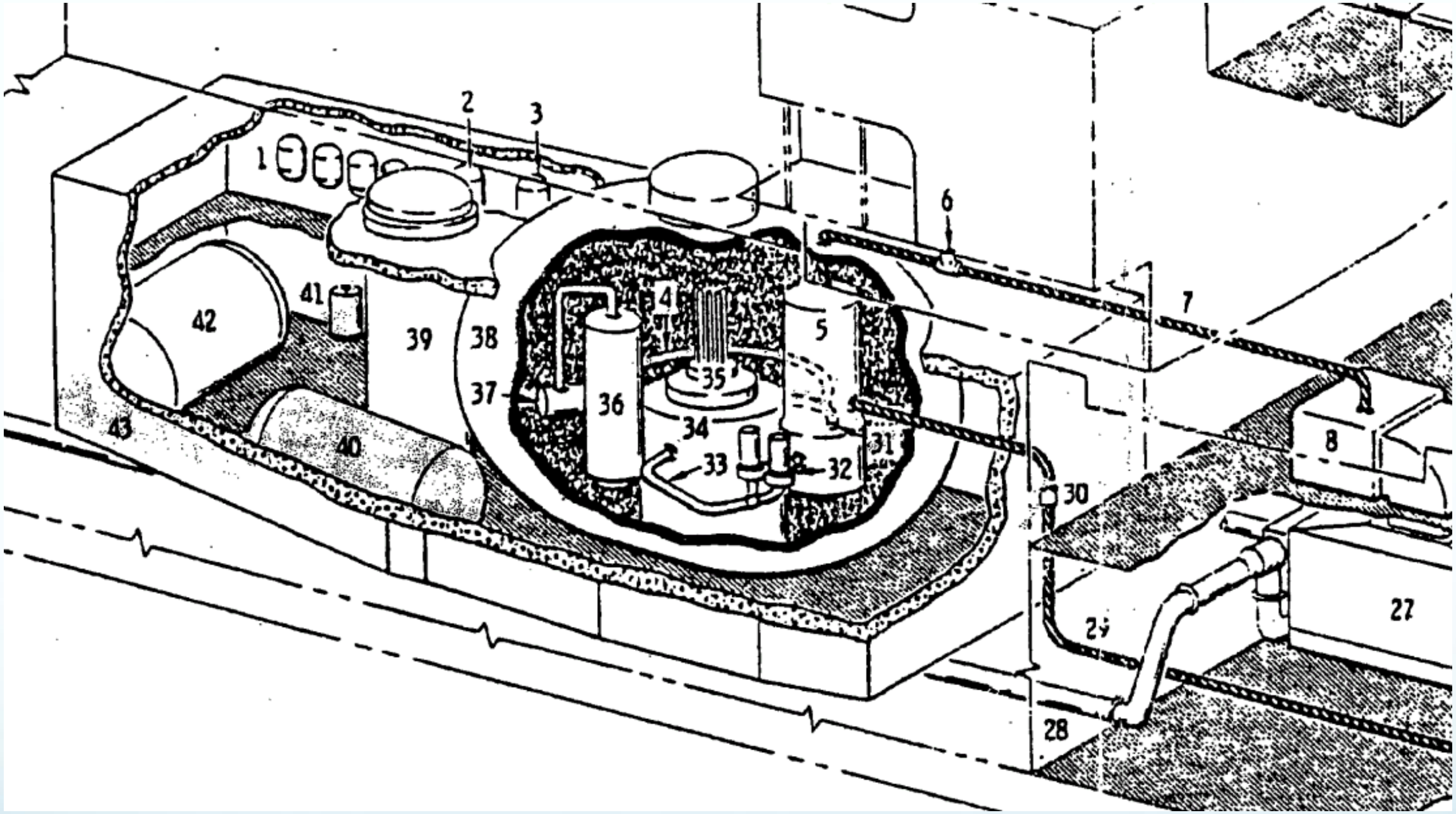


Source: US Army Engineer Reactor Group report ED-6923, December 1969

- MH-1A (Mobile, High-power, 1st-of-a-kind) was developed under the Army Nuclear Power Program (ANPP) by Martin Marietta; $17.2 M contract
  - This was the largest and last of the Army's small reactors.
  - 45 MWt, 10 MWe, single-loop PWR
- Fuel: UO_2 fuel pellets in stainless steel rods.
  - Two enrichments: 5.0% (innermost fuel elements), 5.4% (outermost)
- Core: 10 x 10 rods per fuel element; 32 fuel elements; 2-zone core; 12 cruciform control rods.
- 1st refueling occurred in Oct 1969; MH-1A was refueled four times during its 8-year operational life.

MH-1A installation on *Sturgis*

Reactor housed in a 350 ton steel containment vessel



Primary plant
34 - Reactor vessel
4, 33 - Primary loop piping
32 - Main coolant pumps
5 - Steam generator
36 - Pressurizer
35 - Control rod drives

Secondary plant
7 - Main steam line
8 - Turbine generator
27- Main condenser
29 - Main feedwater line
28 - Main cooling water line

Containment & shielding structures
38 - Containment vessel
39 - Spent fuel storage tank
43 - Shielding

Source:
US Army Corps of Engineers

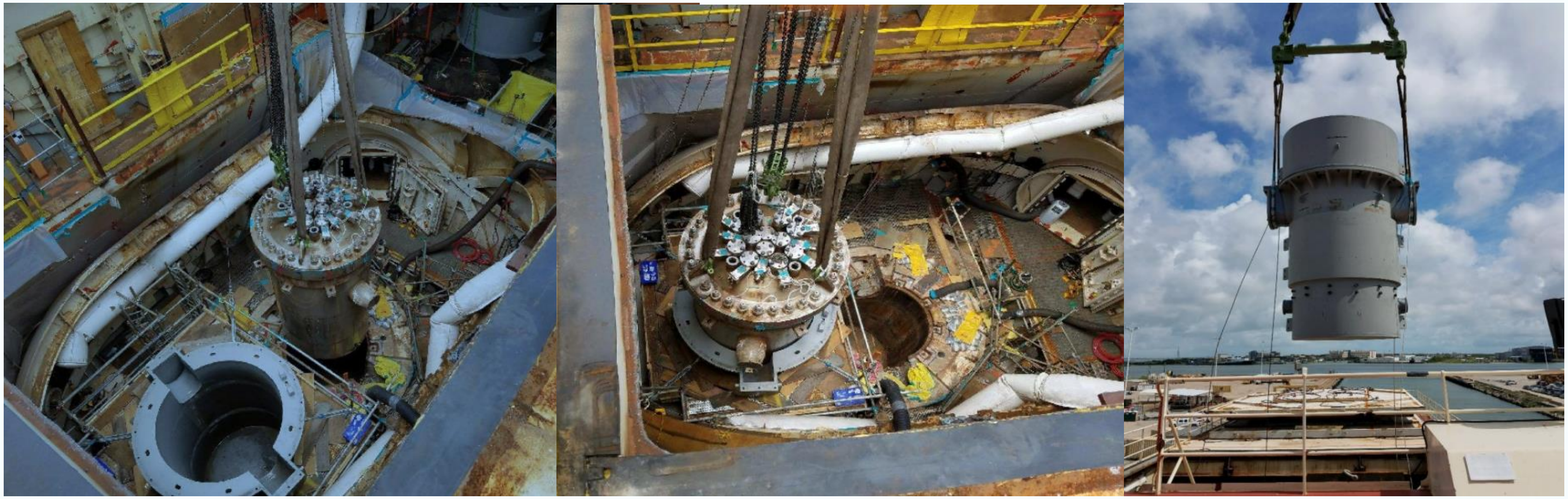
Sturgis

US floating nuclear power plant

- Operation:
  - MH-1A was designed for an operating staff of 48; three 12-person crews worked in 8-hour shifts, with one 12-person relief crew.
  - *Sturgis* was towed to Panama Canal, arriving Aug 1968. Then provided power to the Panama Canal Zone grid from 1968 to 1975, replacing the output of Gatun Hydroelectric Plant. This allowed more water from Gatun Lake to be available to fill canal locks, enabling 2,500 more ships per year to pass through the canal.
  - *Sturgis* was retired due to high cost of operation and termination of the US Army's nuclear power mission; *Sturgis* returned to US in Dec 1976; defueled in June 1977.
  - Contract for *Sturgis* decommissioning was awarded in April 2014. By mid-2017, the steam generator, reactor coolant pumps, pressurizer and reactor vessel had been removed.
  - Decommissioning is to be completed in 2018.
  - For more information, visit http://www.nab.usace.army.mil/STURGIS_Updates/

Source: US Army Corps of Engineers, 2015

Sturgis reactor vessel removal



Reactor compartment top removed, then reactor vessel removed and placed in shielded shipping container in mid-2017.

Source: US Army Corps of Engineers, http://www.nab.usace.army.mil/STURGIS_Updates/

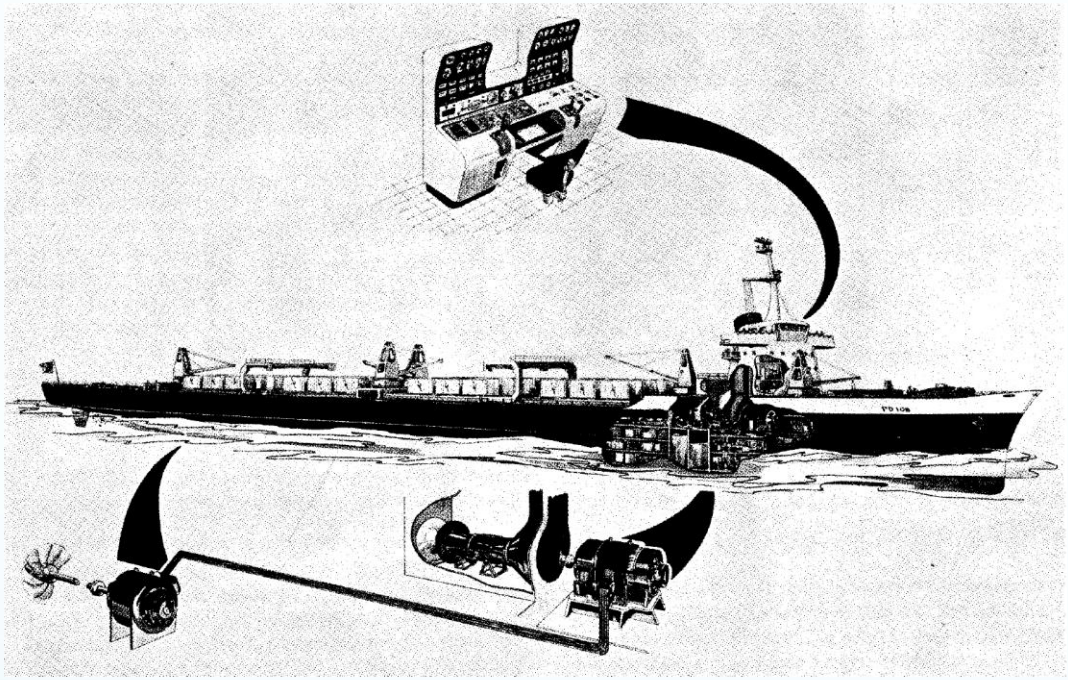
USNS American Explorer

Could have been the world's first nuclear-powered tanker

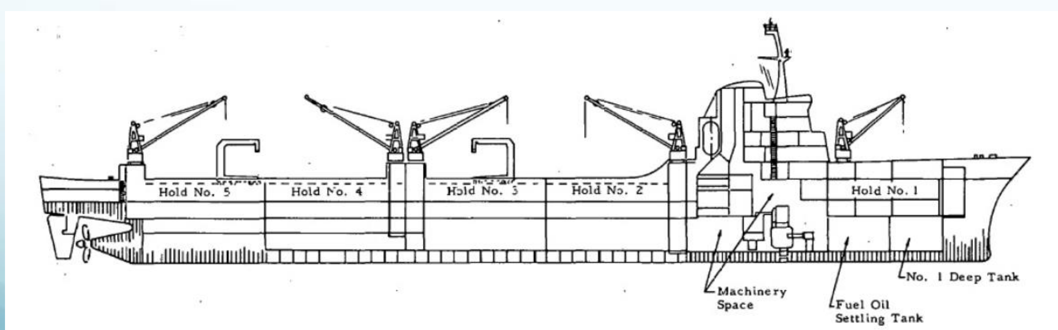
Source: Navsource

- US Military Sea Transport Service (MSTS) type T5-S-RM2a tanker, T-AOT-165, launched 11 April 1958.
  - 14,980 gross tons
  - 595 ft (181 m) length; 80 ft (24 m) beam
  - Speed: 20 knots (37 kph)
- When the keel was laid in 1957, *American Explorer* was intended to be a nuclear-powered vessel.
  - The intended reactor was the General Electric 630A gas-cooled reactor.
- Plans for the nuclear installation were cancelled and *American Explorer* was completed with a conventionally-powered steam plant.
- In 1980, *American Explorer* received the main reduction bull gear from the retired *NS Savannah* to replace its own damaged gear.
- Sold for scrap in 2008.

MARAD PD108 nuclear variant



Source: ASME, R.R. Peterson, “Maritime Gas-Turbine Program” 1963



Source: MARAD via American Nuclear Society, ANS Nuclear Café, 19 January 2017

- MARAD PD108 is a Maritime Administration “benchmark design” for a dry cargo vessel.
- The above figure shows the machinery layout for a gas turbine powered, electric motor driven version. Electric drive enables the forward location of propulsion engines and provides the required propulsion performance while avoiding a long, mechanical drive train.
- The second figure shows the machinery layout of a PD108 with an integral PWR in place of the gas turbines in the first figure. A nuclear PD108 was never built.

Other US civilian marine reactor designs

Other US civilian marine reactor designs

- Water cooled and moderated reactors:
  - Babcock & Wilcox (B&W) Consolidated Nuclear Steam Generator (CNSG I, II & III and CNSS) marine pressurized water reactors (PWRs)
  - Combustion Engineering indirect cycle marine PWR & UNIMOD PWR
  - United Nuclear U1U & U2U PWRs
  - General Electric (GE) marine boiling water reactor (BWR)
- Gas-cooled reactors:
  - General Electric (GE) indirect cycle 630A Nuclear Steam Generator
  - General Atomics (GA) direct cycle Maritime Gas-Cooled Reactor (MGCR) & Experimental Beryllium Oxide Reactor (EBOR)
  - Ford Instrument Company (FICo) and American Turbine Company Closed-Cycle Gas-Cooled Reactor (CCGCR)
  - General Motors direct cycle gas-cooled marine reactor
  - Westinghouse direct cycle Light Weight Nuclear Propulsion (LWNP) package
- Other reactor types:
  - Atomics International marine Organic Moderated and Cooled Reactor (OMCR)
  - Gen4Energy marine application of their liquid metal cooled G4M modular reactor

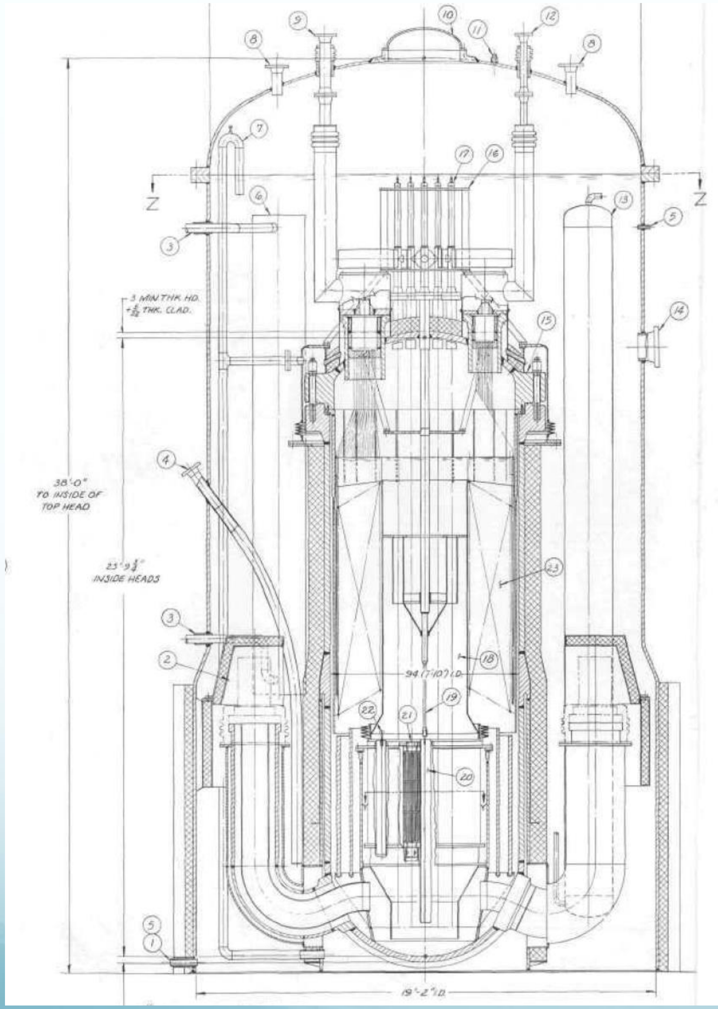
Marine water-cooled and moderated reactor designs

Babcock & Wilcox Consolidated Nuclear Steam Generator (CNSG)

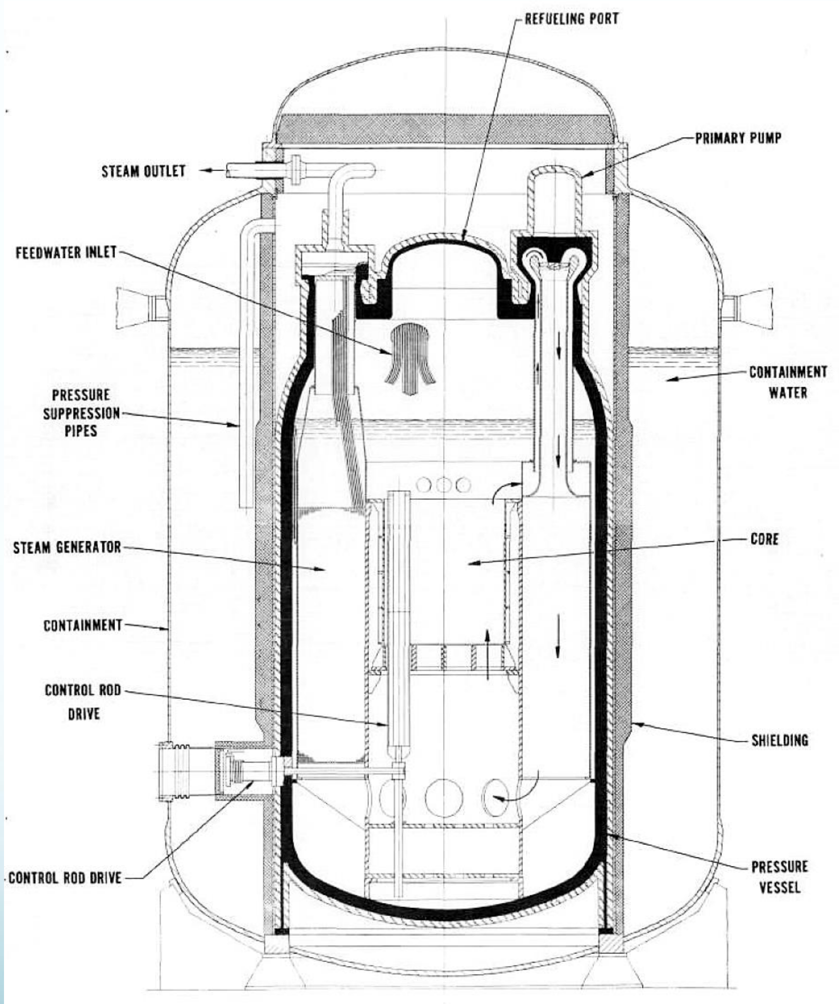
- CNSG is a compact, integral pressurized water reactor (PWR) plant. The reactor, once-through steam generators, and pumps are all housed in a single primary vessel.
- CNSG I, 38 MWt, 1961
  - UO_2 pellets in zircaloy (Zr-4) fuel rods; 3.5% and 6.6% enrichment
  - Pumps at bottom of vessel
  - Dry containment
  - Used on German vessel Otto Hahn
  - Built by B&W–Interatom consortium
  - Reactor began operation in 1968; refueled in 1972; decommissioned in 1979
- CNSG II, 184 MWt, 1963
  - Core raised to mid-vessel
  - Control rods enter the core from the bottom
  - Low-enriched UO_2 fuel
  - Wet containment
  - Pumps at the top of the vessel

Babcock & Wilcox CNSG

CNSG I, 38 MWt, 1961



CNSG II, 184 MWt,1963



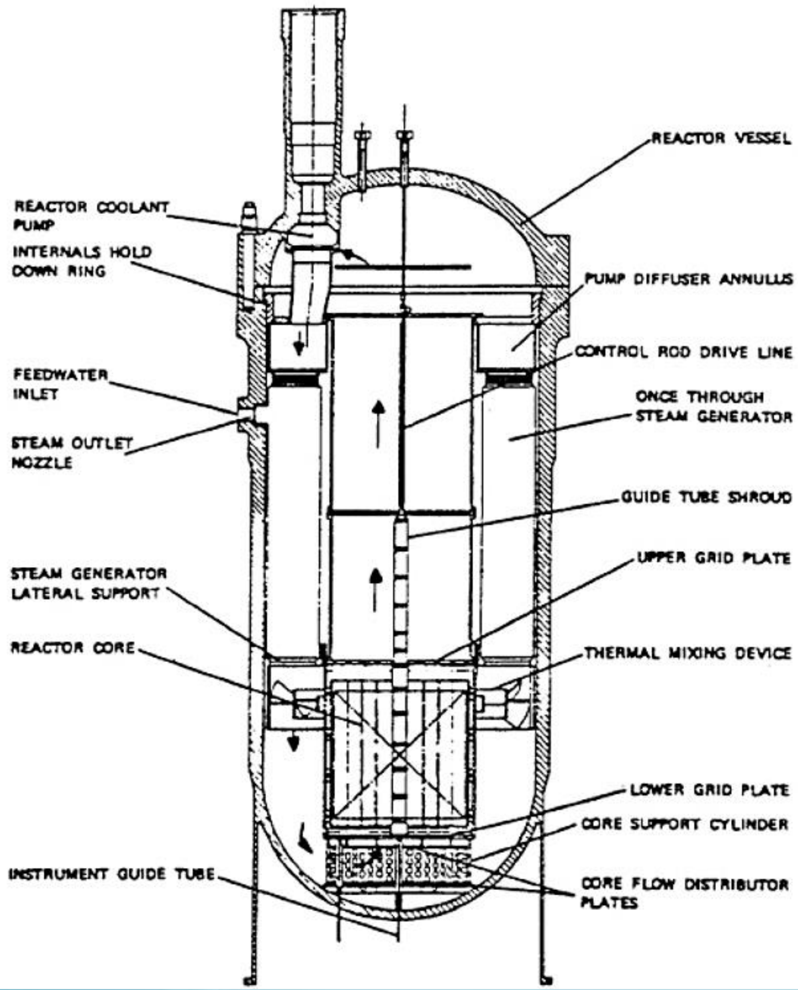
Source, two pictures: B&W report 1280, 1963

Babcock & Wilcox Consolidated Nuclear Steam Generator (CNSG)

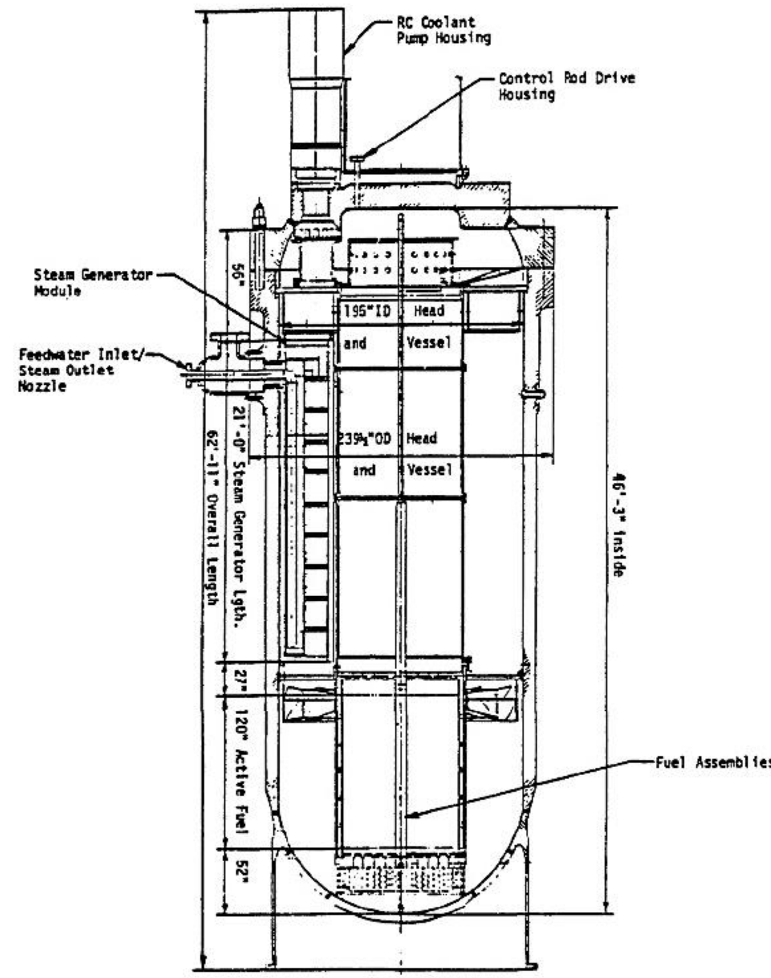
- CNSG III, 313 - 365 MWt, 1976
  - Core moved back to the bottom of the vessel
  - Control rods enter the core from the top
  - Pumps at the top of the vessel
  - US Maritime Commission sponsored a 313 MWt version targeted for propelling a 600,000 ton tanker
  - DOE (then ERDA) sponsored a 365 MWt land-based version capable of delivering 91 MWe.
  - A design for a barge-mounted version of CNSG III was developed, providing either electrical or steam output to on-shore users.
- CNSS (Consolidated Nuclear Steam Supply), 1,200 MWt, 1978
  - The CNSS is the result of a B&W study of a CNSG III design extrapolated to 1,200 MWt.
  - CNSS was expected to deliver 400 MWe.
- The CNSG and CNSS design principles can be found today in the mPower small modular, land-based reactor being developed by B&W.

Babcock & Wilcox CNSG & CNSS

CNSG III, 313 - 365 MWt, 1976



CNSS, 1,200 MWt, 1978

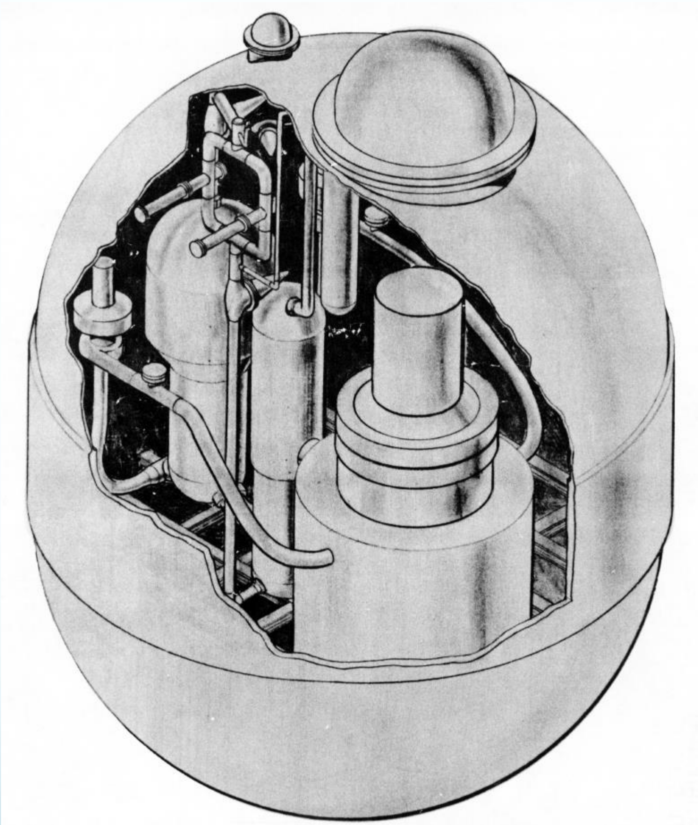


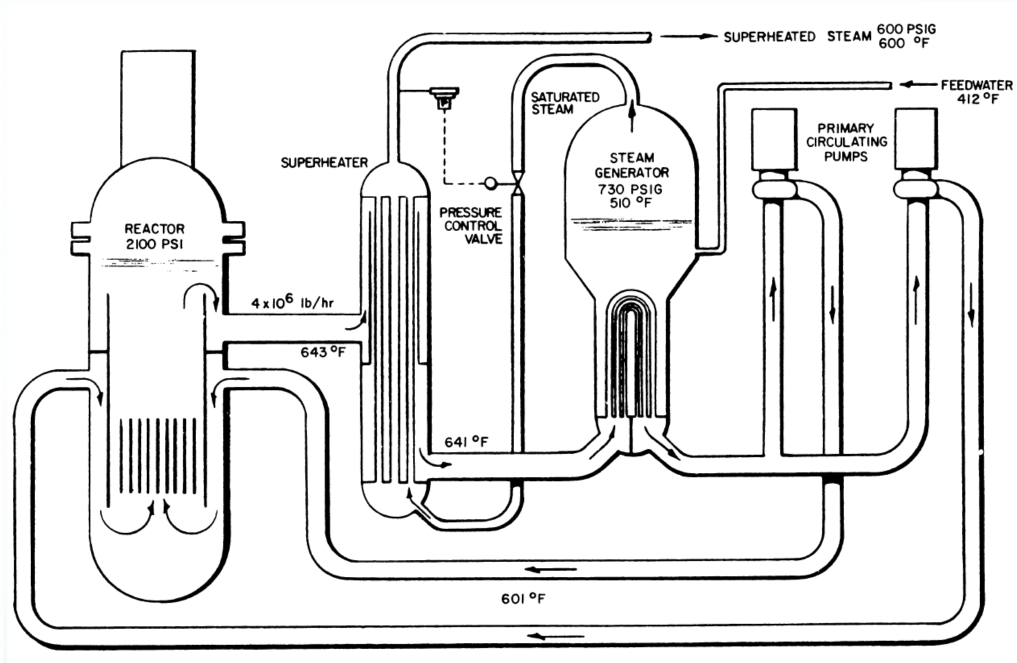
Source: Daniel Ingersoll, "Historical Perspective on Small Modular Reactors", ORNL, 2010

Combustion Engineering indirect cycle marine PWR

- 1962 C-E reports describe marine reactor applications in a 30,000 shp propulsion plant for a 43,000 DWT, 18.3 kt tanker.
- 80 MWt pressurized water-cooled and moderated reactor with a compact single-loop, indirect cycle primary system with self-pressurization (no pressurizer) and steam superheat.
  - Core outlet is at saturation conditions, with some boiling in the core permitted.
  - Steam bubble in the dome of the reactor vessel functions as the pressurizer
- Fuel: UO_2 fuel pellets in stainless steel rods; average enrichment 4.3%
- Core: Single-pass, 3-zone core with 61 hexagonal fuel assemblies
  - 49 fixed fuel assemblies and 12 movable “neutron rectifier control assemblies” that are part fuel element and part neutron absorber.
  - During core life, the neutron absorber part is gradually withdrawn from the core, being replaced by the attached fuel element part of the assembly.
  - Large negative reactivity coefficients (temperature, Doppler and void) permit the reactor to be self-regulating during ship maneuvering transients.
  - 4 year core lifetime for a specified tanker duty cycle.
- Study concluded that a competitive nuclear-powered tanker was feasible.

Combustion Engineering indirect cycle marine PWR





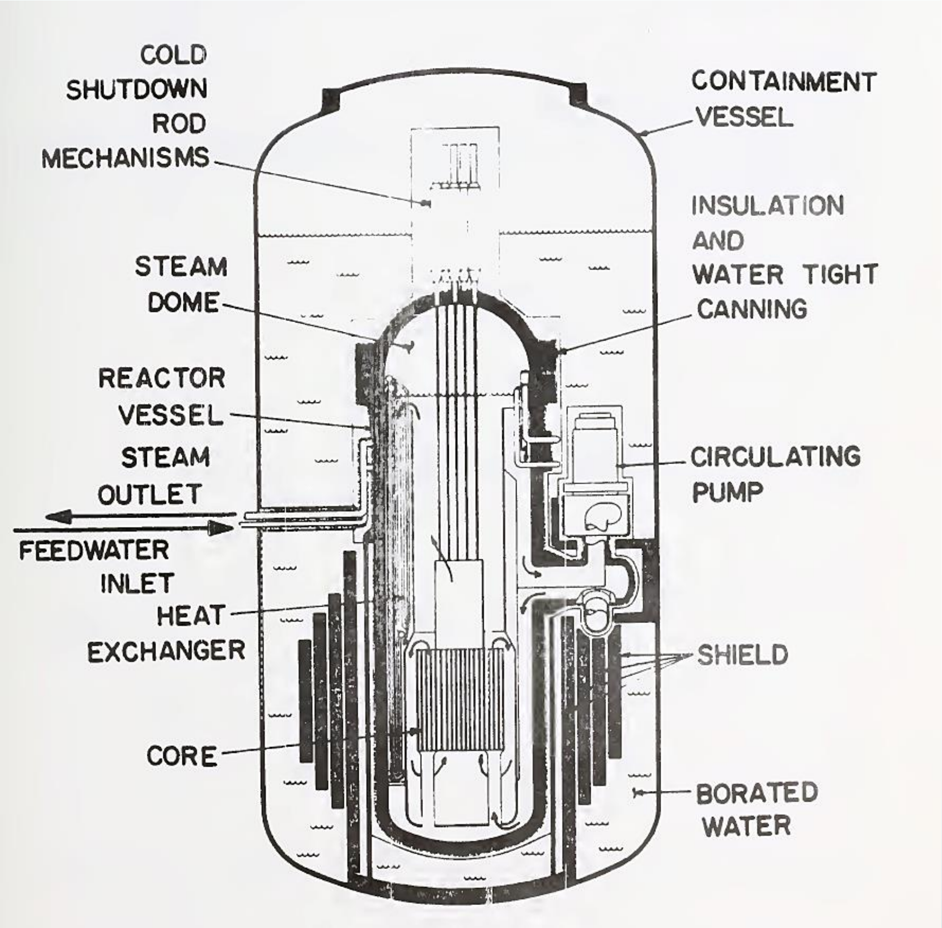
Source: CEND-150 (Pt. II), metadc172540, March 1962

- Single primary loop comprised of a superheater, a steam generator and two primary circulating pumps.
- Entire primary system is housed in a steel containment vessel.

Combustion Engineering UNIMOD marine PWR

- Unified Modular (UNIMOD) PWR has an integrated primary system.
- Basic characteristics of a 30,000 shp UNIMOD plant are:
  - 80 MWt pressurized water-cooled and moderated reactor with self-pressurization (no pressurizer)
    - Core outlet is at saturation conditions, with some boiling in the core permitted.
    - Steam bubble in the dome of the reactor vessel functions as the pressurizer
  - Fuel: UO_2 fuel pellets in stainless steel rods; average enrichment 5.9%
  - Core: 2-zone, 2-pass core; 61 hexagonal fuel elements (49 fixed, 12 movable)
    - The 12 movable fuel elements are fully inserted in the core during power operation and are moved out of the core and are replaced by control rods during shutdown.
    - Large negative reactivity coefficients (temperature, Doppler and void) permit the reactor to be self-regulating during ship maneuvering transients. Direct reactivity control is not needed during operation.
    - Lifetime core reactivity is managed with burnable poison and the 2-zone core
  - Reactor design life is 3.4 years at 80% utilization (23,000 equivalent full power hours)

Combustion Engineering UNIMOD marine PWR



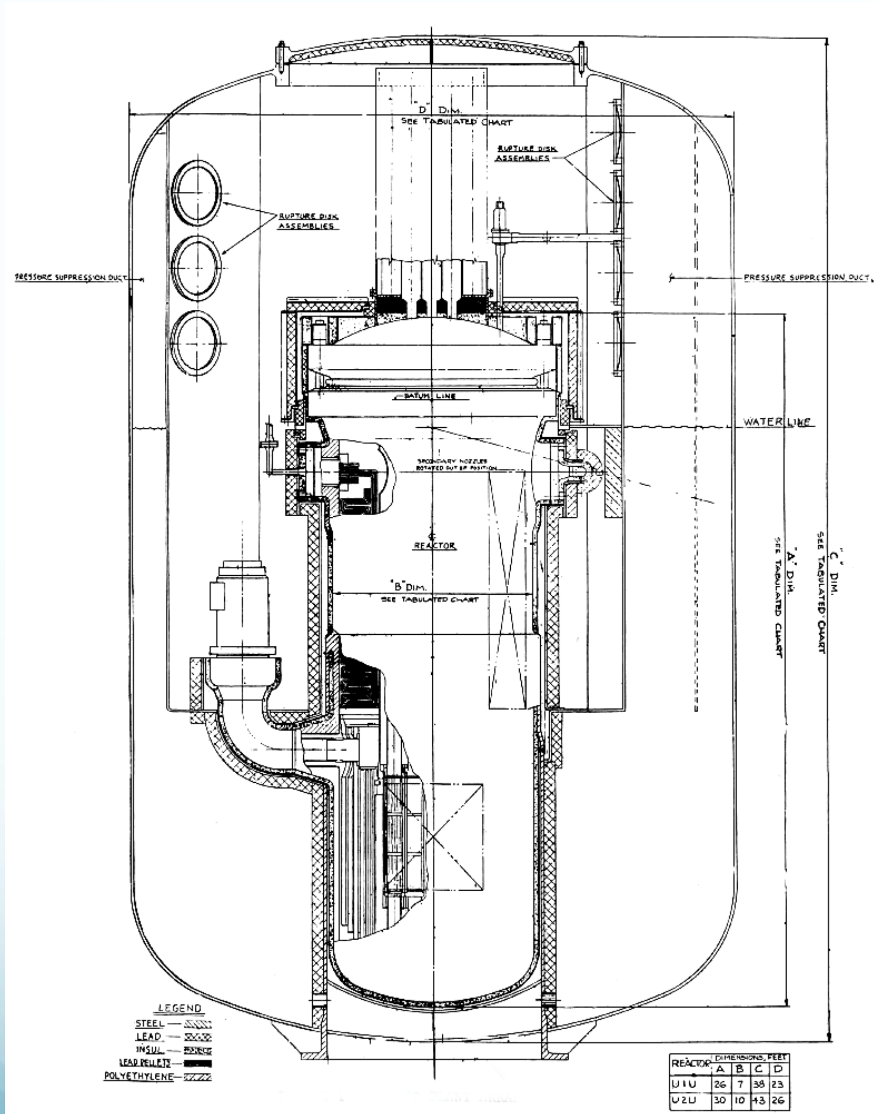
- Six steam generating modules and three circulating pumps are inside the reactor vessel.
- The containment vessel is filled with water to above the level of the reactor vessel head. This water provides shielding and also provides pressure suppression in the event of a primary system breach. Design pressure is 300 psig.
- The containment vessel measures 16 feet (4.9 m) in diameter and 34 feet (10.4 m) tall, comparable to the size of a marine oil-fired boiler, and weighs 430 tons with the reactor and associated equipment.

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

United Nuclear marine PWRs

- United Nuclear developed marine PWR designs with integrated primary systems that evolved into the similar U1U (Utility, number 1, United Nuclear) and U2U integrated PWRs.
- Basic characteristics of the U1U and U2U reactors:
  - Pressurized water-cooled and moderated reactors with self-pressurization (no pressurizer)
    - Core outlet is at saturation conditions at 1050 psia
    - Steam bubble in the dome of the reactor vessel functions as the pressurizer
  - Reactor power:
    - U1U: 63 MWt/16.5 MWe (equivalent to 22,100 shp)
    - U2U: 187 MWt/51.6 MWe (equivalent to 69,200 shp)
  - Fuel: UO_2 fuel pellets in zircaloy rods; average enrichment 4.5% (U1U), 3.9% (U2U)
  - Reactivity control is via control rods. Lifetime core reactivity also is managed with lumped burnable poison
  - Reactor design life is about 4 years

United Nuclear U1U / U2U



Source: COO-284, Vol. 2, "Small Nuclear Power Plants," Atomic Energy Commission, March 1967

- Three integral, once-through steam generator modules deliver steam at 415 psia with about 70°F superheat.
- Three primary coolant pumps provide forced circulation through the reactor.
- Natural circulation can provide adequate core cooling up to 20% power.
- The reactor is enclosed in a containment vessel with a dry inner region surrounded by the shield water tank that also provides pressure suppression following a primary system breach. Design pressure is 155 psia.
- The U1U containment vessel measures 23 feet (7 m) in diameter, 38 feet (11.6 m) tall, and weighs 610 tons. The U2U containment vessel measures 26 feet (7.9 m) in diameter, 43 feet (13.1 m) tall, and weighs 1,038 tons.

General Electric marine BWR

- 1958 GE reports describe boiling water reactor (BWR) marine reactor applications in a 22,000 shp propulsion plant for tanker.
  - 59.7 MWt BWR operating at 1,000 psig
  - The preferred configuration was a simple, compact natural circulation BWR with an external steam drying drum
- Fuel: UO_2 fuel pellets in zirconium-2 (Zr-2) cladding; average initial enrichment 2.1%.
- Core: Single-pass core; 88 fuel assemblies, each comprised of 6 x 6 fuel rods in a shrouded assembly.
- Reactivity control: Normal reactivity control provided by 21 cruciform boron steel control elements that enter from the bottom of the reactor vessel.
  - Backup reactivity control provided by a liquid poison (sodium pentaborate) system.
- Design study demonstrated the feasibility of using a BWR for ship propulsion.
  - Reactor was relatively insensitive to ship's motion
  - Capable of responding to rapid power transients typical of ship maneuvering (i.e., ahead 100% to astern 100% in 10 seconds)

Source: James Robert Bauman, "Analysis of Past, Present and Future Applications of Nuclear Power for Propulsion of Marine Vehicles," MIT, May 1972

Westinghouse marine PWR

Nuclear Propulsion Plant for High-Speed Merchant Ships

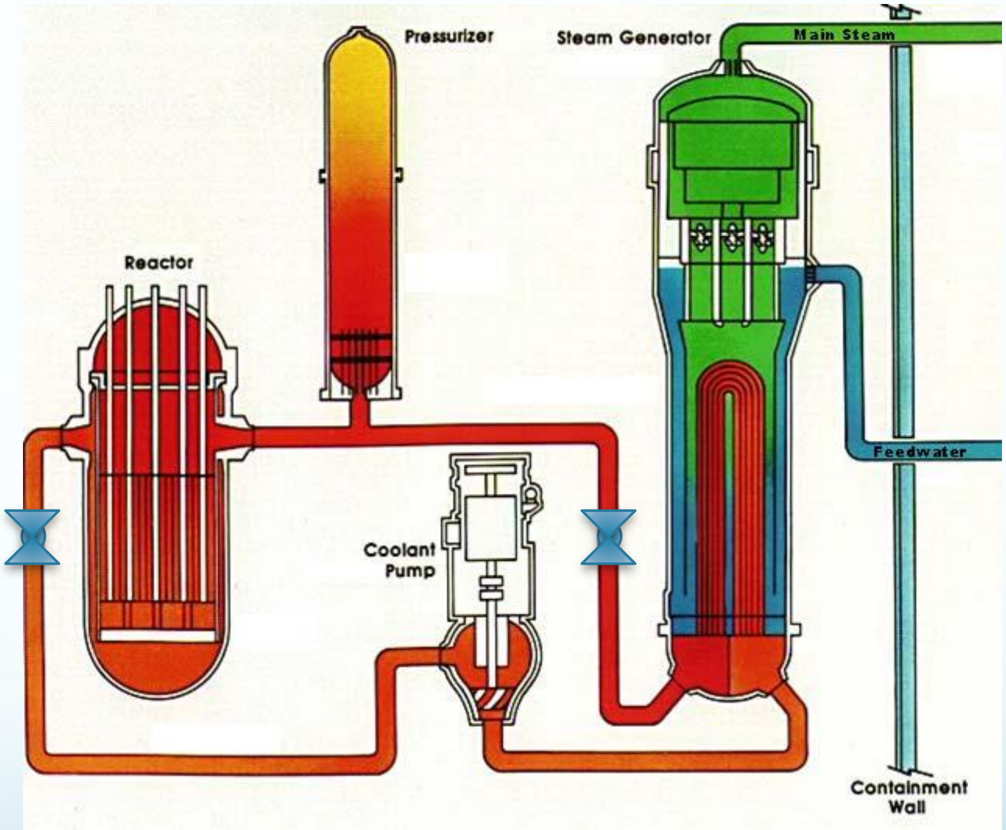
- The NSSS design was based on proven central station designs and component technology. This Westinghouse marine reactor concept was a 2-loop PWR designed for use in a 75,000 shp propulsion plant, but was scaleable to about 140,000 shp.
- The NSSS:
  - Reactor was rated at 220 MWt
    - Active height 6 ft (1.83 m) and effective diameter 6 ft-6.5 in (2.0 m)
    - The core consists of 52 fuel assemblies. Each was a 13 x 13 square array of 149 zircaloy-clad tubes containing UO_2 fuel pellets with an 3.7 w/o U-235 average enrichment. The 20 vacant array locations were allocated to stainless steel clad control rods.
    - Core life is 32,000 effective full power hours, giving a fuel burnup of 20,000 MWD/t and an operating period at 85% load factor between refuelings of over 4 years.
  - Each primary loop consisted of a vertical U-tube steam generator with integral moisture separator, a single main coolant pump, and two gate valves for loop isolation.
    - Coolant core inlet temperature is 550° F and outlet temperature was 583° F
    - Coolant pressure was maintained at 2,000 psia by an electrically-heated pressurizer
    - Full power steam conditions were 620 psia, 490° F saturated steam

Source: James Robert Bauman, "Analysis of Past, Present and Future Applications of Nuclear Power for Propulsion of Marine Vehicles," MIT, May 1972

Westinghouse marine PWR

Nuclear Propulsion Plant for High-Speed Merchant Ships

- The basic design of this marine NSSS was similar to the design of a Westinghouse commercial two-loop PWR, with the addition of loop gate valves in each primary loops



A representative Westinghouse PWR single-loop flow diagram.
Source: adapted from, W E Cummins & R. Matzie, “Design evolution of PWRs: Shippingport to generation III+,” progress in Nuclear Energy, Vol. 102, January 2018, pp 9 - 37

Westinghouse marine PWR

Nuclear Propulsion Plant for High-Speed Merchant Ships

- Containment:
  - The containment vessel was a vertical cylindrical, steel and concrete structure that is an integral part of the ship's structure.
    - Dimensions: OD of 31 ft; height of 37 ft to the top of its ellipsoidal head, and a 33 in. thick concrete wall,
  - The containment vessel was situated at the forward end of an engine room measuring 83 ft wide, 90 ft long, 37 ft high.
- Propulsion plant:
  - The propulsion plant consisted to two main propulsion steam turbines rated at 37,500 shp driving two shafts.
  - A 2,200 kw diesel generator and two 1,250 SHP electrical propulsion motors driving their associated shafts through their reduction gears provided emergency “take –home” power.
  - The weight of the reactor plant, including containment vessel and shielding, was 1,636 tons; the entire propulsion plant weighted 3,023 tons.

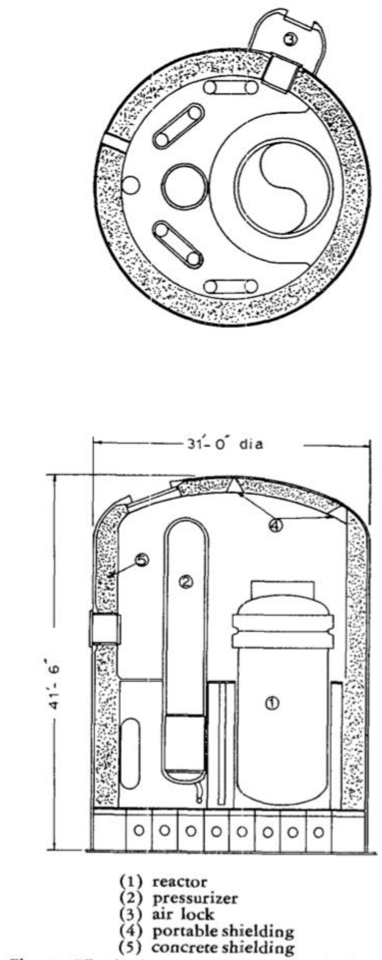
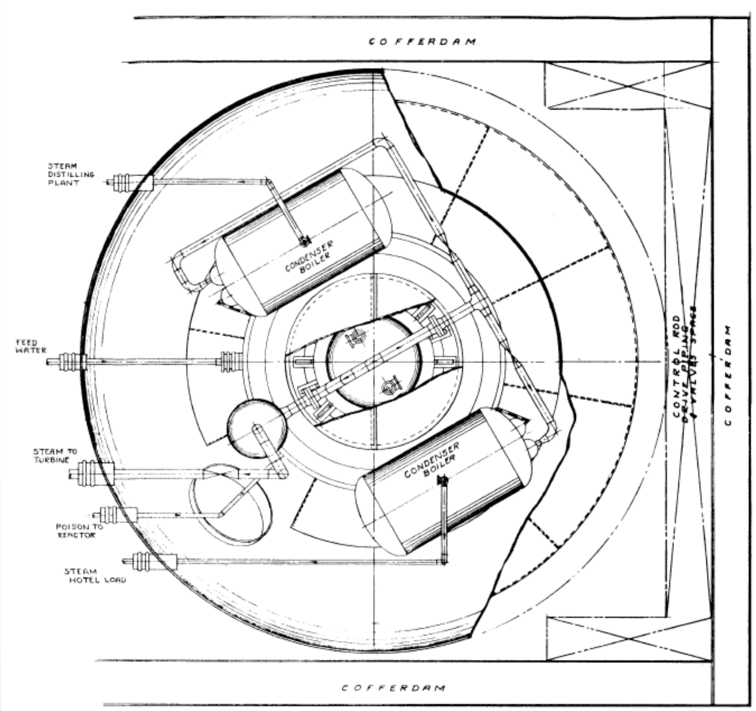


Fig. 7 Westinghouse marine reactor (reference [58])

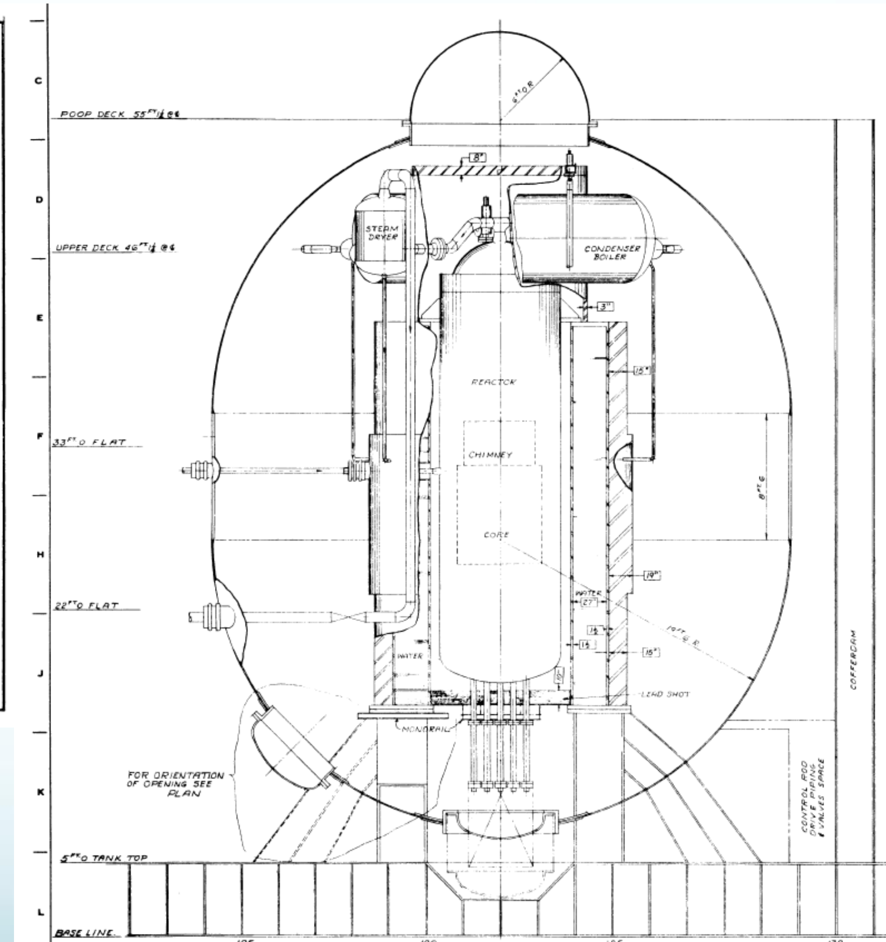
Source: James Robert Bauman, “Analysis of Past, Present and Future Applications of Nuclear Power for Propulsion of Marine Vehicles,” MIT, May 1972

General Electric marine BWR

Plan view



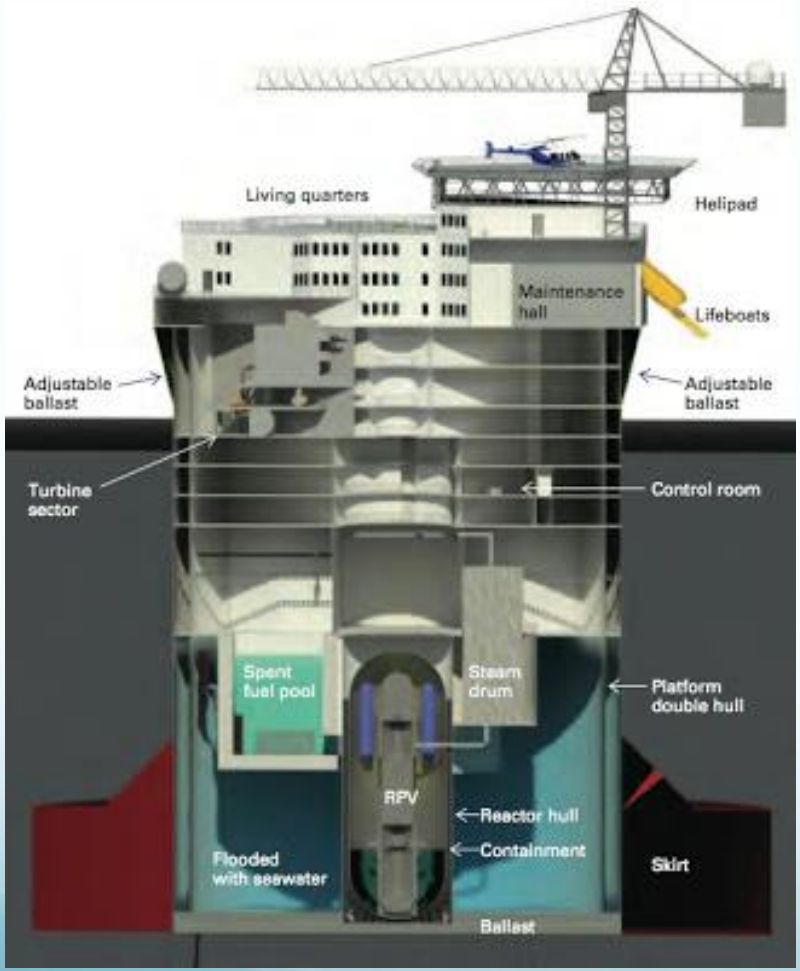
Elevation view



- BWR primary system housed in a compact steel containment vessel.
- Steam and feedwater line penetrations are at the left in the above plan view.

Source: General Electric report GEAP-3088, December 1958

MIT offshore floating nuclear plant concept



Source, two images: Massachusetts Institute of Technology (MIT)

- MIT recently developed concepts for two floating PWR nuclear power plants: a 45 meters (148 feet) in diameter 300 MWe power plant, and a much larger 75 meters (246 feet) in diameter 1,100 MWe power plant.
- These offshore power plants are designed for construction in shipyards. They are intended to serve as critical components of a low-carbon energy future.

Marine gas-cooled reactor designs

Maritime Administration gas-cooled reactor program

- Initiated in 1956, with nine firms responding to a Maritime Administration request for design studies of a closed-cycle nuclear gas turbine propulsion plant for a planned second nuclear powered oil tanker projected to enter service in 1961 (the first nuclear tanker was intended to be powered by a PWR).
  - The propulsion system was to deliver 22,000 shp for a 38,000 ton DWT vessel, enabling a speed of 20 – 21 knots.
- The firms responding included:
  - General Electric (GE)
  - General Atomics (GA) Division of General Dynamics
  - Ford Instrument Company, in conjunction with American Turbine Company
  - General Motors (GM)
- Only GE and GA continued their work into the mid-1960s.
  - GE's 630A indirect cycle Nuclear Steam Generator and the 630A Reactor Critical Experiment
  - GA's direct-cycle Marine Gas Cooled Reactor (MGCR) and the Experimental Beryllium Oxide Reactor (EBOR) test reactor.

General Electric 630A Nuclear Steam Generator

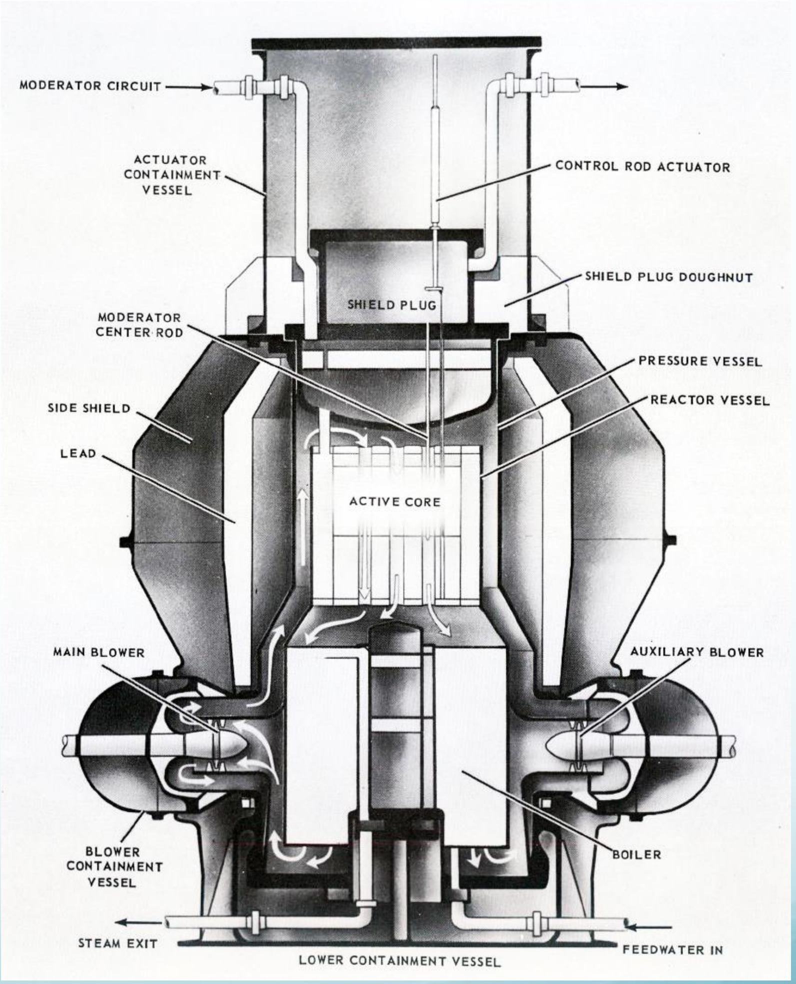
- In 1961, General Electric began design work on the 630A maritime gas-cooled reactor, which was based on their work developing the HTRE-1 (Heat Transfer Reactor Experiment) reactor for the Air Force Aircraft Nuclear Propulsion Program (ANPP). The 630A program was managed by the Atomic Energy Commission (AEC) office in Oak Ridge, TN.
- The 630A was a nuclear steam generator-superheater about the same size and somewhat heavier than a conventional marine boiler, which it could replace in merchant ships.
  - It has a gas primary circuit, transferring heat from the reactor to a once-through boiler-superheater that is integrated within the primary pressure vessel.
  - Feedwater delivered to the boiler is discharged as high superheated steam (1,500 psi; 1,000°F).
  - Power conversion was by conventional steam turbo-machinery.
- Core lifetime was reported as 15,000 (equivalent full power) hours. It also was described as giving a 30 knot merchant ship the ability to make thirteen 28-day round trips of 14,000 miles each, for a total of 182,000 miles on a single reactor core. On this schedule, refueling would be required at 2.6 year intervals.

General Electric
630A Nuclear Steam Generator

- By 1965, the 630A had gone through five major design iterations:
  - The first three 630A design concepts, Mark I, II and III, were all closed-cycle, air-cooled reactors with 85 fuel elements, each comprised of concentric fuel rings with highly-enriched UO_2 [fuel design is similar to that used in the Heat Transfer Reactor Experiment (HTRE) series of test reactors].
  - Two different Mark IV versions were developed:
    - Air-cooled (A-version); calandria-type water moderator container as in earlier cores.
    - Helium-cooled (B-version); moderator water containment tubes located centrally in each fuel element cluster.
    - The core was smaller, with 55 fuel elements, but of similar design to the earlier models. Zircaloy moderator tubes and encapsulated gas-bearing circulators were introduced.
  - Mark V utilized all the features of the Mark IV except that the reactor used low-enrichment (6%), pin-type UO_2 fuel.
- A 630A was planned for installation on the oil tanker *USNS American Explorer*. However, that vessel was completed with an oil-fired boiler.
- The 630A program was suspended on 31 December 1964 and ultimately cancelled.
  - Life-cycle economic comparison indicated that the PWR was a better economic choice than a 630A. The 630A system cost less to install than a PWR, but long-term fuel cycle cost for 630A were higher than for a PWR.

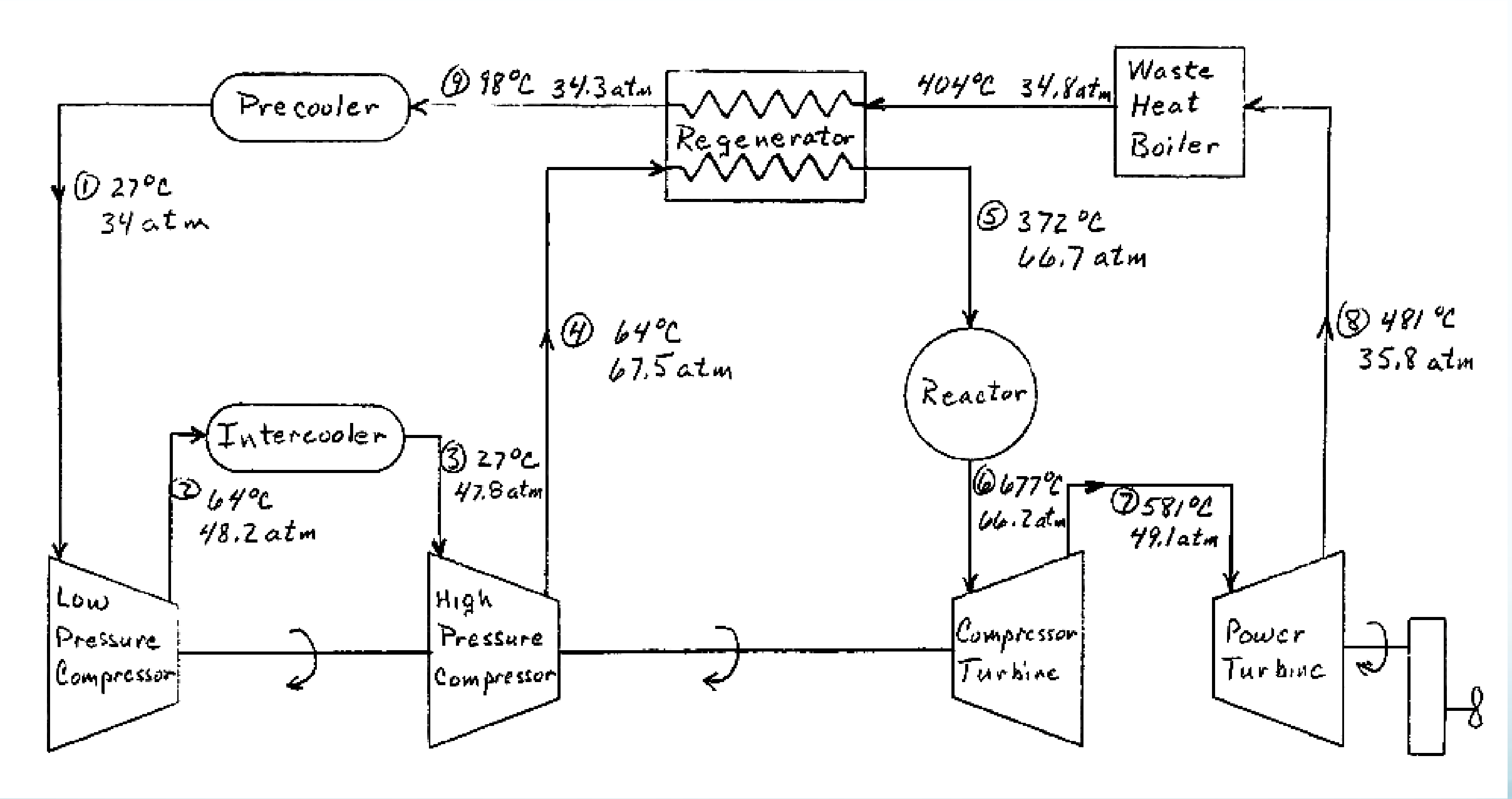
General Electric 630A Nuclear Steam Generator

- Reactor power: 66 MWt
- Fuel: high enriched (93%) UO_2 in concentric fuel rings (Mk I - Mk IV); low enriched (6%) pin type fuel (Mk V); cladding 80Ni-20Cr
- Core: 85 fuel elements (Mk I – III); 55 fuel elements (Mk IV & V)
- Coolant: Air only (Mk I, II & III); air or helium (Mk IV & V)
- Moderator: Water; calandria (Mk I – III & Mk IV A and Mk V A); central moderator tubes (Mk IV B and V B)
- Reflector: Beryllium oxide
- Primary system conditions: 830 psig, core outlet temperature 1,200°F (649°C)
- 2 x gas circulators
- Main steam conditions: 1,500 psig and 1,000°F (538°C)
- Intended to deliver a nominal 27,300 shp propulsion power (30,000 maximum)
- Module height: 38.25 ft; 11.7 m (Mk IV)
- Module diameter: 19.67 ft; 6 m (Mk IV)
- Module weight: < 500 tons (Mk IV)



Source: General Electric report GEMP-175, January 1963

General Electric 630A process flow diagram



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

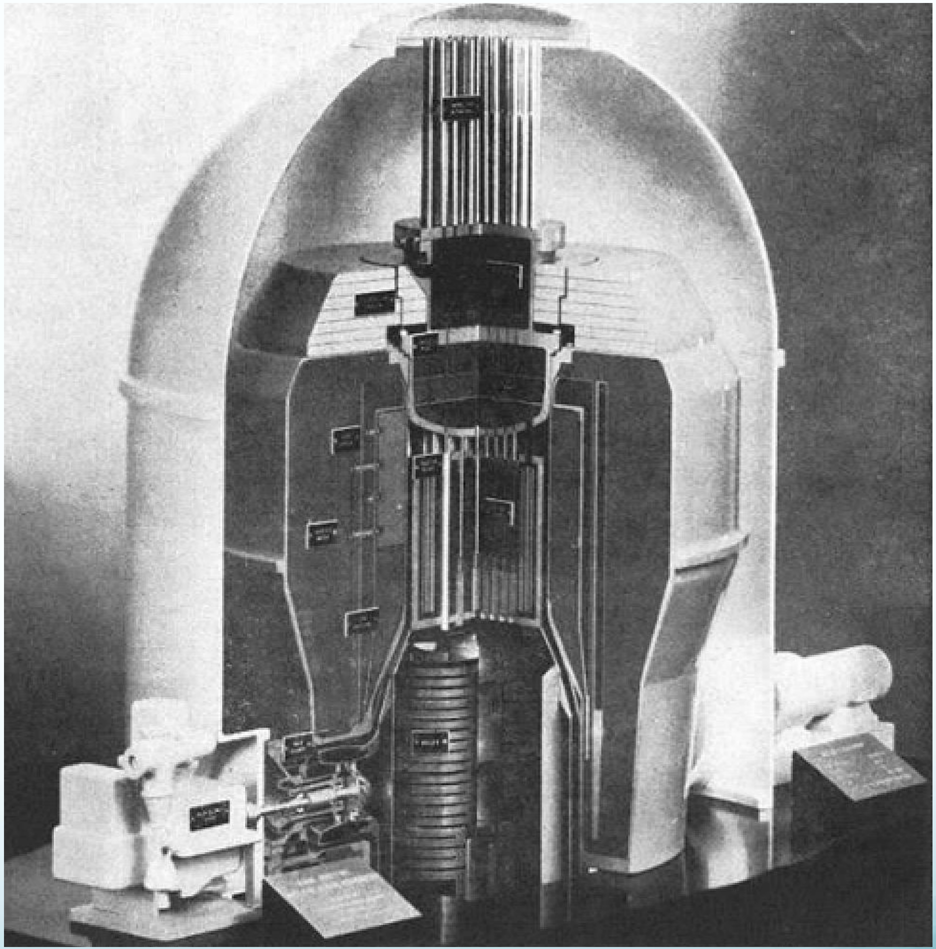
General Electric
630A Reactor Critical Experiment

- GE set up and operated the 630A Reactor Critical Experiment at the Low Power Test Facility (LPTF) in Test Area North (TAN) at Idaho National Lab (INL).
- The reactor achieved initial criticality in 1962
- The hexagonal core grid consisted of 85 fuel cartridges and varying numbers of control (shim) rods (initially 132, later 96) for testing various fuel and rod configurations.
- In 1964, measurements were made of core power distributions, reactivity characteristics, end-of-life-conditions, and shutdown margin with the core flooded with water and scrammed (all rods inserted).

Feb 1965 aerial view of Low Power Test Facility (TAN-640 & -641 on left)
and Shield Test Facility (TAN-645 & -646 or right).
Source: INEL via Library of Congress

General Electric
630A prototype reactor concept

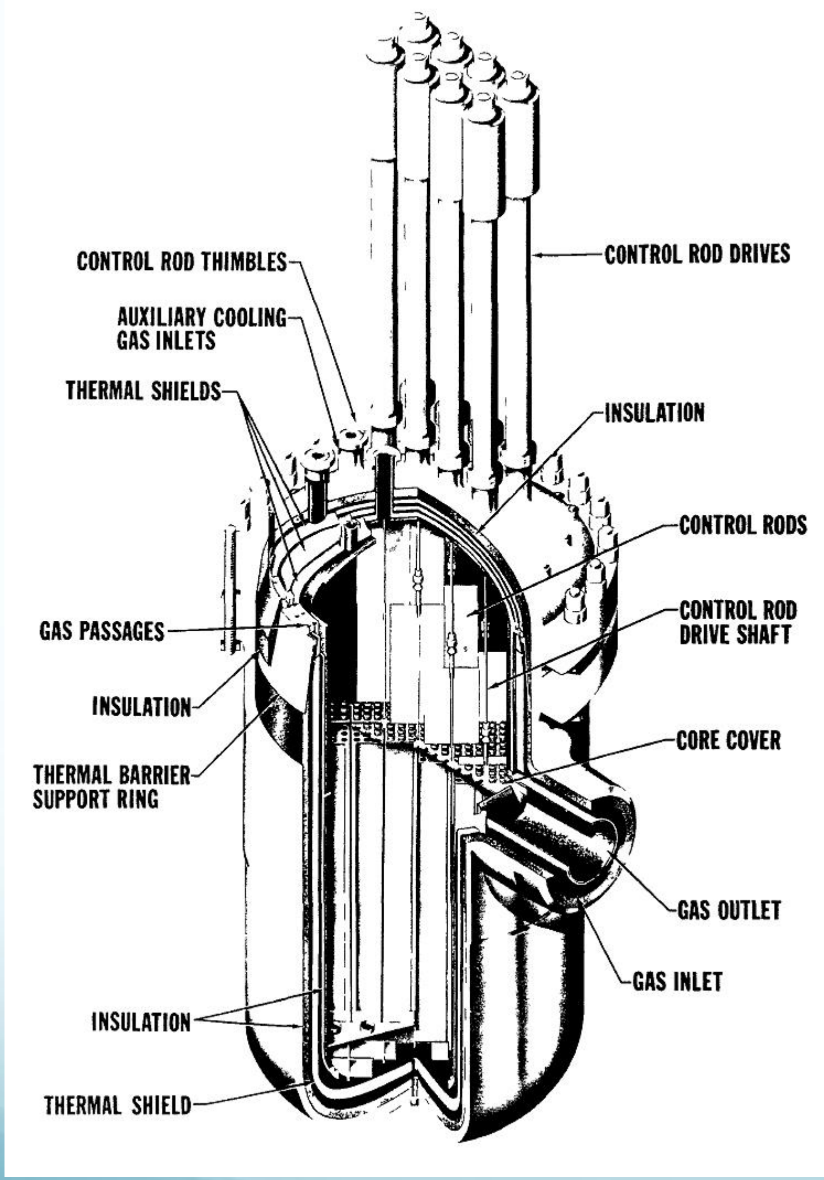
- In 1962, GE displayed the model of a conceptual 630A prototype reactor shown in the accompanying photo.
- In late 1962, GE confirmed the feasibility of converting the new Experimental Organic Cooled Reactor (EOCR) facility near the Central Facilities Area (CFA) of INL for testing a 630A prototype reactor.
- In spring 1964, GE confirmed the feasibility of adapting the old Initial Engine Test (IET) facility in TAN (former Aircraft Nuclear Power Program site) for testing a 630A prototype reactor.
- No prototype was ever built.



GE 1962 concept for a 630A Mk II prototype.
Source: Aviation Week and Space Technology magazine, 19 Nov 1962

General Atomics Maritime Gas-Cooled Reactor (MGCR)

- 1958 – 1963: The goal of the MGCR Project, funded under a joint Atomic Energy Commission - Maritime Administration contract, was to produce a nuclear power plant for commercial maritime use with propulsion power of 22, 000 – 32,000 shaft horsepower.
- In June, 1961, the Electric Boat Division of General Dynamics Corporation completed its studies of the shipboard arrangement for an MGCR and other propulsion system equipment.
- Reactor trade studies initially selected a graphite-moderated, helium-cooled reactor but ultimately focused on a beryllium oxide moderated and reflected, helium-cooled reactor, which was more compact and better suited as a maritime powerplant.
- MGCR was cancelled in 1963, but work continued under the Experimental Beryllium Oxide Reactor (EBOR) project.

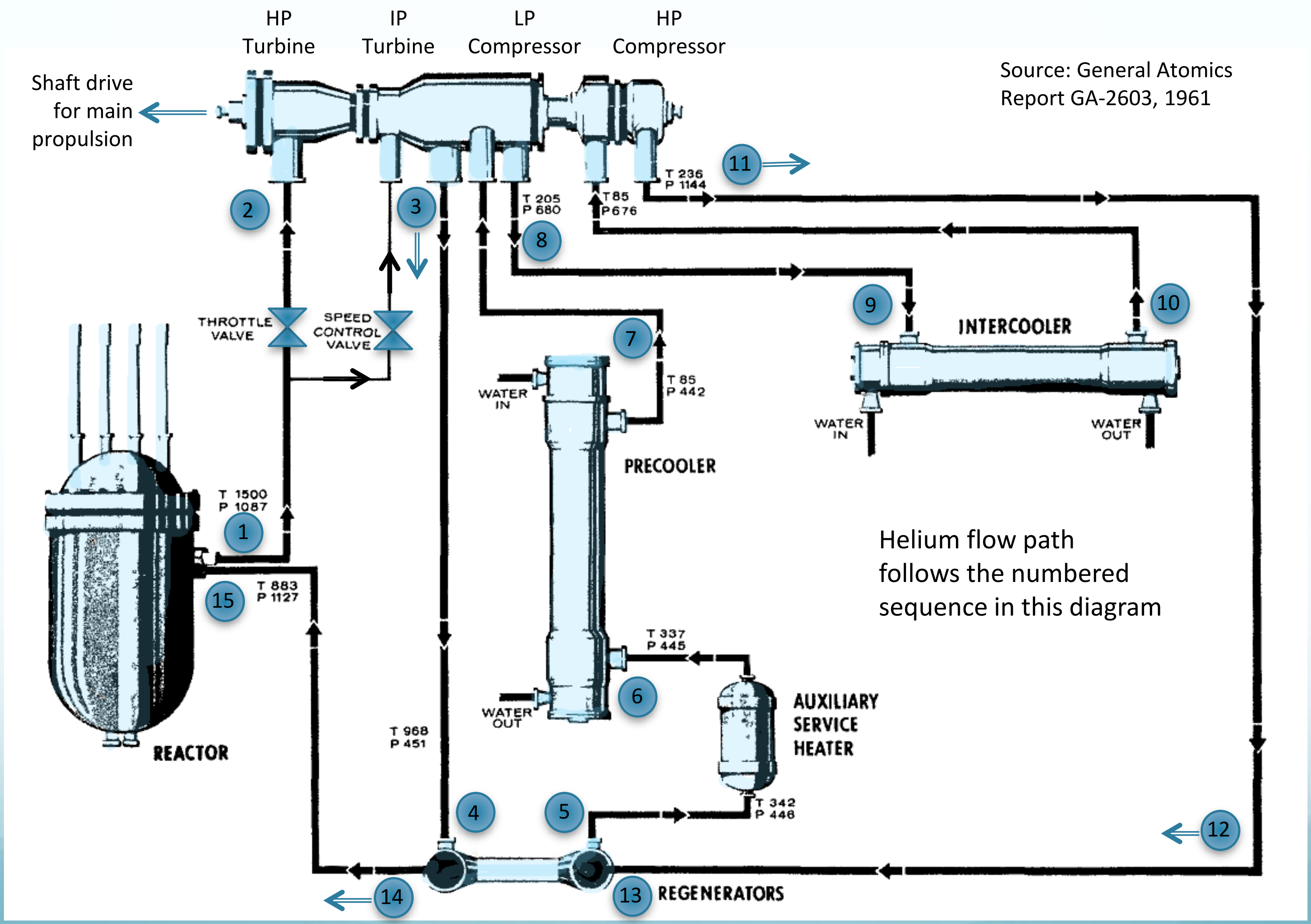


Source: General Atomics Report GA-2603, 1961

General Atomics MGCR

- Reactor: helium cooled; beryllium oxide (BeO) moderated; 74 MWt
- Fuel: UO_2; enrichment 8.85%
- Cladding: candidates included Inconel, Hastalloy-X and SS 316L
- Core: diameter 6.37 feet (1.94 m); height 6.37 feet (1.94 m); 308 fuel elements
- Core lifetime: 1.5 – 2.7 years
- Primary conditions: 1,080 psia, 1,300°F (704°C) core outlet temperature; coaxial gas duct connected the reactor to the turbo-machinery
- Propulsion output: 32,000 shp

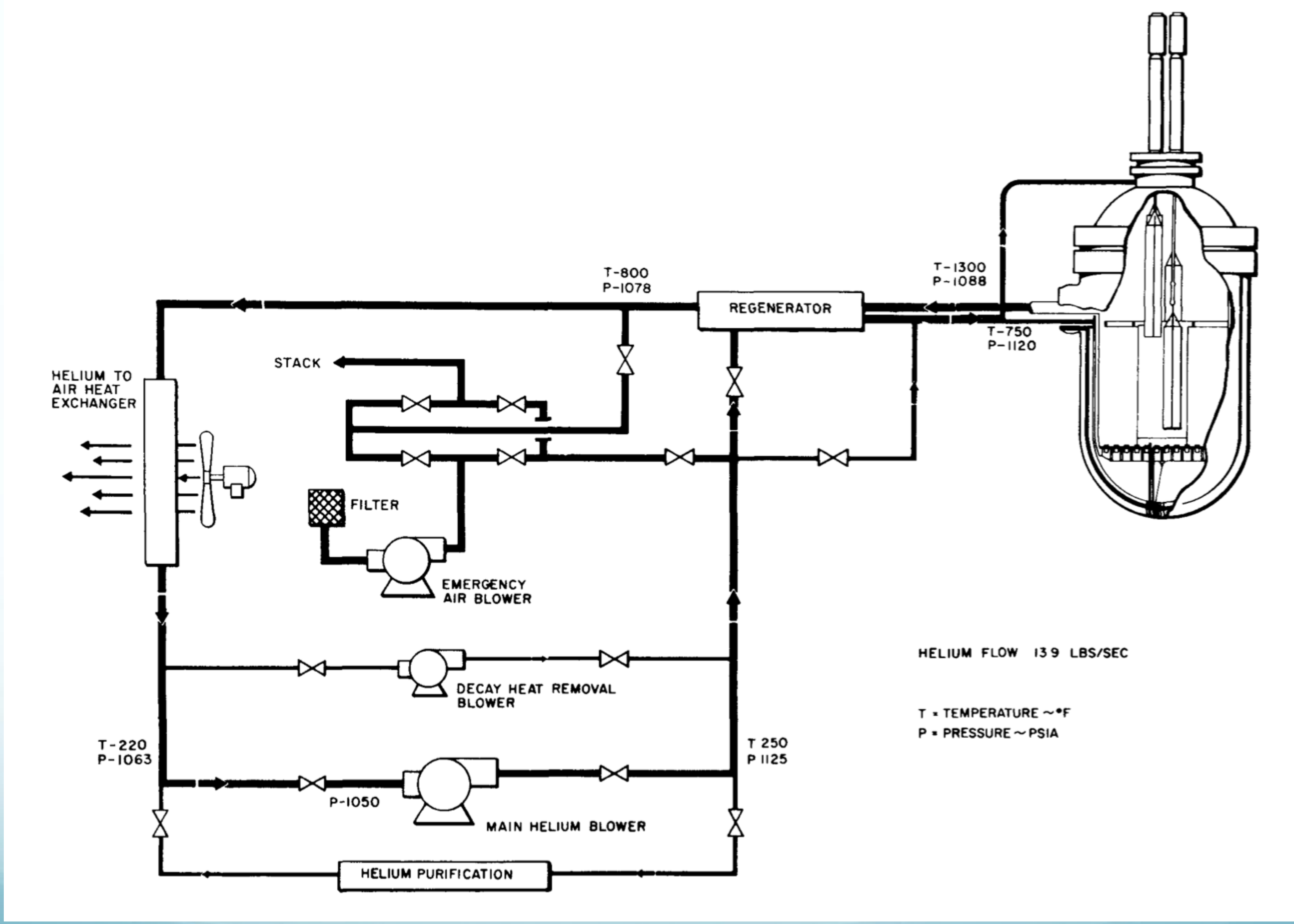
Maritime Gas-Cooled Reactor (MGCR) process flow diagram



General Atomics Experimental Beryllium Oxide Reactor (EBOR)

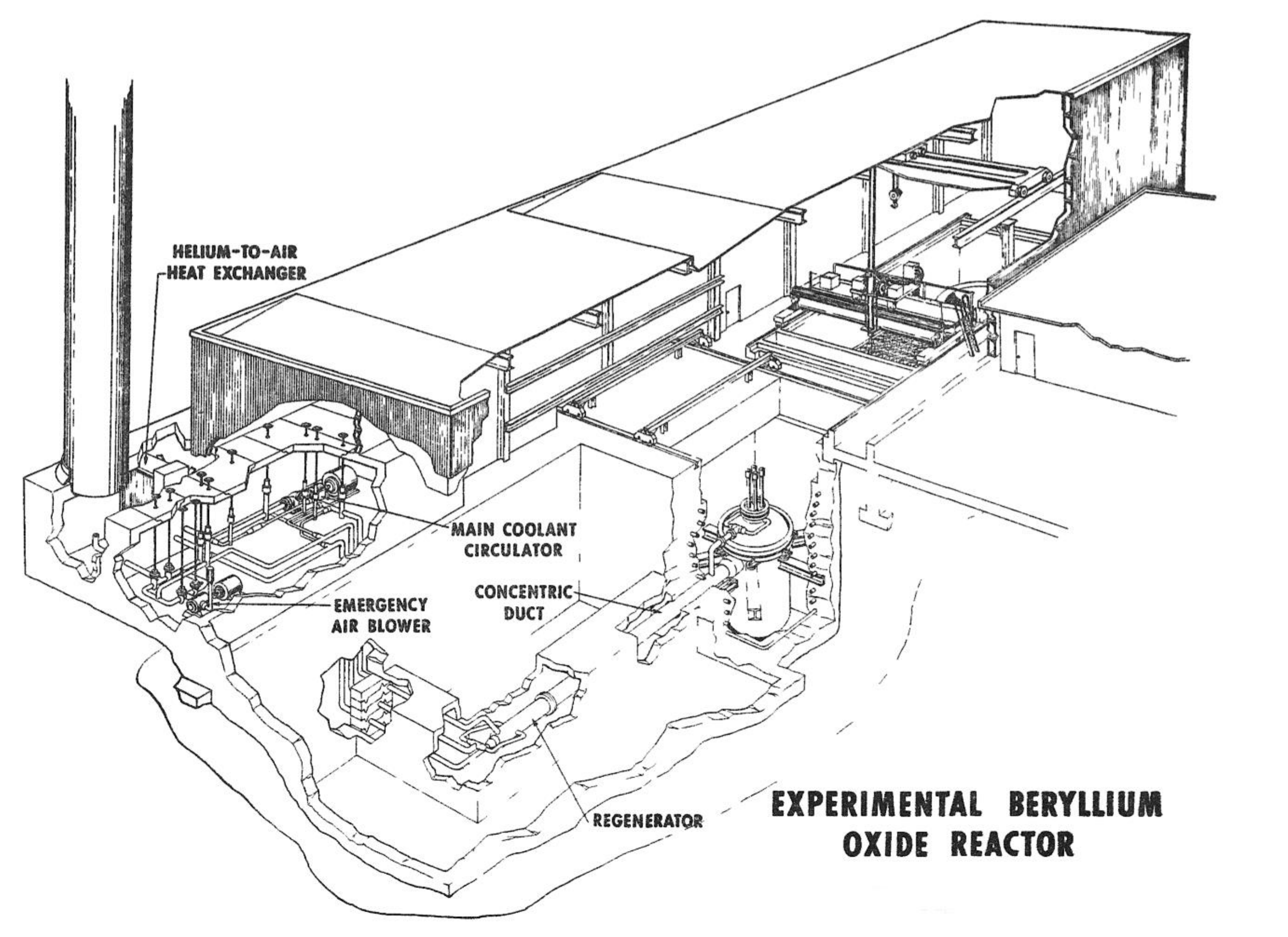
- EBOR was a 10 MWt helium-cooled, beryllium oxide (BeO) moderated test reactor built at the Idaho National Lab (INL) to demonstrate the technology needed for MGCR.
- Basic EBOR characteristics:
  - Fuel: enriched (62.5%) UO_2 – BeO rods; Hastalloy-X cladding
  - Primary conditions: 1,100 psig, core outlet temperature 1,300°F (704°C)
  - No power conversion system was included. Waste heat was rejected to the atmosphere.
- EBOR was not completed before the project was cancelled in 1966. Fuel was never loaded into EBOR.

EBOR process flow diagram



Source: General Atomics Report GA-2603, December 1961

EBOR facility diagram

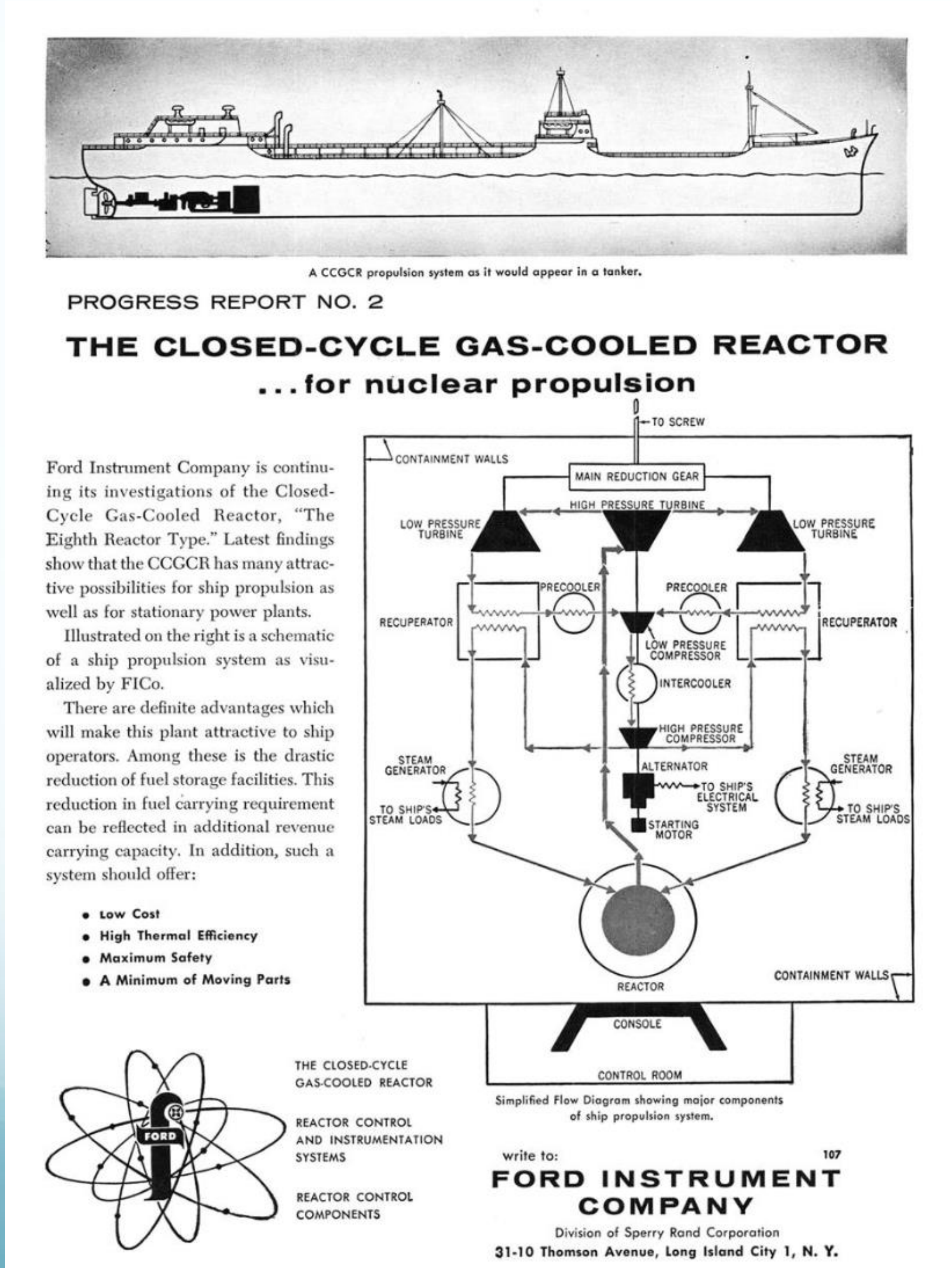


Source: General Atomics Report GA-2385, July 1961

Ford Instrument Company (FICo) marine CCGCR

- In the mid-1950s, FICo, then a division of Sperry Rand Corporation, conducted a feasibility study for a 15 MWt closed-cycle gas-cooled reactor (CCGCR) prototype. Nitrogen and helium coolant were considered.
- FICo, in conjunction with American Turbine Company, developed a 44 MWt CCGCR design concept for a 22,000 shp tanker propulsion plant.
- Fuel: 10% enriched UO_2 fuel in stainless steel clad hexagonal fuel elements measuring 4.5 inches (11.4 cm) on a side, 4 feet long (1.22 m)
- Graphite moderator
- Gas coolant conditions: 530 psia, 1300°F (704°C) core outlet temperature.

Ad source: Scientific American, 1956



A CCGCR propulsion system as it would appear in a tanker.

PROGRESS REPORT NO. 2

THE CLOSED-CYCLE GAS-COOLED REACTOR

...for nuclear propulsion

Ford Instrument Company is continuing its investigations of the Closed-Cycle Gas-Cooled Reactor, "The Eighth Reactor Type." Latest findings show that the CCGCR has many attractive possibilities for ship propulsion as well as for stationary power plants.

Illustrated on the right is a schematic of a ship propulsion system as visualized by FICo.

There are definite advantages which will make this plant attractive to ship operators. Among these is the drastic reduction of fuel storage facilities. This reduction in fuel carrying requirement can be reflected in additional revenue carrying capacity. In addition, such a system should offer:

- Low Cost
- High Thermal Efficiency
- Maximum Safety
- A Minimum of Moving Parts

Simplified Flow Diagram showing major components of ship propulsion system.

THE CLOSED-CYCLE GAS-COOLED REACTOR

REACTOR CONTROL AND INSTRUMENTATION SYSTEMS

REACTOR CONTROL COMPONENTS

write to: 107

FORD INSTRUMENT COMPANY

Division of Sperry Rand Corporation

31-10 Thomson Avenue, Long Island City 1, N. Y.

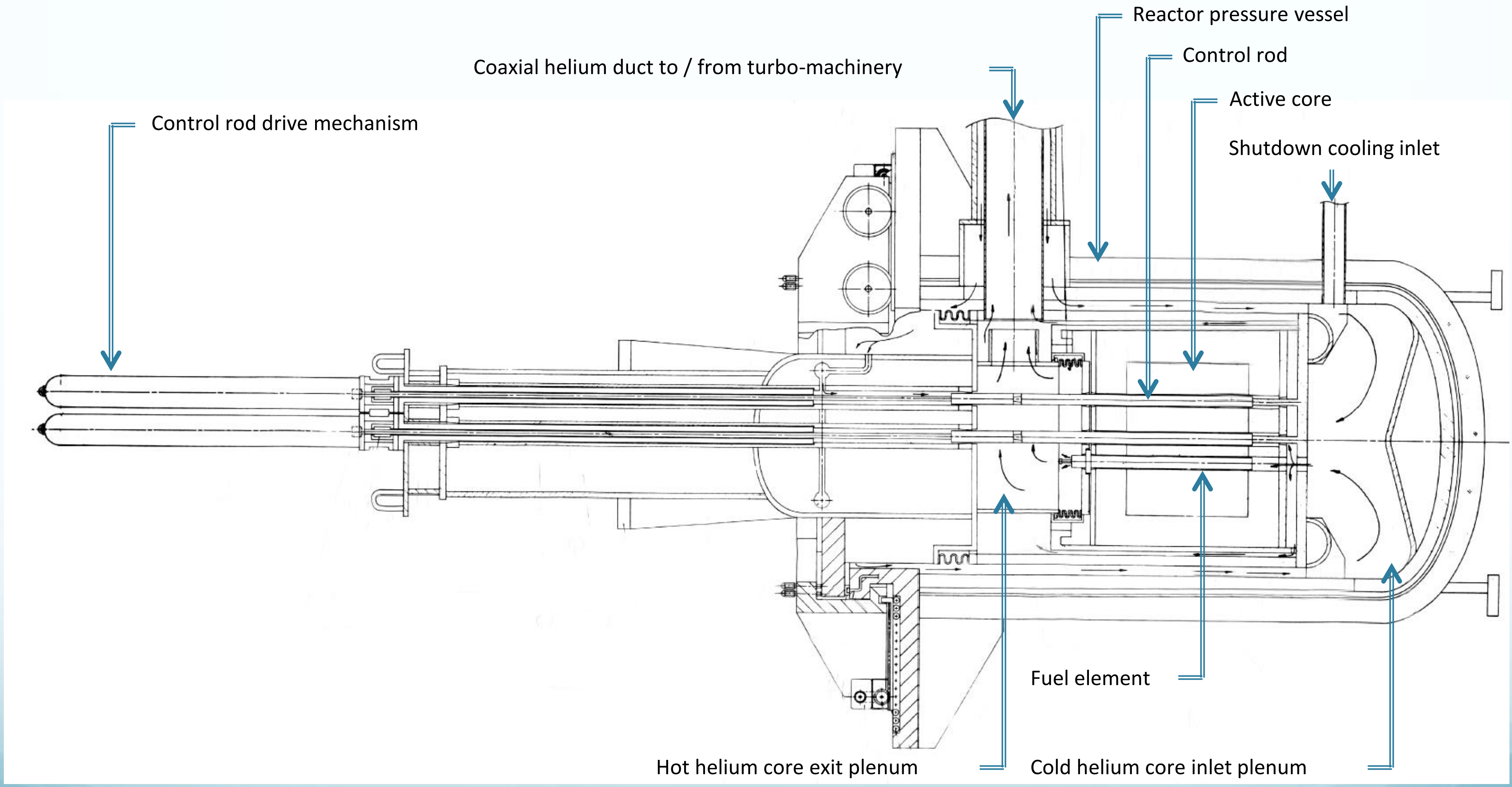
Ford Instrument Company (FICo) marine CCGCR

- Core is comprised of 30 hexagonal fuel elements plus hexagonal moderator elements surrounded by a graphite reflector.
- Reactivity control is by means of a central "regulating rod" and six "shim rods" that compensate for fuel burnup.
- Refueling interval: 1 year
- Study concluded that a marine CCGCR was technically and economically feasible.

Ad source: Aviation Week & Space Technology, 8 Oct 1956

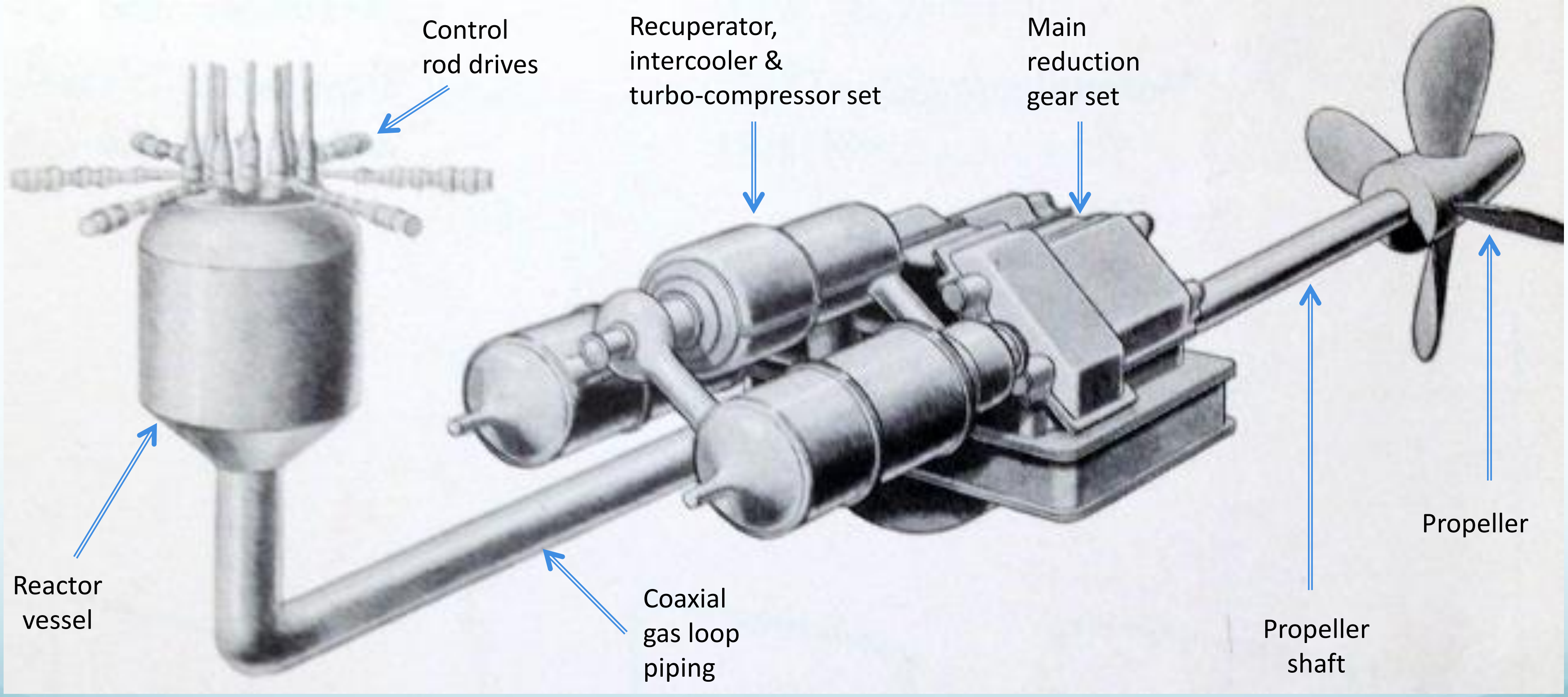
FICo 15 MWt CCRGR core & vessel arrangement

(rotated 90° left)



Source: adapted from FICO-101, “15 MWt gas-Cooled Closed-Cycle Reactor Power System Study – Final Report,” 1 April 1957

American Turbine Company CCGCR marine propulsion plant concept



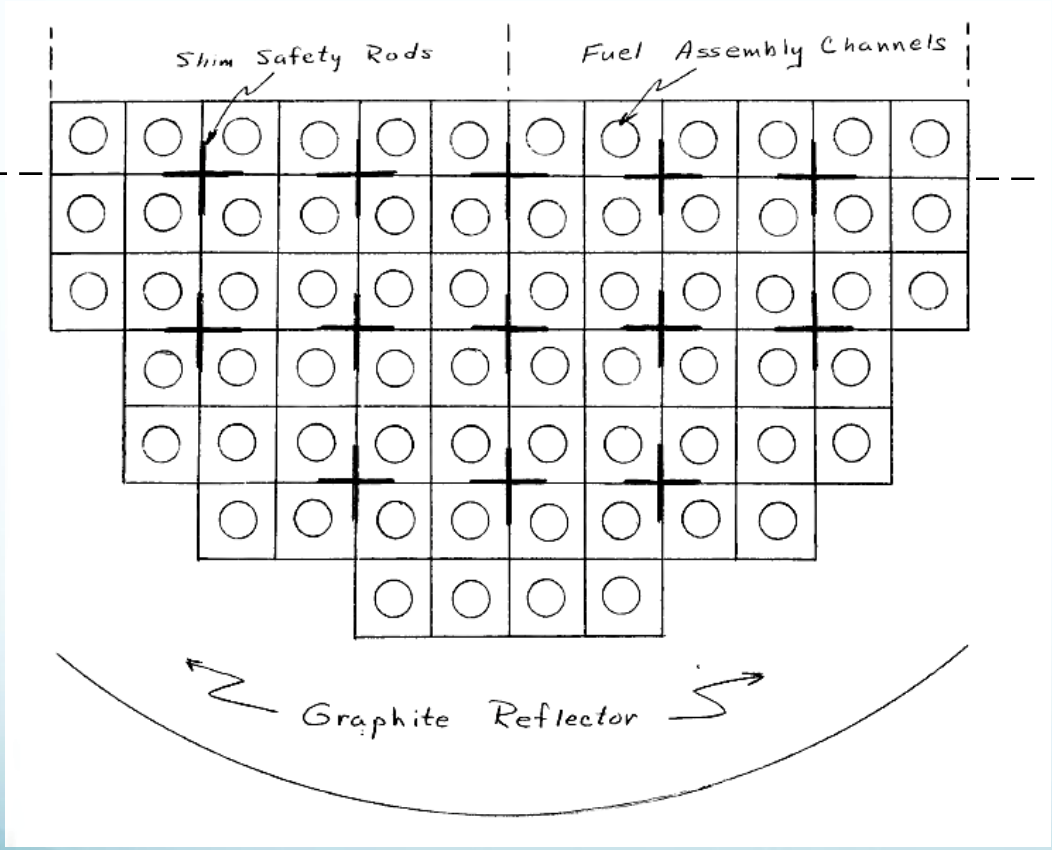
Source: adapted from American Turbine Company brochure via American Nuclear Society, ANS Nuclear Café, Will Davis library, 19 January 2017

General Motors (GM) gas-cooled marine reactor

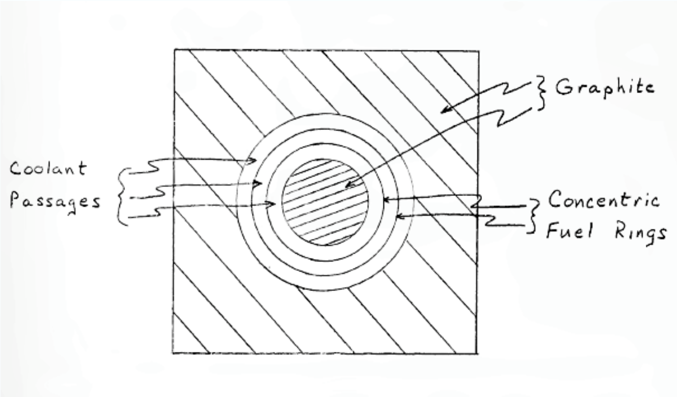
- In September 1956 General Motors, and its contractor Internuclear Corporation, began a design study for a closed-cycle gas-cooled reactor (CCGCR) system capable of delivering 20,000 shp for installation in a 38,000 ton DWT tanker.
  - Study funded under the Maritime Administration's Maritime Gas Cooled Reactor Program. GM's study report was issued in April 1957
- Basic reactor characteristics:
  - Reactor rated at 55 MWt
  - Helium coolant at 1,000 psig, 1,300°F (704°C)core outlet temperature
  - Graphite moderated and reflected
  - Fuel: highly-enriched (93%) UO_2 dispersion in 316 stainless steel matrix
  - Fuel element: Concentric fuel rings clad in 316 stainless steel inside a square graphite block and surrounding a central graphite rod. Maximum fuel surface temperature: 1,600°F (871°C)
  - Core: 112 fuel elements, 21 cruciform control rods (Europium oxide neutron poison); core diameter: 5 feet (1.5 m); core height 6.5 feet (2 m)

General Motors (GM) gas-cooled marine reactor

Reactor core layout



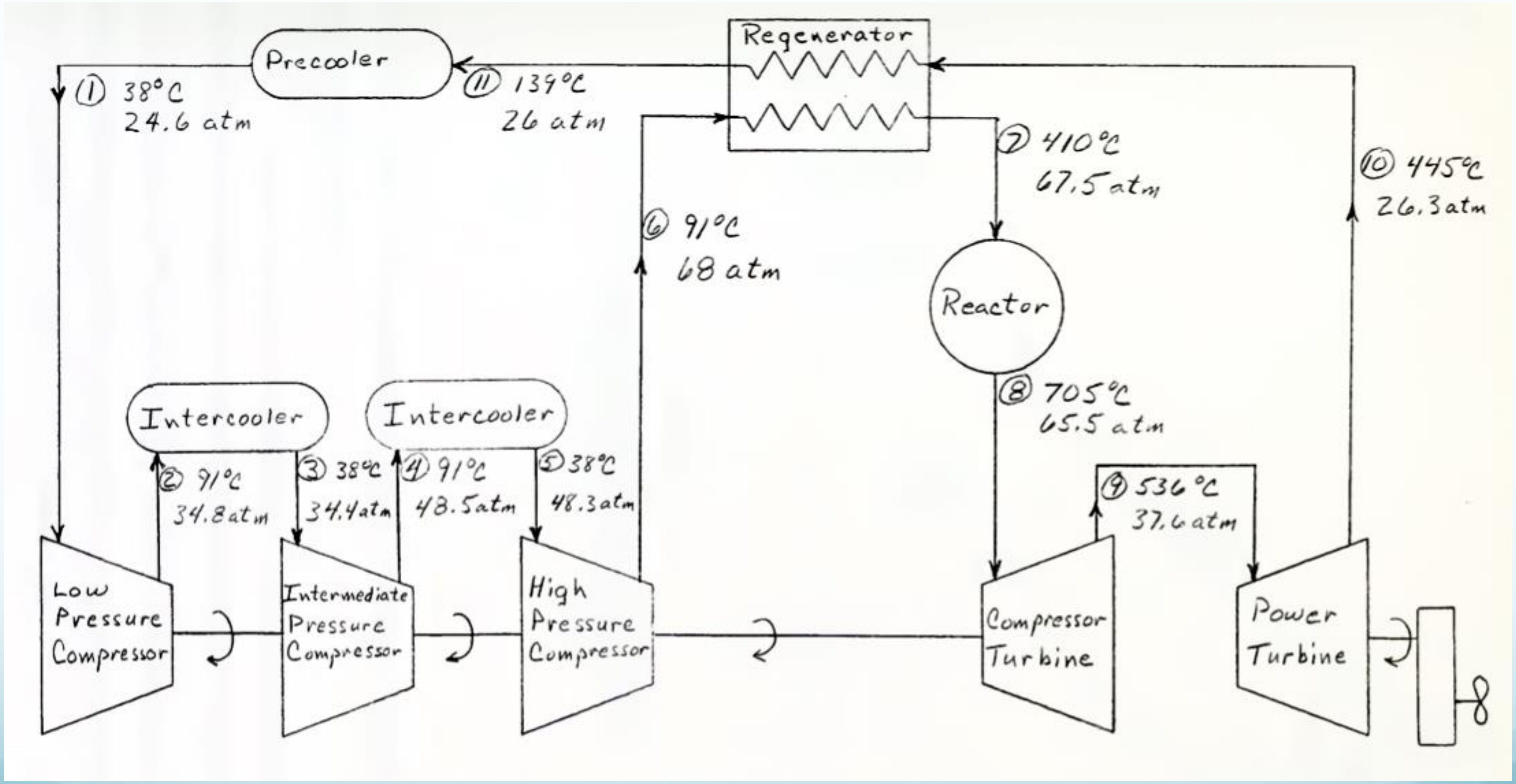
Fuel element design



- Helium coolant flows through the three concentric passages formed by the fuel rings and the graphite moderator

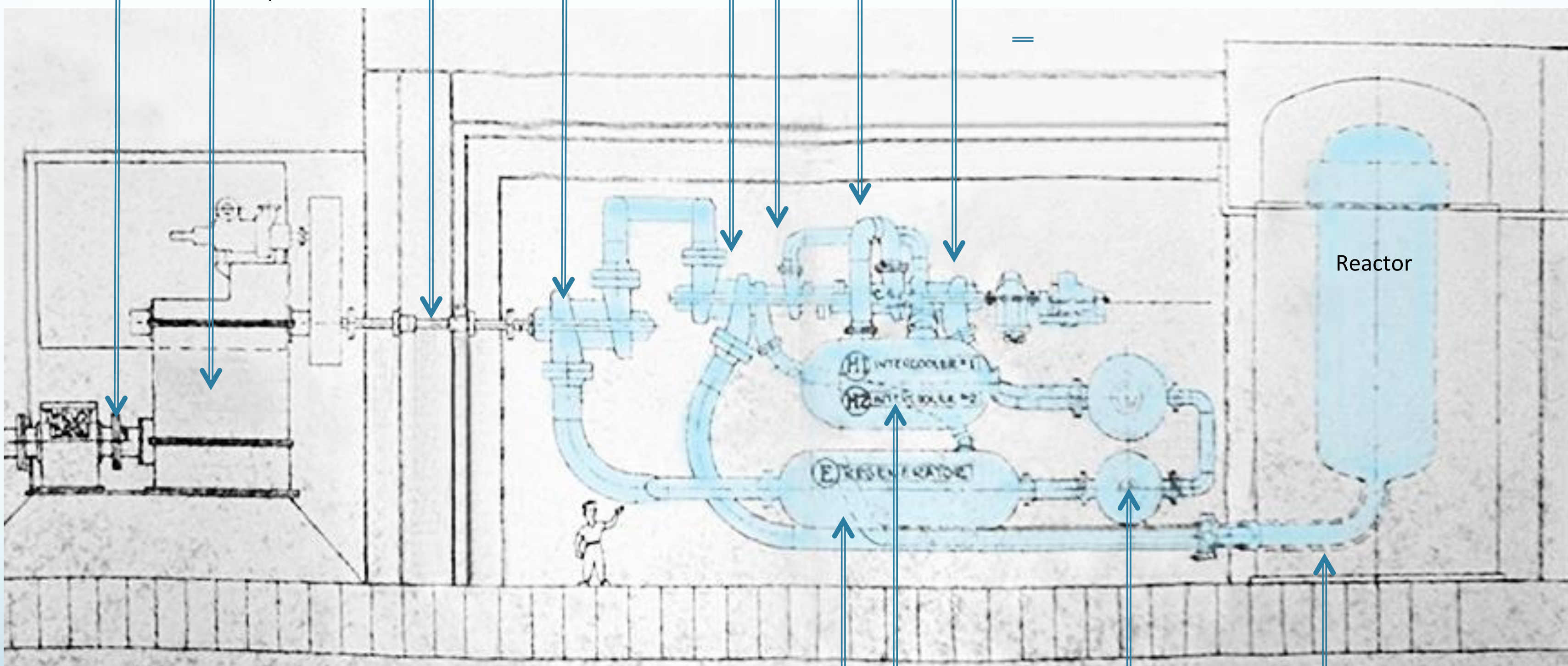
Source: Current, Donavon C., "Status of maritime gas-cooled reactors," The Pennsylvania State University, Department of Nuclear Engineering, August 1973

General Motors (GM) CCGCR power conversion cycle



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

General Motors (GM) CCGCR shipboard installation

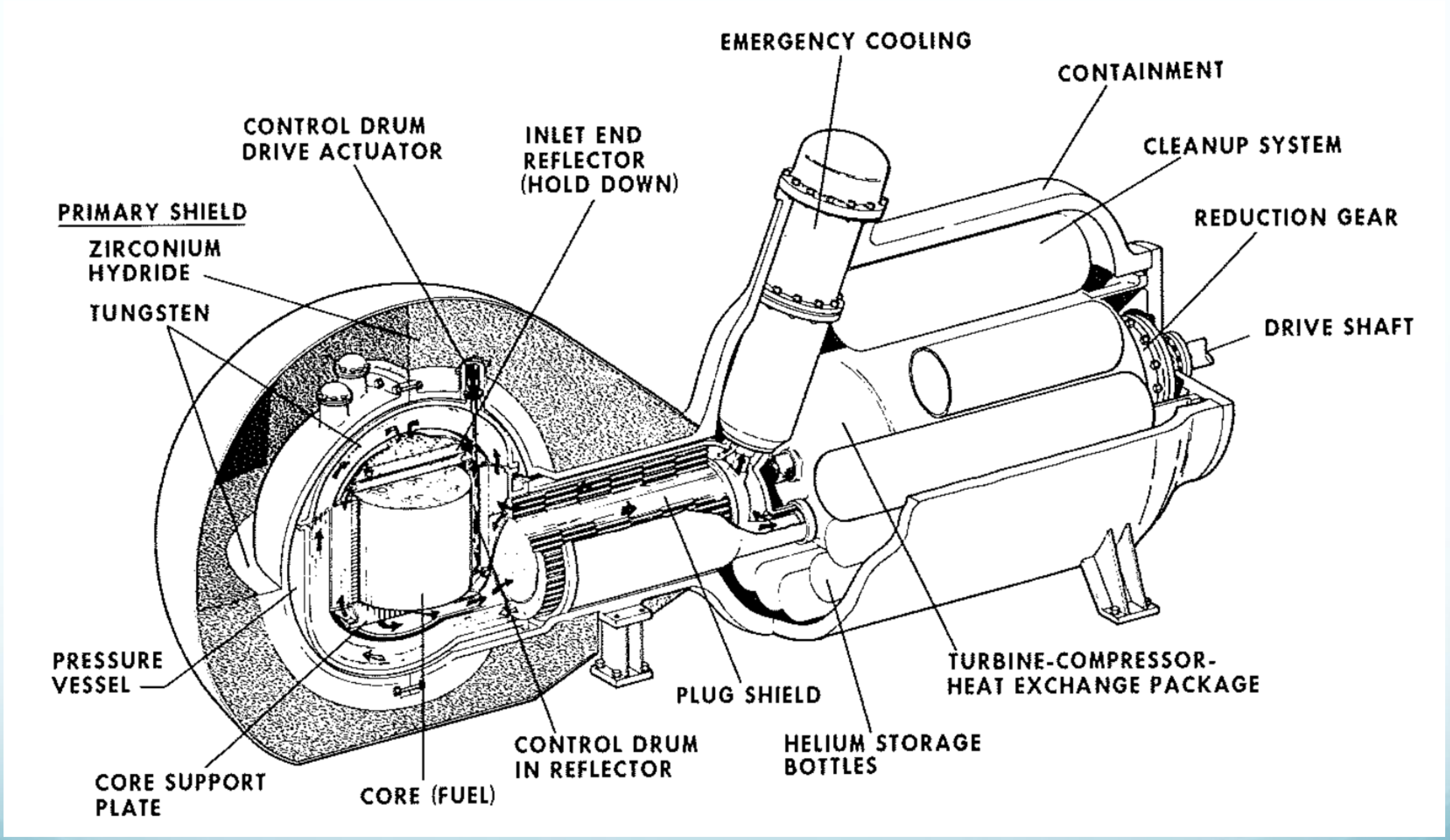


Source: adapted from General Motors blueprint, via American Nuclear Society, ANS Nuclear Café, 19 January 2017,

Westinghouse gas-cooled LWNP marine propulsion plant

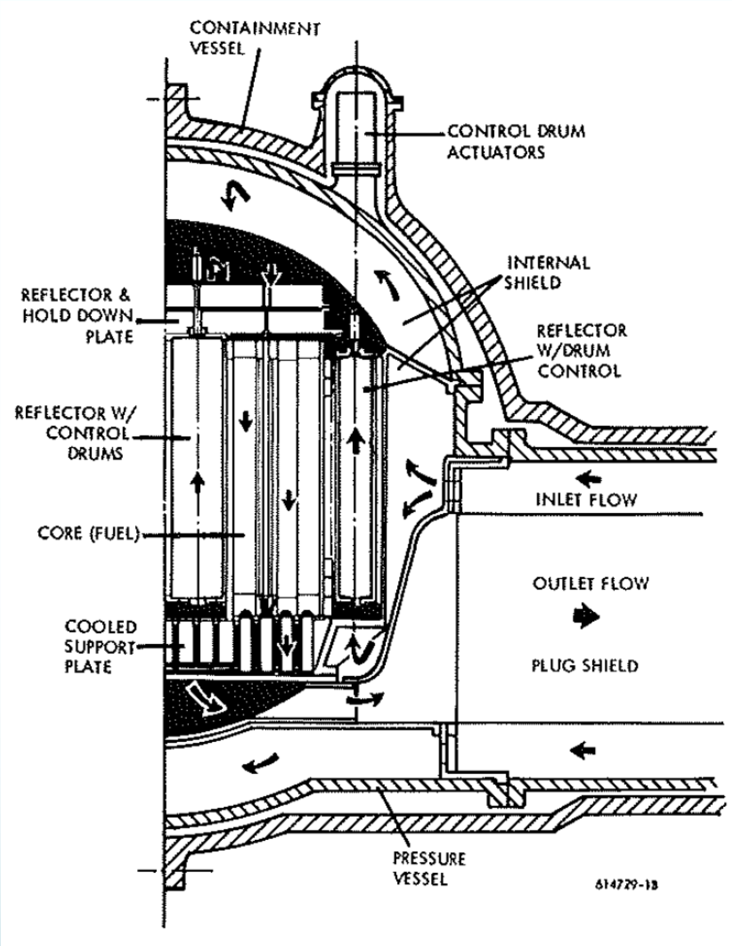
- The Light-Weight Nuclear Propulsion (LWNP) system is design concept for a compact, scalable, closed-cycle, gas-cooled, high-temperature reactor and propulsion machinery package that is designed to replace existing marine gas turbine powerplants; for example:
  - 25,000 shp General Electric LM-2500
  - 30,000 shp Pratt & Whitney FT4A
  - 60,000 shp General Electric LM-5000
- An LWNP is much heavier than the gas turbine it is intended to replace:
  - 274 tons/LWNP unit vs. 22.8 tons/LM-2500 unit
  - While there are substantial addition weight savings from removal of marine gas turbine auxiliaries and fossil fuel, replacing a marine gas turbine with an LWNP imposes a modest weight penalty on the host vessel.
- LWNP is designed for modular replacement. A whole unit can be removed for refueling / refurbishment on shore to minimize vessel turnaround time.
- LWNP reactor and fuel technologies are derived from the AEC / NASA NERVA program (Nuclear Engine for Rocket Vehicle Applications), which was disbanded in 1972. LWNP fuel technology also is derived from commercial High-Temperature Gas-Cooled Reactor (HTGR) programs.
- The Westinghouse study concluded than an LWNP is feasible and practical, particularly for high-performance displacement ships.

Westinghouse gas-cooled LWNP marine propulsion package layout



Source: R.E. Thompson & T.T. Miller, "Marine applications of an advanced gas-cooled reactor propulsion system," The Society of Naval Architects and Marine Engineers, May 1977

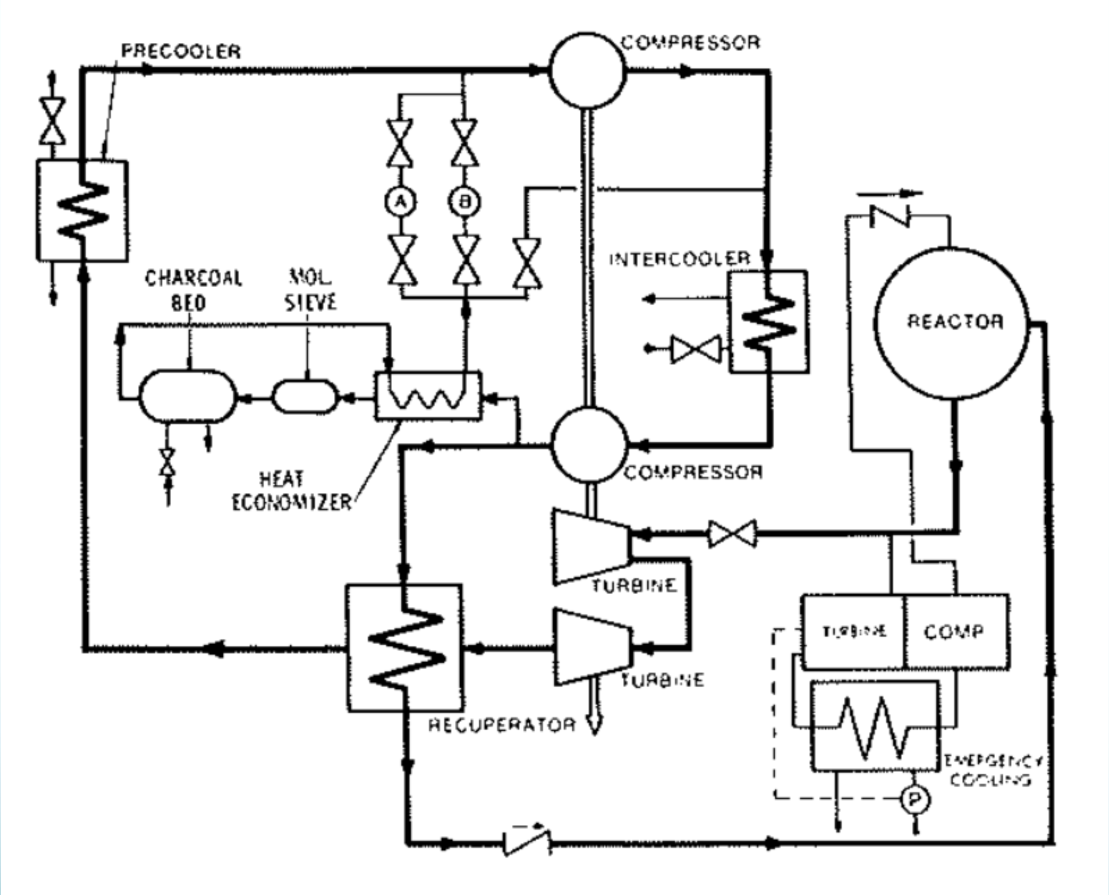
Westinghouse gas-cooled LWNP marine propulsion reactor details



Source: R.E. Thompson & T.T. Miller, "Marine applications of an advanced gas-cooled reactor propulsion system," The Society of Naval Architects and Marine Engineers, May 1977

- Fuel: enriched UO_2 / UCO in TRISO-coated (SiC & PyC) fuel beads incorporated into extruded graphite fuel compacts (short cylindrical fuel pellets)
- Fuel elements: Hexagonal graphite with axial channels for the fuel compacts and separate axial flow channels for helium coolant
- Core: diameter 35 inches (0.89 m); height 30 inches (0.76 m)
- Reactivity control via control drums at the periphery of the core
  - One drum sector is a beryllium reflector
  - The other drum sector is a neutron absorber made of stainless steel tubes containing boron carbide
- Reactor lifetime is 10,000 equivalent full power hours.

Westinghouse gas-cooled LWNP process flow diagram



Source: R.E. Thompson & T.T. Miller, "Marine applications of an advanced gas-cooled reactor propulsion system," The Society of Naval Architects and Marine Engineers, May 1977

- Closed loop; Brayton cycle
- Helium coolant at 1,500 psia, 1,700°F (927°C) core exit temperature
- Integrated, very compact turbo-machinery and associated heat exchangers

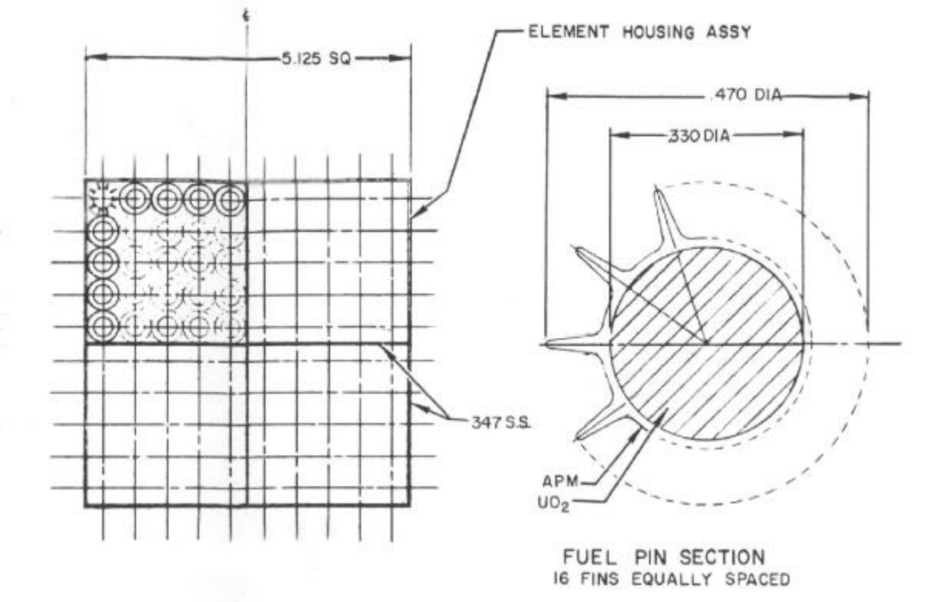
Marine OMCR and liquid metal-cooled reactor designs

Atomics International (AI) marine OMCR

- In 1959, AI, with support from De Laval Steam Turbine Company, conducted a design study for the Maritime Reactor Branch of the Atomic Energy Commission to examine the feasibility of adapting an Organic Moderated and Cooled Reactor (OMCR) for a 30,000 shp propulsion plant for an T-7-class oil tanker.
    - AI designed and operated the Organic Moderated Reactor Experiment (OMRE) at Idaho National Laboratory since 1957
- Inherent characteristics of an OMCR enable this nuclear plant to load-follow the rapid power demand transients common in ship maneuvering, for example, 20 to 80% nominal power in 10 seconds.
- The marine OMCR produced superheated steam at 450 psig and 650°F, which was close to conditions used in contemporary marine applications. Off-the-shelf marine propulsion hardware could be used.
- The study concluded that 60,000 ton DWT tanker powered by a 75 MWt (approximate) OMCR could be built and operated at a cost only slightly higher than the cost of a conventionally-propelled vessel. At the time, the price of fuel oil was $2.70 per barrel. Various design opportunities were identified to improve marine OMCR economics.

Al marine OMCR reactor design

- Fuel: Low-enriched (3.7%) UO_2 in finned, aluminum powder metal (APM) tubes (alloy of aluminum and aluminum oxide powder designated M-257). Maximum cladding temperature is 825°F (441°C).
- Core: 88 fuel elements; each with 2 x 2 sub-assemblies, which contain 5 x 5 finned fuel pins (100 fuel pins per fuel element), all enclosed in a stainless steel box (347 SS)

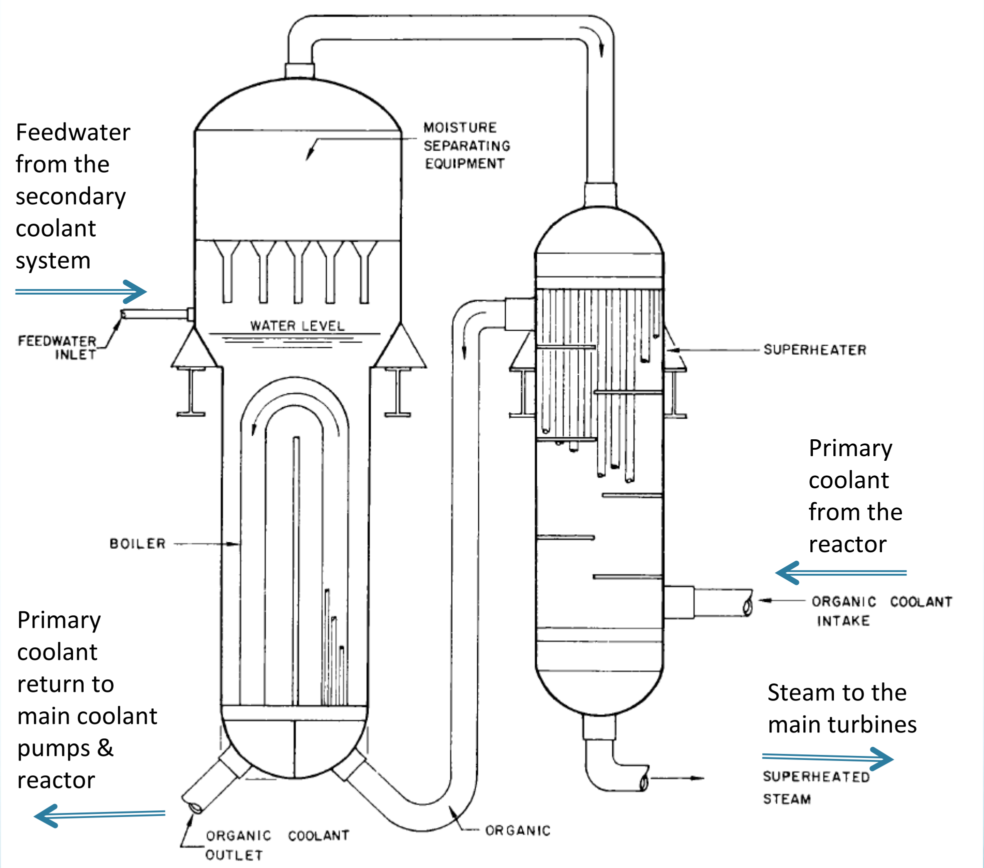


Source: NAA-SR-3859, "Maritime Organic Cooled and Moderated Reactor," May 1959

- Reactivity control: 21 cruciform, stainless steel clad control rods with Eu_2O_3 poison manage two core zones: inner 2/3 "control zone" and outer 1/3 "buckling zone." Fuel is shuffled between zones during refueling.
- Coolant & moderator: a mixture of terphenyls ($C_{18}H_{14}$), commercially available as Santowax-R. Ignition temperature is about 1,150°F (621°C) which is hundreds of degrees higher than the maximum temperatures (bulk or surface) encountered in the OMCR.

AI marine OMCR primary system design

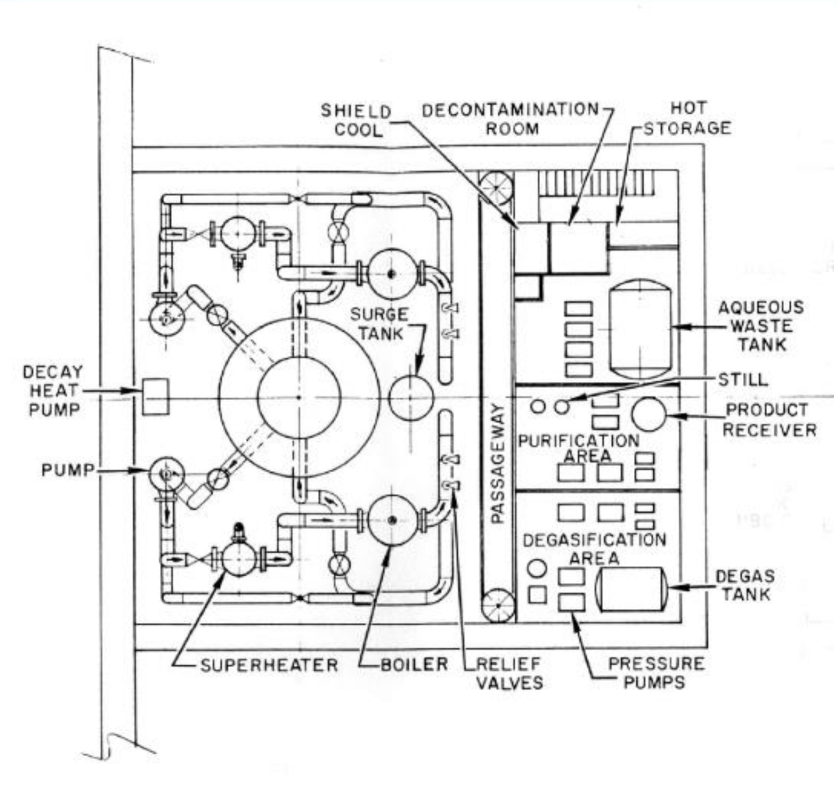
- Two-loop primary system; each loop is comprised of a circulating pump, superheater, steam generator, and a bypass flow path.
- Design pressure is 300 psig.
- All components are carbon steel, which is compatible with the organic coolant.
- Constant secondary steam pressure is maintained at varying loads by bypassing some of the primary organic coolant flow around the superheater & steam generator and routing it directly back to the reactor vessel.
- A surge tank with nitrogen cover gas manages minor pressure transients in the primary system.



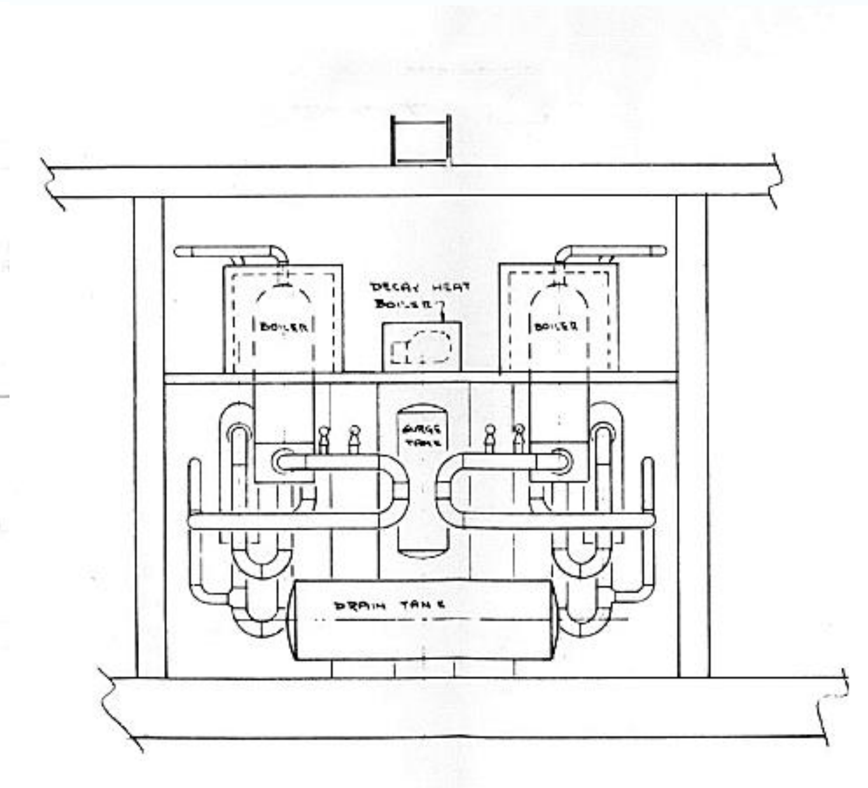
OMCR steam generator and superheater (reactor not shown in this diagram). Source: NAA-SR-3859, "Maritime Organic Cooled and Moderated Reactor," May 1959

AI marine OMCR nuclear plant layout

Plan view

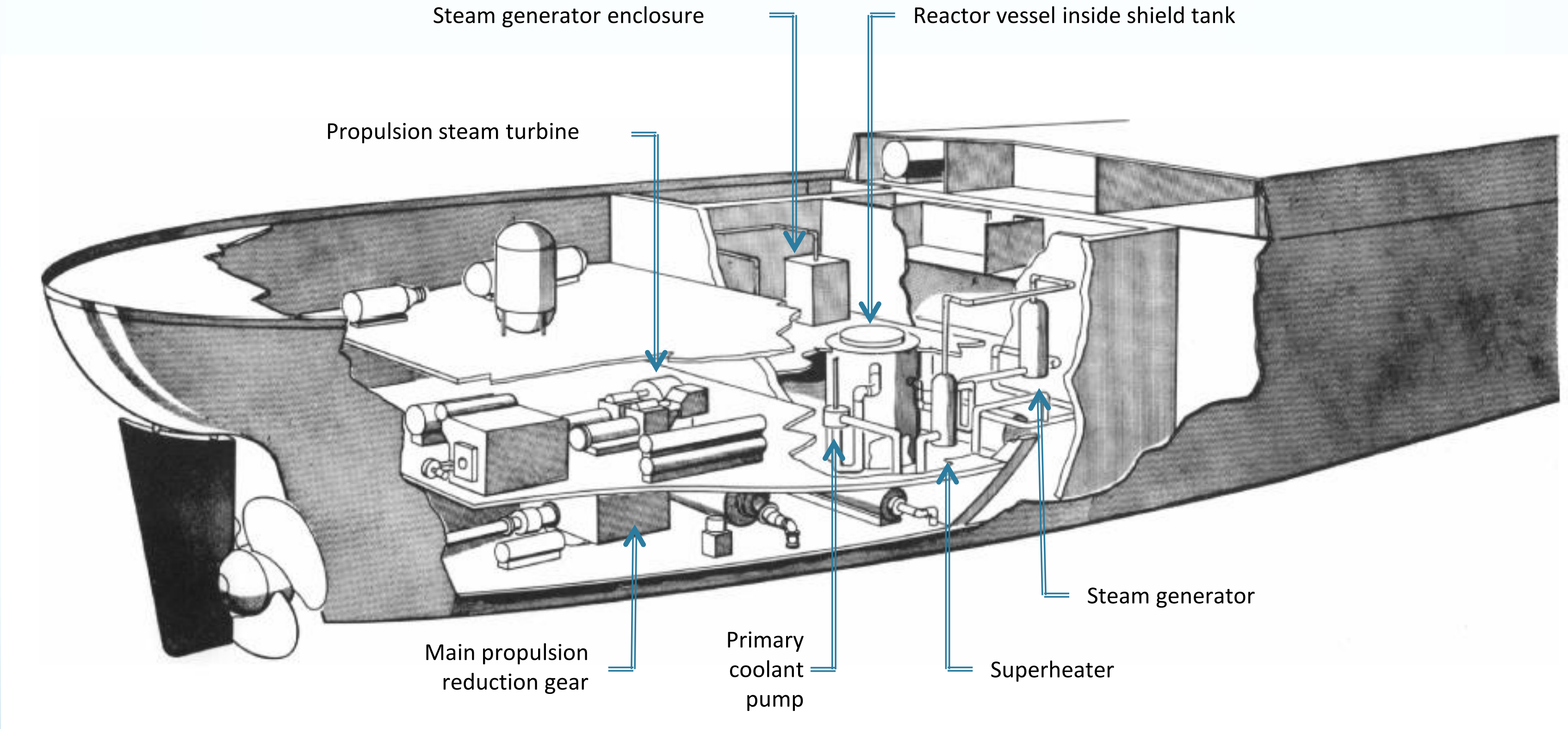


Elevation view



Source: NAA-SR-3859, "Maritime Organic Cooled and Moderated Reactor," May 1959

AI marine OMCR propulsion plant layout



Source: adapted from NAA-SR-3859, “Maritime Organic Cooled and Moderated Reactor,” May 1959

Gen4Energy marine application of G4M modular reactor

- The 70 MWt Gen4 Module (G4M, formerly Hyperion Power Generation) is a small fast-neutron reactor using lead-bismuth eutectic coolant. It is capable of delivering about 25 MWe (33,525 shp) for propulsion.
- Reactor life is 10 full-power years. In marine service, a G4M will last for the typical 25-year operational life of a commercial vessel.
- 2010 -12: British Maritime Technology and Lloyd's Register conducted a study for a Greek shipping company of the use of a G4M reactor for propulsion of a 155,000 ton ”Suezmax” tanker.
  - The study results were published in 2014.
  - The study considered the option of leasing the nuclear power plant.

Radioisotope thermoelectric generator (RTG) marine applications

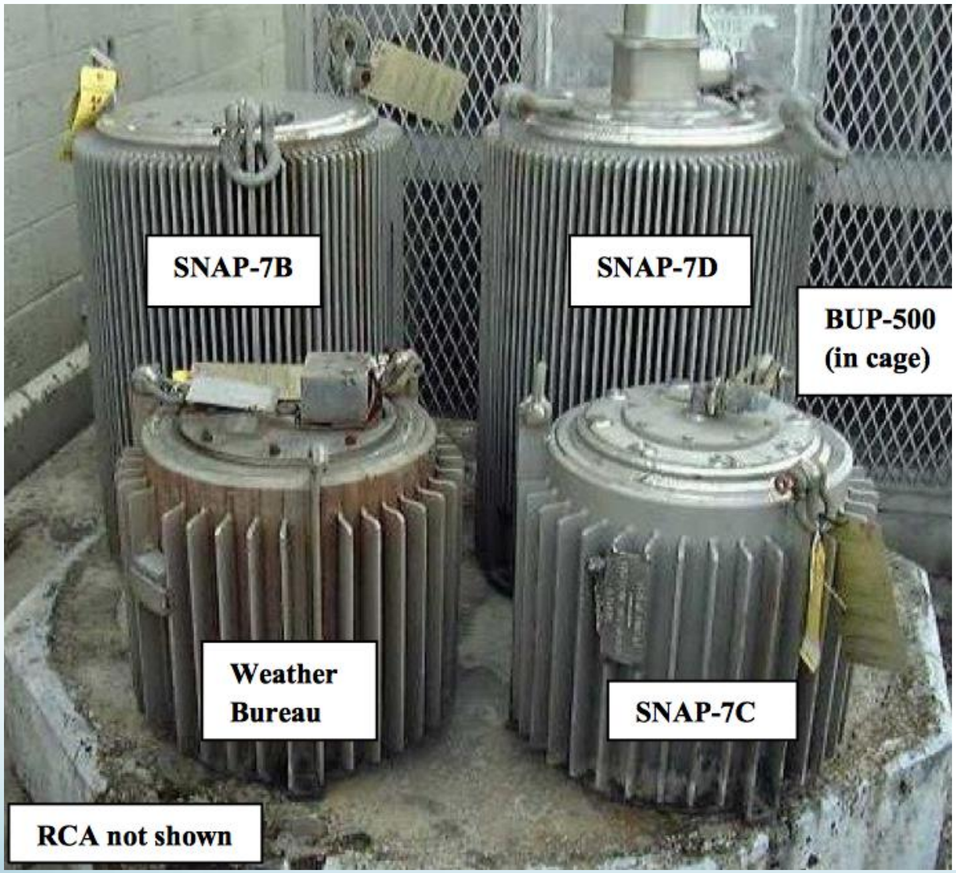
RTGs at sea

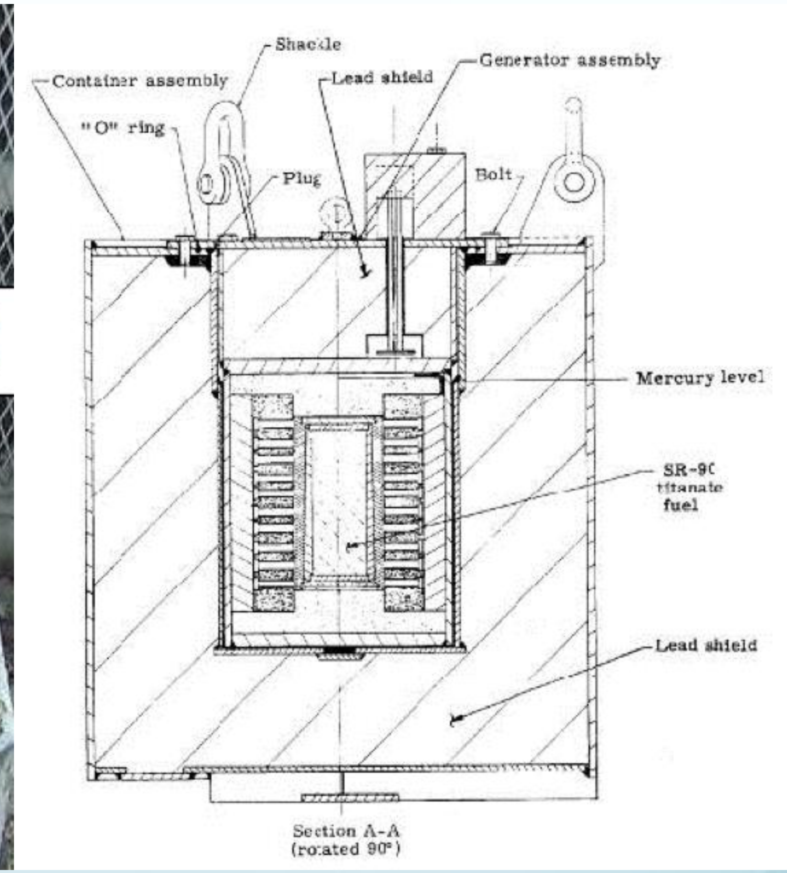
- An RTG is an electric generator with no moving parts. It uses an array of thermocouples to convert heat released from radioactive decay into electricity. The heat source can be one of several radioisotopes.
  - Sr-90 (Strontium 90)-fueled RTGs are the common type of RTG used by the US Navy and /or Coast Guard.
    - Beta (β) emission, with minor gamma (γ) emission; requires considerable biological shielding; 28.8 year half-life; power density 0.46 watts per gram
  - In the late 1970s, the US Navy tested Pu-238 (Plutonium 238)-fueled RTGs. Operational applications are not known.
    - Alpha (α) emission; does not require shielding; 87.7 year half-life; power density 0.54 watts per gram
- The US has employed RTGs in many marine and terrestrial applications where they function as "super batteries", serving in remote locations as reliable electric power sources with operating lives of 5 to 10 years or more, with no maintenance required.
- Typical marine uses of RTGs include providing power for meteorological and oceanographic sensors and data collection systems, communications systems, navigational aids, and undersea surveillance systems.
- RTGs used in marine applications are the SNAP-7, -21, & -23-series, the Sentinel-25 series, and the Minibatt-1000.

US RTGs at sea

- SNAP-7-series RTGs
  - Fuel element: Sr-90
  - Electrical power generation: 7.5 – 60 watts
  - Pressure hull rating: 10,000 psi
  - Example applications: US Coast Guard buoys & lighthouse; US Navy NOMAD (Navy Oceanographic Meteorological Automatic Device); deep water sonar transducer
- SNAP-21-series RTGs
  - Fuel element: Sr-90
  - Electric power generation: 10 watt and 20 watt versions
  - Pressure hull rating: not known
  - Example applications: powering sonars, boosting underwater cable power, navigational aids, and research instruments.
- SNAP-23-series RTGs
  - Fuel element: Sr-90
  - Electric power generation: 25 watt, 60 watt, and 100 watt versions
  - Pressure hull rating: terrestrial, 0 psi
  - Example applications: surface applications, including powering weather and navigational buoys

SNAP-7 RTG





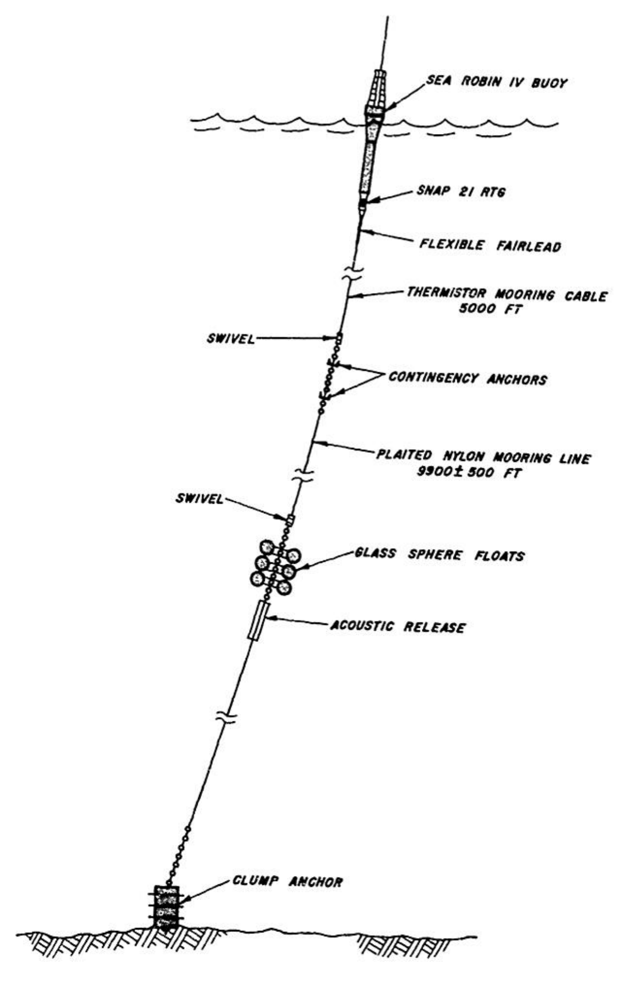
Source: Disposition of Radioisotope Thermoelectric Generators Currently Located at the Oak Ridge National Laboratory – 12232, WM2012 Conference, 2012

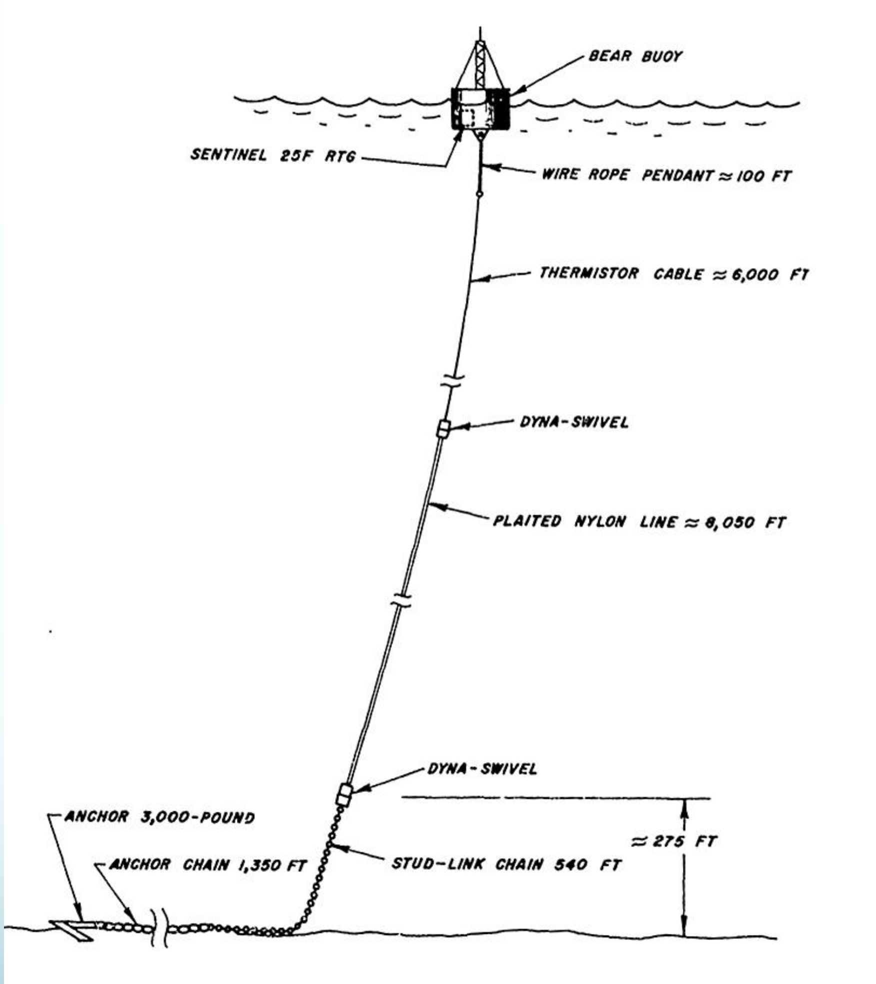
US RTGs at sea

- Sentinel-25-series RTG
  - Fuel element: Sr-90
  - Electrical power generation: 25 watts
  - Pressure hull rating: terrestrial, 0 psi (25A); 500 psi (25C3 & 25F); 1,000 psi (25D); 6,000 psi (25C1); 10,000 psi (23E)
  - Example applications:
    - Navy's Inter-Seamount Acoustic Range (ISAR) transmitter at a depth of 2,200 ft;
    - Wave Gage System in Gulf of Mexico (3 RTGs in series to provide 60 watts); drum-type data buoy system (BEAR Buoy)

- Millibatt 1000
  - Fuel element: Sr-90
  - Electrical power generation: 25 watts
  - Pressure hull rating: 10,000 psi
  - Example application:
    - Air Force Deep Ocean Transponder Systems (geodetic reference points) on the Eastern Missile Test Range.

Example RTGs installations for deep-water buoy applications





Source: Radioisotope Thermoelectric Generators of the Navy, Naval Nuclear Power Unit, Port Hueneme, 1 July 1978

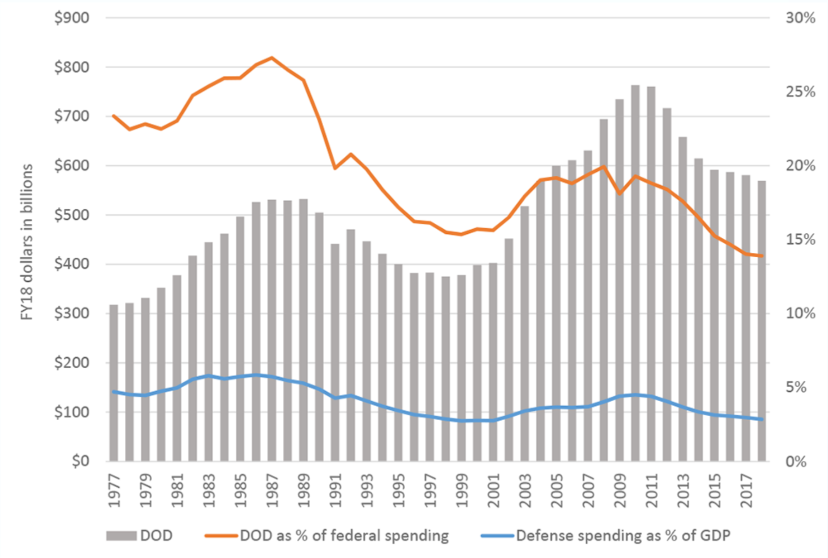
US marine nuclear power current trends

- Defense budget
- Operations
- New build
- Refurbishment / modernization
- Phase-out / replacement of aging vessels
- Submarine hull, mechanical and electrical system innovation
- New nuclear vessel development
- New marine reactor development
- New weapons system development / deployment
- Final disposition of retired naval nuclear vessels
- Long-term naval nuclear waste management
- Final disposition of retired civilian nuclear vessels
- On-going monitoring of sunken US nuclear submarine deep water sites
- Naval nuclear technical support for other nations

US current trends

- **Defense budget:**
  - **The US defense budget is stable in FY 2018 and is expected to grow.**
    - The FY 2018 DoD budget request of $581 B (plus an additional $66 B for overseas contingency operations, OCO) is greater than the defense budget at the peak of the Reagan buildup in the 1980s.
    - In following years, Secretary of Defense James Mattis and House Armed Services Committee Chairman Mac Thornberry have called for, at a minimum, a sustained 5% annual increases to the defense budget above the FY 2018 requested level.

DoD budget trends, not including OCO, in terms of FY18 dollars (grey), % of Federal budget (orange) and % of GDP (blue)



Source: Center for Strategic & Budgetary Assessments (CSBA), http://csbaonline.org/reports/defense-spending-in-historical-context

- CSBA reported: "Although total defense spending over the past 15 years has reached historic highs in absolute terms, it represents a historically low percentage of GDP……Spending a lower percentage of GDP on defense indicates that national security consumes a relatively small proportion of overall national economic activity, compared to the FY 1979 – FY 1985 defense buildup. Similarly, defense spending's relatively low share of federal spending in historical terms indicates that more money could be allocated to defense, if the political will to do so existed.
- Real budget growth may allow the Navy to increase the production rate of Virginia-class SSNs while also dealing with the budget challenges of recapitalizing both the SSBN and CVN fleets during the following decades.

US current trends

- **Operations:**
  - **The Navy will continue to operate all-nuclear fleets of aircraft carriers and submarines.**
  - **There will be a constant-size aircraft carrier (CVN) fleet.**
    - Carrier fleet is back to 11 CVNs after *USS Gerald R. Ford* joined the fleet in July 2017, but *Ford* will not be ready for operational deployment until 2019 - 2020.
  - **Carrier Strike Groups (CSGs) are facing increasing challenges that may limit their operational effectiveness.**
    - Anti-access/area denial (A2/AD) challenges
      - A2/AD challenges can be raised even by small nations armed with modern, long-range, precision-guided anti-ship cruise and ballistic missiles, quiet conventional submarines, and layered anti-aircraft defenses. The proliferation of these types of weapons systems is redefining the role of the Carrier Strike Group in international conflicts.
    - CSG logistics challenges
      - The gradual inactivation of the large, fast Supply-class T-AOEs makes each carrier strike group more dependent on a larger number of smaller, slower supply vessels for aviation fuel, naval vessel fuel (for destroyers and cruisers in the CSG), ammunition, and other provisions. This more complex supply chain adds risk to the supportability of a deployed CSG.

US current trends

- **Operations (continued):**
  - **Attack submarine (SSN) fleet size will continue to decline, but operational tempo will remain high, stressing the available submarines and crews and delaying some maintenance.**
    - Los Angeles-class SSNs are being retired faster than replacement Virginia-class SSNs are being built. For several years (1991 – 96) Los Angeles-class SSNs were built at a rate of 3 per year and now are retiring at that rate.
    - Without a significant increase in SSN production rate (currently 2 per year), the Navy will have fewer SSNs for the next 30 years than it has in 2018.
    - Naval Reactors noted in FY 2004 that the smaller SSN fleet has been operating at a higher tempo than was assumed in the design of their "life-of-the-boat" reactor cores. This situation may necessitate refueling or a shorter service life for the affected SSNs.
    - This smaller US SSN fleet is facing worldwide submarine fleets that are growing in numbers and capabilities, including new generations of Chinese and Russian nuclear submarines and very quiet and capable conventional submarines that are particularly well-suited for operations in littoral waters.
    - Ship submerged operations are not allowed with an expired maintenance OPINTERVAL or OPCYCLE. Delayed maintenance and limited availability of space in shipyards has created a bottleneck that is leaving several SSNs unable to operate.
    - Improved networked communications systems are enabling SSNs to operate more closely with surface fleets, airborne assets and unmanned systems.

US current trends

- **Operations (continued):**
  - **There will be a smaller strategic ballistic missile submarine (SSBN) fleet with fewer submarine-launched ballistic missiles (SLBMs).**
    - The current fleet has a total of 14 Ohio-class SSBNs, with at least 2 out of service for maintenance / overhaul at any time. Each SSBN is armed with 20 SLBMs, for a total of 240 launchers on 12 deployable SSBNs.
      - The first Ohio-class SSBN will reach the end of its 42 year service life in 2029, two years before the first replacement Columbia-class SSBN is delivered in 2031.
      - The last Ohio-class SSBN will reach the end of its service life in 2040, two years before the last Columbia-class SSBN is delivered in 2042.
    - The future fleet currently is planned to have a total of 12 Columbia-class SSBNs, with a maximum of 2 out of service for maintenance / overhaul at any time. Each SSBN will be armed with 16 SLBMs, for a total of 160 launchers on 10 deployable SSBNs.
    - During this fleet replacement period, the SSBN force will fall to 10 submarines for about 10 years, between 2032 and 2042, with a deployable fleet (a mix of Ohio- and Columbia-class boats) as small as 8 submarines.

US current trends

- **Operations (continued):**
  - **There will be a significant decline in the number of cruise missile launchers in the submarine fleet.**
    - There will be a significant decline in the number of submarine tactical cruise missile launchers in the fleet over the next decade. In early 2018, the submarine fleet had 1,156 vertical launch system (VLS) tubes available.
      - All 4 Ohio-class SSGNs, with a total of 616 VLS tubes, are scheduled to be retired between 2023 – 2026.
      - All 30 Los Angeles-class Flight II and 688i SSNs, with a total of 360 VLS tubes, are scheduled to be retired between 2019 – 2029.
      - Virginia-class SSNs are not entering the fleet fast enough to maintain the number of available tactical cruise missile launchers. When all 20 planned Block V, VI and VII Virginia-class SSN have entered the fleet by the early 2030s, the number of tactical cruise missile launchers in the submarine fleet will be almost restored to the level in early 2018.
    - Special operations forces (SOF) capabilities: some gains, some losses.
      - A Virginia-class SSN has better SOF capabilities than a retiring Los Angeles-class SSN, but can't match the Ohio-class SSGN capabilities to host a large SOF contingent and operate as a Small Combatant Joint Command Center.
      - SOF assignments will have greater competition from other tasking for the smaller fleet of SOF-capable, multi-purpose, Virginia-class SSNs.

US current trends

- **Operations (continued):**
  - **There have been significant improvements in the opposing nuclear fleets.**
    - Russia: New Borei-class SSBNs and Yasen-class multi-mission SSNs have been delivered to the fleet; Oscar II-class SSGNs and Akula- , Sierra- and Victor III-class SSNs are being modernized.
    - China: New Type 095 SSN & Type 096 SSBN should appear soon.
  - **There is a worldwide proliferation of very quiet, long-range, non-nuclear submarines with capable tactical systems and armaments that can challenge the performance of US nuclear submarines on some missions and threaten Carrier Strike Groups. For example:**
    - **Shortfin Barracuda-class** by French shipbuilder DCNS, which was selected by Australia as its new submarine.
    - **Scorpene-class** by French shipbuilder DCNS, which was selected by Brazil as the basis for their indigenous **S-BR-class** submarine.
    - **Dolphin 2-class** diesel-electric submarine developed from Howaldtswerke-Deutsche Werft AG (HDW) based on their Type 212 and constructed by HDW in Germany for Israel.
    - **Gotland-class** diesel-electric submarines designed and built by the Kockums shipyard in Sweden.
    - **Lada-class (Project 677)** advanced diesel-electric attack submarine designed by Russia's Rubin Design Bureau. It is an improved and quieter version of the Kilo-class (Project 636) with new combat systems and possibly air-independent propulsion.
    - **Type 039A (Yuan-class)** submarine is a Chinese diesel-electric submarine and China's first AIP powered submarine. It is believed to be one of the quietest diesel-electric submarine classes in service.
    - **Sōryū-class** submarines are Japanese AIP diesel-electric attack submarines.

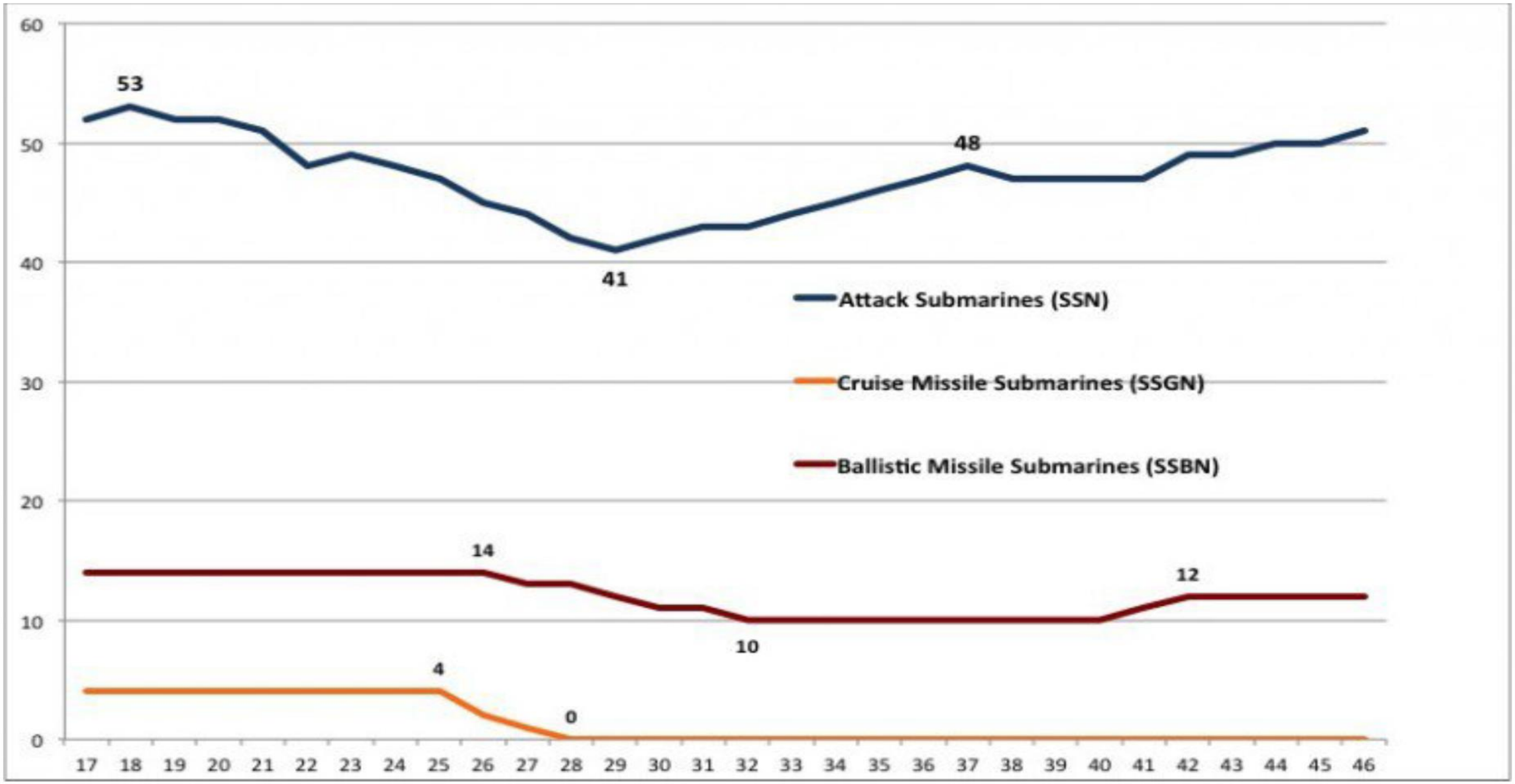
Planned production rates for US nuclear submarine

FY2017 Submarine Shipbuilding Plan for FY 2017 – 2030, modified by the FY 2018 President's Budget additions of one Virginia (VA) Block V SSN in FY 2021 and 2022.

FY	17	18	19	20	21	22	23	24	25	26	27	28	29	30	TOTAL
SSN	VA BLK IV		VA BLOCK V					VA BLOCK VI					VA BLK VII		
	2	2	2	2	2	2	2	1	2	1	1	1	1	1	22
SSBN					COLUMBIA Class BLOCK I					COLUMBIA Class Follow-on Ships					
					1			1		1	1	1	1	1	7
TOTAL	2	2	2	2	3	2	2	2	2	2	2	2	2	2	29

Source: "Report to Congress – The Submarine Industrial Base and the Ability of Producing Additional Attack Submarines Beyond the Fiscal Year 2017 Shipbuilding Plan in the 2017 – 2030 Timeframe," US Navy, Program Executive Office, Submarines, July 2017

Future US nuclear submarine fleet size estimate



Submarines in service by type and year. Source: Navy 30-Year Shipbuilding Plan for 2017

Note: SSN quantities do not include one additional Virginia-class SSN in FY21 and 22, as proposed in the FY2018 President's Budget.

US current trends

- **New build:**
  - **Virginia-class SSN new-build program continues with Blocks III to VII.**
    - 48 Virginia-class SSNs have been ordered or are planned as of early 2018.
    - Virginia-class SSNs currently are being procured at a rate of two boats per year (FY2011 – FY2023). Thereafter, the Navy's 2017 Shipbuilding Plan shows procurement rate dropping to one boat per year to compensate for the start of Columbia-class SSBN procurement.
    - In 2014, General Dynamics Electric Boat was awarded a prime contract for ten Block IV boats. The keel for the first Block IV boat was laid in July 2017.
    - Current average unit procurement cost for Block III boats is about $2.7 B. The Navy's target price for later units is $2.0 B.
    - Build time has been dropping and averages 66 months for Block III boats, and is expected to drop to 60 - 62 months for Block IV boats.
    - The Navy has agreed the design of the Block V boats, and long-lead item procurement has started. The design of Blocks VI and VII boats is expected to be similar to Block V.
  - **Ford-class CVN new-build program continues with the second ship.**
    - The lead ship, *USS Gerald R. Ford*, was delivered to the Navy in July 2017 at a cost of about $12.9 B.
    - In 2015, Huntington Ingalls Industries received a $3.35 billion prime contract for the detailed design and initial construction of the *USS John F. Kennedy* (CVN-79).
    - CVN new-build rate is expected to be one ship every three to four years.

US current trends

- **New build (continued):**
  - **Columbia-class SSBN new-build program will be starting.**
    - The 12 Columbia-class SSBNs will be procured over a period of 14 years from FY2021 thru FY2035.
    - In May 2016, Electric Boat was selected as the prime contractor for the Columbia-class SSBNs and will perform about 80% of the construction work.
    - Construction of the 1st boat is expected to start in 2021, with first delivery to the Navy in 2027 and first operational patrol in 2031.
    - Average unit procurement cost for boats 2 – 12 is expected to be $6.5 B in constant FY2017 dollars.
    - Total program cost is expected to be about $100.2 B in constant FY2017 dollars.
  - **A 355 vessel fleet should require additional nuclear-powered vessels.**
    - The current authorized US fleet size limit is 308 vessel. The Heritage Foundation's *2017 Index of US Military Strength* reported that the Navy's actual fleet size in early 2017 was 274 vessels.
    - In early 2017 the Navy announced plans to increase the fleet to 355 vessels over an undetermined period of time.
    - The US nuclear vessel industrial base may have limited ability to increase its new vessel construction capacity any time soon given the demands already in place for replacing whole fleets of aging US nuclear vessels, namely: all remaining Los Angeles-class SSNs, all Nimitz-class CVNs, and all Ohio-class SSBNs and SSGNs. The Navy will have to make greater use of private shipyards and rebuild the industrial base infrastructure and skilled labor base.

US current trends

- **Refurbishment / modernization:**
  - **The number of missile tubes on Ohio-class SSBNs is being reduced.**
    - To comply with New START, four missile tubes have been deactivated on each of the 14 Ohio-class SSBN. Starting in 2015, the work was completed by 5 February 2018. This removed 56 strategic launchers from the US inventory.
  - **Aging electronic systems are being modernized to ensure supportability.**
    - Certain aging electronic systems are not sustainable and are being replaced. Examples of two modernized systems are the Submarine Warfare Federated Tactical Systems (SWFTS) intended for all submarines, and the Consolidated Afloat Networks and Enterprise Services (CANES), intended for all classes of Navy ships.
  - **Capabilities to operate with Unmanned Underwater Vehicle (UUV) and Unmanned Aerial System (UAS) are being significantly expanded.**
    - The Navy sees UUVs and UASs as cost-effective force multipliers that can help extend the reach of its submarine fleet, and in some cases, to allow the sub to conduct other missions while the drone has its own assignment.
      - Operational use of a "free-flying" UUV during a military operation first occurred in July 2015.
      - The Navy is developing a Universal Launch and Recovery Module (ULRM) as a readily deployable, standard interface module for submarines to handle UUVs.
    - Armed UUVs and UASs will add a new dimension to submarine warfare. For example, an armed UAS could give a submarine the ability to engage and defeat an aerial threat (i.e., an ASW helicopter or patrol aircraft).

US current trends

- **Submarine hull, mechanical and electrical system innovation:**
  - **Advanced propulsors are being developed**
    - Advanced Material Propeller (AMP)
      - AMP will demonstrate the potential capability gains from a composite submarine propeller. This is a collaborative project with the Australian Navy.
    - Hybrid Multi-Material Rotor (HMMR) for pump-jets
      - When *USS South Dakota* (SSN-790) is commissioned in 2019, it will be the first submarine equipped with the new HMMR, which is intended to reduce the cost and weight of the pump-jet rotor as well as improve overall acoustic performance.
    - Shaftless propulsion
      - The goal is to develop submarine alternative propulsion and stern configurations, including a variety of shaftless drives such as podded electric motors outside the pressure hull and a class of motors known as “rim-drives” where the motor is integral with the propulsor. A shaftless drive prototype is being tested.
  - **Hydraulics will be reduced through electrification**
    - The goal is to replace complex hydraulic systems with distributed electrical actuators, including control surface electric actuation:
      - Retractable Bow Planes (RBP) Electric Actuation System (EAS).
      - Direct drive electric motors for stern X-plane control surface actuation.
      - The goal is to reduce submarine total life cycle cost.
  - **Advanced secondary propulsion system controls are being developed**
    - Reflects the greater use of electrical actuators and opportunities for automation.

US current trends

- **Phase-out / replacement of aging vessels:**
  - **Most Los Angeles-class SSNs are being retired at the end of their 33-year service life and are being replaced on a less than 1-for-1 basis by Virginia-class SSNs:**
    - The last 2 Flight I boats are scheduled for decommissioning in 2018.
    - All 8 Flight II boats are scheduled for decommissioning from 2019 – 2022.
    - All 22 688i boats are scheduled for decommissioning from 2021 – 2029.
    - The Navy is considering extending the service life of Los Angeles-class Flight II and 688i SSNs to 36 – 37 years to help mitigate the impending fleet shortfall in SSNs.
  - **The 10 Nimitz-class CVNs are scheduled to be retired at the end of their 50-year service life and will be replaced on a 1-for-1 basis by Ford-class CVNs.**
    - The lead ship, *USS Nimitz,* is scheduled for retirement in 2025.
    - The last ship in the class, *USS George H. W. Bush*, will reach its retirement age 34 years later, in 2059.
    - Operational problems with several new systems of the *USS Gerald R. Ford* (CVN-78) are increasing the risk that the new Ford-class CVNs will not be operationally ready and able to replace Nimitz-class CVNs on time.

US current trends

- **Phase-out / replacement of aging vessels (continued):**
  - **The 4 Ohio-class SSGNs are scheduled to be retired at the end of their 42 year service life**.
    - These SSGNs are the oldest Ohio-class hulls.
    - They are scheduled for decommissioning at a rate of about one per year from 2023 - 2026.
    - Their SSGN function will be partially replaced by a Virginia-class Block V, VI and VII multi-purpose SSNs, each of which will carry far fewer cruise missiles than an Ohio-class SSGN and lack certain SOF capabilities.
  - **The 14 Ohio-class SSBNs are scheduled to be retired at the end of their 42 year service life.**
    - The first Ohio SSBN will reach its retirement age in 2029.
    - These SSBNs are scheduled to be decommissioned at a rate of about one per year, with the last being decommissioned in 2040.
    - They will be replaced by 12 Columbia-class SSBNs. Any significant delays in the Columbia-class construction schedule will place the size of the active SSBN fleet at risk as the Ohio-class SSBNs are retired.
    - Extending the service life of Ohio-class SSBNs beyond 42 years does not appear to be an option for the Navy.

US current trends

- **New nuclear vessel development:**
  - **Columbia-class SSBN program is moving toward initial procurement in 2021.**
    - In the 2013 budget, DoD delayed the start of lead ship construction by two years (from FY 2019 to FY 2021), creating a tight schedule for replacing the aging Ohio-class SSBNs at the end of their service life.
    - The US is collaborating with the UK to co-develop elements that are common with their new Dreadnought-class SSBN program.
  - **SSN(X) / Improved Virginia program has been initiated but initial procurement has been delayed.**
    - Procurement of the first submarine has been pushed back to 2033/2034.
    - SSN(X) program delays may result in additional procurement of late-model Virginia-class SSNs.
    - There is no indication that SSN(X) would use a low-enriched uranium (LEU) core.

US current trends

- **New marine reactor development:**
  - **A new core has been developed for the S8G land-based prototype.**
    - The replacement core to be installed during the 2018 – 2021 refueling and major overhaul of the S8G prototype, will incorporate new cladding and fuel system technology for the S1B reactor for the Columbia-class SSBNs.
    - The S1B will be a life-of-the-ship (42+ years) core, which would be impossible with the current cladding in fleet reactors. Alternate clad and manufacturing processes have been developed to enable longer core life. Testing in the S8G core will enable the new design and manufacturing processes to be validated prior to full-scale production and procurement of S1B cores.
  - **S1B reactor plant development was fully funded starting in FY2015.**
    - This reactor for the Columbia-class SSBN will be the longest-lived naval reactor core ever developed: 42+ years without refueling.
    - Research, development, and design began in FY 2010. This new design will leverage Virginia-class S9G reactor technology, as well as manufacturing development and demonstration efforts to be performed as part of the S8G land-based prototype refueling program.
    - In the 2013 budget, DoD delayed the start of construction for the lead ship by two years (from FY 2019 to FY 2021) and reactor plant advanced procurement from FY 2017 to FY 2019.

US current trends

- **New marine reactor development (continued):**
  - **Transformational Technology Core (TTC) development was stopped in FY2007.**
    - Originally intended as a high-performance, 97% enriched, forward-fit reactor plant for Virginia-class SSNs, with 30% more energy than current S9G cores.
    - The project was stopped at completion of fuel system design.
  - **Next Generation Reactor (aka NGR-93) should be entering the fleet.**
    - This is expected to be a lower-cost, 93% enriched forward-fit reactor plant for Virginia-class SSNs.
    - The schedule for inserting this core into Virginia-class SSN new construction boats is not known.
  - **Development of an A1B core using lower enriched uranium (likely 93%) should be in progress.**
    - Intended for "CVN21 follow ships" (i.e., Ford-class CVN units 2 and beyond).
    - NR initiated this work in FY 2004. Current status is not known.
  - **Development of LEU fuel for naval reactors does not appear to be progressing.**
    - A program to investigate, develop and possibly validate low-enriched uranium (LEU) fuel in naval reactors was proposed by NR in 2014.
    - There has been no action to allocate funds for this effort.

US current trends

- **New weapons system development / deployment:**
  - **Trident II (D5) SLBM life extension missiles are being deployed.**
    - The life-extended Trident II D5 missile (D5LE) initial operating capability (IOC) was in March 2017.
    - The Trident II D5LE is expected to remain in service until 2042.
    - The draft Nuclear Posture Review (NPR) 2018 indicated that the Navy will begin studies in 2020 on an SLBM that will replace the Trident II D5LE and be deployed on the new Columbia-class SSBN.
  - **A naval Conventional Prompt Global Strike (CPGS) capability is being developed.**
    - This is a system than is intended to deliver a precision conventional warhead to strike any point in the world within 1 hour of launch.
    - The Navy is developing CPGS technology into a deployable package. The likely delivery platform will be an Ohio-class SSGN or a Virginia Block V – VII SSN.
      - Navy Strategic Systems Program (SSP) Director Vice Adm. Terry Benedict said on 2 November 2017 that: “I’m very proud to report that at 0300 on Monday night (30 October) SSP flew from Hawaii (Pacific Missile Range Facility)…the first conventional prompt strike missile for the United States Navy in the form factor that…could eventually be utilized...in an Ohio-class tube...that could one day be fielded from guided-missile submarines.”

US current trends

- **New weapons system development / deployment (continued):**
  - **Modernized and next-generation submarine-launched cruise missiles are being developed.**
    - The UGM-84A Harpoon submarine-launched, anti-ship cruise missile has been in service since 1977. The newest Block II UGM-84L entered service in 2017.
    - The Next Generation Land Attack Weapon (NGLAW) with anti-ship capabilities is expected to be the Harpoon replacement. It is being developed for a 2030 IOC.
    - The UGM-109E Block IV Tomahawk land-attack cruise missile mid-life recertification is scheduled to start in FY 2019. This program will modernize the missiles, increase their service-life and keep them operational into the 2040s.
    - A UGM-109 Maritime Strike Tomahawk is being developed as a long-range anti-ship missile with an expected FY2022 IOC. The prior anti-ship Tomahawk, UGM-109B, was retired in the 1990s.
    - Development of a new Nuclear Strike Tomahawk was recommended in the 2018 Nuclear Policy Review (NPR). The prior nuclear strike Tomahawk, UGM-109A, was retired in the 1990s. All W80-0 nuclear warheads were dismantled by FY 2012. Development of a new nuclear strike cruise missile and warhead could take much longer than a decade.
    - During the past two decades, the Navy has fallen behind the “power curve” of naval cruise missile development and deployment. While the several new cruise missile versions listed above belatedly are under development, they lack the high-performance of several more powerful cruise missile counterparts being developed and deployed by other nations; for example: Russia’s 3M55 Oniks and 3M54 Kalibr / Club supersonic anti-ship cruise missiles and the 3M22 Tsirkon hypersonic missile.

US current trends

- **New weapons system development / deployment (continued):**
  - **Armed unmanned underwater vehicles (UUVs) and unmanned aerial systems (UASs) are being developed and tested.**
    - Several vehicles are being developed and tested. However, none are known to have been operationally deployed (other than the Mk-67 submarine launched mobile mine that has been in service since the 1980s).
  - **The Navy is not developing new submarine-launched mines.**
    - The aging Mark 67 Submarine Launched Mobile Mine (SLMM) is the only submarine-launched mine currently in service and usable for sea control missions in littoral waters.
    - Development and procurement of the Mark 76 Improved Submarine Launched Mobile Mine (iSLMM) has not been funded.
  - **CVNs will be receiving new types of aircraft that have the potential to revolutionize carrier aviation.**
    - Stealth fighters: The Navy version of the Joint Strike Fighter, the F-35C, has an expected IOC of 2021.
    - Unmanned air vehicles for various combat and support roles: The first that is likely to lead to a procurement is the Navy competition for the MQ-25 Stingray unmanned tanker aircraft, which may be decided in 2018.

US current trends

- **New weapons system development / deployment (continued):**
  - **Various energy weapons are being developed for future deployment on surface ships, including the Ford-class aircraft carriers.**
    - Examples of such weapons include include high-energy lasers and electromagnetic rail guns shooting hyper-velocity projectiles.
      - The Navy has requested funds in the FY 2019 budget for procurement and operational demonstration within about two years of the High Energy Laser and Integrated Optical-dazzler with Surveillance (HELIOS), which will be integrated with the Aegis Combat System.
      - Deployment of a naval rail gun appears to be delayed. However, use of hyper-velocity projectiles on conventional naval guns also is being developed.
    - Ford-class carriers have an electric power generating capacity of about 104 MWe; significantly more than the generating capacity of Nimitz-class CVNs.

US current trends

- **Final disposition of retired naval nuclear vessels:**
  - The existing NSSRP program will continue managing the recycling of retired nuclear vessels at the Puget Sound Naval Shipyard (PSNY), including the on-going recycling of all retired nuclear submarines.
  - The scale of work associated with recycling retired nuclear aircraft carriers will introduce new challenges and will require new infrastructure.
    - The 1st nuclear-powered aircraft carrier, *USS Enterprise*, was decommissioned in 2017. The Navy is seeking an alternative to PSNY because the magnitude of work on *USS Enterprise* could interfere with the existing schedule for submarine recycling at PSNY.
    - The next CVN to be retired will be *USS Nimitz*, which will reach its 50-year design operating life in 2025. *USS Dwight D. Eisenhower* reaches that milestone in 2027. Then there is a 5-year break before the next CVN, *USS Carl Vinson*, is ready for retirement.
- **Long-term naval nuclear waste management:**
  - A "Spent Fuel Handling Recapitalization" project is underway to modernize the 50-year old Expended Core Facility (ECF) at the Naval Reactors Facility (NRF) in Idaho.
    - New shipping casks needed + updates to the ECF are needed to handle the longer fuel elements from aircraft carriers.
  - As per agreement with the state of Idaho, all spent nuclear fuel must be in dry storage by 2023 and removed from Idaho by 2035.
    - NR is developing a plan for longer-term safe management of naval spent fuel and nuclear waste.

US current trends

- **Final disposition of retired civilian nuclear vessels:**
  - *Sturgis* floating nuclear power plant was defueled in 1977. Decommissioning in Galveston, TX is expected to be completed in 2018, after which the remaining vessel will be scrapped.
  - *NS Savannah was* defueled in 1975. The ship has been in a state of dockside "maintained storage" in Baltimore, MD with some minor decommissioning and cleanup work in progress under Maritime Administration funding. Full funding for final nuclear cleanup and decommissioning was included in the federal omnibus spending bill signed into law in March 2018. Decommissioning and final nuclear license termination are expected to be completed by 2031. The final fate of the ship has not been determined, but one option is to serve as a museum ship.
  - Nuclear waste from decommissioning processes is managed by contractors licensed by the US Nuclear Regulatory Commission.
- **On-going infrequent monitoring of two sunken US nuclear submarine deep-water sites:**
  - *USS Thresher* (SSN-593), sank off Cape Cod, at a depth of 2,560 m (8,400 ft.).
  - *USS Scorpion* (SSN-589), sank in the mid-Atlantic, at a depth of 3,000 m (9,800 ft.).
  - Currently there is no indication of significant radioactive contamination of the ocean environment.

US current trends

- **Naval nuclear technical support to other nations:**
  - **The US collaborates with the UK on SSBN, SLBMs and naval reactors:**
    - The US and UK are collaborating on the development of common elements of the Columbia-class SSBN program and the UK's new Dreadnought SSBN program (Vanguard SSBN replacement, formerly Successor-class).
    - The new Dreadnought SSBN will be armed with US Trident D5LE SLBMs, which are leased from the US under the March 1982 Trident Sales Agreement.
    - The new Rolls-Royce PWR3 nuclear reactor for the Dreadnought SSBN will be 'based on a modern US plant' and US support will be provided. Candidates include a version of the S9G reactor used on Virginia-class subs or the new S1B reactor being developed for the Columbia-class SSBNs.
  - **The US does not provide naval nuclear technical support to any other nation.**