Maritime Nuclear Applications

> Alexander DeVolpi, PhD

> Based on my two recent books:

- *Cold War Brinkmanship: Nuclear Arms, Civil Rights, Government Secrecy*
- *Nuclear Brinkmanship: Challenges for the Trump Presidency*

> Some variance in data due to different sources

Relevant Experience

> Military/Navy: NROTC in college (1950 – 1953)
> Active Duty: (LST in naval amphibious forces nearly 3 yrs -- part Korean War, Cuba, Atlantic fleet; Mediterranean)
> Navy Reserves: 20 years; Naval Research Lab/Naval Radiological Defemse Lab; retired as LCDR-USNR; no nuclear ships.

> Nuclear/Professional: Virginia Tech: MS/PhD; International School Nuclear Science and Engineering/Argonne National Lab

> Publications/Books: latest *Nuclear Brinkmanship: Challenges for the Trump Presidency* (2018). While preparing books, learned more about marine nuclear applications.

Argonne: Nuclear Reactors

> Argonne's first critical reactor: CP-1 (at University of Chicago) and later Nautilus PWR design.

> My assignments: 40 years **nuclear physics**/engineering; critical facilities; small reactors (nothing to do with marine reactors)

> R&D: research, test, and prototype reactors; arms control and treaty verification: Visited reactors around the world, including Former Soviet Union.

Current International Nuclear Context

> Increased consideration of **greenhouse gas emissions from fossil fuels** on land and sea: **renewed attention to nuclear-powered surface ships**.

> **Nuclear-powered submarines and warships** have earned major worldwide role.

> Merchant shipping total capacity of 410 GWt (corresponds to about **1/3 of world nuclear-power plant capacity)**.

> Ship propulsion: **frequency of refueling** a major consideration

> **Maritime nuclear power promising for:** Large bulk carriers, cruise liners, nuclear tugs to take conventional ships across oceans, and bulk shipping (where speed is important); seems to have **better prospects than civilian nuclear power**.

World Status of Reactors: Perspective

> **450 Electrical Power Reactors worldwide** (According to World Nuclear Association) provide **11% of the world's electricity** and **second largest source of low-carbon power** (>30% in 2015)

> 50 countries utilize 225 **research reactors** (some of which produce industrial and medical isotopes) (medical treatment involving radioisotopes has kept me going).

> **US**: ~100 nuclear reactors producing **electrical power**.

> **nuclear-electric power** **cheaper** than fossil fuels coal and gas
(with current exception of natural gas in the United States)

> **U.S. market approach**: not compensating for **substantial public benefits** of nuclear power**:**
(much lower air and water pollutant discharges, negligible carbon emissions, stable electricity supply, economic stability, high peak-demand capacity)

U.S. Navy Nuclear-Ship Propulsion

> 86 submarines and aircraft carriers powered by

> 100 U.S. shipboard nuclear reactors

- producing onboard electricity, heat, fresh water, and propulsion

> America's nuclear navy one of oldest and largest nuclear organizations in the world: Has **best safety record of any industry**

> NRC performs **classified reviews** on new U.S. Navy submarine and aircraft-carrier reactor plants; provides advice to the Navy on the designs.

Nuclear Power Particularly Suitable for Ships

> Especially submarines, which need to be at sea for long periods without refueling

> Work on nuclear marine propulsion started in the 1940s

- First test reactor started up in 1953
- Basic reactor plant design used in first nuclear-powered sub USS *Nautilus* developed together with Westinghouse
- Now accumulated more than 12,000 reactor years of maritime operation

> Over 140 vessels now worldwide powered by more than 180 small nuclear reactors.

- Most are subs, but they range from icebreakers to aircraft carriers.

> Currently in military service around the world are 20 aircraft carriers

- **12 of which are nuclear powered**.
- One is French and the others are American.

Nuclear: Crucial Advantages in Submarines

> Consumes no air

> Zero-emissions

- **Ensures near invulnerability**

> History: Criticality physics experiments supporting design performed at Argonne

- first actual prototype (for the *Nautilus*) constructed and tested in Idaho
- *Nautilus* put to sea in 1955: capable of sustaining 20-25 knots submerged for weeks on end

Nuclear-Powered Warships

> *USS Enterprise* (**aircraft carrier**) suffered fire onboard in 1969

- but returned to service and not decommissioned until 2017.

> By **1962** the U.S. Navy had 26 nuclear **submarines** operational and 30 under construction

> U.S. nuclear technology was shared with Britain

- French, Soviet and Chinese developments separate

> **Safety record** of the U.S. nuclear navy is excellent (two subs, *Scorpion* and *Thresher* lost at sea)

USSR/Russia Nuclear-Powered Vessels

> Built between 1950 and 2003: **248 nuclear submarines**
  - and **5 naval surface vessels (plus 9 icebreakers)**.
> Powered by **468 reactors**/operating about 60 nuclear naval vessels.
> Near the end of the Cold War over 100 Russian submarines.
> Russian Navy logged over 6000 nautical reactor-years
  - 8 strategic submarines,13 nuclear-powered attack submarines
  - plans to build 8 new nuclear ballistic-missile submarines.
> Early **Soviet** endeavors resulted in **some serious accidents**:
  (K-19 submarine 1961 reactor cooling failure had at least 8 deaths from acute radiation).

Other Navies

> **China** has about 12 nuclear-powered submarines

> **France** has a nuclear-powered aircraft carrier and ten nuclear submarines

> **UK** has 12 submarines, all nuclear powered.

> **India** launched its first nuclear submarine in 200; has built or acquired more than a dozen more.

> **By 1990 more nuclear reactors powering ships (mostly military) than generating electric power in commercial power plants worldwide.**

Nuclear-Powered Submarines

> Nuclear power allowed submarines to become **true submersibles**: Unlike conventional counterparts, limited only by crew endurance and supplies

> Work on nuclear marine propulsion started in the 1940s, the first test reactor started up in 1953.

> Basic reactor plant design used in the **USS *Nautilus***: the **first nuclear-powered submarine**, developed together with Westinghouse.

> Nuclear power has crucial advantage in submarine propulsion because its zero-emission process **consumes no air**.

Nuclear-Powered Military Surface Ships

> Admiral Rickover reduced size of nuclear reactor to fit onboard a ship or submarine, and encased it so radiation hazards would not be a safety concern.

> Now in US Navy **all subs and aircraft carriers nuclear-powered**. Several cruisers were nuclear-powered but since retired.

> **US Navy has most nuclear-powered aircraft carriers**: 11 in service.

> France's aircraft carrier, the *Charles de Gaulle*, is nuclear-powered (2 PWRs)

- used against Isis in Syria.

> United Kingdom rejected nuclear power for aircraft carriers on cost grounds.

- Planned Indian and the Chinese carriers feature nuclear propulsion.

> 20 aircraft carriers in service today **(12 nuclear powered)**.

- Seven carriers not nuclear powered: Great Britain; India; China; Italy; Brazil; Russia.

Seagoing Reactors

> Nuclear particularly suitable for ships, especially submarines at sea for long periods without refueling.
> Worldwide, more than **140 ocean vessels now powered by 180 small nuclear reactors**. Most nuclear-powered marine vessels are subs, the rest range from icebreakers to aircraft carriers.
> Lloyd's Register: **about 200 nuclear reactors at sea now** (including barges), some 700 built since the 1950s. Over 12,000 reactor years nuclear marine operation accumulated.
> Russian icebreakers increased Arctic navigation from 2 to 10 months/yr, and in the Western Arctic, to year-round.
> Russian icebreaker Lenin commissioned in 1959; world's first nuclear-powered surface vessel; remained in service for 30 years.
> Nuclear power **revolutionized the submarine**: true "underwater" vessel, rather than a "submersible" craft, which could only stay underwater for limited periods.

Icebreakers

> With global warming, Arctic Ocean now much more navigable

> Increasing role of icebreakers to enable year-round ship transit of merchant (and cruise) ships.

> Nuclear propulsion technically and economically essential in the Russian Arctic

- Operating conditions beyond the capability of conventional icebreakers

> **Russian nuclear fleet: 6 icebreakers and a freighter**

U.S. Nuclear Navy

> Nuclear-driven sub ***SSN Nautilus*** led to development of aircraft carrier ***Enterprise*** with eight reactor units, in service 1961 through 2012.
> Cruiser ***Long Beach***, powered by two reactors followed in 1961.
> By 1962, 26 nuclear subs operational, 30 under construction. Safety record topnotch: due to standardization, maintenance, training.
> 219 nuclear-powered vessels to mid-2010; **U.S. has most nuclear-powered aircraft carriers and subs, able to remain on station during any crisis throughout the world.**
> Both U.S and Russia have had nuclear-powered cruisers (USA: 9; Russia: 4).

- ***SSN Seawolf*-**class nuclear-attack sub in commission since 1997.
- U.S. Navy over 6200 reactor-years accident-free experience: 526 reactor cores.
- **2017**: **81 U.S. nuclear-powered vessels** (11 aircraft carriers, 70 subs) with 92 reactors; 10 ***Nimitz*-class** carriers, each 50-year service life.

Submarines: Other Nations

> **Total subs in world today:** **about 120.**

> **India** launched its first nuclear sub in 2009, a second and slightly larger sub due to be launched in 2018 and commissioned by 2022.

> **UK and France** less than 20 each.

> **China** has about 12 nuclear-powered subs and was building 21 more.
- first nuclear powered sub was decommissioned in 2013 after almost 40 years of service.

> **France** has 10 nuclear subs; UK has 12.

> Because of endurance, invisibility and survivability, nuclear-powered sub particularly **secure and stabilizing** from a strategic viewpoint.

Nuclear Navy: Safety and Lifetime Record

> **Excellent Safety**, attributed to a high level of standardization, maintenance, and training

and:

> Marine-propulsion reactors have **long core lives**

- refueling needed only after 10 or more years.

> New reactor cores

- designed to last **50 years in carriers**
- **30-40 years in most subs** (logging over 1 million miles)

.

Lloyd's Register: Nuclear Reactors at Sea

> Altogether **700 maritime reactors built since the 1950s**.
- more than 12,000 reactor years nuclear maritime operation accumulated.
- total **today at sea: about 120 reactors** (81 for US Navy).

> Altogether between 1950 and 2003: 248 nuclear subs and five naval surface vessels (plus nine icebreakers) [powered by 468 reactors].

> **Russian Navy** logged over 6500 reactor-years to 2015
- 8 strategic subs in operation,13 nuclear-powered attack subs, plus some diesel subs.

> **UK**: 12 subs, all nuclear powered

> **China:** about 12 nuclear-powered subs, building 21 more; its first nuclear-powered sub decommissioned 2013 after almost 40 years of service.

>**France**: nuclear-powered aircraft carrier and 10 nuclear subs

Civil Vessels: Arctic Operation

> Nuclear-ship propulsion proven technically and economically essential in Russian Arctic.

- operating conditions beyond the capability of conventional (diesel) icebreakers.
- **six Russian nuclear icebreakers and a nuclear freighter**: increased Arctic navigation from 2 to 10 months per year, in Western Arctic, to year-round.

> Icebreaker *Lenin* world's first nuclear-powered surface vessel.

- commissioned in 1959; remained in service for 30 years to 1989;
- led to a series of larger icebreakers, six launched from 1975.

> 7th and largest *Arktika* class icebreaker entered service 2007;

- designed to break through ice up to 2.8 meters thick.

> new *Arktika* launched June 2016.

Floating Power Plants

> Marine reactor supplied power (1.5 MWe) to **US Antarctic base** for ten years until 1972, testing feasibility of air-portable units for remote locations.

> Between 1967 and 1976 ex-Army US Liberty ship functioned as floating nuclear power plant moored at **Panama Canal** Zone. Provided power for nine years.

> **Russia** has under construction at St. Petersburg the first in a series of floating power plants for their northern and far eastern territories.

> **China** General Nuclear Power Group announced in January 2016 development of its floating-reactor design.

About Russian Floating Nuclear Power Plants

> Floating reactor *Akademik Lomonosov* expected online **2019** when nearby land-based nuclear power plant shuts down.

> Floating nuclear-power stations self-contained for heat and power.

- Towed to destination ports of cities experiencing deficit of power.
- Rosatom plans to manufacture at least seven vessels.

> Floating nuclear-power station not self-propelled (length 144 metres; crew 69).

- Each vessel has **2 modified naval-propulsion reactors** up to 70 MW electricity or 300 MW heat, or cogeneration, enough for a city of 200,000.
- Could be a desalination plant.
- Floating power stations refueled every three years, saving 200,000 metric tons of coal and 100,000 tons of fuel oil a year. Every 12 years entire plant towed home, overhauled.

> Floating nuclear-power stations planned mainly in the Russian Arctic.

- 5 for offshore oil- and gas-field development with 40-yr lifespan.

Civilian Ships (besides Icebreakers)

> US-built *Savannah* commissioned 1962, decommissioned 8 years later: technical success, but not economically viable.
> German-built *Otto Hahn* cargo ship and research facility sailed 650,000 miles on 126 voyages over 10 years no technical problems. Proved too expensive to operate; converted to diesel in 1982.
> Japanese *Mutsu*, put into service in 1970, third civil nuclear vessel dogged by technical and political problems.
> In 1988 the Soviet *Sevmorput* built to serve northern Siberian ports.
Overhauled and returned to service in 2015.

- **Russian nuclear-powered Arctic ship experience = over 365 reactor-years.**
- **4 Russian merchant cargo ships built with nuclear marine propulsion still operating.**
- **Russian nuclear-powered vessels now being mass produced.**

U.S. Nuclear Naval Ships and Submarines

> **By 1962** U.S. Navy had 26 operational **nuclear submarines** and 30 under construction.
  - Nuclear power revolutionized U.S. Navy which shared its technology with the UK, while French, Soviet, Indian, and Chinese development proceeded separately.

> U.S. Navy operated an unarmed nuclear-powered submarine: NR-1 Deep Submergence Craft, **between 1969 and 2008**. Not a combat vessel but **smallest nuclear- powered submarine** at 400 tons.

> **Aircraft carriers**: U.S. (and France) nuclear-powered aircraft carriers.
  - *USS Enterprise*, in service 1962–2012, powered by 8 reactor units
  - (only aircraft carrier built with more than two nuclear reactors).
  - French carrier is *Charles de Gaulle*, commissioned in 2001.

> **All U.S. aircraft carriers are nuclear powered:**
  - 10 *Nimitz-class* and 1 Ford-class in service).

> Nuclear-powered **cruisers** of U.S. Navy (decommissioned).

The *SAVANNAH*: What's Next?

> Federal funds needed to decommission **America's only commercial nuclear-powered vessel**, the NS *SAVANNAH*

- *SAVANNAH* conceived at the end of the 1950's as first commercial nuclear-powered ship. During 1950's Congress pushed for either a nuclear powered bulk freighter (carrying oil, ore or coal) or a nuclear powered icebreaker.

> In operation during the first several years of its life, *SAVANNAH* did its job admirably. The ship then ran for a number of years without passengers.

- **In 1970, *SAVANNAH* taken out of service, reactor defueled in 1971.**
- *SAVANNAH* power plant availability well over 90%. Suffered two significant mechanical failures during its decade of operation.

> Based on experience with *SAVANNAH*, the German nuclear ship *OTTO HAHN* incorporated integral PWR reactor. Uncertainties about construction cost of future nuclear merchant ships, about insurring those ships, and about paying highly qualified staff needed to run them.

Naval Ship or Submarine Reactor Operation

> Feedwater = seawater pumped in, desalinated, and fed to steam generators.
> Russian, US, and British navies rely on steam-turbine propulsion; French and Chinese ships use turbine to generate electricity for propulsion.
> Most nuclear submarines have 1 reactor; Russian submarines and USS Triton had 2. Most American aircraft carriers powered by 2 reactors; USS Enterprise had 8. Marine reactors are PWR (although US and Soviet navies designed warships with liquid-metal-cooled reactors).
>Typical marine propulsion reactor produces less than a few hundred megawatts. Must be physically small, generate higher power per unit of space.
> Components subject to **greater stresses** than a land-based reactor. Must operate flawlessly under adverse conditions encountered at sea, including **vibration** and **pitching** and **rolling** in rough seas. Reactor scram mechanisms **cannot rely on gravit**y to drop control rods into place. **Salt-water corrosion** complicates maintenance. Must be highly reliable and self-sufficient, minimal maintenance and repairs, which might have to be undertaken many **thousands of miles from home** port. Fuel elements must withstand a large amount of radiation damage.

Merchant Ships

> Nuclear-powered, civil merchant ships not developed beyond a few experimental ships.

- **US-built NS *Savannah***, completed 1962, primarily civil nuclear power demo: Too small and expensive to operate economically as merchant ship. Required specialized nuclear shore staff and servicing facility.
- **German-built *Otto Hahn***, a nuclear-powered cargo ship and research facility, sailed 650,000 nautical miles (1,200,000 km) on **126 voyages over 10 years without any technical problems.** Proved too expensive to operate and was converted to diesel.
- **Japanese-built *Mutsu*** dogged by technical and political problems. Reactor had significant radiation leakage, and fishermen protested against vessel's operation.

> Renewed interest in nuclear-ship propulsion;some proposals: preliminary concept-design study carried out for a 155,000 DWT **Suezmax tanker** based on conventional hull form with 70 MWt nuclear plant.

> New proposed Gen4Energy power module: small fast-neutron reactor with lead-bismuth cooling; able to operate 10 full-power years.

> Lloyd's Register evaluating civilian nuclear marine propulsion. **>**

U.S. Nuclear reactors insured by Price Anderson Act.

Soviet Naval Reactors

> Used to power both military and civilian vessels
> Soviet **icebreaker *Lenin*** world's first nuclear-powered surface vessel in 1959; remained in service for 30 years (new reactors were fitted in 1970). ***Sevmorput***, a Soviet/Russian vessel with icebreaking capability, has operated successfully on Northern Sea Route **since 1988**.

- Only nuclear-powered merchant ship now in service.

> Led to a series of larger icebreakers: 23,500 ton ***Arktika* class** of six vessels, launched beginning in 1975. These have two reactors and used in deep Arctic waters. NS *Arktika* first surface vessel to reach the North Pole.
> For use in shallow waters such as estuaries and rivers, ***Taymyr*-class** icebreakers being built in Finland: fitted with single-reactor nuclear-propulsion system in Russia. Conforms to international safety standards for nuclear vessels.

Civilian Nuclear-Powered Ships

> Ships that were or are in commercial or civilian use with **nuclear marine propulsion:**

- **Merchant cargo ships**.*Mutsu*, Japan (1970–1992 but never carried commercial cargo); *Otto Hahn*, Germany (1968–1979 when re-powered with Diesel engine)
- *Savannah*, United States (1962–1972); *Sevmorput*, Russia (1988–present)

> 10 **Nuclear-powered icebreakers** commissioned by the Soviet Union or Russia not counting barge-mounted nuclear reactors (next slide)

- Nuclear propulsion technically, economically feasible in Soviet Arctic
- operate for years without refueling, and vessels have powerful engines, well-suited to icebreaking

Floating (Barge) Power Plants

> Marine reactor-supplied **electrical powe**r (1.5 MWe) to a U.S. **Antarctic** base for ten years to 1972: tested feasibility of air-cooled portable units for remote locations.

> Floating PWR nuclear plant between 1967 and 1976 was ex-U.S. Liberty ship *Sturgis*: moored at **Panama Canal Zone**; provided 10MW **electrical power**; supported civil and military operations nearby, including powering canal locks during drought.

- Decontaminated 1977; decommissioning began 2012 in Texas.

> **Russia:** has under construction the first of a series of floating **nuclear-power plants** for their northern and far-eastern territories.

> **China** General Nuclear Power Group announced in January 2016 development of a **floating-reactor** design.

Summary/Conclusions

> Now many widespread maritime applications of nuclear reactors (military and civilian).

- **Maritime applications have better worldwide prospects than land-based reactors.**

This review based in part on my two recent books:

Cold War Brinkmanship: Nuclear Arms, Civil Rights, Government Secrecy
(2017, Amazon, 680pp) [have copies for sale at $20 after 20% discount]

Nuclear Brinkmanship: Challenges for the Trump Presidency
(2018, Amazon, 228pp) [have copies for sale $8 after 20% discount]

Worldwide Nuclear-Weapons Role

> Land, Sea, and Air: American **tactical nuclear weapons** still stationed in Europe.

At least 180 American variable-yield B61 **nuclear bombs** deployed in seven NATO countries.

> Number of nuclear missiles down considerably from U.S. peak of 7000;

Russia has about 4000 tactical nukes of its own.

Britain and France **retain nuclear weapons** in their homelands and at sea,

as do China and the United States.

> U.S. Navy: submarines, aircraft carriers, and other vessels with nuclear weapons in their inventory.

> Preventive Deterrence: relies primarily on nuclear-armed submarines — a capability among the seven nuclear-weapon states, except for Pakistan.

Cold War Context: Nuclear Deterrence

> “Triad”: underground-based nuclear missiles (ICBMs), submarine based sea-launched missiles (SLBMs), long-range strategic bombers: Assured deterrence against nuclear attack during Cold War
> U.S. Poseidon submarines, armed with long-range Trident I nuclear-armed missiles into service in 1980
> Strategic stability for both sides of the Cold War; subs quietly and safely remain at sea underwater for many months: “run-silent, run-deep”
> Enduring mutual nuclear-retaliatory capability; SLBMs essentially immune to a first-strike; ensuring fearsome counterattack if needed.
[One of the first Cold War flicks was *On the Beach*, a 1959 movie memorably about a U.S. submarine searching off the coast of California for survivors of a nuclear holocaust.]

Nuclear-Weapons Context: Deterrence

> During much of the 1970s and the 1980s **United States deployed about a quarter of its entire nuclear weapons stockpile at sea.**

> All-time high 1975: over **6000 weapons afloat in 1990**, nearly as many deployed at sea.

> All nuclear-weapon nations likely to have some **nuclear weapons deployed** aboard submarines, but probably no nuclear weapons currently aboard surface ships.

Cold War Nuclear-Weapon Events

> **Berlin** 1958-61; **Korean War** 1950-53

> **Nuclear-powered subs**: 1954 U.S. (Nautilus); 1958 Soviet

600 U.S. nuclear torpedoes built between 1963 and 1976

> **Cuban Missile Crisis**: 1962 (Some events dicey)

Soviet submarines off Cuba forced to surface by the U.S. Navy

Soviet submarine commander allegedly ordered arming nuclear torpedo

Falling Dominoes: Soviets were installing nuclear-capable missiles in Cuba, just 90 miles from Florida.

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Major Nuclear-Limitation Treaties

Antarctic Treaty (1961)

SALT I (1972). Strategic Arms Limitation Treaty: mutual deterrence:.

SALT II (1979). Dealt with strategic-arms issues sidelined in SALT I

INF Treaty (1987). Between U.S. and USSR

START I (1994). Strategic Arms Reduction Treaty between US and USSR/FSU

START II (**not consummated**). World facing something like 17,000 nuclear weapons deployed or in reserve.

Principal American Cold War Deterrent

> **F**leet of nuclear-powered submarines

    each carrying sixteen Poseidon missiles

    each missile carried ten nuclear warheads

> **M**ajor stabilizing component during the Cold War and ever since

Soviet/Russian Submarine Accidents

> 5 accidents with reactor destroyed

- Soviet 1961 K-19 accident at sea (cooling failure in early PWR: at least 8 deaths).
- 1968 K-27 accident with 9 deaths at sea involved coolant failure in an experimental liquid-metal-cooled reactor.
- In 1985 the K-431 being refueled in Vladivostok had a criticality accident which killed 10 workers.

> Russia has built 248 nuclear submarines and 5 surface vessels (plus 9 icebreakers) powered by 468 reactors operating about 60 naval vessels altogether.

Commercial Nuclear Ship Insurance

> Lloyd's Register evaluating civilian nuclear marine propulsion
- rewriting draft rules (Not like insurance of conventional ships)
  consequences of an accident could span national boundaries
  magnitude of possible damage is beyond capacity of private insurers.

> Special international agreement never ratified
- owing to disagreement on inclusion of warships.

> Nuclear reactors under United States jurisdiction insured by Price Anderson Act.
- designer/builder to demonstrate compliance with regulatory requirements
  Nuclear ships currently responsibility of their own countries, but none are involved in international trade.

U.S. Nuclear Submarines

> October 2018: Newest U.S. nuclear-powered attack submarine USS *Vermont* christened (19th vessel in the *Virginia* class of submarines).

- $2.7 billion vessel packed with the latest war-fighting technology.

- Equipped with torpedoes and missiles, designed to carry out a wide range of missions, including surveillance and the delivery of special operations forces.

- Crew of more than 130 officers and enlisted sailors, 377 feet long.
- Slated for delivery 2019. Can carry up to 24 torpedoes and Tomahawk cruise missiles.

> September 2018, U.S. Navy took delivery of the 17th Virginia-class SSN, the future USS *South Dakota* (SSN 790).

> Another *Virginia*-class sub, the USS *Indiana* (SSN 789) commissioned.

More Details about Marine Reactors

> Fuel in marine reactors is a metal-zirconium alloy rather than the ceramic UO2 (uranium dioxide) often used in land-based reactors. Marine reactors designed for long core life, enabled by relatively high enrichment of uranium and incorporating "burnable poison." Life of pressure vessel extended by providing internal neutron shield.

> Decommissioning nuclear-powered submarines major task. U.S. practice: cut the reactor section from vessel for disposal in shallow land burial as low-level waste.

> Russia well advanced with plans for a **floating nuclear power plant** in their far eastern territories. Two 35-MWe units based on the KLT-40 reactor used in icebreakers (refueling every four years). Some Russian naval vessels supply electricity for domestic and industrial use in remote far-eastern and Siberian towns.

> In Russia, whole vessels, or sealed reactor sections, typically remain stored afloat, New is concrete-floored facility on land for some submarines.