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Naval Nuclear Propulsion:

The Technical and Strategic Challenges of a Restricted Technology

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Executive Summary

Naval nuclear propulsion (NP) endows surface ships and submarines with unrivaled technical and operational capabilities (discretion, power, autonomy, and maneuverability). During the Second World War, research into nuclear weapons was prioritized, but the end of the conflict provided scientifically advanced nations with an opportunity to reconsider the use of nuclear energy for the purposes of propulsion.

The United States (US) was the first to launch a nuclear-powered submarine, the Nautilus, which began sea trials in January 1955. Initially equipped only with conventional missiles and torpedoes, more diverse forms of submarine emerged during the Cold War and, in 1959, the first nuclear-powered ballistic missile submarine (SSBN, Submersible Ship with Ballistic missiles, Nuclear-powered), the George Washington, entered active service. Requiring close collaboration between industry and the armed forces, the sector gradually became more structured under the impetus of Admiral Rickover, a true pioneer of NP.

Driven by the Cold War dynamic of rivalry between powers, the Soviet Union also began research into NP at the end of the Second World War, but the political obstacles specific to the Stalinist regime and its successors meant that progress was slow. It was not until 1958 that the first sea trials of the Leninsky Komsomol were carried out. This was the first Soviet nuclear attack submarine (SSN, Submersible Ship, Nuclear-Powered), but it would swiftly be followed by SSBNs, whose acquisition was owing not least to an effective policy of espionage on American programs. However, a flawed safety culture, characteristic of authoritarian regimes, led to numerous accidents, some of them fatal, which undermined the effectiveness of Russian submarines.

The other three nuclear-weapon states (NWS) under the Nuclear Non-Proliferation Treaty (NPT) also acquired NP capabilities during the Cold War, albeit in different ways. After tough negotiations, the United Kingdom (UK), a close ally of the US, was supplied with a nuclear reactor with which to equip its first SSN, HMS Dreadnought. Concerned about its independence and faced with a refusal of aid from the US, France initially tried to develop its own program, which ended with the failure of the Q244. In the end, it was only after the adoption of a specific program and procurement of a supply of enriched uranium from the US that the Redoutable, the first French SSBN, was launched in 1967. Finally, it was not until 1974 that the first Chinese SSN entered active service, its reactor apparently heavily inspired by Russian icebreakers. Despite several attempts by Germany, Brazil, Canada and

Japan, no non-nuclear weapon state (NNWS) succeeded in developing NP during the Cold War.

This first age of NP therefore allows us to highlight the close link between nuclear weapons and propulsion technology, even though some nuclear-armed states (Israel, Pakistan, and North Korea) do not have submarines or NP aircraft carriers—or not yet. The stealth and autonomy of SSBNs ensures a state's second-strike capability and therefore contributes to the effectiveness and credibility of a nuclear deterrent. SSNs also provide vital operational support for deterrence via their ability to secure SSBN patrols and enable a flexibility of strategic options.

In addition, the historical legacy of the Cold War brings to bear a number of imperatives relating to the control of NP, along with various technical and operational lessons. While no consensus emerged on the choice of fuel (between low enriched uranium [LEU] and highly enriched uranium [HEU]), the pressurized water option quickly became the preferred choice for all countries interested in NP. In addition, a series of nuclear accidents, particularly in the Soviet Union, along with technical failures, proved the necessity of a nuclear safety culture, essential to the effectiveness of any program, and which must operate through independent bodies and dedicated industrial and administrative channels. Last, NP requires specialized technical and human skills, with specific training and a limited pool of talent. While these human resources can certainly be cultivated through civil nuclear projects, military reactor design and implementation efforts must be ongoing if expertise is to be maintained.

These historical lessons shed a specific light upon NP in the twenty-first century, characterized in particular by the growth and professionalization of the Chinese fleet and, in response, the emergence of new players in the Indo-Pacific. Thanks to Soviet and then Russian support, India became the first nuclear-armed state that is not a signatory to the NPT to introduce NP: Moscow leased a SSN to New Delhi from 1988 onward, and India then developed its own program of domestically built SSBNs, albeit hampered by a number of breakdowns and delays. The rise of China has also sparked an interest in NP in countries which, like Japan and South Korea, already have partial or total fuel cycle capabilities, and already possess conventionally powered submarines. Brazil has also exhibited a long-standing interest in submarines, with development of conventional capabilities aided by France through the Submarine Development Program (known as PROSUB).

Finally, the AUKUS agreement and its submarine version, which provides for the sale of American and British SSNs to Australia, followed by the construction of a class of AUKUS SSNs in the UK and Australia by 2040, represents one of the major twenty-first-century developments in NP. This is the first time that a NNWS—moreover, one highly invested in questions of disarmament—will own nuclear-powered submarines, albeit without nuclear warhead missiles, on terms yet to be defined. This contract bears witness to the growing importance of nuclear-powered submarines as a strategic capability.

Although in the case of Australia the risk of nuclear proliferation, and in particular the risk of the material being used to build nuclear weapons, is minimal to non-existent, the AUKUS agreement nonetheless suggests an adaptation of the International Atomic Energy Agency (IAEA)'s protocols in order to guarantee the safety and security of reactors and manufacturing facilities. In particular, this will require the establishment of an in-depth technical dialogue between Australia and the IAEA in order to implement the specific provisions set out in the additional safeguarding measures. The success of this dialogue should make it possible to establish a legislative and normative precedent to reduce the risks of nuclear proliferation in the event of any replication of such an agreement with other states with less pristine track records.

Although the long-term implementation of the AUKUS program will enable us to learn from the experience of sharing and exporting NP capabilities, the imperatives of safety, industrial stringency, and non-proliferation at present require us to maintain a policy of non-exportation of this technology, and to demand the highest standards from countries already developing NP.

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Introduction

On September 15, 2021, the announcement of the “AUKUS” security partnership between the United States (US), Australia, and the United Kingdom (UK), which includes, among other provisions, the delivery of nuclear attack submarines to Australia by its Anglo-American partners, highlighted the specific features of naval nuclear propulsion (NP). Rarely studied beyond its technical characteristics, and often overshadowed by the nuclear weapons carried by submarines, NP is nonetheless at the heart of nuclear deterrence because of the discretion, maneuverability, and endurance that it enables.

This cloak of secrecy is maintained by the countries concerned: while nine states currently possess nuclear weapons, only six have mastered NP technology, and to varying degrees. The US, the UK, and France are the only countries to have maintained a permanent sea-based strategic deterrent for more than half a century, in other words a constant presence of one or more ballistic missile submarines (SSBNs; Submersible Ship with Ballistic missiles, Nuclear-powered) at sea. Russia’s presence has been interrupted for several years, while China and India rely upon land- and air-based deterrent to compensate for a weaker sea-based one.

Similarly, while processes exist for information-sharing on nuclear arsenals between nuclear-armed states, such as the New START agreement—which, admittedly, was suspended by Russia in February 2023—and the P5 process,[1] exchanges relating to NP are extremely rare and the conditions for aiding the development of British, French, and Indian programs during the Cold War were circumscribed by drastic precautions. For example, the US, the pioneers of atomic energy, initially refused to share their knowledge with their British allies after the first patrol of the Nautilus, the first nuclear-powered submarine, in 1955. Similarly, France’s request for aid was long refused, until finally enriched uranium was delivered to the French teams, enabling work to progress and a reactor to be designed independently.

This Cold War history, punctuated by numerous accidents in the Soviet Union, led to the emergence of a strategic, technical, and military culture within states that possessed NP, a culture from which lessons can be learned today. Over the course of patrols and tensions between the US and the Soviet Union, NP has become an imperative condition for a credible and effective nuclear deterrence, but also a decisive operational asset thanks to the

1. The P5 are the five permanent members of the United Nations Security Council and nuclear-weapon states under the Nuclear Non-Proliferation Treaty. Prior to the war in Ukraine, they met regularly to reduce strategic risks, within the framework of the “P5 Protocol”.

existence of nuclear attack submarines. There are also many technical lessons to be learned, in particular regarding the choice of fuel and the prevalence of the pressurized water reactor (PWR) option to the detriment of other alternatives. Finally, a solid human, military, and political organization appears to be the mainstay of safe NP.

In this context, the sharing of technology under the AUKUS partnership is an exception, and seems to reflect a new development in NP. Since the early 2000s, new players keen to master this technology have been emerging—particularly in Asia, in the face of China's growing power. In fact, it was Beijing's increased influence that motivated this trilateral partnership, breaking with a restrictive policy on exchanges in the domain of NP. This raises once again the question of the exportability of NP technology, in relation to the risks of the proliferation of fissile material, but also to compliance with nuclear safety standards.

The first age of nuclear propulsion

The idea of applying the scientific discoveries made in the late 1930s concerning the fission of a uranium nucleus to the production of energy and the propulsion of submarines emerged very early on. However, with the outbreak of the Second World War, priority was given, first in Great Britain and then in the US, to the production of nuclear weapons. The US Navy relaunched the naval NP project at the end of the conflict, becoming a pioneer in the field, whose secrets it carefully guarded and only reluctantly shared with the British. The acquisition and development of this technology by a small number of states during the first decades of the Cold War deeply shaped the landscape of naval NP, albeit in different ways and at different speeds from one country to another.

The United States, pioneers of nuclear propulsion

The industrial and scientific power of the US, and its status as the world's leading power at the end of the Second World War, enabled it to pioneer the use of atomic energy for NP.

The first scientific discoveries

The use of atomic energy to propel US Navy ships had been under consideration even before the US entered the Second World War. This journey began with the experiment conducted in 1938 by Otto Hahn, Lise Meitner, and Fritz Strassmann at the Kaiser Wilhelm Institute for Chemistry in Berlin, which demonstrated how energy was released from a uranium-235 atom when bombarded by neutrons. The account of this experiment by Niels Bohr and Enrico Fermi at the Fifth Washington Conference on Theoretical Physics held in January 1939 attracted the attention of Ross Gunn, a physicist employed at the Naval Research Laboratory (NRL). Gunn managed in turn to interest the head of the engineering office of the US Navy staff, who however had only a very limited budget for further research into how to take advantage of these discoveries. That same year, having understood the potential implications of the Hahn-Meitner-Strassmann experiment, in particular for the manufacture of atomic bombs, the Hungarian physicist Leo Szilard succeeded, through his exchanges with Albert Einstein, in alerting President Roosevelt to its strategic importance. Szilard went on to set up an advisory committee on uranium, headed by engineer Lyman J. Briggs.

At the beginning of November 1939, this committee reported to the president that, although as yet untested, if it could be controlled, the nuclear chain reaction could potentially constitute a means of propulsion for submarines. The report also indicated that it could provide unparalleled destructive energy, comparable to no other known explosive.[2] The work undertaken within the NRL led to the production of an experimental device for the isotopic separation of uranium in 1941. This work did not yield its first results until February 1942, by which time Roosevelt had already handed over responsibility to the US Army for what was to become the Manhattan Project, its aim being to produce a nuclear weapon. As a result, the navy was frozen out of the atomic field for the remainder of the war.

In the immediate post-war period, preoccupied by demobilization and questions about the resilience of a surface fleet to attack by atomic weapons, the US Navy held back from launching any NP projects. Certain top officials agreed between themselves that the navy's priority should be to develop and acquire nuclear weapons and the means to operationalize them.[3]

Against the backdrop of a reorganization of atomic weapons research and development, which resulted in the introduction of civilian control in January 1947 with the founding of the Atomic Energy Commission (AEC), replacing the military control exercised by the "Manhattan District", an experimental atomic reactor project was developed in Oak Ridge, Tennessee. The navy decided to second a team of officers to train there, under the direction of Admiral Hyman Rickover. Owing to his remarkable qualities as a leader, organizer, and rigorous engineer, Rickover spearheaded the extraordinary development of NP in the US Navy, and in consequence, initiated the development of civilian nuclear power based on pressurized water reactors (PWRs).

The Second World War had demonstrated the increasingly important role played by submarines in naval operations, but also their vulnerability arising from the need to return periodically to the surface, and their low speed while submerged. In 1947 this led Chief of Naval Operations (CNO) Admiral Nimitz to issue an initial expression of interest in the development of an atomic-powered propulsion system for a submarine. At the end of 1948, Admiral Rickover succeeded in creating and securing recognition for a naval NP organization under the dual authority of the CNO and the chairman of the AEC, subsequently dubbed "Naval Reactors", which Rickover would direct for more than three decades. Pursuit of two technological approaches was approved by President Truman on August 8, 1950: the first, developed by General Electric, was based upon the chain reaction produced by fast neutrons, and used liquid sodium as coolant; the other, developed by

2. R. G. Hewlett and F. Duncan, *Nuclear Navy, 1946-1962*, Chicago: University of Chicago Press, 1974, pp. 15-18.
3. *Ibid.*, p. 46.

Westinghouse, used thermal neutrons with pressurized water as both coolant and moderator.[4]

Operation of a pressurized water reactor (PWR)

This technical solution is based upon two circuits: a primary circuit containing the PWR, and a secondary circuit containing a "conventional" steam engine.

Primary circuit

The absorption of a neutron by the nucleus of a heavy atom such as uranium-235 (i.e., a nucleus with 92 protons and 143 neutrons) induces fission. This fission produces two or more other nuclei (fission products), as well as energy and two or three other neutrons. These neutrons, known as fast neutrons, have very high energy. The probability of their creating new fissions is very low. On the other hand, when slowed down or "moderated", the probability of creating new fissions with U-235 is high. These so-called thermal neutrons have about 1000 times less energy than fast neutrons.

To maintain a fission chain reaction, each fission of a U-235 atom must create a thermal neutron that can be used to generate a new U-235 fission. The operation of the reactor is then said to be "critical".

PWRs use the energy released by the thermal neutron fission of U-235 atoms. The core of a PWR is a container a few cubic meters in volume containing the fuel, located in cladding around which water circulates. This water is used as a "moderator" to slow down the neutrons and as a "coolant" to recover the heat produced by the fuel and transport it to the steam generators. To prevent the water boiling and overheating the fuel elements, it is kept at a constant high pressure by a pressurizer.

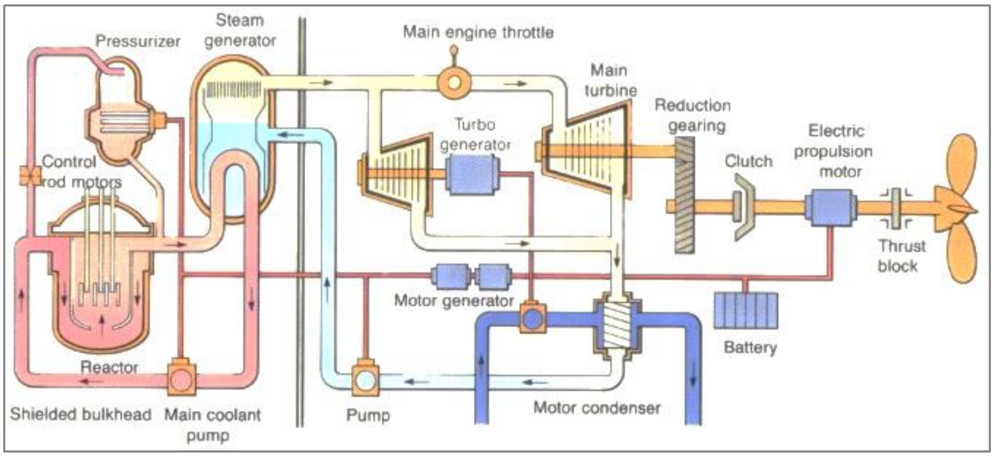
Contained in a primary circuit, the water is generally circulated by one or more primary pumps. Control rods, which absorb neutrons and are inserted between the fuel cladding, are used to monitor core reactivity and to shut down the reactor. A reactor is started up by lifting the control rods to reach the critical state. This is called the divergence phase.

Secondary circuit

The water contained in the secondary circuit passes from a liquid to a gaseous state in the steam generators. The steam is sent to one or more turbines, before being condensed in a seawater-cooled condenser and pumped back to the steam generators. The expansion of the steam in the turbines sets them rotating, providing electricity and propelling the submarine or surface vessel (see diagram).

4. R. G. Hewlett and F. Duncan, *Nuclear Navy, 1946-1962, op. cit.*, p. 163. In addition to approving nuclear-powered submarines, President Truman also approved the construction of a closed-cycle submarine based on technology developed by the Germans during the Second World War. This was never built, however, as studies demonstrated the operational superiority of nuclear propulsion over the closed cycle.

Diagram 1: Operation of a pressurized water reactor (K-15 boiler on the aircraft carrier Charles de Gaulle)



Source: Wikipedia.

Operation of a fast neutron reactor (FNR)
Fast neutron reactors (FNR) exploit the "fertility" of uranium-238 (which contains 92 protons and 146 neutrons). When bombarded by fast neutrons, uranium-238 is converted into fissile plutonium-239. In this type of reactor, the coolant is a liquid metal (sodium or a lead-bismuth alloy) which, within a steam generator, exchanges heat with the water in the secondary circuit, transforming it into steam to power the turbines.

Toward the establishment of a submarine program

This presidential decision reflected the navy's confirmed interest in atomic energy, which Rickover had succeeded in arousing by transforming a research project into a fully-fledged submarine program in just a few months, with the appropriate combination of government and industry bodies.

The construction of onshore prototypes was the first stage in the development of these two technologies. PWR technology soon took the lead ahead of FNR. Construction, on a site in Idaho, of the experimental Mk1 reactor (providing 70MW of power) began in December 1951, while construction of the FNR MkA reactor did not begin until June 1953, in West Milton (New York State).

Rickover also managed to get the navy to agree to start to build nuclear-powered submarines without waiting for tests on land-based prototypes to be completed. The keel for the Nautilus submarine was laid down at the Electric Boat Shipyard in Groton, Connecticut, in June 1952, even though tests on the Mk1 reactor did not begin until 1953, with a critical state first being achieved on March 30, 1953. A first high-power test, representing a submarine crossing between Groton and Ireland lasting 100 consecutive hours, was successfully carried out in June 1953, confirming the hopes pinned on this new mode of propulsion. Not satisfied with this initial success, and at a time when the navy, still made up of ships built during the Second World War, was considering the renewal of its fleet following the Korean War, Rickover was able to launch studies into other reactors for submarines that would be more compact or capable of reaching higher speeds, as well as reactors for surface ships.

1955 was a particularly important year for NP:

- The Nautilus submarine's Mk2 reactor, virtually identical to the one operating in Idaho, diverged for the first time at the end of 1954, and was operating at full power by January 3, 1955. On January 17, the commander of the Nautilus began sea trials, and was able to transmit the famous radio message that inaugurated the operational era of naval NP: "Underway on Nuclear Power.";
- The S1G onshore reactor (fast neutron technology, 78MW power output) also diverged in 1955, and the Seawolf submarine equipped with the similar S2G reactor was launched in July. However, tests on the S1G gave rise to some initial doubts about the reliability of this type of reactor, leading to its rapid abandonment;[5]
- Following the launch of the Seawolf, the keel of a new type of nuclear submarine, the Skate, was laid at Groton. Construction of the next two in the series, Swordfish and Sargo, began shortly afterward at Portsmouth and Mare Island dockyards, marking the start of the industrial expansion of shipyards capable of building atomic-powered vessels. These Skate-class submarines were equipped with S3W/S4W PWRs (38MW);[6]
- A new submarine was designed using a hydrodynamic hull form optimized for high speeds (the "Albacore") and a new reactor, the S5W (78MW power), capable of producing the significant power needed to reach such speeds. The hull of the first of this series, the Skipjack, was laid the following year, in May 1956;
- In fall 1955, the new CNO, Admiral Arleigh A. Burke, decided to accelerate programs for nuclear-powered vessels, ordering the conversion of two conventionally powered submarines currently under construction into nuclear submarines. Indeed, he decided to launch only nuclear-powered submarine programs from then on, also ordering the initiation of studies into equipping surface ships (aircraft carriers, cruisers, and frigates) with NP.

5. The Seawolf was later fitted with a pressurized water reactor.
6. Reactors of identical design, but with some differences in construction.

All in all, 1955 was a year of transition, paving the way for the move from an experimental phase involving the construction of the first prototypes both onshore and submarine, to an operational production phase, with a greater number of shipyards involved and the planning of five different atomic propulsion devices.

Acceleration and diversification of programs

Work on the launching of missiles from the ocean began in 1955, when a project team was set up under the direction of Admiral William F. Raborn. After eliminating Redstone, the only liquid-propellant missile in existence in 1955, studies focused for a time on the solid-propellant missile Jupiter, which however was also abandoned by the navy on account of its size. At the end of 1956, progress made by the teams responsible for nuclear weapons made it possible to launch a new project for a lighter solid-propellant missile with a range of 1,500 nautical miles: the Polaris. The first submarine to be equipped with this missile was scheduled to become operational in 1963.

The shock of the Soviet Union's 1957 launch of the first Sputnik satellite and the revelation of the existence of a Soviet intercontinental missile program, the R-7 Semyorka (NATO code-name SS-6), by revealing the vulnerability of Strategic Air Command (SAC) bases, served to accelerate this program. It was decided to transform one of the Skipjack-class submarines launched at the end of 1957 by cutting out the bow and stern sections and inserting between them an approximately forty-meter-long section containing sixteen missile tubes.

This new submarine, renamed the George Washington, which entered active service at the end of 1959, was the first nuclear-powered ballistic missile submarine (SSBN; Submersible Ship with Ballistic missiles, Nuclear-powered) in history. Four other SSBNs were built on the same model, before two new classes of SSBN entered service, armed with the same Polaris missiles (which would be replaced in the early 1970s by Poseidons) and equipped with the S5W reactor: the Ethan Allen class (five units) from 1961 on, and then the Lafayette class (thirty-one units) from 1963 on.

At the same time, a new class of attack submarine, the Thresher, equipped with the S5W reactor, as well as an aircraft carrier, the USS Enterprise, equipped with eight reactors, and a cruiser, the Long Beach, were under construction. With these new accelerated programs, construction reached a peak of thirty-seven ships in 1961, with six shipyards involved: Electric Boat, Portsmouth, Mare Island, Newport News, Bethlehem (Quincy) and Ingalls (Pascagoula). The short Thresher series was followed by the Sturgeon series (thirty-seven units) built from 1961 until the early 1970s, also equipped with the S5W reactor, and which made up the US Navy's main anti-submarine warfare battle group during the Cold War.

Table 1: Classes of US nuclear attack submarines in service during the Cold War

Name/Class	Number	Admission to active service	Reactor
Nautilus	1	1954	S2W
Seawolf	1	1957	S2G then S2W
Skate	4	1957/1959	S3W/S4W
Skipjack	6	1959/1961	S5W
Thresher	14	1961/1967	S5W
Sturgeon	37	1967/1975	S5W

Table 2: American experimental submarines (only one built per class)

Name	Admission to active service	Reactor
Triton (radar picket SM)	1959	S4G (2 reactors)
Halibut (Regulus dedicated SM)	1960	S3W
Tullibee (SSN hunter-killer prototype)	1960	S2C
Narwhal (modified Sturgeon)	1969	S5G
Glenard P. Lipscomb	1974	S5W

Table 3: Classes of American SSBNs in service during the Cold War

Name/Class	Number	Admission to active service	Reactor
George Washington	5	1959/1961	S5W
Ethan Allen	5	1961/1963	S5W
Lafayette/ Benjamin Franklin	31	1963/1967	S5W

On the other hand, the nuclearization of the US Navy's surface ships proceeded at a more faltering pace, with the question of the cost of these programs in relation to operational gain a permanent point of contention. Construction of the USS Enterprise, the first nuclear-powered aircraft carrier, commissioned in 1961, was followed by that of a conventionally powered aircraft carrier, the USS John Kennedy, of the Kitty Hawk class. The choice of NP for naval aviation was not permanently confirmed until the 1968 budget vote for the Nimitz class. As far as aircraft carrier escort ships are concerned, in addition to the Long Beach cruiser commissioned in 1961, eight other cruisers of four different types (one Bainbridge, one Truxtun, two California and four Virginias) were built in the 1960s and 1970s.

Table 4: Nuclear-powered surface ships in service with the US Navy (1961–1998)

Type	Name/Class	Number	Admission to active service	Reactor (number)
AC	Enterprise	1	1961	A2W (8)
Cruiser	Long Beach	1	1961	C1W (2)
Cruiser	Bainbridge	1	1962	D2G (2)
Cruiser	Truxtun	1	1967	D2G (2)
Cruiser	California	2	1974/1975	D2G (2)
Cruiser	Virginia	4	1976/1980	D2G (2)
AC	Nimitz	3	1975 /1982	A4W/A1G (2)
AC	Improved Nimitz	5	1986 /1998	A4W/A1G (2)

In the 1970s the nuclear-powered submarine fleet continued to expand with the construction of a new series of eighteen Ohio-class SSBNs equipped with the S8G reactor and capable of carrying twenty-four Trident missiles boasting a far greater payload and range than the Polaris or Poseidon, which were in commission between 1981 and 1997. The Los Angeles class of SSNs, (Submersible Ship, Nuclear-Powered), fitted with the S6G reactor and in commission from 1976 to 1996, represents the largest class of units of this type in the world, with sixty-two submarines built.

By the end of the Cold War, the US Navy had built 185 nuclear-powered vessels, including 170 submarines, seven aircraft carriers, and eight cruisers. No serious nuclear incidents were recorded. However, there were two submarine accidents, one involving the USS Thresher which took place off the coast of Connecticut on April 10, 1963, the other involving the USS Scorpio which took place southwest of the Azores on May 22, 1968, and resulted in the sinking of the submarine and its reactor—and the death of the entire crew. The extreme depth of the accident areas meant that the vessels could not be refloated.

In addition to the propulsion programs for the US Navy, the US also invested in a civilian program, completely separate from the organization set up by Rickover. Two years after his speech to the United Nations (UN) on December 8, 1953, promoting the peaceful use of atomic energy (the "Atoms for Peace" program), President Dwight Eisenhower launched the NS Savannah nuclear-powered civilian ship project, piloted by the AEC, the Department of Commerce, and the US Maritime Administration (MARAD). Launched in 1959, this 20,000-ton merchant ship was equipped with a 74MW reactor, and was commercially active from 1962 to 1971. Initially used to promote the Atoms for Peace program, it was subsequently used as a cargo ship from 1965 on. However, high operating costs and a low capacity compared with a conventional cargo ship of the same tonnage undermined the ship's commercial appeal. After the atomic core was removed in 1976, the ship was donated to the city of Savannah, to be transformed into a museum.

All in all, the remarkable and entirely safe development of NP in the United States gave the US Navy a clear advantage over the Soviet Navy during the Cold War. In particular, from the early 1960s onward it encouraged the development of a fleet of SSBNs, which backed up the US nuclear deterrent with a permanent second-strike capability. It also made possible the construction of a fleet of high-performance, low-noise SSNs able to keep a close eye on the movements of Soviet ships from their bases, and ensured clear naval superiority in the North Atlantic. Finally, nuclear aircraft carriers were at the heart of the US's power projection capabilities and of the Reagan-era Maritime Strategy which, in the event of war, planned to attack Soviet forces from US bases on the Kola Peninsula or in eastern Siberia.[7]

A chaotic Soviet program

The initial projects of the Stalin era

NP began to be developed in the Soviet Union in reaction to the advances made in the US. However, the scientific research carried out in European laboratories and published in scientific journals up until 1939 was known by a few physicists in the Soviet Union. In 1939, following Hanh and Strassmann's discoveries, the Russian scientist Igor Tamm suggested that a single uranium bomb could destroy an entire city.[8] However, in the context of the reign of terror in force in the USSR at the time, few scientists dared to

7. J. B. Hattendorf and P. M. Swartz (eds.), "U.S. Naval Strategy in the 1980s", *The Newport Papers*, Vol. 33, Naval War College, 2008.
8. S. Zaloga, *Target America: The Soviet Union and the Strategic Arms Race, 1945-1964*, Novato, CA: Presidio Press, 1993, p. 4.

pursue this line of research, which Stalin considered pointless because it had no immediate military application. After the commencement of Operation Barbarossa, scientists specializing in nuclear physics worked on other projects until 1942.

According to official Soviet historiography, it was a letter sent to Stalin in May 1942 by a young scientist, Georgy N. Flyorov, that prompted the resumption of atomic research. Noting the absence of any research results in nuclear physics in reputable scientific journals since 1939, Flyorov reportedly deduced that they had become subject to official secrecy, which suggested the probable existence of a military application for such research.[9] More prosaically, Soviet espionage, in Great Britain as well as in the US, was what had actually sparked renewed Soviet interest in this research.

However, very few resources were dedicated to this program up until July 1945. Upon his return from the Potsdam Conference, where Truman had revealed the existence of a bomb with unprecedented destructive power, Stalin ordered the director of the nuclear program, Igor V. Kurchatov, to speed up research, with no limit on resources, so that the USSR could acquire an atomic bomb as soon as possible. Beria was appointed as political director of the project. The first nuclear explosion took place at Semipalatinsk on August 29, 1949. For several years afterward, Soviet efforts continued to focus on the development of nuclear weapons.[10]

The idea of propelling a submarine using a nuclear reactor first emerged in 1946 in a physics institute run by Pyotr Kapitsa. Upon hearing of it, Lavrentiy Beria, head of the NKVD (People's Commissariat for Internal Affairs), promptly had Kapitsa replaced, as he was in breach of the absolute priority given to the development of an atomic weapon. His replacement, Anatoly P. Aleksandrov, re-examined the NP program in 1948, only to close the file again upon Beria's orders. But Beria's attitude shifted in 1952. Once the hydrogen bomb had been mastered, the major problem was to find ways to deliver it to US targets, so bomber and missile programs were launched. One of the new ideas that emerged was that of a "super-torpedo" carrying a nuclear weapon capable of reaching American ports, to be launched from a nuclear-powered submarine. The launch of the nuclear-powered submarine project ("code 627") was confirmed on September 9, 1952, and entrusted to Central Bureau 143 in Leningrad. The chief of staff of the Soviet Navy, Admiral Nikolai G. Kuznetsov, who had initially been kept out of the project, opposed the super-torpedo concept, given the risks it posed to the carrier submarine. The super-torpedo was abandoned, but Project 627 (known as "November" in the NATO classification) for a class of nuclear-powered submarines did go ahead.

9. *Ibid.*, p. 10.
10. *Ibid.*

The move toward nuclear-powered submarines

The project began with the construction of an onshore prototype at Obninsk, the first Soviet "scientific city" in the Moscow region. The first divergence took place on March 8, 1956. This prototype was also used to train the first Project 627 submarine crew.[11]

Two years later, on July 4, 1958, the K-3 Leninsky Komsomol nuclear attack submarine began its first sea trials. The first of a series of thirteen, it was equipped with two VM-A-type PWRs, each with a capacity of 70MW. Two other classes of submarines equipped with the same type of reactors were launched in the late 1950s and early 1960s: a cruise-missile submarine (Project 659/Echo 1 and Project 675/Echo 2, with five and twenty-nine units built respectively), and a nuclear-powered ballistic missile submarine, Project 658 ("Hotel" in NATO designation).

Like the Golf-class conventionally powered ballistic missile submarines, the Hotel-class SSBNs had three missiles stored in the submarine's large sail. These vessels had to surface in order to launch, making them highly vulnerable during this phase and limiting their strategic value. Unlike the first American nuclear submarines, the Soviet versions were equipped with two reactors to ensure redundancy, as the need for accelerated development in response to the American lead in this field had prevented the Soviets from making this generation of reactors entirely reliable and safe.[12] As a result, there were a number of nuclear accidents, ranging from criticality accidents[13] (on two occasions, in 1965 on a November and in 1985 on an Echo 2, both while docked)[14] to leaks from the primary circuit leading to core degradation (in 1961 on board a Hotel 1 at sea, and in 1989 on board an Echo 2 at sea).

At the same time as developing reactors for submarines, the USSR also developed a reactor for an icebreaker, the Lenin. Introduced in September 1959, the Lenin was both the first surface vessel and the first civilian ship in the world to be equipped with atomic propulsion. The Lenin was equipped with three OK-150 PWRs of around 90MW, all located in the same compartment. These reactors were also subject to two serious accidents, one leading to a partial core meltdown following human error resulting in a primary coolant leak (1965), the other being the consequence of damage to the neutron shielding and to one of the reactors, inflicted while attempting to locate a primary leak (1967). Following this later accident, the entire reactor compartment was replaced in 1970 with two new second-generation

11. L. Giltsov, N. Mormoul, and L. Ossipenko, *La Dramatique histoire des sous-marins soviétiques*, Paris: Robert Laffont, 1992, p. 82.

12. O. Reistad and P. L. Ølgaard, "Russian Nuclear Power Plants for Marine Applications", *Nordic Nuclear Safety Research* NKS-138, April 2006, p. 11.

13. A criticality accident occurs when the fission of an atom of fissile material creates, in a sustained and uncontrolled manner, a greater number of fissions, resulting in a runaway chain reaction.

14. Reistad and Ølgaard, "Russian Nuclear Power Plants for Marine Applications", p. 29.

OK-900 reactors, each rated at 159MW, which were also used, in a modified form (the OK-900A, rated at 171 MW), to power a new series of six Artika-class icebreakers.

New, more operational generations

Starting in early 1964, this first generation of Soviet submarines was swiftly followed by a second generation equipped with new, more powerful, and more compact VM-4 PWRs. Comprising the Victor I, II, and III SSNs, the Charlie I and II SSGNs (Submersible Ship, Guided missile, Nuclear Powered; nuclear-powered cruise-missile submarine), as well as the Yankee SSBNs and their derivatives (Delta I, II, III and IV SSBNs), this second generation would form the core of the Russian submarine forces during the second half of the Cold War. There were several versions of the VM-4 reactors ranging in power from 72MW (Victor) to around 90MW (Charlie, Yankee, Delta). The Yankee-class SSBNs, the first of which was commissioned in 1967, were the first true Soviet SSBNs, capable of remaining below the surface for long periods and launching submerged missiles in the same way as the American SSBNs equipped with Polaris missiles.

In parallel with these series of nuclear submarines equipped with PWRs and using low-enriched uranium (LEU; 20 percent maximum), submarines using fast neutron reactors (FNRs) were also built. The first of these, the K-27, using the hull of a November SSN, was fitted with two RM-1 reactors cooled by a lead-bismuth liquid metal alloy, and using highly enriched uranium. This submarine, which entered service in 1963, suffered a serious reactor accident in 1968. The presence of impurities in the liquid metal led to a blockage in the primary circuit of one of the two reactors, loss of refrigeration, and partial core meltdown[15]. The high level of radiation and the delay in taking action on the part of the commander led to the deaths of nine men and the contamination of eighty-nine others. Having returned to port, the K-27 could not be repaired. Finally withdrawn from active service in 1979, in 1981, after the damaged compartment had been filled with bitumen, she was submerged in shallow water in Stepovogo Bay, north of New Zealand, where she remains to this day. Another class of submarine, the Alpha class, also used fast reactors. Built with a titanium hull enabling them to dive operationally to 600 meters, and each equipped with a 155MW liquid-metal-cooled reactor (using a lead-bismuth alloy), these submarines suffered a number of setbacks. Four of them were withdrawn prematurely from active service, in particular after the primary coolant leaked into the reactor compartment, where it solidified.

15. *Ibid.*, p. 37

Table 5: First generations of Soviet submarines (NATO designations)[16]

	SSN	SSGN	SSBN
1st generation	November	Echo 1 and 2	Juliet
2nd generation	Victor 1, 2,3 Alfa	Charlie 1 and 2	Yankee
3rd generation	Akula Sierra	Oscar 1 and 2	Delta 1,2,3,4 Typhoon

New classes of submarines were built from the 1980s onward around a third-generation nuclear reactor, the OK-650B (190MW): the SSNs of Project 971 (NATO Akula-class, one reactor) and 945 (Sierra, one reactor); the SSGNs of Project 949 (Oscar 1 and 2, two reactors); and finally, the largest class of submarines in the world, the SSBNs of Project 941 (Typhoon, two reactors).

The 1970s and 1980s also saw the construction of four nuclear-powered cruisers (Kirov-class), each equipped with two 300MW KN-3 PWRs, as well as a command ship equipped with two OK-900 reactors, the Kapusta. In terms of civilian ships, the Lenin icebreaker was followed by a series of six Arktika-class icebreakers, each with 159MW of power, and subsequently by the Taymyr-class icebreakers, which were equipped with a new generation of reactors (the 171MW KLT-40), as was the only cargo ship designed in the USSR, the Sevmorput.

At the time of its break-up, the USSR had built around 220 nuclear-powered submarines, as well as eight icebreakers, four cruisers, and a command ship.

In addition to the nuclear accidents mentioned above, the Soviet Navy suffered many other accidents, both at sea and in dock, which were not directly related to propulsion.[17] In particular, several Soviet nuclear submarines sank:

- The K-8 (November-class) sank on April 11, 1970, following a fire, off the Bay of Biscay, at a depth of 4600m;
- The K-429 (Charlie-I class) sank in June 1983 south of the Kamchatka peninsula at a depth of 50m. It was salvaged in August 1983;

16. *Ibid.*, p. 10.
17. For a review of accidents and incidents involving Russian submarines, see L. Gilstov, N. Mormoul, and L. Ossipenko, *La Dramatique histoire des sous-marins soviétiques, op. cit.* For a more general review of accidents and incidents involving nuclear-powered vessels, see P.L. Ølgaard, "Accidents in Nuclear Ships", *Nordic Nuclear Safety Research*, Vol. 2, 1996.

- The K-219 (Yankee-class) sank some 800 km off the coast of Bermuda following a fire in the liquid propellant of the SS-N-6 missile on October 6, 1986;
- The experimental submarine K-278 Komsomolets sank on April 1, 1989, in the Norwegian Sea following a fire;
- After the end of the Cold War, the SSGN Kursk sank on August 12, 2000, in the Barents Sea.

All in all, the Soviets built a formidable nuclear-powered fleet, including the largest submarines ever built, only a few years behind the Americans. For ideological reasons, this delay had to be made up as quickly as possible, even at the expense of nuclear safety. The first decades of the use of this technology in the USSR remain associated with the many accidents that occurred as a result, with major human and environmental consequences.

A British program dependent on American aid

The Royal Navy, in 1945 the world's second largest navy, became interested in NP early on. Technical and financial difficulties delayed rapid mastery of this technology, but American aid enabled the Royal Navy to become the third naval force to have nuclear submarines at its disposal.

A faltering start

In 1948, the British Admiralty, aware of the potential contribution of atomic energy to submarine propulsion, sent a number of officers to the Atomic Energy Research Establishment (AERE) in Harwell, England. The first designs for naval reactors were developed from the early 1950s onward. At a time when the production of highly enriched fissile material was reserved for weapons, research focused upon graphite-gas reactors using very low-enriched uranium. However, these studies soon showed that such a reactor would be too heavy and fragile to be carried on board a submarine. The design of a nuclear-powered submarine was therefore suspended in October 1952, with the Royal Navy deciding that work of this type could not be resumed until the 1960s[18]. When the British learned of the construction of the Nautilus in the US, it rekindled their interest in this type of vessel. However, the US Congress's Joint Committee on Atomic Energy, on the advice of Admiral Rickover, who was firmly resolved not to exchange secrets in this field with any state, was opposed to supporting the British.

It took all the skill—and the status—of Admiral Mountbatten, then First Sea Lord, negotiating with his American counterpart, Admiral Arleigh Burke,

18. E. Grove, *Vanguard to Trident: British Naval Policy since World War II*, Maryland, MD: Naval Institute Press, 1987, p. 230.

and Rickover himself, to obtain an agreement in June 1956 on the exchange of information in the field of atomic propulsion. Research resumed at the Harwell laboratory in early 1957, leading to the choice of a PWR using enriched uranium from the Capenhurst plant. The decision was also taken to build an onshore prototype at Dounreay, in the north of Scotland.

American support proves decisive

Initial difficulties in coordinating the new project led to the creation in October 1957 of a single unified organization, the Dreadnought Project Team (DPT), but this did not prevent the schedule from slipping. An agreement between the Americans and the British to supply an American reactor for the first British submarine was signed in the summer of 1958. The S5W reactor supplied equipped the first British SSN, the HMS Dreadnought. Launched in 1960, she underwent her first sea trials at the end of 1962 and was admitted to active service in 1963.

The British naval reactor project continued in parallel with these developments. Taking into account the initial lessons learned from the operation of the Dreadnought's S5W, the Dounreay onshore prototype, named HMS Vulcan, was commissioned in 1965. HMS Valiant, the first SSN to use the British-designed and built PWR1 reactor, was admitted to active service in 1966, with a second following in 1967. At the same time, another class of nuclear-powered submarines was given priority in the British program. Following the Nassau Agreement signed on December 21, 1962, between US President Kennedy and UK Prime Minister MacMillan, in which the US undertook to deliver Polaris-type SLBMs (Submarine-Launched Ballistic Missile), the UK launched an SSBN program. Also equipped with PWR1 engines, this series of four ships (the Resolution class) was admitted to active service between 1968 and 1969.

The 1970s saw the continuation of British SSN programs with the construction of three Churchill-class SSNs followed by a series of six Swiftsure-class SSNs, and finally, during the 1980s, seven Trafalgar-class SSNs. Thus, during the last three decades of the Cold War, the Royal Navy had at its disposal a high-performance nuclear-powered submarine fleet, providing active support to the US Navy in its bid to gain maritime superiority over the Soviet Navy in the Northeast Atlantic. In addition, a British SSN, HMS Conqueror, was the only nuclear-powered submarine to use torpedoes in naval combat during the Falklands War, sinking the Argentinian cruiser Belgrano on May 2, 1982.

French independence

The French Navy, bled dry by the Second World War, made its first attempt to acquire NP in the 1950s, a period that marked the beginning of the rebuilding of its military capacity. However, it took until the 1960s, with the creation of an independent nuclear deterrent force, to bring the attempt to fruition.

The salutary failure of Q244

In 1939, Frédéric Joliot-Curie's team at the Collège de France was working on obtaining a controlled chain reaction from uranium fission. Joliot-Curie's objective was to create a means to generate energy, but he also had in mind the idea of a submarine propulsion device.[19] Subsequently, in the post-war period, the possibility of using atomic energy to propel submarines was raised as early as 1947, amid discussions surrounding the renewal of the French fleet, although it was estimated that it would not be possible before the middle of the following decade.[20]

In 1954, on the initiative of Pierre Guillaumat, then administrator-general of the Commissariat à l'énergie atomique et aux énergies alternatives (CEA) (French Alternative Energies and Atomic Energy Commission), a joint navy-CEA committee was set up to conduct studies on NP. Those concerning the reactor (primary circuit) were entrusted to the CEA, while those relating to the secondary circuit, the steam generator, the propulsion turbines, and the rest of the submarine were the responsibility of the Service technique des constructions et armes navales (STCAN) (Technical Department of Naval Construction and Armaments), at the time attached to the navy.

The decision to build the Q244 submarine was taken in July 1954. In the absence of enriched uranium, and drawing upon French experience with the ZOE reactor that had diverged in 1948, the reactor envisaged was a model that would use natural uranium as fuel and heavy water as coolant and moderator. However, in addition to the problem of the availability of heavy water in sufficient quantities, neutron calculations indicated a low reactivity, leading to the installation of reflectors and an increase in the mass of the reactor and therefore the size of the submarine. In addition, the construction of an onshore prototype, which would have eliminated the risks, was abandoned. Faced with an accumulation of technical difficulties and the lack of any structured organization to manage the project, and taking advantage of US President Eisenhower's announcement in December 1957 on the possibility of supplying enriched uranium, the natural uranium/heavy water option was abandoned. The Agreement for Co-operation on the Uses of Atomic Energy for Mutual Defense Purposes, signed at Washington on May 7, 1959, mandated the transfer to France of 440 kg of U-235 (including 300 kg enriched to 90 percent)[21] for exclusive use in an onshore prototype.

19. B. Goldschmidt, *Pionniers de l'atome*, Paris: Stock, 1987, p. 97.
20. P. Quérel, *Vers une marine atomique, la marine française, 1945-1958*, Brussels: Bruylant, 1997.
21. F. Torres and B. Dänzer-Kantof, *Les Atomes de la mer*, Paris: Le Cherche-Midi, 2022, p. 132.

The failure of Q244 was nonetheless a salutary lesson in both technical and organizational terms.[22] Meeting in May 1959, the Navy-CEA liaison committee proposed the construction of a *prototype à terre* (PAT) (onshore prototype) of a two-circuit PWR using the uranium supplied by the US, and agreed upon the creation within the CEA of a Groupe de propulsion nucléaire (GPN) (Nuclear Propulsion Group) under the supervision of the talented navy engineer Jacques Chevallier, who commanded great authority in the field. Construction of the PAT began in 1960 on a CEA site in Cadarache. From the outset, reliability and nuclear safety objectives were considered essential.[23] The first divergence of the PAT was performed on August 14, 1964, the year in which the Defense Council decided to launch the oceanic component of the deterrent.

A gradual process of improvement

The Redoutable, the first French SSBN, was launched in Cherbourg on March 29, 1967. The first divergence of the reactor was performed on February 26, 1969, with the first sea trials taking place during the summer of 1969. Admitted to active service on December 1, 1971, she began her first operational patrol at the end of January 1972. The Redoutable was followed by five other SSBNs admitted to service in January 1973 (the Terrible), June 1974 (the Foudroyant), December 1976 (the Indomptable), May 1980 (the Tonnant), and April 1985 (the Inflexible).

With the construction of SSBNs proceeding at an accelerated pace, work continued on new boiler concepts, particularly with a view to equipping submarines smaller than SSBNs. The "compact boiler concept", which consists of joining together the tank, steam generator, control rod mechanisms, and primary circulation pumps, results in a reduction in the weight of the radiological protection. Construction of a new prototype reactor, the "Chaufferie avancée prototype" (CAP) (Advanced Prototype Boiler), began at Cadarache in 1971, with the first divergence performed in 1975. The concept of a compact boiler was subsequently applied in all French naval reactor programs, starting with the K-48 boilers fitted to the Rubis-class. These nuclear attack submarines, the smallest in the world, were admitted to active service in 1983.

To sum up, by the end of the Cold War, the French Navy had six SSBNs and four SSNs in operational service, the last two of the Rubis series being commissioned in 1992 and 1994. At the same time, work began on a nuclear-powered aircraft carrier: although plans had initially been made in the 1970s for the development of a helicopter carrier (the PH 75 program), this was abandoned at the turn of the 1980s and replaced by the Charles de Gaulle

22. T. d'Arbonnea (ed.), *Encyclopédie des sous-marins français,* Vol. 3, Paris: Éditions SPE Barthélémy, 2012, p. 163.
23. Lecture series by Yves Bonnet on the design of onboard nuclear boilers, 1993/1994.

project. Construction of the Charles de Gaulle began in 1987, and the ship entered active service in May 2001,[24] thereby ensuring the long-term viability of the nuclear boiler manufacturing technique. Finally, in addition to its independence, the French program was characterized by the fact that the first nuclear-powered ship was a SSBN, not an SSN as in the other three programs studied above. The success of this SSBN program meant that the French Navy could maintain a permanent maritime presence of SSBNs from 1972, with this permanent fleet increasing to three SSBNs in the early 1980s.

Cold War China: An underdeveloped nuclear program

China was the fifth marine power to undertake the development of naval NP, although during the Cold War period this effort went no further than a small sample fleet.

China launched its nuclear-powered submarine program in 1958, shortly after the launch of its nuclear weapons program. Highly enriched uranium (HEU) was reserved for this program, so the decision was taken to use LEU for naval propulsion reactors.[25] An onshore prototype was built, but it was not until 1970 that the first divergence took place. The first nuclear-powered submarine, the Type 091 Han SSN, was first trialed in August 1971, and was admitted to active service in 1974. Its reactor appears to have been derived from the 58 MW OK-150 PWR fitted to the Soviet icebreaker Lenin.[26] It was followed by four others of the same type, which became operational in 1980 and 1992. China's first SSBN, the Xia-class (Type 092), was launched in 1982 and went into operational service in 1987 with the JL-1 ballistic missile (1,700 km range). However, this SSBN did not carry out any operational patrols owing to a number of technical problems and damages incurred.[27]

The long delays between the launch of programs and their initial deliverables owed partly to ideological debates about how nuclear weapons fitted into the Maoist strategy of Protracted People's War, but also to economic and technological delays, along with the disorganization caused by the Great Leap Forward (1958–1962) and the Cultural Revolution (1966–1968).[28]

By the early 1990s, China had commissioned only six nuclear-powered submarines, which were considered to have little operational value.

24. O. Pauly, "En six dates, l'histoire de la construction du *Charles de Gaulle* à Brest", *Ouest-France*, March 12, 2020, www.ouest-france.fr.
25. H. Zhang, "Chinese Naval Reactors", International Panel on Fissile Materials, May 10, 2017, available at: fissilematerials.org.
26. *Ibid.*
27. H. Kristensen, "China's Strategic Systems and Programs", in J. M. Smith and P. J. Bolt (eds.), *China's Strategic Arsenal: Worldview, Doctrine and Systems*, Washington, DC: Georgetown University Press, 2021, p. 108.
28. N. Leveringhaus, "Chinese Nuclear Force Modernization and Doctrinal Change", *Briefings de l'Ifri*, Ifri, August 19, 2022.

Initiatives by non-nuclear weapon states

During the period studied in this section, other states also tried to develop or to acquire NP capabilities for civil or military purposes, without any of them achieving lasting success.

The Federal Republic of Germany (FRG) constructed an atomic-powered cargo ship, the Otto Hahn, equipped with a compact 38MW reactor, which began sea trials in 1970. This cargo ship was initially used to gain experience in the operation of future commercial vessels. It transported phosphate between Morocco and Germany, and took part in several transits to South America. One of the aims here was to strengthen links with Brazil, which hoped to make progress in acquiring and mastering nuclear energy. All of the NP technology was finally removed in 1979, and replaced by conventional diesel propulsion.

At the end of the 1950s, under the impetus of Chancellor Konrad Adenauer and his defense minister, Franz Josef Strauss, the FRG also took an interest in acquiring a nuclear reactor for submarines from the US. Washington responded with a categoric refusal, as the agreements between the Allies following the Second World War only authorized Germany to build small conventional submarines with a maximum tonnage of 350 tones.[29]

In Japan, the government launched a project for a nuclear-powered merchant ship in 1963. Equipped with a 36MW reactor, the Mutsu was launched in 1970, and core loading was completed in September 1972. However, confronted by protests from local residents and fishermen in the port of Ohminato where the Mutsu was nearing completion, the NP tests could not be carried out. After numerous negotiations between the Japanese government, the Japanese Atomic Energy Agency, and the protesters, the decision was taken to tow the Mutsu out to sea to carry out the first divergence, which took place on August 28, 1974. Three days later, as the reactor was approaching maximum power, an alarm went off indicating an increase in radiation, caused by undersized neutron shielding. Media reports of a "radioactive leak" sparked major concerns, and local residents initially refused to let Mutsu return to the harbor. After negotiations, she was able to return to port in mid-October. She remained there before undergoing modifications between 1978 and 1982 in the port of Sasebo, while the entire project was re-examined by the Japanese authorities. Subsequently based in the port of Sekinehama, it was not until 1990 that she undertook new NP tests during three sea trials. The nuclear boiler was finally removed from the Mutsu in 1992.

29. J. Rohweder and P. Neumann, *Quieter, Deeper, Faster: Innovations in German Submarine Constructions*, Hamburg and Bonn: E.S Mittler & Sohn, 2015, pp. 70-72.

Between 1961 and 1969, the Netherlands conducted studies into the development of a reactor, the NERO, designed for use in a container ship. The project never got beyond the initial study stage.[30]

In 1959, Prime Minister Giulio Andreotti announced Italy's intention to build an SSN, the Guglielmo Marconi. In 1963, he announced the aim to build a surface ship with a nuclear reactor for the Italian Navy, and then to build an SSN. A request for help from the US government was turned down. Rickover and the US Naval Reactors office did not wish to transfer the technological secrets of NP, fearing that this would jeopardize American national security, and also felt that Italy did not have the nuclear infrastructure required to carry out such a program. The Italian Navy continued to pursue the Enrico Fermi surface ship project during the 1960s, only to finally abandon it in 1971.[31]

At the end of the Cold War, Canada also turned its sights toward NP. A white paper published in June 1987 envisaged the acquisition of ten to twelve nuclear-powered submarines to enable Canada to assert its sovereignty in the Arctic Ocean. Canada's call for tenders met with responses from the British, with a proposal for a Trafalgar-class SSN, and the French, with a proposal for an Améthyste[32] modified to be able to penetrate pack ice. The French offer was provisionally accepted. However, Canada withdrew its bid in April 1989, partly under pressure from the US.[33]

In conclusion, at the end of the 1980s and beginning of the 1990s, only four countries (the US, Russia, the UK, and France) had mastered NP; a fifth, China, had managed to build some initial units using the technology, although it could not be said to have fully mastered it. Developments for civilian use were not followed up, while attempts by several countries to develop or obtain supplies of nuclear reactors or nuclear submarines met with firm opposition from the US. The very limited membership of this naval NP club can be explained by a number of technical, organizational, and human factors, which will be discussed in the second part of this study.*

30. J. R. Bauman, "Analysis of Past, Present and Future Applications of Nuclear Power for Propulsion of Marine Vehicles", Thesis, Massachusetts Institute of Technology, 1972, pp. 87-89.

31. P. Lobner, "Marine Nuclear Power: 1939-2018, Part 4: Europe & Canada", The Lyncean Project, July 2018, available at: lynceans.org.

32. Named after the fifth Rubis-class SSN, which, at the time of its construction, incorporated major improvements in acoustic discretion, the weapons system, and transmissions.

33. F. Torres and B. Dänzer-Kantof, *Les Atomes de la mer*, *op. cit.*, pp. 362-368.

Lessons from the first age of nuclear propulsion

Aside from the observation that only a limited number of states possess NP, and that these are the nuclear-weapon states (NWS) within the meaning of the Nuclear Non-Proliferation Treaty (NPT), a number of operational, technical, and strategic lessons can be drawn from this initial period.

Operational lessons

The first lessons to be learned, which entirely justify the interest shown in the technology, are primarily operational in nature.

Mobility, endurance, and stealth: Exceptional assets

The operational qualities that NP offers submarines, in particular high-speed mobility for extended periods without the constraint of having to regularly return to periscope immersion in order to recharge batteries, were highlighted at the start of the Cold War. When the Nautilus was first tested, its commander stated that "the results of the tests so far conducted definitely indicate that a complete re-evaluation of submarine and anti-submarine strategies will be required"[34] in view of the performance enabled by NP. Initial exercises with the Atlantic fleet demonstrated the inability of surface ship groups and anti-submarine warfare aircraft to detect and engage the submarine. Comparisons with the most recent conventional Guppy-class submarines reinforced these initial impressions.

These exceptional qualities were demonstrated on a number of distant deployments or operations in areas previously inaccessible to submarines. The first transpolar transit was carried out by the Nautilus in the summer of 1958 between Pearl Harbor (Hawaii) and Portland in Great Britain. That same year, the Skate followed in its wake, and demonstrated the feasibility of submarine operations beneath the Arctic ice pack the year after that. The Soviets also used the deployment of their first SSN, the K-3, to the North Pole, in July 1962 and in October of that same year when it surfaced there, to assert their operational mastery of atomic propulsion.

34. Cited in R. G. Hewlett and F. Duncan, *Nuclear Navy, 1946-1962, op. cit.*, p. 220.

The achievement of an underwater circumnavigation of the globe by a nuclear-powered submarine also served as an operational milestone and a vehicle for strategic communication. The US Navy's Triton was the first to pull off this feat, completing the journey in eighty-three days in early 1960. The Soviets announced that two nuclear-powered submarines, the K-113 (November-class) and the K-116 (Echo II-class), would circumnavigate the globe in 1966.[35]

The operational added value of atomic propulsion had its greatest strategic impact once the principal protagonists of the Cold War had built up fleets of SSBNs. By providing the US, then the USSR, the UK, and France with forces that were virtually invulnerable to a nuclear first strike and themselves unlikely to take part in an anti-forces strike given the mediocre accuracy of the SLBMs they initially carried, SSBNs had a major stabilizing effect between the two blocs. This effect was reinforced when the range of the SLBMs was extended, enabling the SSBNs to patrol areas in which it would be difficult for the enemy to try to track and, if necessary, engage them.

NP, combined with the additional development of atmosphere regeneration systems, which made it possible to extend patrols without the need to return to periscope immersion, are the primary reasons for the invulnerability of SSBNs and their ability to play a leading role in a second strike. This makes a very direct contribution toward achieving the greatest possible technical and operational credibility for nuclear deterrent forces.

The strategic contribution of SSNs

In addition to the contribution of SSBNs to deterrence, SSNs also made a considerable contribution. In the West, American, British, and to a lesser extent French SSNs played a key role in establishing the Atlantic Alliance's naval superiority. Deployed near Soviet naval bases in the Pacific Fleet and the Northern Fleet, American and British SSNs provided close surveillance of Soviet fleet movements, gathering technical intelligence and initiating tracking operations against Soviet units deployed in the Atlantic and Mediterranean and in the Pacific. Soviet SSNs and SSGNs, on the other hand, were the principal option available to Soviet armies in order to challenge this superiority. Deployed in the Atlantic or Mediterranean, they were able to threaten lines of communication and deployments of American aircraft carrier groups.

Submarine surveillance, tracking operations, and even special operations made possible by NP, thus proceeded continuously and discreetly throughout the last three decades of the Cold War. Despite friction and a few collisions, many of which remain confidential to this day, no weapons were used during this period by the various protagonists of the Cold War. The only

35. In reality, this round-the-world expedition proved only partial. On this subject, see L. Gilstov, N. Mormoul, and L. Ossipenko, *La Dramatique histoire des sous-marins soviétiques, op. cit.*

weapon launched by an SSN was HMS Conqueror's torpedo against the Belgrano during the Falklands War, which illustrated the capacity of a nuclear submarine to deploy rapidly at considerable distance from its bases and then to ensure, through decisive combat action, that an opposing surface fleet was denied access to a maritime zone.

The question of surface nuclear propulsion

As far as surface ships are concerned, the operational contribution of NP was demonstrated when the USS Enterprise aircraft carrier was first deployed during the Cuban crisis in 1962, and again when it was deployed during the Vietnam War. Its endurance within an area of operations and its ability to respond rapidly to changes in operational orders was well noted. The ability of a nuclear task force to deploy rapidly and sustainably was demonstrated in 1964 when the USS Enterprise, accompanied by the USS Long Beach and USS Bainbridge nuclear cruisers, circumnavigated the globe in sixty-five days. Despite this operational added value, the question of whether to pursue NP for the US Navy's surface ships was widely debated in the administration and in Congress, for reasons of cost and because of the need for a sufficient number of escort ships. Despite the fact that the range of these escorts would be reduced when using conventional propulsion, the decision was made to reserve NP for aircraft carriers.

Technical lessons learned

Choice of fuel

As indicated in the above historical overviews of its origins, NP was in constant competition with nuclear weapons programs for the use of fissile fuels. The systematic priority given to nuclear weapons programs in the five countries studied has resulted in a time lag in the development of atomic propulsion, and underlines just how central the fuel issue is.

Some NP programs favor HEU (enriched above 20 percent), while others have moved toward technologies using LEU. Both technologies pose potential security and proliferation risks. In a state context, HEU can be diverted from its intended use in NP to be used in a weapons program. If diverted by terrorist or criminal groups, it can be used directly to make dirty bombs. LEU, on the other hand, is a potential source of plutonium, and therefore of material for a nuclear weapon, if a reprocessing plant is available. Any state wishing to be autonomous in either technology must have an enrichment plant.

Since their programs began, American and British naval reactors have used HEU enriched above 90 percent. The use of this technology and the development of new cores has meant that they can use a single core for the entire life of their submarines (around thirty years). These two countries, which currently no longer enrich their own fuel, have stocks of HEU that will enable them to meet the needs of their navies for fifty years in the case of the US, and eighty years in the case of the UK.

The USSR also used HEU for its first naval reactors, but with an enrichment rate of between 20 and 40 percent, except for a few reactors such as the VT-1 which powered the K-27, where the rate was 90 percent. France also began its NP program using HEU. It then switched to LEU cores, with enrichment rates equivalent to those of civil power reactors. This choice was the consequence of the closure in 1996 of the plant intended for the production of HEU for weapons manufacture. The choice of LEU means that the fuel used for these purposes can also be sourced from the civilian market, thereby significantly reducing costs.[36] Finally, it seems that China has been using LEU for its NP programs since they began.

The choice of pressurized water technology

As discussed above, Admiral Rickover planned for the development in parallel of two different reactor systems. The first would use thermal neutrons to maintain the chain reaction and would employ pressurized light water as a moderator and coolant, while the second would use fast neutrons, with liquid sodium as a coolant.

While the fast process had advantages in terms of efficiency and compactness, its technical disadvantages soon became apparent. The violent reaction of sodium with water requires a special device to prevent any leakage from the steam generator. The solution devised for the S1G reactor fitted to the Seawolf was to use double-walled tubes for the steam generator, with mercury between the walls; detection of mercury in the sodium or water would then indicate the occurrence of a leak. This example illustrates the complexity involved in constructing such a fast reactor. In Rickover's own words, these reactors were "expensive to build, complex to operate, susceptible to prolonged shut down as a result of even minor malfunctions, and difficult and time-consuming to repair."[37] The US Navy soon abandoned this technology and switched to the exclusive use of PWRs.

The USSR also experimented with fast neutron technology. Despite the failure of the K-27, the Soviets persisted with FNRs in their Alpha-class SSN series. Their reactor's liquid lead-bismuth coolant required systematic reheating in the event of a shutdown. Special facilities were therefore constructed at the Zapadnaya Litsa base on the Kola Peninsula to heat the primary circuit at dockside and maintain the coolant in a liquid state. Owing to the inadequate reliability of these onshore facilities, the reactors frequently had to remain in operation while in dock. As a result, four out of seven units

36. A. Tournyol du Clos, "France's Choice for Naval Nuclear Propulsion: Why Low-enriched Uranium was Chosen", Federation of American Scientists, June 2016, available at: fas.org.
37. R. G. Hewlett and F. Duncan, *Nuclear Navy, 1946-1962, op. cit.*, p. 273.

had to be withdrawn from active service before their scheduled retirement date owing to problems with this type of reactor. Dismantling these submarines was also complicated because the lead-bismuth mixture trapped the control rods as it solidified. This dismantling, carried out in the 1990s, was only made possible by the use of special tooling supplied by the CEA.

The complexity of implementing a FNR on board a submarine left PWRs as the only option that could be used operationally in complete safety.

Nuclear safety, an absolute imperative

From the outset, the risks[38] inherent in any use of nuclear energy led those responsible for Western naval nuclear programs to place nuclear safety and security at the heart of their concerns. In the early stages of the first NP program, Rickover was already mindful of the dangerous nature of nuclear installations and the importance of nuclear safety from his first days at Oak Ridge in 1946. He fully understood that any nuclear accident on a US Navy ship could have a severe impact upon American public opinion, and would pose a potential threat to the NP program.[39] He succeeded in setting up an organization and procedures to enable the development of propulsion programs, both within industry—in particular Westinghouse, General Electric, and the shipyards mentioned above—and within the Navy. Above all, he selected and trained personnel capable of submitting to the "discipline of nuclear technology".[40]

The succession of nuclear accidents that occurred on board Soviet nuclear vessels, with their consequences for the personnel on board and the environment, indicate, in contrast, how low a priority safety tended to be in Soviet communist culture. Radiation protection on board Soviet submarines was not properly taken into account, leading many Soviet submariners to absorb "considerable doses of radiation, sometimes fatal, often disabling".[41] The USS Thresher accident, which was probably caused by a welding defect in the hull[42] rather than a fault in the reactor or its operation, demonstrated that the expected quality requirements for NP should also apply to all carrier vessels and onshore facilities used in their construction, maintenance, and support.

Nuclear security comprises four elements: safety, radiation protection, prevention of and action against malicious acts, and civil protection measures in the event of an accident.[43] It therefore involves all technical and

38. Specific risks related to radioactivity, high energy concentration in the core, and residual power after reactor shutdown.

39. R. G. Hewlett and F. Duncan, *Nuclear Navy, 1946-1962, op. cit.*, p. 342.

40. F. Duncan, *Rickover and the Nuclear Navy: The Discipline of Technology*, MD, Annapolis: Naval Institute Press, 1989, pp. 279-94.

41. L. Gilstov, N. Mormoul, and L. Ossipenko, *La Dramatique histoire des sous-marins soviétiques, op. cit.*, p. 212.

42. F. Duncan, *Rickover and the Nuclear Navy: The Discipline of Technology, op. cit.*, p. 52*ff*.

43. Article L-591-1 of the French Environment Code.

organizational measures relating to the design, construction, operation, shutdown, and decommissioning of basic nuclear installations and the transport of radioactive substances, all with a view to preventing accidents or limiting their effects. It is based on a three-pronged approach:

- A priori analysis of the potential failures to be considered, so that means to avoid them or to limit their consequences can be worked out and put in place;
- Learning, based upon gathering of feedback from the field;
- Securing mechanisms of last resort to prevent the occurrence of certain beyond-design-basis accidents.

Although nuclear safety does rely on the principle of putting procedures into place, it depends first and foremost upon the men and women who put them into practice. An example cited by Russian engineer Nicolaï Mormoul illustrates this point.[44] During the first ignition of one of the two boilers on the Soviet K-19 submarine (Hotel class) in July 1961, the primary circuit was pressurized without the pressure sensors being connected. The result was an overpressure in the circuit (400 bars instead of 200) which deformed the circuit. The captain did not report this accident. Shortly afterward, during naval maneuvers, a rupture occurred in this circuit, causing loss of coolant in the reactor which then went into alarm. With no emergency injection circuit to evacuate the residual power, the crew had to build a makeshift cooling system. Several sailors who entered the reactor compartment were subject to serious radiation exposure and contamination, seven of them dying in the weeks following the accident, several others some years later. Although procedures must be in place, in themselves they are no substitute for the acquisition of a safety culture.

According to the World Association of Nuclear Operators (WANO), "Nuclear safety culture is defined as the core values and behaviours resulting from a collective commitment by leaders and individuals to emphasise safety over competing goals, to ensure protection of people and the environment."[45] This safety culture may also be defined as "the set of traits and attitudes of organizations and individuals which ensure that issues relating to the safety of nuclear installations and activities receive the priority and attention they deserve given their importance."[46] Safety culture is a collective responsibility, based on two key factors: adequate organization and staff competence. It requires the constant involvement of managers at the highest level of implementation.

44. L. Gilstov, N. Mormoul, and L. Ossipenko, *La Dramatique histoire des sous-marins soviétiques, op. cit.*, p. 221-225.
45. World Association of Nuclear Operators, "PL 2013-1 Traits of a Healthy Safety Culture", May 2013, available at: www.wano.info.
46. French government decree of February 15, 2022, setting the general regulations relative to defense-related nuclear installations and activities, available at: www.legifrance.gouv.fr.

Keys to success in nuclear propulsion

A dedicated and efficient organization

The success of the American NP program in the years following the Second World War owed much to the organization put in place by Admiral Rickover. At a time when the Navy had been sidelined by the Manhattan Project and the new civilian atomic energy agency, and the shipyards had just gone through a period of massive production of ships and submarines, it took all of Rickover's force and pugnacity to bring together all parties into an appropriate organization. The creation of Naval Reactors, an organization headed by Rickover and placed under the dual authority of the office responsible for the Navy's new ship programs (Bureau of Ships or BuShips) and the AEC, was able to rise to the challenge. The secondment of engineers to each laboratory or shipyard reporting exclusively to Rickover completed the system, enabling tight, responsive control, ensuring the success of the program.[47]

In France, the failure of the Q244 project, although owing primarily to an incorrect initial technical choice, also highlighted the weakness of the organization chosen. The decision to provide France with an independent deterrent force made it possible, with strong political will, to overhaul the structures concerned. The first step was Jacques Chevalier's 1959 creation of a group within the CEA, the GPN, which soon became the Département de propulsion nucléaire (DPN) (Nuclear Propulsion Department). The second step was the creation on April 5, 1961, of the Délégation ministérielle de l'armement (DMA) (Directorate General of Armament), which brought together all of the technical and industrial services of the armed forces with three objectives in mind:

- The creation of an independent strategic nuclear force;
- Management of conventional weapons programs;
- A restructuring of the defense industry.

The third step was the creation on June 13, 1961, of the joint project (*œuvre commune*) between the Armed Forces and CEA, which clearly defined the responsibilities of the various organizations under the Ministry of the Armed Forces and the CEA in the management of atomic programs. The fourth and final stage was the creation in 1962 within the DMA of the Coelacanthe organization, designed to manage all programs contributing to the creation of the Force océanique stratégique (FOST) (Strategic Oceanic Force).

It was this organization that made possible the successful conduct of France's deterrence programs, in particular the first of them, that of the

47. See R. G. Hewlett and F. Duncan, *Nuclear Navy, 1946-1962, op. cit.*, in particular chapters 3, 4, and 9.

SSBN Redoutable. It has undergone a number of changes over the years, including the transfer of the NP department to TechnicAtome[48] in 1974 and, in 1994, the creation of the Service technique mixte des chaudières nucléaires de propulsion navale (STXN) (Naval Propulsion Reactors Joint Technical Service), bringing together experts from the DGA,[49] the CEA, and the French Navy. This organizational structure makes it possible to clearly define the responsibilities of project owner and primary contractor, and promotes close proximity between designers, constructors, operational staff, and maintenance managers, with a very high level of safety. In addition, majority state ownership of TechnicAtome means that the NP ecosystem has always remained within the bosom of the French state, leading to close intellectual ties between principal managers in the field, and enabling any technical problems to be resolved quickly.

The imperative of nuclear safety must also be reflected in an organization that clearly defines design and operating responsibilities in all situations involving nuclear-powered vessels or associated onshore facilities (design, construction, operational use at sea and during maintenance periods, decommissioning, and dismantling). Finally, a safety authority independent of designers and operators is needed to validate safety objectives and to monitor safety throughout the life of a nuclear system. These are the organizational principles defined in France by the Defense Code and the Operator's Order (*arrêté exploitant*).

A well-trained workforce

Another key factor was Admiral Rickover's identification of personnel at the outset of the first NP program. He attached particular importance to the training and education of both officers and crews, as well as personnel working in the Naval Reactors organization. Rickover personally met and selected the officers who would go on to operate nuclear submarines and surface ships before being sent off for training, which lasted a year.[50] The professional training of crews was also the subject of particular attention in the Soviet fleet, but alongside the "ideological" disciplines, which were largely responsible for serious errors of command, as in the case of one of the K-19 accidents described above.[51]

The importance of having skilled personnel was also recognized in France from the outset, with the creation in 1956 of the École d'application maritime de l'énergie atomique (School of Maritime Application of Atomic Energy), which later became the École des applications militaires de l'énergie atomique (EAMEA) (School of Military Applications of Atomic Energy),

48. It became AREVA TA in 2006 and TechnicAtome in 2017.

49 La direction générale de l'Armement (Directorate General of Armament) was created in 1977 to replace the DMA.

50. R. G. Hewlett and F. Duncan, *Nuclear Navy, 1946-1962, op. cit.*, p. 216.

51. L. Gilstov, N. Mormoul, and L. Ossipenko, *La Dramatique histoire des sous-marins soviétiques, op. cit.*, p. 217.

located in Cherbourg. The EAMEA provides theoretical and practical training for officers and operators who are responsible for—or are involved in—the running of nuclear boilers on board French Navy vessels. This education system is supplemented by centers in the ports of Brest and Toulon which house simulators on which crews train regularly. Last, a theoretical and practical knowledge test is carried out annually to ensure that the level of the operating teams on board the submarines and the aircraft carrier Charles de Gaulle is up to the standard required by the nuclear industry. First and foremost, the priority here is "ensuring professionalism rather than creating more sophisticated structures and procedures".[52]

This need for highly skilled personnel concerns the entire industry, in particular the government and industrial sectors involved in the design, manufacture, assembly, and maintenance of nuclear-powered vessels and nuclear facilities. These skills in NP have a great deal in common with those of the civil nuclear industry, particularly in the fields of metallurgy, thermodynamics and thermohydraulics, neutronics, and fluid mechanics. However, they differ because of the specific characteristics of a combat vessel: its small size, which complicates radiation protection requirements given the presence of crews close to the reactors, platform movement, significant speed variations, shock resistance,[53] and so on.

While the existence of a strong civil nuclear industry in the scientific, technological, and industrial fields favors the development of NP, it alone cannot guarantee its existence and the maintenance of skills in these specific fields without a continuous effort. For example, small modular reactor (SMR) programs encourage synergies, particularly within industry, and consolidate NP. However, they do not allow us to maintain NP-specific knowledge and skillsets. Continuity in the implementation of NP programs, particularly as regards the design of onboard boilers, is vital to guarantee the technical credibility of the nuclear deterrent, as is the knowhow of subcontractors.[54]

In conclusion, given their added operational value, nuclear-powered vessels remain one of the foundations of naval power in the first part of the twenty-first century. In a context of pronounced naval rearmament, this capability will gradually come to interest a greater number of navies. The imperative of nuclear safety, of ensuring a responsible organization, and of maintaining a sufficient skills base to operate and maintain them, will remain major challenges for new entrants.

52. Remarks by Michel Crozier, sociologist, quoted by Admiral Casabianca at the inaugural session of the EAMEA on October 26, 2022.

53. Interview with Laurent Sellier, Director of Naval Propulsion, CEA/Direction des applications militaires (DAM) (Military Applications Division), October 21, 2022.

54. Minutes of the in-camera hearing of F. Jacq, administrator-general of the Commissariat général à l'énergie atomique et aux énergies alternatives (CEA) (French Alternative Energies and Atomic Energy Commission) and V. Salvetti, director of Military Applications, CEA, on nuclear deterrence, National Defense and Armed Forces Commission, National Assembly, January 18, 2023.

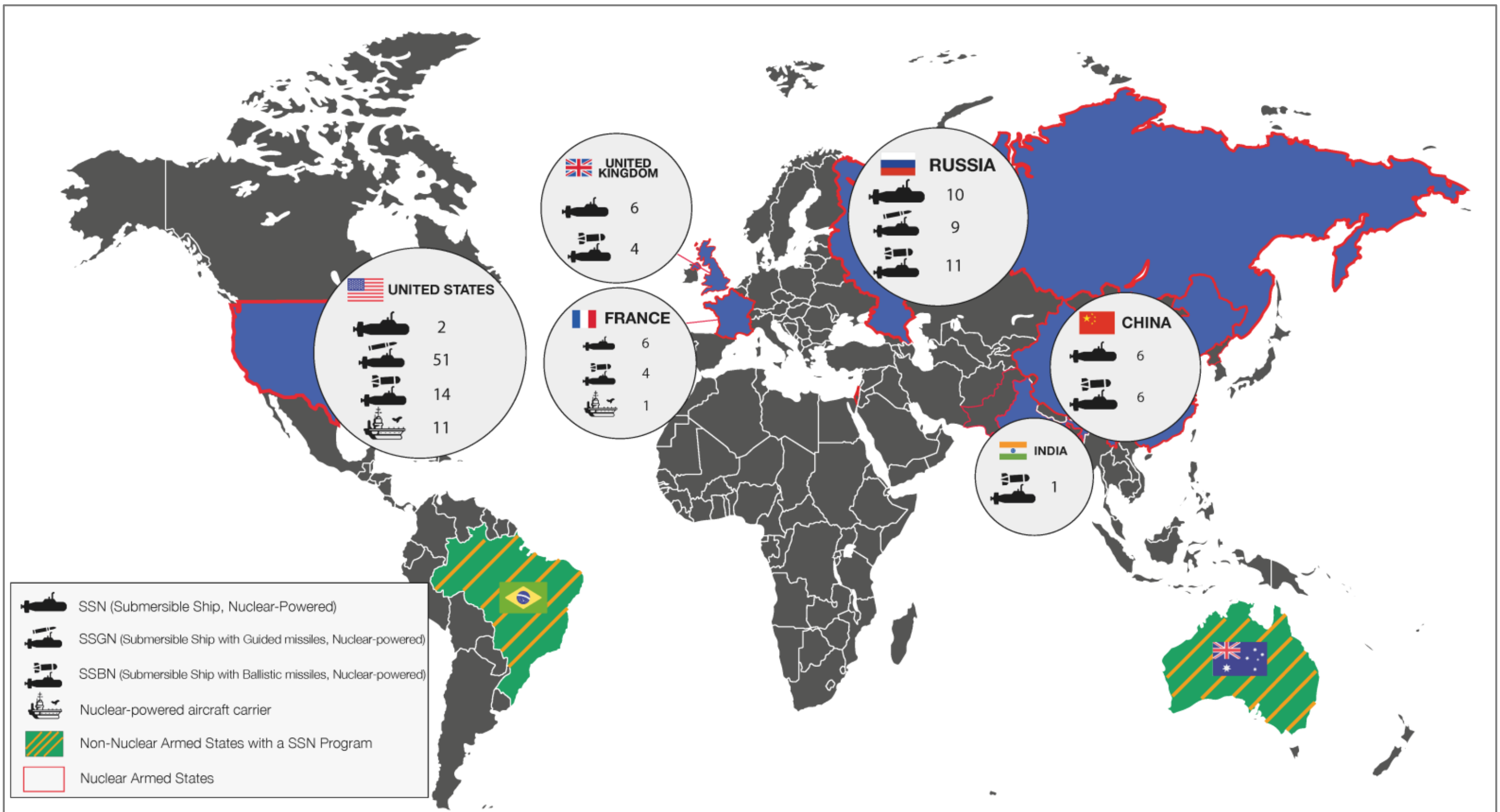
Nuclear propulsion in the twenty-first century

During the Cold War, NP seemed to be the sole prerogative of NWSs because of the stringent technical requirements and the use of a common fuel by nuclear weapons and boilers. The turn of the millennium, however, saw an expansion of NP technology with the emergence of several new programs, mainly in Asia. Although no concrete plans have yet emerged (with the exception of India), the issue of technology sharing, or even autonomous acquisition, particularly by non-nuclear-weapon states (NNWSs), seems to be a current concern once again.

The strategic landscape is being altered by recent technological developments—above all by the spectacular rise of the Chinese Navy. It was largely in response to this challenge that the tripartite defense cooperation agreement between Australia, the UK, and the US (AUKUS) was signed in September 2021, providing, among other things, for the delivery to Australia of a fleet of nuclear-powered submarines.

This new context raises the question of the political, strategic, industrial, and even legal and security implications of the transfer of this technology. It naturally raises questions about the future decisions of other major players such as India, Japan, the Korean peninsula, and Brazil. Finally, it requires a rethinking of the IAEA's standards for combating nuclear proliferation.

Nuclear naval propulsion in the world in 2023



Source: Military Balance 2023.

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Continuation and adaptation of NP among historical actors

Post-Cold War adaptations

The break-up of the USSR in 1991 and the end of the Cold War led to significant reductions in the size and breadth of the nuclear fleets of the four states with NP capabilities. In the US, around twenty Lafayette- and Benjamin Franklin-class SSBNs were decommissioned between 1989 and 1995, while France reduced its SSBN fleet from six to four units, and limited its Rubis-type SSN fleet to six units instead of the eight initially envisaged.

However, these reductions in scale were accompanied by a stronger nuclearization of the fleets along with the continuation of already-launched programs. The UK and France decommissioned their conventionally powered submarines in the 1990s and 2000s.[55] France also acquired a nuclear-powered aircraft carrier, the Charles de Gaulle, in the early 2000s,

55. France did, however, temporarily recommission a conventional submarine, the Ouessant, to train Malaysian submariners.

and commissioned four Triomphant-class SSBNs between 1997 and 2010, all equipped with 150MW K-15-type boilers. The US switched to a fully nuclearized fleet of aircraft carriers in 2005 with the withdrawal of the USS Kennedy from active service, and adapted its submarine fleet. Four Ohio-class SSBNs were converted into cruise-missile submarines (SSGNs), each carrying 154 Tomahawk missiles. The new Seawolf class of SSNs, designed for the Cold War, was limited to three units and replaced by the Virginia class, better suited to the new context.

In the UK, there have been a number of difficulties in maintaining NP, which have only been resolved by increasing the UK's dependence upon its American partner. The construction of the first Astute-class SSN at BAE Systems yard in Barrow-in-Furness was delayed by the decline in domestic engineering skills. The arrival of around a hundred American engineers and technicians from General Dynamics Electric Boat enabled a successful relaunch of the program.[56] Following expert reports attesting to the vulnerability of the PWR2 reactors that powered the SSBN Vanguard and SSN Astute, in particular in the event of a leak in the primary circuit, the choice of reactor for the third-generation Dreadnought-class SSBNs moved to the PWR3 reactor, derived from the S9G reactor that powers the American Virginia SSNs.[57]

In France, the sequence of programs for the SSBN Triomphant, the SSN Suffren (with a K-15-derived boiler system), the RES[58] onshore reactor and, by 2035, a third-generation SSBN (also equipped with a K-15-derived boiler system) ensures that the expertise of TechnicAtome and Naval Group, along with that of their subcontractors, will be maintained over the long term. Work on the K-22 boilers which, by 2038, will equip the future next-generation aircraft carrier (Porte-avions de nouvelle generation; PA-NG), is also helping maintain design skills. An important concern here is to ensure that the teams are able to bridge the gap between initial design and commissioning, and to provide feedback on the process that will be useful in future.[59]

The upheavals that followed the end of the Cold War had a major impact on the Russian fleet, particularly its submarine fleet, which faced industrial difficulties both in the design of new types of submarines and in the construction of new units and the maintenance of existing ones. Nuclear submarine deployments became rare during the 1990s and early 2000s. For example, the Russian Navy was unable to deploy nuclear-powered units during the Kosovo crisis in spring 1999. The SSGN Kursk was not deployed to the Mediterranean until the summer, after the crisis had been resolved. The most dramatic moment during this period was the sinking of the Kursk

56. J.F. Schank *et al.*, "Learning from Experience: Lessons from the United Kingdom's *Astute* Submarine Program", RAND Corporation, 2011, available at: www.rand.org.
57. C. Mills, "Replacing the UK's Strategic Nuclear Deterrent: Progress of the Dreadnought Class", House of Commons Library, May 3rd, 2023, available at: commonslibrary.parliament.uk.
58. The RES, or *Réacteur d'essais à terre* (land-based test reactor), is a pressurized water reactor.
59. Interview with Loïc Rocard, CEO of TechnicAtome, October 25, 2022.

a year later. While Western countries offered to help rescue the few submariners still alive, President Putin refused, sealing the submariners' tragic fate.[60]

The 2010s saw the beginnings of a renewal of the Russian fleet, with the commissioning in 2013 of the SSGN Severodvinsk, the first of the Yasen class, and the first Borei-class SSBN.

More stringent requirements

The withdrawal from active service of the first generations of nuclear-powered vessels, accelerated by the end of the Cold War, has brought to light a new challenge, that of their dismantling. The Americans were the first to set up a program to tackle this issue in 1992: the Ship-Submarine Recycling Program (SRP). France also began to dismantle its first Redoutable-class SSBNs in the early 1990s, disassembling the cores and removing the reactor compartments, which are treated using specialized procedures. Dismantling of the hulls began in 2018.

The British, on the other hand, were later to the party. As a result, twenty submarines, nine of which had yet to be defueled, were awaiting dismantling at the beginning of 2019.[61] A program, the Submarine Dismantling Project, was finally launched by the UK in 2021.[62]

The management and dismantling of the legacy of the Soviet nuclear fleet required a vast international effort, led in particular by Norway, the G7 member states, and the European Union (EU), all of which provided the necessary funding. This effort led to the dismantling of nearly two hundred ex-Soviet nuclear submarines and the securing of large stocks of nuclear waste.[63] Despite this action, the fate of several wrecks or nuclear compartments that were deliberately submerged, particularly near New Zealand, remains a cause for concern, as in the case of the K-27 submarine (see above). While Russia pledged to undertake the refloating of this wreck in spring 2021 at the start of its chairmanship of the Arctic Council, the invasion of Ukraine and the ensuing Western sanctions could jeopardize this prospect.[64]

In addition to the dismantling of nuclear units and associated onshore facilities, this period has been marked by the strengthening of nuclear safety requirements, at least in Western navies. These requirements apply not only

60. Z. Barany, "The Tragedy of the Kursk: Crisis Management in Putin's Russia", *Government and Opposition,* Vol. 38, No. 3, 2004, pp. 476-503.
61. UK Government National Audit Service report, "Investigation into Submarine Defueling and Dismantling", April 3, 2019, available at: www.nao.org.uk.
62. "Project to Dismantle Ex-Royal Navy Nuclear Submarines Inches Forward", Navy Lookout, February 7, 2022, available at: www.navylookout.com.
63. C. Digges, "Norway and Russia Mark 25 Years of Cooperative Work on Radiation Security", Bellona, October 4, 2021, available at: bellona.org.
64. C. Digges, "Will Russia raise its sunken subs now that it has invaded Ukraine?", Bellona, December 5, 2022, available at: bellona.org.

to onboard reactors, but also to infrastructure, particularly following the tsunami of March 2011 and its aftermath at Fukushima. For example, the new infrastructure renovation programs for new nuclear units, such as those at the Toulon naval base for Suffren-class SSNs, now take into account the more stringent requirements regarding the risks generated by exceptional environmental events (tsunamis, earthquakes, flooding, etc.).[65]

This increased awareness of seismic risks led the US Navy to temporarily close four dry docks used for nuclear submarine maintenance, in Puget Sound and at the Bangor Naval Submarine Base in Washington State, at the beginning of 2023.[66]

The rise of China

Of no operational value up until the end of the twentieth century, China's nuclear-powered submarine fleet has gradually gained momentum. The entry into active service in 2010 of four Jin-class (or Type 094) SSBNs, equipped with two 75MW reactors each,[67] stationed at the partly underground Longpo base on the island of Hainan in the South China Sea, gave Beijing second-strike capability for the first time. However, this remains limited by the range of its JL-2 missile, estimated at around 7,000km, making it impossible to target US territory from patrol zones close to China. In addition, the Jin's lack of discretion would render it vulnerable if deployed in the eastern Pacific.[68] This series is set to be extended to six units. It will be followed by a new class of SSBN, Type 096, intended to be equipped with a new missile, the JL-3, with an estimated range of between 10,000 and 12,000 km and fitted with a single reactor and a pump-jet propulsion system to improve acoustic discretion.[69]

The Chinese Navy's SSN fleet has also been strengthened by the entry into service of six Type-093 Shang-class submarines, also equipped with two 75MW engines each, replacing the Han class. Initially limited to six units produced between 2002 and 2023, construction appears to have accelerated, with an eighth Type-093 SSN entering production in January 2023.[70] However, the pace remains fairly slow, perhaps reflecting the limitations of

65. N. Cuoco, "'On change de siècle…'. À Toulon, les infrastructures de la base navale se modernisent", *Var Matin*, September 19, 2022.
66. S. La Grone and M. Shelbourne, "Navy Closes 4 Puget Sound Submarine Dry Docks Following Earthquake Risk Study", *USNI News*, January 27, 2023, available at: news.usni.org.
67. C. P. Carlson and H. Wang, "China Maritime Report No. 30: A Brief Technical History of PLAN Nuclear Submarines", U.S. Naval War College, August 2023, p. 18.
68. H. Kristensen, "China's Strategic Systems and Programs", p. 109.
69. C. P. Carlson and H. Wang, "China Maritime Report No. 30: A Brief Technical History of PLAN Nuclear Submarines", p. 19.
70. C. Biggers, "China Launches Second Possible Type 093B Hull", Janes, February 1, 2023, available at: www.janes.com.

China's sole nuclear-powered submarine construction yard at Bohai, which is also responsible for building the SSBNs.[71]

Finally, the construction of a nuclear-powered icebreaker was announced back in 2018, but information on this project remains scarce.[72] A reactor developed for an icebreaker could also be used in the future for a nuclear-powered aircraft carrier project.[73]

New players

As a result of the rise of the Chinese Navy,[74] the emergence of new challenges in the Indo-Pacific and, more prosaically, the great distances to be covered, most of the new countries that have become interested in NP to date have been in Asia, with the exception of Brazil and Canada,[75] which had already begun the process of acquiring NP in the late 1980s.[76] The European countries interested in NP during the Cold War (Germany and Italy) eventually turned to diesel-electric propulsion, Berlin having developed sufficient expertise to offer its own TKMS submarines—designed by ThyssenKrupp Marine Systems—for export, particularly to Italy, but also to Greece, Portugal, Turkey, Norway and Israel.[77]

The Indian exception

India is still the only non-signatory to the Non-Proliferation Treaty (NPT) to have nuclear-powered submarines, namely two Arihant-class SSBNs. These two vessels complement a sizable fleet of diesel-electric attack submarines, with seventeen units currently in service, of three different classes: the Shishumar class, developed jointly by India and Germany, the Sindhughosh class derived directly from the Kilo class developed by the Soviet Union and then Russia, and finally the Kalvari class, adapted from the Scorpène, a conventionally powered submarine designed by France's Naval Group for export. The six Scorpène submarines scheduled under the contract signed in

71. H. I. Sutton, "Chinese Navy Type 093 Shang Class Submarine", Covert Shores, December 10, 2020, available at: www.hisutton.com.
72. T. Eiterjord, "Checking Back in on China's Nuclear Icebreaker", *The Diplomat*, February 13, 2023, available at: thediplomat.com.
73. G. Honrada, "China's Next Aircraft Carrier Likely to be Nuclear", *Asia Times*, October 10, 2022, available at: asiatimes.com.
74. In the space of twenty years, the Chinese navy has gone from being a brown-water to a blue-water navy, with an estimated growth in tonnage of 138 percent between 2008 and 2030. See in particular "Le réarmement naval dans le monde", Études marines, Centre d'études stratégiques de la Marine, January 2023.
75. T. Choi and C. Spedding, "Canadian Submarine Recapitalization within the Context of Climate Change", *BASIC*, November 2022, available at: basicint.org.
76. There has also been interest from Poland, which wishes to relaunch its conventional submarine acquisition program, but without ruling out the choice of nuclear propulsion, even though its strategic interest would be reduced. See T. Grotnik, "Orka Reactivation—Which Submarines for Poland?", Naval News, June 1, 2023, available at: www.navalnews.com.
77. V. Groizeleau, "Fincantieri lance la construction du nouveau sous-marin italien", Mer et Marine, January 13, 2022, available at: www.meretmarine.com.

2005 have now been launched, the last of which, the Vagsheer, was launched in April 2022. However, the French shipbuilder has decided to withdraw from the tender to supply the successors to the Kalvari class within the framework of the P-75(I) project,[78] although it is still involved in helping Indian manufacturers to modernize and maintain the existing Kalvari vessels.[79]

While the plan to acquire a fleet of nuclear-powered submarines dates back to the origins of India's nuclear weapons program in the 1970s, the development of the first SSBN as part of Project Varsha was much more slow-going, and external assistance was required. Just as the British received support from the US to develop their first submarine, so India received substantial support from Russia, enabling Moscow to undermine American influence in Asia and help one of China's competitors to develop.[80] In 1981, an assistance agreement was signed between the Soviet Union and India to help the latter develop nuclear naval propulsion. This collaboration took the form of skills-sharing and the training of Indian atomic scientists by their Soviet counterparts, as well as the delivery, in 1988, of a Soviet SSN, the INS Chakra, which was transferred to the Indian fleet. Indian shipbuilders drew inspiration from this design, again with Soviet help, for INS Arihant, the first Indian-built SSBN, equipped with twelve K-15 Sagarika SLBMs with a range of 750 km.[81]

This vessel was launched in 2009, but numerous incidents involving damage, technical difficulties, and accidents delayed its entry into service: a divergence of the reactor was not achieved until July 2013, and the INS Arihant did not carry out its first operational patrol, described by Prime Minister Narendra Modi as a "deterrent patrol", until November 2018. Construction of the second Arihant-class submarine, the INS Arighat, was launched in 2017, and is expected to enter active service in 2024. More powerful than the Arihant, it is designed to carry four Agni-III/K-14 SLBMs with a range of 3,500 km. Two other Arihant-class SSBNs are planned for the 2020s, while work on the second generation of strategic submarines was launched in 2017. The latter includes three submarines armed with between twelve and sixteen K-6 multiple independently targetable reentry vehicle (MIRV)-capable missiles, bringing the Indian strategic submarine fleet to seven units by 2040.[82]

78. Not to be confused with Project 75 Alpha, which concerns the delivery of SSNs. See L. Lagneau, "Le français Naval Group se retire de l'appel d'offres lancé par l'Inde pour six sous-marins supplémentaires", Zone Militaire, May 1, 2022, available at: www.opex360.com.
79. V. Raghuvanshi, "Indian Lab Teams Up with France's Naval Group on Submarine Tech", Defense News, January 24, 2023.
80. K. R. Bolton, "Indo-Russian Defence Cooperation and *INS Arihant*: Some Geopolitical Implications", *World Affairs*, Vol. 17, No. 1, 2013.
81. E. Maitre, "Où en est la composante océanique indienne?", *Bulletin de l'Observatoire de la dissuasion*, Vol. 72, Fondation pour la recherche stratégique, January 2020, available at: www.frstrategie.org.
82. *Ibid.*

Finally, India is also seeking to strengthen its nuclear attack submarine capability: while the two vessels once on loan from the Soviet Union have been withdrawn from service—the INS Chakra I in 1991 and the INS Chakra II in 2021[83]—Project 75 Alpha envisages India building six SSNs of its own, while the Russian Akula-class SSN, approved for lease by New Delhi in 2019 at a cost of $3 billion, is expected to join the Indian Navy by 2025.[84] Although India's ambition is to build these SSBNs and SSNs independently, it is not clear whether it has the human and technical resources to do so, given the slow pace of the program. In the wake of the AUKUS announcement, some Indian analysts have nudged France toward a closer collaboration, arguing that the partnership had "opened the door" for Paris and New Delhi to move into technology transfer and go beyond the delivery of Scorpène-class conventional submarines.[85]

With this fleet, India therefore has a complete nuclear triad, enabling it to increase the effectiveness of its deterrent tenfold to cover all regional threats, in particular Pakistan but also China, while retaining a second-strike capability. This triad is part of a doctrine of "minimum deterrence", in line with its rather limited arsenal, and a no-first-use policy, which is however being increasingly called into question in Indian strategic debates.[86]

Pakistan's interest in NP, possibly with Chinese help, is also growing: Islamabad does not currently have an SSBN, and there is growing criticism of the credibility of its nuclear-tipped cruise missiles, which can be carried on its conventional submarines.[87]

Japan, South Korea, and Australia: The other temptations of the Indo-Pacific

India is the only other Asian country apart from China to have nuclear-powered submarines, but the People's Liberation Army (PLA)'s naval rearmament and growing instability in East Asia are also prompting the middle powers to consider acquiring nuclear-powered SSNs.

There are fierce debates on the subject in Japan, following, as we saw above, initial research in the 1950s. The signing of the AUKUS agreement, which coincided with the election campaign to appoint the leader of the ruling party, and therefore the new Japanese prime minister, Fumio Kishida, who took office at the end of September 2021, has led to a clear resurgence of interest in the public debate. While expressing his support for Australia's project, he was cautious, even opposed, to Japan's acquisition of

83. "INS Chakra (II)", Red Samovar, November 27, 2021, available at: redsamovar.com.
84. F. Torres and B. Dänzer-Kantof, *Les Atomes de la mer, op. cit.*, p. 476.
85. V. Robert, C. Dieterich and A. Bauer, "Après la crise des sous-marins, l'Inde cherche à ménager la France", *Les Échos*, September 23, 2021.
86. S. Kaushal *et al.*, "India's Nuclear Doctrine: The Agni-P and the Stability-Instability Paradox", RUSI, July 8, 2021, available at: rusi.org.
87. S. Ullah, "Strategic Calculation Behind Pakistan's Pursuit of Sea-Based Nuclear Deterrence", South Asian Voices, June 11, 2020, available at: southasianvoices.org.

a nuclear-powered submarine, arguing that it was not a priority issue,[88] a position confirmed by his defense minister. On the contrary, some of his opponents were in favor of the project, claiming that this capability would increase Japan's capacity for "deterrence"—even if the submarines were not equipped with nuclear weapons—and implying that technology transfer from the US to Japan was now possible thanks to the AUKUS precedent. More broadly, several Japanese analysts and op-ed writers are even calling for their country to be included in the agreement, which would enable it to develop a more resolutely Asian dimension while opening up the field of possibilities to Japan.[89]

At this stage, however, it seems unlikely that Japan will move toward acquiring a nuclear-powered submarine. First of all, the defense budget remains limited: despite the Kishida government's decision to cast off a political convention dating back to 1974 that capped defense spending at 1 percent of GDP, it is not clear whether the planned increase to 2 percent will be sufficient to begin a costly program for the development or acquisition of NP.[90] In addition, Japan's fleet of conventionally powered submarines, comprising twenty-two vessels, is considered one of the best in the world, with the recent commissioning of the Taigei class to replace the Soryu class.[91] The current missions assigned to this fleet, that is, the defense of Japanese national territory in accordance with the "peaceful" Japanese Constitution, are therefore being properly fulfilled, with no obvious need to move toward NP.

However, should Japan ever wish to enter into strategic competition with China and, for example, carry out joint patrols with the American SSNs deployed in the region, the question would probably arise again. Similarly, if the transfer of nuclear-powered submarines to Australia by the US is completed, Japan would then be the only country in the Quadrilateral Security Dialogue (QUAD) not to have NP, once again increasing the imbalance between the members of this alliance (US, India, Australia, and Japan).

Similar considerations are making waves in South Korea, where interest in nuclear-powered submarines dates back to the 2000s and the discovery of a secret uranium enrichment and NP research program, which was halted in 2004 owing to fears about the proliferation of material. However, interest has never waned and, during his 2017 presidential campaign, former South Korean President Moon Jae-In demonstrated his determination to acquire

88. "In Debate, Kishida Voices Caution on Japan Acquiring Nuclear Sub", *The Japan Times*, June 19, 2022, available at: japantimes.co.jp.
89. "AUKUS Sub Deal Is One Pillar of Regional Security", *The Japan Times*, March 17, 2023, available at: www.japantimes.co.jp.
90. C. Pajon, "Nouvelle stratégie de sécurité et de défense au Japon. Comment dit-on *Zeitenwende* en japonais?", *Lettre du Centre Asie*, No. 101, Ifri, December 19, 2022.
91. C. Lee Bell, "Is Japan Likely to Acquire Nuclear Powered Submarines?", *Australian Defence Magazine*, February 24, 2022, available at: www.australiandefence.com.

nuclear-powered submarines for South Korea by sharing knowledge with the US, and even to develop these skills domestically if such negotiations fell through.[92] Similar reasoning is in evidence on the question of nuclear weapons, with President Yoon Suk-yeol unhesitatingly threatening to develop an arsenal if confidence in US security guarantees against North Korea is lost, prompting the US to make further shows of reassurance in spring 2023 (see below).[93] Meanwhile, surveys indicate that 71 percent of the South Korean population would be in favor of developing a national military nuclear program.[94]

This desire comes largely in response to the flurry of nuclear activity in North Korea, which is stepping up tests of SLBMs and is reportedly currently developing its own nuclear-powered submarine, to add to an already substantial fleet of sixty to eighty conventionally powered submarines.[95] In September 2023, Pyongyang also presented a diesel-electric submarine capable of carrying nuclear ballistic and cruise missiles, confirming their desire to acquire a second-strike capability.[96] This increase in the North Korean threat, along with the development of China's arsenal, have prompted Seoul to reinforce American security guarantees, including through exercises and strategic signaling: the beginning of 2023 saw a renewal of the alliance between the two countries, an increase in the number of joint maneuvers between South Korea and the US, and an American SSN calling into a Korean port,[97] followed by an SSBN.[98] Finally, "techno-nationalist" competition with Japan appears to be another motivation for Seoul, which is keen to go further than Tokyo along the road to NP.

However, as in the case of Japan, there are many obstacles to the development or acquisition of nuclear-powered submarines by South Korea. The objective of denuclearizing the Korean peninsula, as set out in the 1992 joint declaration by North and South Korea,[99] would appear to be incompatible with the kind of uranium enrichment program necessary for the development of NP, even if South Korea were to opt for LEU as France

92. G. Honrada, "South Korea Has Nuclear Subs Firmly in Its Sights", *Asia Times*, June 6, 2022, available at: asiatimes.com.
93. A. Panda, "The Washington Declaration Is a Software Upgrade for the U.S.-South Korea Alliance", Carnegie Endowment for International Peace, May 1, 2023, available at: carnegieendowment.org.
94. J. Mohan, "Nuclear Weapons Gaffe in South Korea Is a Warning to Leaders Everywhere", *The Bulletin of Atomic Scientists*, March 15, 2023, available at: thebulletin.org.
95. L. Kim, "A Race for Nuclear-Powered Submarines on the Korean Peninsula?", The National Bureau of Asian Research, March 31, 2021, available at: www.nbr.org.
96. T. Rogoway, "North Korea's Diesel-Electric Ballistic Missile 'Frankensub' Emerges", The Drive, September 7, 2023, available at: www.thedrive.com.
97."US nuclear-powered Submarine Arrives in South Korea Amid North Provocations", *The Korea Times*, February 26, 2023, available at: www.scmp.com.
98. H. Mongilio, "USS Kentucuky Make Port Call in South Korea, First SSBN in 40 Years", USNI News, July 18, 2023, available at: news.usni.org.
99. The Joint Declaration of the Denuclearization of the Korean Peninsula committed both North and South Korea not to possess, manufacture, or use nuclear weapons, and prohibited the enrichment of uranium and the reprocessing of plutonium. While North Korea is clearly in breach of this agreement, South Korea is not—yet.

has done. Although restrictions on the sharing of sensitive nuclear technologies between the US and South Korea were recently eased when Seoul joined the US small modular reactor program,[100] fears of proliferation remain high. Similarly, the operational value of NP for South Korea, which already has nineteen conventional submarines,[101] is limited: they are capable of effectively carrying out their conventional deterrence missions against North Korea, and Seoul has not yet positioned itself in the kind of strategic competition in the South China Sea that would require the acquisition of NP.

Faced with China's growing power, Australia is also positioning itself to acquire nuclear attack submarines through the AUKUS partnership announced in September 2021. In addition to increased intelligence sharing and partnerships on official intelligence and quantum technology, the core of the agreement is the supply of SSNs to Australia, according to a plan presented in March 2023 by the US president and the British and Australian prime ministers.[102] Initially, Australian military and civilian personnel are to be seconded to the British and American submarine forces, as well as their industrial bases, enabling the Australian Navy to acquire familiarity with NP. From 2027, a rotation of British (Astute-class) and American (Virginia-class) submarines is planned within the Australian submarine base in Perth, again as part of this knowledge-transmission process and the building of a skilled Australian workforce for future maintenance of its own vessels. The final two stages of the partnership involve the sale of three American Virginia-class submarines to Australia, which would then be operated independently by the Australian Navy, and finally the co-construction of the AUKUS class, combining a British hull—for which BAE Systems won the tender in October 2023[103]—and American technology. This class of SSN would then enter into service with the Australian and British navies.

While this partnership, in which NP appears as an "active core with a strategic dimension in its own right",[104] sends strong signals to China (who were quick to voice their opinion on the matter),[105] many questions remain unanswered about the feasibility of such a maneuver, on the technical, budgetary, and above all on the human resources level. As demonstrated during the first age of NP, this technology requires highly qualified personnel and a shared nuclear safety culture, which would surely be difficult to acquire in a country without a nuclear scientific and industrial base. It also requires

100. The Foundational Infrastructure for Responsible Use of Small Modular Reactor Technology (FIRST) program. See "United States–Republic of Korea Leaders' Joint Statement", The White House, May 21, 2022, available at: www.whitehouse.gov.

101. "South Korea Submarine Capabilities", The Nuclear Threat Initiative, October 7, 2022, available at: nti.org.

102. "Fact Sheet: Trilateral Australia-UK-US Partnership on Nuclear-powered Submarines", The White House, March 13, 2023, available at: www.whitehouse.gov.

103. D. Afanasieva, "BAE Systems Wins £4 Billion UK Contract for Nuclear Submarines", Bloomberg, October 1, 2023, available at: www.bloomberg.com.

104. F. Torres and B. Dänzer-Kantof, *Les Atomes de la mer, op. cit.*, p. 434.

105. N. Camut, "China warns AUKUS: You've Gone Down a 'Dangerous Road' with Nuclear Subs Deal", Politico, March 14, 2023, available at: www.politico.eu.

a well-developed industrial base, with adequate long-term resources, which Australia does not currently have and which seems too complex a thing to develop in less than ten years.[106] What is more, the budget estimates are substantial: the project would require an investment of 240 billion Australian dollars up to 2055, which would probably mean cuts in other military areas that could also be useful for strategic competition against China.[107] In the US, the Strategic Posture Commission (SPC) highlights the strain that this additional submarine production will place upon the US naval industry, called upon to build one Columbia-class submarine a year, to support the Virginia-class production effort, and to maintain the Ohio class, all with common infrastructure.[108]

Regionally, the countries of the South Pacific, marked by past nuclear tests whose consequences for the environment have still not been properly assessed, are exhibiting a degree of concern about the project.[109] Last, while the risks of nuclear proliferation are minimal, if not non-existent, in relation to Australia, this decision does set a precedent in terms of the transfer of military nuclear technology to a country that does not possess nuclear weapons (see below).

Iran, a potential candidate?

Iran, whose proliferative tendencies now speak for themselves, has also confirmed that it wishes to develop nuclear-powered submarines: statements by officials from the Iranian Navy,[110] the Revolutionary Guard, and the Atomic Energy Organization of Iran (AEOI) to this end have been issued repeatedly since 2012.[111] Likewise, in 2018, Iran sent a letter to the IAEA, informing it of its desire to develop such a program, without involving any nuclear facilities in the first five years.[112] This capability would complement an already substantial fleet of conventionally powered submarines (seven diesel-electric attack submarines and twenty-seven mini-submarines), some of which would be capable of firing cruise missiles. Iran has also reportedly retrofitted a Russian Kilo-class conventional submarine to demonstrate its advanced technological capabilities.

106. J. Edwards, "The Limits on Australia's Submarine Industry", *The Interpreter*, March 17, 2023, available at: www.lowyinstitute.org.
107. M. Ryan, "AUKUS Submarine Agreement: Historic but Not Yet Smooth Sailing", Center for Strategic & International Studies, March 17, 2023, available at: www.csis.org.
108. "America's Strategic Posture: The Final Report of the Congressional Committee on the Strategic Posture of the United States", October 2023, available at: armedservices.house.gov.
109. M. Keen, "AUKUS in the Pacific: Calm with Undercurrents", *The Interpreter*, March 20, 2023, available at: www.lowyinstitute.org.
110. O. Heinonen, "Nuclear Submarines Program Surfaces in Iran", Power & Policy Blog, July 23, 2012, available at: www.belfercenter.org.
111. "Iranian Navy: Building Nuclear-Powered Submarine is a 'Top Priority'", *Naval Today*, April 16, 2020, available at: www.navaltoday.com.
112. "Iran Looking to Build Nuclear Submarines, Watchdogs Say", *The Times of Israel*, February 23, 2018, available at: www.timesofisrael.com.

However, at this stage, it is unlikely that Iran will be able to access NP in the short term;[113] any submarines designed would in any case only be able to carry conventional missiles, as Tehran has not (yet) developed missiles with nuclear warheads. Nevertheless, the burgeoning relationship between Iran and Russia as a result of the war in Ukraine could eventually lead to Moscow providing technical assistance to Iranian scientists to develop a submarine, or even delivering a functional vessel, along the lines of the Russian-Indian partnership.

Brazil: A long-standing interest

Finally, to conclude this overview of NP in NNWSs, it is of interest to look at the case of Brazil. Having developed a civilian nuclear program in the 1950s through Atoms for Peace, Brazil briefly attempted to militarize this program in the 1970s and 1980s, in the combined context of a military junta in power and growing rivalry with Argentina.[114] Although ambitions to develop a military nuclear program came to an end in the 1990s with the signing of the Tlatelolco Treaty in 1994 (which made South America a nuclear-weapons-free zone) and then the NPT in 1998, the objective of developing naval NP was maintained, based on increasing mastery of the fuel cycle.[115] The Brazilian army justifies the need for a nuclear-powered submarine by the need for effective surveillance of the Brazilian coast, home to the majority of the population and to Brazil's oil wells.[116]

This project is also part of a process to develop conventional submarines, with the help of France. Signed in 2008 between Paris and Brasilia, the Submarine Development Program (PROSUB) aims to build four diesel-electric propulsion submarines, the Riachuelo class, derived from the Scorpène, the first of which was commissioned in 2022,[117] as well as a nuclear-powered submarine (the SN-10). However, the latter is to be designed solely by the Brazilian Navy and the Brazilian manufacturer Itaguaí Construções Navais, with French involvement limited to influencing the choice of fuel (LEU, like the French SSNs and SSBNs), the design of the hull,[118] and the acquisition of technical capabilities through the joint manufacture of the Riachuelo class. This agreement officially excludes any

113. "Iran Submarine Capabilities", The Nuclear Threat Initiative, February 17, 2023, available at: nti.org.
114. V. Narang, *Seeking the Bomb: Strategies of Nuclear Proliferation*, Princeton, NJ: Princeton University Press, 2022, p. 100*ff*.
115. D. Rocha, "Les maîtres silencieux des océans: les enjeux stratégiques et de non-prolifération des sous-marins à propulsion nucléaire en Australie et au Brésil", Institut d'études de stratégie et de défense, January 2023.
116. L. Rodriguez, "Brazil Moves Closer to Developing a Nuclear-Powered Submarine", Nuclear Network, Center for Strategic and International Studies, July 13, 2022, available at: nuclearnetwork.csis.org.
117. P. Chapleau, "Le sous-marin brésilien *Riachuelo* de type *Scorpène* mis en service", *Ouest-France*, September 2, 2022, available at: lignesdedefense.blogs.ouest-france.fr.
118. For example, the design of the Brazilian SSN was reportedly approved in the presence of French authorities. See X. Vavasseur, "Brazil's Nuclear-Powered Submarine Project SN-BR Making Progress", *Naval News*, December 6, 2021, available at: www.navalnews.com.

French involvement in the nuclear elements of the submarine, although there is probably communication at a very high level.[119] The domestic development of the reactor, whose onshore prototype only began to be assembled in 2020,[120] seems to partly explain the delays in the program. The aim is now to complete the nuclear reactor by 2027, and the submarine by 2033.

The challenge of non-proliferation

Debate over whether naval NP ought to be included in the activities prohibited by the NPT is nothing new: as early as the 1960s and the first negotiations on the treaty, states including Italy and the Netherlands insisted that NP should not be included in the NPT, because they wanted to develop nuclear reactors for commercial or military surface vessels. Similarly, the UK argued against international legislation on the subject, since it wished to continue to benefit from US aid for the development of its nuclear-powered submarines.[121] Finally, the strictly civilian prerogatives of the IAEA, which, in order to respect the confidentiality of state programs, cannot inspect military nuclear sites, stood in contradiction to any project to control nuclear-powered submarines.

Published in 1972, IAEA Circular No. 153 (INFCIRC/153) represents an initial stage in the IAEA's consideration of NP in relation to the non-proliferation regime. Paragraph 14 provides for a mechanism enabling a state to exempt from IAEA safeguards nuclear material used for a "non-peaceful purpose", provided that it is not used for a purpose prohibited by the NPT, that is, to manufacture a weapon or for any other "explosive" use. Although it does not mention use for NP, this provision is generally understood to allow the enrichment of fissile material—or the transfer of fissile material—by a NNWS, with a view to developing NP.

This provision, which must be part of a specific agreement between the country concerned and the IAEA, has never been implemented to date, although several states have considered it, including Canada, and Brazil as part of its SN-10 program (see above).[122] Initial negotiations were opened in June 2022 between the Argentine-Brazilian Agency for Accounting and Control of Nuclear Materials (ABACC)[123] and the IAEA to draw up an

119. A. Lepigeon, "Le Brésil en négociations avec la France pour son sous-marin nucléaire", *Le Marin*, October 25, 2023, available at: lemarin.ouest-france.fr.

120. A. Galante, "Marinha inicia montagem de reator do protótipo de propulsão nuclear em Aramar", *Poder Naval*, October 21, 2020, available at: www.naval.com.br.

121. J. C. Moltz, "Closing the NPT Loophole on Exports of Naval Propulsion Reactors", *The Nonproliferation Review,* 1998, pp. 108–14.

122. L. Rockwood, "Naval Nuclear Propulsion and IAEA Safeguards", Federation of American Scientists, August 2017.

123. The Guadalajara Agreement, signed in 1991, led to the creation of the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC), which provides for the strictly peaceful use of nuclear energy produced by both countries.

additional safeguards protocol, which Brazil is yet to benefit from.[124] The process is likely to be even more complex[125] than for Australia, which already has a more established relationship with the IAEA.

The consequences of AUKUS

In addition to specifying the format of the partnership and the planned delivery schedule (see above), the trilateral declaration of March 13, 2023, on AUKUS provided an opportunity to clarify the terms and conditions relating to the risk of nuclear proliferation, a concern widely shared at the time of the initial announcements. Demonstrating its commitment to the highest standards of non-proliferation, Australia announced that it would enter into negotiations with the IAEA under Article 14 of its Comprehensive Safeguards Agreement (CSA) with the agency, which incorporates the provisions of INFCIRC/153. Traditionally seen as a "disincentivizing" means of preventing countries from acquiring NP,[126] the process remains a legally and technically complex affair, according to the director of the IAEA.[127]

These legal provisions are accompanied by technical precautions to keep the handling of fissile material by Australia to a minimum. The reactors are to be delivered sealed and should not require any operations to be carried out on them during their lifetime,[128] in particular thanks to the use of HEU in the American and British submarines, unlike the French choice of LEU, which requires one or more core changes over a submarine's lifetime. This fuel will also not be processed by Australian operators, and cannot be used to manufacture nuclear weapons without a major reconditioning process, which Australia does not have at its disposal.[129] However, this "turnkey" delivery does raise questions about nuclear safety and the action to be taken, for example in the event of a porous fuel element contaminating the primary circuit or an onboard incident.

It is clear that the risks of nuclear proliferation in Australia in the context of AUKUS are minimal if not non-existent: the Australian state has traditionally been opposed to atomic weapons—hence the major debates in the country about the acquisition of NP—and is a signatory to the NPT and the Treaty of Rarotonga, which makes the South Pacific a nuclear-weapons-free zone. Some analysts point to the possible use of these submarines to

124. I. J. Stewart, "Brazil Wants Special Treatment for its Nuclear Submarine Program—Just Like Australia", *The Bulletin of Atomic Scientists*, June 28, 2022, available at: thebulletin.org.
125. M. Spektor, "Prospects for Safeguarding Brazil's Naval Nuclear Propulsion Program", Federation of American Scientists, August 2017.
126. T. de Champchesnel, "AUKUS, un nouveau défi pour le régime de non-prolifération", *Revue défense nationale*, Vol. 852, No. 7, 2022, pp. 61-65.
127. Statement by the director general of the IAEA on the AUKUS announcement, International Atomic Energy Agency, March 14, 2023, available at: www.iaea.org.
128. "The AUKUS Nuclear-Powered Submarine Pathway: Nuclear Non-Proliferation Fact Sheet", Australian Ministry of Defence, March 2023, available at: www.defence.gov.au.
129. *Ibid.*

carry dual key US nuclear weapons, similar to the US gravity bombs stored in certain NATO countries. However, this approach would necessitate legal workarounds to circumvent Australia's membership of a nuclear-weapons-free zone, thereby creating a dangerous precedent for non-proliferation.[130]

The main consequence of the AUKUS partnership is the creation of a "double standard", or at least the perception that the US is manipulating international standards to serve its own interests in the Indo-Pacific region. Until now, Washington had discouraged the transfer of technology from a NWS to a NNWS, in particular from France to Brazil and, previously, Canada (see above). Similarly, since the end of the Cold War, the US has been working to reduce the use of HEU in research reactors, even though the US Navy continues to use HEU in the reactors of its submarines,[131] and could use the Australian precedent to export this model.

The Tenth NPT Review Conference, held in August 2022 and therefore the first to be convened post-AUKUS, provided an opportunity for certain countries to express their grievances about this American "double standard". China, supported by other non-aligned Asian states, claimed that this was an "illegal transfer of weapons-grade fissile material", that the three signatory countries were attempting to "mislead public opinion", and called into question the "unilateral sanctions" imposed on NNWSs that acquire and develop a civilian nuclear program.[132] Beijing reiterated these grievances when AUKUS was formally announced in March 2023, arguing that the risks of nuclear proliferation were high and that the transfer violated the NPT, while also criticizing the guarantees provided by Australia to the IAEA.[133] Indonesia also raised the issue, proposing a working paper at the review conference and stating that NP could pose a "big risk to world peace and safety".[134] Similar positions were expressed at the preparatory meeting for the Eleventh NPT Review Conference in Vienna in September 2023.

In more general terms, AUKUS ultimately appears to be a means of filling the "legal vacuum" in NP by setting new standards, provided that the negotiations between Australia and the IAEA on the implementation of Article 14 of the CSA are successful. Ultimately, the quality of these standards will influence the ability of other states to develop NP in a non-proliferation compliant manner, which is not a given for certain countries that are already

130. T. Dalton and A. Levite, "AUKUS as a Nonproliferation Standard?", *Arms Control Today*, July 2023, available at: www.armscontrol.org.
131. E. Maitre, "Sous-marins à propulsion nucléaire et prolifération", Fondation pour la recherche stratégique, Observatoire de la dissuasion, Bulletin No. 92, November 2021, available at: www.frstrategie.org.
132. "Commentary III on AUKUS: the US, UK and Australia Mislead Public Opinion by Playing with Concepts", Permanent Mission of the People's Republic of China to the United Nations and Other International Organizations in Vienna, August 10, 2022, available at: vienna.china-mission.gov.cn.
133. "China firmly opposes AUKUS' Coercing IAEA to Endorse its Nuclear Submarine Cooperation: FM", *The Global Times*, March 15, 2023, available at: www.globaltimes.cn.
134. "Indonesia Mainstreams Issue of Nuclear Naval Propulsion at UN", *Antara News*, August 28, 2022, available at: kalsel.antaranews.com.

interested in a military nuclear program, such as South Korea, Brazil, and Iran (see above).

Toward new uses?

In addition to propulsion for submarines, nuclear energy is also being considered as a means of propulsion for other devices, and is at different stages of development for both civil and military applications. These projects pose their own challenges in terms of the risk of accidents and the proliferation of fissile materials.

The use of nuclear power for space propulsion is being seriously considered by several countries, including the US through a number of National Aeronautics and Space Administration (NASA) programs. In partnership with the Defense Advanced Research Projects Agency (DARPA), NASA announced in July 2023 that it had chosen Lockheed Martin to design and manufacture a nuclear thermal rocket vehicle and engine. The first tests are expected in 2027. In France, the CEA also launched two feasibility studies in the summer of 2023 on behalf of the European Space Agency, on the development of a nuclear thermal propulsion engine similar to the American project. These projects share a similar technique: because of the heat produced by the nuclear reactor, the rocket fuel is rapidly heated to extreme temperatures, making it possible to obtain a very advantageous ratio between energy and propulsion (more than 10,000 times greater than electric propulsion, and two to five times greater than chemical propulsion).[135] Other projects, based on technological breakthroughs in small modular reactors, envisage SMRs supplying the electricity needed to operate space facilities on the surface of other planets.[136] These technologies could also be applied to military satellites, potentially improving their maneuverability and thus reducing their vulnerability to anti-satellite attacks, a project already explored in the 1970s by the Soviet Union.[137]

On more advanced lines, there are also plans for a nuclear-powered torpedo, which would greatly increase the weapon's range, speed, and maneuverability, making it potentially unstoppable by existing interception systems. Russia is said to be currently developing the Poseidon, a nuclear-powered underwater torpedo capable of carrying a nuclear warhead.[138] This project was unveiled by Russian President Vladimir Putin in a speech in March 2018, but the torpedo has so far never been seen on exercise or in operation. The test scheduled for November 2022 from the Belgorod, the

135. L. Dupin, "Lockheed Martin va concevoir des fusées à propulsion nucléaire", *Revue générale nucléaire*, July 28, 2023, available at: www.sfen.org.

136. W. Picot, "Nuclear Technology Set to Propel and Power Future Space Missions, IAEA Panel Says", International Atomic Energy Agency, February 18, 2022, available at: www.iaea.org.

137. S. Erwin, "Report: Nuclear Propulsion Would Help Military Satellites Maneuver Out of Harm's Way", *SpaceNews*, January 14, 2022, available at: spacenews.com.

138. H. I. Sutton, "Russia's New 'Poseidon' Super-Weapon: What You Need to Know", *NavalNews*, March 3, 2022, available at: www.navalnews.com.

largest SSBN in the Russian Navy, assumed to be the firing platform for the Poseidon, is alleged to have failed.[139] On the other hand, work on the Burevestnik, a nuclear-powered subsonic cruise missile, appears to be more advanced, with a test said to have been successfully carried out in September 2023. While the advantages of this combination in terms of endurance and maneuverability are undeniable, its low speed and the potential instability of the reactor mean that at this stage it is more a device for strategic signaling than a functional weapon.[140]

China is also said to be developing a nuclear-powered torpedo project, but principally for conventional purposes, with the reactor used mainly to bring the missile closer to the target before detaching. The weapon would therefore be much less expensive than a Poseidon-type torpedo.[141]

Last, as far as surface ships are concerned, the enthusiasm of the 1970s for building nuclear-powered frigates and destroyers rapidly faded owing to the high cost of maintenance, leaving only aircraft carriers. To date, only Russia still has nuclear-powered surface ships other than aircraft carriers: the Kirov-class cruisers and the Arktika- and Taymyr-class icebreakers. Like nuclear-powered submarines, technological expertise in the construction of nuclear-powered aircraft carriers is still rare and, at this stage, only two countries have such vessels: the US, with eleven atomic-powered aircraft carriers, and France, with the Charles de Gaulle.

139. M. Evans, "Russia's Nuclear-powered Torpedo 'Failed Test on Technical Issues'", *The Times*, November 11, 2022, available at: www.thetimes.co.uk.
140. T. Wright, "Russia Claims to Have Tested Nuclear-Powered Cruise Missile", International Institute for Strategic Studies, October 13, 2023, available at: www.iiss.org.
141. H. Altman, "China's Nuclear Powered Super Long-Range Torpedo Concept Fits Concerning Pattern", The Warzone, July 21, 2022, available at: www.thedrive.com.

Conclusion

The history of NP bears witness to the extreme complexity involved in the development and safe operation of this technology, particularly when applied to submarines. This explains why, at the close of the Cold War, the technology had only been mastered by four countries (the US, the USSR—at the cost of numerous nuclear accidents—the UK, and France), and was still in its infancy in China. NP undeniably played a key role in the Cold War, enabling the creation of fleets of SSBNs with a permanent second-strike capability, and giving the US Navy operational capabilities that enabled it to acquire naval superiority thanks to its fleets of SSNs and aircraft carriers. This strategic added value explains why the US blocked exports of reactors and exchanges of information on this technology with countries that were seeking them, including France, Germany, and Italy. The UK, a close ally since the Second World War and already a nuclear power possessing not only nuclear weapons but also the infrastructure and, above all, the skills needed to implement it, was the exception here.

Looking at this first age of nuclear power allows us to isolate some of the conditions necessary for the development and long-term mastery of this technology. In addition to a dedicated organization enabling design offices and industrial partners specializing in the nuclear or naval fields to work effectively together, the most crucial point is the maintenance of skills. This of course concerns operations, with the need to train and retain crews over the long term. But it also involves skills in design, construction, maintenance, and dismantling, as well as those essential for analyzing feedback and facts that may affect nuclear safety.

The case of the UK, which suffered a hiatus in these areas, forcing it to turn to American aid for the construction of the Astute-class SSNs and to adopt American technology for its PWR3 reactor, should encourage a country like France to err on the side of utmost vigilance. One of the challenges of the next round of military programming laws will be to ensure that we retain mastery of this technology over the long term, and that the necessary skills are maintained in order to guarantee the long-term credibility of France's nuclear deterrent. Finally, priority should be given to nuclear safety, particularly on the part of organizations and individuals, through control bodies that are independent of those in charge of implementation. The numerous accidents that occurred in the USSR, and later in Russia, are a reminder that this priority can easily be trumped by other concerns in totalitarian, authoritarian, or corrupt regimes.

The NP landscape of the twenty-first century is in a state of flux. The five countries that already possess the technology have maintained nuclear naval programs, while China has caught up on its technological lag. However, it has been relatively slow to produce new units, especially in comparison with the extraordinary growth of its navy in the field of conventionally powered submarines and surface vessels. India, with Russian help, has joined the club, while Brazil is making even more strenuous efforts to get there.

The AUKUS agreement, and its submarine component providing for the supply of SSNs to Australia, breaks with a policy put in place by the US itself in the field of technology exchanges relating to military NP. In a region marked by China's political, military, and maritime ambitions, and where the acquisition of this technology could eventually be of interest to other states including South Korea and Japan, this agreement marks a new stage in technology sharing. It is the first time that nuclear-powered submarines, whatever the technological solution chosen, have been supplied to a country that does not have a nuclear scientific, research, or energy infrastructure or the associated skills. While it lends itself easily to criticism of a "double standard" on the part of the US, and sets a potentially dangerous precedent with regard to states less reputable than Australia, it does not raise serious concerns about the risk of nuclear proliferation or about Australia's compliance with its obligations under the NPT. On the other hand, firm commitments must be expected from the three states parties to the agreement, and particularly Australia, to cooperate fully with the IAEA in order to avoid further criticism.

However, AUKUS does raise serious doubts about nuclear safety. This seems to be the most sensitive point when it comes to exporting propulsion technology, especially to a country with no nuclear culture. While the introduction of procedures for exchanging feedback and joint analysis of events affecting nuclear safety would seem to be a minimum condition for exporting this technology to a country that already has a strong nuclear safety culture, stricter conditions in this area are required.[142] From this point of view, the signatory countries of the agreement will have a duty of transparency toward the entire world community. This last, very sensitive, point justifies France's refusal to reconsider its policy of not exporting this technology, despite the door having been clumsily opened by the three signatory states of the AUKUS agreement.

142. In 1959, Admiral Rickover asked to be allowed to personally select the British officers who would have responsibility for operating the reactors supplied by the United States. This request was refused, but it illustrates the kind of scrutiny required to effectively control the skills of reactor operators. See E. Grove, *Vanguard to Trident*, p. 233.

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