NATO ENERGY SECURITY
CENTRE OF EXCELLENCE

ENERGY HIGHLIGHTS

The Future Role of Nuclear Propulsion in the Military

by **Mr. Lukas Trakimavičius**

INTRODUCTION

The splitting of the atom is without a doubt one of humanity's greatest technological achievements. Regardless if one is a fan or foe of nuclear fission, the fact that scientists have found a way for this tiny speck of matter to generate large amounts of heat and power is nothing short of spectacular. Even more remarkably, in just seventy years nuclear power became a major source of energy for many countries across the globe. Nowadays, it accounts for some 10 percent of the world's electricity supply, it is a key source of power for countries such France or Ukraine, and some of the militaries also use it to propel their ships, submarines and aircraft carriers.

Given the versatility of this source of energy, it is hardly surprising that some countries have decided to take it further and came up with even more innovative ways of harnessing the atom. The most notable example of this is Russia, whose President Vladimir Putin announced back in 2018 the development of a flurry of so-called "doomsday weapons".[1] Some of them will use nuclear energy as their primary source of propulsion. These include: an autonomous, submarine-launched, nuclear-powered and nuclear-capable underwater vehicle, called *Poseidon*, and a nuclear-powered, nuclear-armed cruise missile, called the *Burevestnik*. [I]

In the West, this announcement was met with mixed reactions. There were those who claimed that these weapons – provided they would ever leave the testing grounds and become deployment-ready – could have a significant impact on the global security landscape and somewhat tilt the balance of power in Russia's favor.[2] Others claimed the opposite and argued that these weapons are unlikely to bring anything particularly useful to the table.[3] Then there were also those who stressed that these technologies were neither as new nor as innovative as they may have initially appeared. This was done by highlighting the fact that both the United States and the Soviet Union had toyed around with similar ideas at the height of the Cold War.[4]

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[I] While these weapons were introduced to the public at large during the address to the Federal Assembly in March 2018, they were anything but new. First public evidence about the development of the Poseidon surfaced back in 2015 and first glimpses of the development of the Burevestnik missile appeared in 2016.

Regardless of what one thinks about these "doomsday weapons", it is eminently clear that, if anything, Moscow has succeeded in drawing everyone's attention. Therefore, it is only reasonable to assume that as Russia continues to develop these weapon systems, some security analysts or media pundits will eventually start raising questions if Western powers should follow in Moscow's footsteps? In other words, should the West – in a bid to fill some perceived military technology gap (a theme all too common in history) – revisit long-abandoned, Cold War-esque plans for nuclear propulsion? Or, as small and micro modular reactor technology makes nuclear energy more accessible, the atom could finally be used to power land vehicles, small surface ships or even airplanes?[II] And, if so, would there be any operational advantages for Western militaries to gain from these developments? Questions about the future of nuclear propulsion might also be asked in light of the growing pressure for the military to tackle climate change and decrease its acute reliance on fossil fuels.

This is where this article comes into play. It will review existing nuclear propulsion systems and examine if the development of nuclear-powered vehicles and weapon delivery systems would benefit Western militaries. However, instead of focusing on the potential impact of this technology on strategic stability and nuclear deterrence, this article will shift its attention to the more technical, political and operational issues related to the development of nuclear propulsion systems.

This article will be broadly divided into three parts. First, it will provide a brief history of the use of nuclear propulsion in the military. Second, it will review the existing nuclear propulsion technologies and plans for future development.[III] Third and finally, it will review the potential pros and cons of developing new nuclear propulsion-based military vehicles and weapon delivery systems in the air, land and sea domains.[IV]

HISTORY OF NUCLEAR PROPULSION IN THE MILITARY

Earliest records suggest that serious thinking about nuclear propulsion began even before the end of World War 2. Once the secrets of the atom were cracked and controlled fission was achieved, both the United States and the Soviet Union quickly realized the untapped military potential of this source of energy. The atom promised a seemingly endless supply of power and, at the time, it seemed that the prospects of long-range flight could prove to be a decisive factor in the Cold War rivalry that was slowly taking shape.

In the US, research on nuclear propulsion began in 1946 when the Air Force initiated the *Nuclear Energy for the Propulsion of Aircraft* project, later known as the *Aircraft Nuclear Propulsion* (ANP) program. In one of the research projects, the scientists decided to place a small nuclear reactor within a converted *Convair B-36 "Peacemaker"* bomber and see if the airplane could fly with a functioning nuclear engine on board (though it did not actually power the aircraft). In total, the *Convair NB-36H* (the name of the experimental aircraft) completed some 47 test flights (with the reactor being switched on during most of them) between 1955 and 1957, and it was proven that it is technically possible to mount an operational nuclear reactor on a flying aircraft. However, the ANP program was eventually scrapped in 1961 as the development of nuclear-powered aircraft proved to be far more difficult than initially expected.[5] The program was also plagued by a number of problems, including difficulties of shielding the aircraft crew from deadly doses of nuclear

[II] For a discussion about small modular nuclear reactors and their potential use in the military see: Lukas Trakimavičius, "The future role of small modular nuclear reactors (SMRs) in the military", Energy Highlights, 2 December 2020, https://www.enseccoe.org/data/public/uploads/2020/11/02.-solo-article-lukas-smr-eh-15-web-version-final.pdf

[III] This article will only focus on more or less mature technology. It will omit the discussion of such futuristic technologies as nuclear fusion, because, as the joke goes, nuclear fusion is 30 years away...and always will be. On a more serious note, even if nuclear fusion would somehow manage to achieve significant technological breakthroughs over the next decades, it is rather unlikely that nuclear fusion reactors could somehow be used by the military anytime soon.

[IV] While space is becoming increasingly viewed as an operational domain by militaries and international organizations alike, it is still unclear when, and if at all, it will become as militarily important as the three traditional military domains. Therefore, for practical purposes, this article will not include any broader discussions about the militarization of space.

radiation, high development costs, and public concerns about the dangers of a nuclear reactor flying overhead.[6]

In 1957, the Air Force also initiated a program called *Project Pluto*, which sought to develop nuclear-powered engines for use in cruise missiles. The project was somewhat more successful than the ANP program, but in 1964 it was also cancelled.[7] By that time, the emergence of intercontinental ballistic missiles (ICBMs) such as the *Atlas, Minuteman* and *Titan*, and the introduction of heavy payload bombers like the *B-52 "Stratofortress"* reduced the need for nuclear-powered cruise missiles. Moreover, there were serious concerns that the unshielded reactor core of these cruise missiles would emit copious amounts of radioactive exhaust along its flight path, endangering everyone between the launch site and the target.[8]

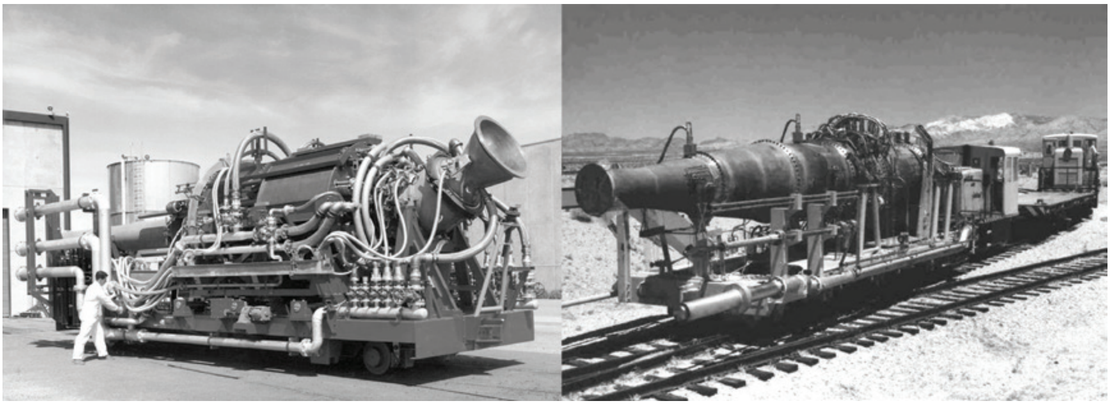


Figure 1. Engines used for Project Pluto (Tory II-A, Tory II-C), left to right. (Credit: Wikipedia Commons)

Meanwhile, in parallel to the Air force, in 1948, the US Navy also began research on nuclear-propelled vessels, from submarines to aircraft carriers. Its research program proved to be vastly more successful than that of the Air Force and, in 1954, it built the *USS Nautilus*, the world's first nuclear-powered submarine. In 1959, the Navy launched *USS Long Beach*, the world's first nuclear-powered missile cruiser, and, one year later, it launched the *USS Enterprise* — the world's first nuclear-powered aircraft carrier.

Given the enormous potential of this technology, it is not surprising that right from the start of the Cold War, the Soviet Union was also busy developing an extensive naval nuclear propulsion programme. In a bid not to fall behind in the arms and technology race against the US, the Soviets initiated work on a nuclear-powered submarine in 1952.[9] Despite a series of setbacks, including radiation leaks and engine problems, the first Soviet submarine, the *K-3 Leninsky Komsomol*, entered service in 1958.[10] Much later, in 1977, the Soviet Navy launched its first nuclear-powered missile cruiser, named *Kirov*. Finally, in 1988, the Soviets started working on the *Ulyanovsk* — the country's first nuclear-powered aircraft carrier. However, after the collapse of the Soviet Union the project was cancelled in 1991.

Back in 1955, the Soviet government also started work on a nuclear-powered aircraft. Following years of research, the designers inserted a small nuclear reactor within the bomb bay of a retrofitted *Tupolev Tu-95* bomber, which began its test flights in 1961 (see Figure 2.). In total, the *Tupolev Tu-95LAL* (*Letayushchaya Atomnaya Laboratoriya* or "flying nuclear laboratory" in English) made some 40 missions with the reactor switched on only on a few of the flights.[11] As it was the case with the US-built *Convair NB-36H*, the reactor did not actually power the aircraft and the main goal of these flights was to test radiation shielding. However, the project was scrapped in 1969 as the idea of nuclear-powered aircraft proved to be far too impractical. It was challenging to shield

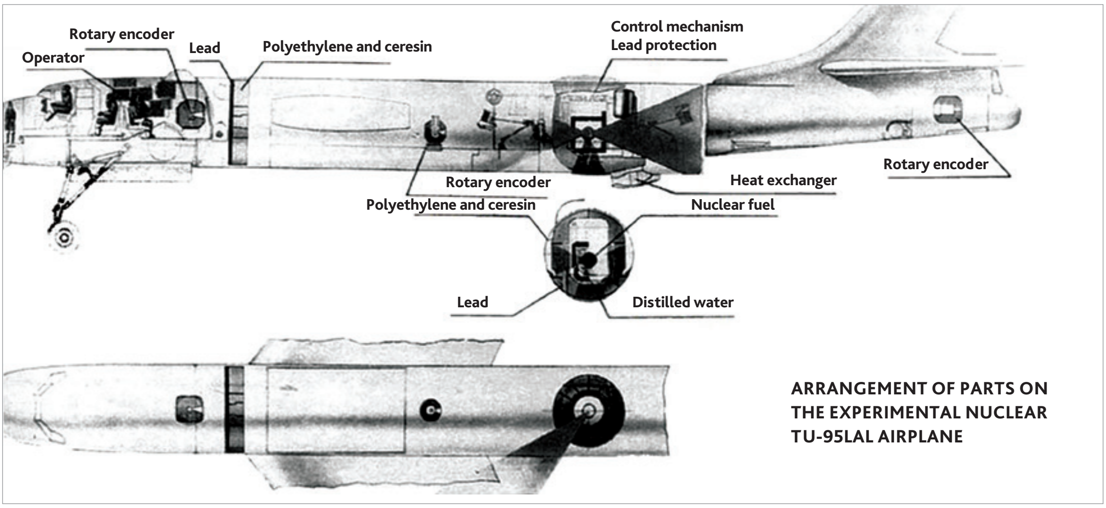


Figure 2. Tupolev Tu-95LAL blueprint. (Credit: Tu-95.net; translation from Russian to English: Lukas Trakimavičius)

the crew from nuclear radiation, the emergence of ICBMs made the high costs of nuclear-powered aircraft unwarranted and there also were concerns that the crash of such a plane would lead to catastrophic consequences.[12]

At around the similar time, the Soviets were also considering the development of cutting-edge nuclear engines for airplanes. For this reason they designed a prototype of the *M-60* long-range bomber, which, it was planned, would rely on four turbojet nuclear engines.[13] The bomber was supposed to take off and land using conventional engines, but, once in the air, it would turn on the nuclear reactors. In theory, these nuclear turbojet engines should have provided the *M-60* with an estimated range of at least 25,000 kilometres and maximum speed of 3,200 kilometres per hour. However, the *M-60* did not make it out of the planning stage and, because of reasons similar to those of the ill-fated *Tupolev Tu-95LAL* (and the US-built *Convair NB-36H*), the program was shelved in 1959.[14]

Overall, during the Cold War the militaries of the US and the Soviet Union had by far the most advanced and extensive nuclear propulsion research programs. Due to a number of reasons, including cost and utility, other countries had fairly little interest in nuclear propulsion beyond the realms of naval engineering.[V]

THE SCIENCE BEHIND NUCLEAR PROPULSION

In most cases, at least in the naval domain, the concept of nuclear propulsion is relatively straightforward. Nuclear reactors are basically heat engines, which drive the propulsion plant of a ship or submarine. The heat comes from the fissioning of nuclear fuel (mostly uranium) contained within the reactor. Since the fissioning process also produces radiation, shields are placed around the reactor so that the crew is protected. In fact, it is estimated that on some ships well over 100 tons of lead shielding is used for the reactors.[15]

To date, virtually all militaries have relied on pressurized water reactors (PWRs) to power their vessels. PWRs are the most common type of nuclear reactors and around two-thirds of all reactors in the world are of this type. These reactors make use of light water (basically, ordinary tap water)

[V] The first British nuclear submarine, the HMS Dreadnought, was commissioned in 1963, and the first French nuclear submarine, Le Redoutable, was commissioned in 1971. The first Chinese nuclear submarine, the Changzheng 1, went into service in 1974.

as their coolant and neutron moderator, as opposed to other reactors that use heavy water (a type of water that contains high amounts of the hydrogen isotope deuterium), or gasses (such as helium) or liquid metals (sodium, lead, etc.). A notable exception to this rule is the Soviet Union, which during the Cold War operated a number of lead-bismuth cooled nuclear reactors on its submarines. The US military also entertained idea of using sodium-cooled nuclear reactors (it temporarily had one on board the 1955-built *USS Seawolf*), but eventually it dropped this design (due to technical and budgetary reasons) in favour of using PWRs on all of its ships.[16]

In general, PWR-based naval propulsion systems use two basic circuits – a primary and a secondary one (see Figure 3.). In the primary circuit, the coolant (in this case water) is pumped under high pressure to the reactor core, where it is heated by the energy released from the fission of atoms. The heated, high pressure water then flows to a steam generator, where it transfers its thermal energy to lower pressure water of a secondary circuit. Subsequently, in the secondary circuit, the steam flows from the steam generators to drive the turbine generators, which supply the ship with electricity, and to the main propulsion turbines, which drive the propeller.[17]

Though PWRs can reliably power surface ships and submarines, due to a number of technical difficulties (mostly related to weight), this technology is wholly unsuitable for flight. As a result, most experimental nuclear reactors that were designed to power either aircraft or missiles used other types of reactors. For example, the ANP program that was developed by the US Air Force used a molten-salt reactor on board the *Convair NB-36H*, which employed molten fluoride salts as the primary coolant. This type of reactor was smaller and lighter than a PWR, but, for all intents and purposes, it was still too unwieldy to be used for flight.

Meanwhile, an honourable mention should be made of the scientists behind the US Air Force's *Project Pluto* who decided to opt for an even more radical engine design for its nuclear-powered cruise missile. They created the world's first nuclear ramjet — an air-breathing jet engine that operated with no major moving parts (regular jet engines rely on either axial or centrifugal compressors). This engine had a fairly simple design: the missile pushed air in through the front of the missile, an unshielded nuclear reactor heated the air and then the hot air was expanded at a high speed through a nozzle at the back, providing thrust. If deployed, it is believed, the *Project*

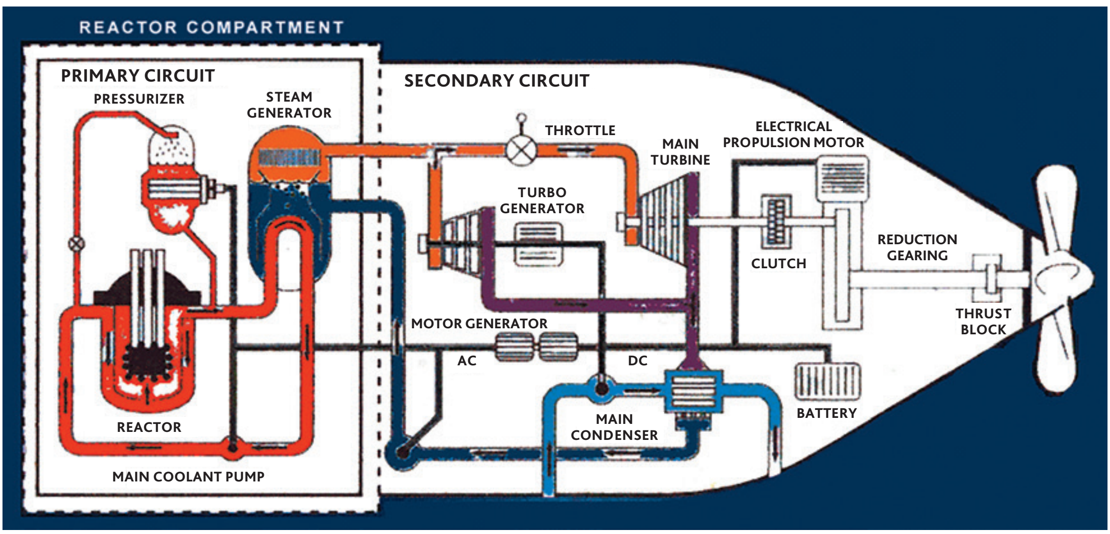
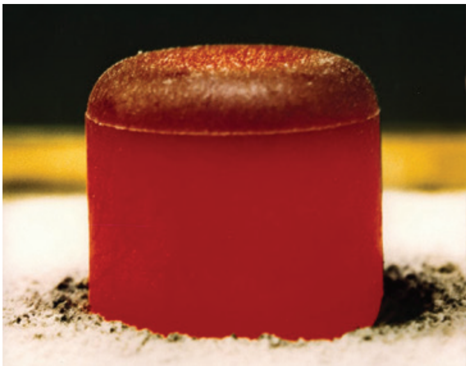


Figure 3. Pressurized-water naval nuclear propulsion system. (Credit: World-nuclear.org)



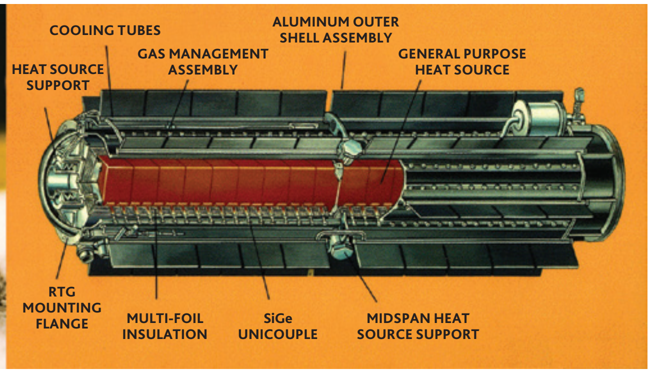


Figure 4. Red hot pellet of Pu-238; blueprint of a basic RTG, left to right. (Credit: Wikipedia Commons)

Pluto missile would have flown at three times the speed of sound, while the red-hot reactor would produce a deafening roar of 150 decibels and incinerate everything in its path.[18]

ALTERNATIVE NUCLEAR SOURCES OF ENERGY

Though unrelated to military vehicles, weapon delivery systems or nuclear propulsion *per se*, there are other ways how radioactive materials have been used to power various equipment. For example, satellites and spacecraft such as the *Voyager* and the *Cassini* probes, or the most recent *Perseverance* rover, just to name a few, use radioisotope thermoelectric generators (RTGs) to power their systems.[VI] Thought technically they could not be classified as nuclear reactors because there is no fission involved, they still draw energy from either the same or similar materials as nuclear reactors. Highly radioactive materials, such as plutonium, give off heat as they decay, which in turn can be converted into electricity.

At first glance, RTGs may seem as ideal sources of power for the military, but at closer inspection, nothing could be further from the truth. One of the advantages of RTGs is that they are simple, compact and relatively robust. They have no moving parts and there is not much that can break down. However, the main problem with RTGs is that thermoelectric modules have a very low conversion efficiency, and, therefore, they cannot generate much power compared to other sources of energy. Therefore, most RTGs are only suitable to power equipment that requires a few hundred watts or even less. For instance, the *Cassini* space probe used three RTGs that each produced some 292 watts of electricity at the beginning of its mission.[19]

On top of that, there is also the issue of cost. Plutonium (Pu-238 in particular) is one of the most expensive substances known by weight, with some sources giving a price estimate of around €4,000 per gram.[20] Hence, hypothetically speaking, the sheer amount of plutonium that would be needed to power a small land vehicle would inevitably result in a price tag that would run into the tens of millions, if not much more.

There are also alternatives that sit between low-power RTGs and full-blown nuclear fission reactors, which are called Stirling radioisotope generators, or SRGs in short. They tend to produce power more efficiently than RTGs and require significantly less radioactive fuel, but come with a downside of having some moving parts that may break down over time.[21] Still, considering their relatively low energy output (if compared to combustion engines), potential fuel costs and safety and security matters, it is very unlikely that SRGs could see any meaningful use on military vehicles or weapon delivery systems. As a result, it is fair to conclude that if the military would decide to significantly expand the use of

[VI] Countries like the US and the Soviet Union also used RTGs to power various remotely-located equipment on the Arctic coast, including lighthouses, navigation beacons, etc.

nuclear propulsion anytime soon, the technology most likely would have to involve some degree of fission.

MILITARY INTEREST IN NUCLEAR PROPULSION

As it was the case during the Cold War, out of all the military branches, the navies are still the only users of nuclear propulsion. Currently, there are over 160 vessels, which are powered by more than 200 nuclear reactors.[22] Most of them are submarines, but they also include aircraft carriers.[VII] These are driven by PWRs with power ranges everywhere between 48 megawatts (MW) (French *Rubis*-class submarines) to around 700 MW (US *Gerald Ford*-class aircraft carriers). The vast majority of all the nuclear-propelled vessels belong either to the US or Russia. Countries such as China, the United Kingdom, France and India also maintain vessels that rely on nuclear power. As things stand right now, it seems that over the next decades all of these countries seem to be planning to either expand or modernize their nuclear-powered fleets.[23]

Out of all the countries, Russia is the only one that has future plans for nuclear propulsion that goes beyond the naval domain.[VIII] Over the coming years it not only plans to receive a number of new *Yasen-M* class nuclear submarines, upgrade its nuclear-powered *Kirov* class battlecruiser, but also develop an array of so-called “doomsday weapons”, some of which will use nuclear energy as their primary source of power.[24]

POSEIDON

One of these “doomsday weapons” is the autonomous, nuclear-powered and nuclear-capable underwater vehicle, called *Poseidon*.[IX] Though there is relatively little reliable information about this weapon delivery system on the public domain, media sources describe *Poseidon* as a giant nuclear-powered torpedo, which might become operational in 2027.[25] It reportedly measures around 1.6 meters in diameter, about 24 meters in length, and relies on a tiny nuclear reactor to power a pump-jet propulsion system.[26] The torpedo is also believed to have an operational speed of up to 70 knots (around 130 kilometres per hour) and is rumoured to be able to dive as deep as 1,000 meters.[27] It is claimed that this weapon will be carried on specially equipped *Belgorod*-class nuclear submarines, which would operate in both Northern and Pacific fleets. Media reports also suggest that each of these submarines would be capable of carrying up to six of these torpedoes.[28] In turn, these torpedoes could reportedly deliver either a conventional payload or a nuclear warhead with a yield of around two megatons.[X]

Based on publicly available sources, it is believed that the *Poseidon* torpedo would likely be used as a second strike weapon. It not only would avoid missile defence systems, but it could also inflict damage against enemies, even if a first nuclear strike seriously degrades Russia’s ability to retaliate with ICBMs. In fact, back in in 2015, a leaked Kremlin briefing slide stated that the

Figure 5. Snapshot of the Poseidon/Kanyon nuclear-powered torpedo. (Credit: Russian MOD)

[VII] Russia also operates the world's only nuclear-powered icebreaker fleet. However, it's operated by FSUE Atomflot (a subsidiary of ROSATOM) and these ships are generally used for civilian purposes (cargo transportation, tourism, etc.).

[VIII] One exception to this rule is the Defense Advanced Research Projects Agency (DARPA), the Pentagon's research and development arm, which is funding the construction of the world's first nuclear thermal propulsion system for spacecraft. However, even if successful, this technology could not be used for military mobility needs i.e. for powering aircraft or land vehicles.

[IX] Formerly this weapon was known as Status-6 Oceanic Multipurpose System. Its NATO reporting name is Kanyon.

torpedo was aimed at "damaging the important components of the adversary's economy in a coastal area and inflicting unacceptable damage to a country's territory by creating areas of wide radioactive contamination that would be unsuitable for military, economic, or other activity for long periods of time."[29] However, in practice it is somewhat unclear to what extent this weapon would be capable of causing this much havoc. This is because upon the detonation of an underwater bomb, most of the explosive energy would be lost and only a small part of it would go into a wave.[30]

BUREVESTNIK

The *Burevestnik* ("announcer of the storm" in English) is another of Russia's nuclear-powered weapon delivery systems, which is currently under development.[XI] In terms of concept and design, this cruise missile looks as if it was taken straight from a Cold War-era playbook and is rather similar to the US Air Force's *Project Pluto* weapon concept. To date, the *Burevestnik* has been shrouded in secrecy and only limited information about this missile is publicly available. Still, based on the imagery provided by the Russian military, it can be assumed that the missile is likely around 12 metres in length and up to 1.5 metres in diameter.[31] It has been speculated that the *Burevestnik* has a booster engine (that likely uses solid fuel) to lift the missile into flight speed and that it has a small nuclear reactor, which then carries the missile to its target. Some sources claim that the missile employs a nuclear ramjet, others claim that it uses a nuclear turbojet engine.[32] Regardless of what the engine is, it is thought that *Burevestnik* could fly at a subsonic speed, maintain an altitude of 50-100 metres throughout most of its flight and cover distances as long as 20,000 km.[33] To date, there has been no indication about the yield of this missile and it is unclear when it would become deployment-ready.[XII]

According to open source data, *Burevestnik* is intended to be a second-strike, retaliatory weapon. It is claimed by the Kremlin that this missile was developed in response to the US withdrawal from the Anti-Ballistic Missile Treaty and its advancements in missile defense systems.[34] More specifically, it is believed by some that the main rationale for the *Burevestnik* stems from Russia's general fears that Washington's missile defense systems could neutralize Moscow's nuclear arsenal (and, by extension pose a threat to its great

Figure 6. Snapshot of the Burevestnik/SSC-X-9 Skyfall nuclear-powered cruise missile. (Credit: Russian MOD)

[X] Initial estimates and media reports put the nuclear yield of the Poseidon torpedo to around 100 MT. This would have meant that it would have been twice as powerful as the Soviet Tsar Bomba (50 MT yield), the most powerful nuclear explosive that was ever created. However, more recent estimates greatly reduced this initial number, which was likely deliberately overinflated for political purposes. See: Amy Woolf, "Russia's Nuclear Weapons: Doctrine, Forces, and Modernization", Congressional Research Service, 20 July 2020, https://fas.org/sgp/crs/nuke/R45861.pdf

[XI] Its NATO reporting name is SSC-X-9 Skyfall.

[XII] In 2019, reports have surfaced that the Burevestnik may become deployment-ready in 2025. However, realistically, its deployment could be a decade away, if ever. See: Jill Hruby, "Russia's New Nuclear Weapon Delivery Systems: An Open-Source Technical Review", Nuclear Threat Initiative, 13 November 2019, https://www.nti.org/analysis/reports/russias-new-nuclear-weapon-delivery-systems-open-source-technical-review/

power status). Though, admittedly, few Western security analysts have this much faith in the effectiveness of missile defense systems.[XIII] Or, alternatively, *Burevestnik* could be used as a bargaining chip in future arms control negotiations.[25] Regardless, when President Putin announced the development of his "doomsday weapons", he emphasized how the missile "can reach any point in the world" and how it is "invincible against all existing and prospective missile defence and counter-air defence systems."[26]

THE FUTURE POTENTIAL OF NUCLEAR PROPULSION IN THE MILITARY

As things stand right now, it is very unlikely that, with the exception of Russia, nuclear propulsion would see any military use outside the navy. Evidence clearly suggests that all other countries are only interested in developing either nuclear-powered aircraft carriers, nuclear submarines or both.

However, it does not necessarily mean that it will always remain so. It is only fair to assume that, as Russia continues to develop (and eventually might even deploy) its "doomsday weapons", some militaries in the West might feel the pressure to follow a similar path. The fear of falling behind in this new arms race, coupled with the necessity to maintain a competitive edge against other strategic rivals, can force some of the militaries to reassess the potential utility of nuclear propulsion for vehicles or weapon delivery systems.

Yet, before starting the commissioning of feasibility studies and delving too deep into the matter, it would be wise to examine the potential of this technology at a more general policy level. Granted, it is important to note that even such a broad analysis is no easy task. This is because one has to heavily rely on incomplete and speculative data, and do a lot of guesswork. As a result, any conclusions reached about the advantages and the disadvantages of nuclear propulsion should be taken with a hefty grain of salt. Still, based on the historical experience from the Cold War, the lessons (indirectly) learned from Russia's ongoing experiments with its "doomsday weapons", and some rough scientific estimates, it is possible to make at least a number of fairly educated guesses about what might and might not work, and why.

SEA

Out of all three military domains, sea has arguably the greatest potential of seeing nuclear propulsion being used much more frequently in the decades to home. This is not surprising, as some Western countries have hundreds if not thousands of accident-free reactor years under their belts, and nuclear submarines and aircraft carriers have long been the staple of their naval might. Also, unlike land vehicles or planes, warships – even as small and lightweight as corvettes or frigates – could be reasonably well suited to accommodate heavy nuclear reactors and their components.[XIV]

At first glance, the reasons for installing nuclear reactors on relatively small surface ships can seem rather compelling. First, nuclear propulsion could significantly expand their operational capabilities. For example, nuclear-powered aircraft carriers can go around 20 years without refuelling (though they still need to stop for water, food and other provisions), and, by some estimates, nuclear-powered ships can go about 50 percent faster than petroleum-fired ships of the same size.[37] Second, nuclear propulsion could play an important role in reducing the greenhouse gas (GHG) emissions of the navy. Unlike petroleum-fired engines, nuclear reactors produce electricity via fission rather than combustion. As a result, nuclear-powered ships would not produce

[XIII] It is generally believed that Russia's existing nuclear arsenal is too large and too diversified to be successfully intercepted by the US missile defense system. At the same time, the current track record of US missile defence system against short- and medium-range ballistic missiles, not to mention ICBMs, does not inspire great confidence. See: Jeffrey Lewis and Shea Cotton, "The Global Missile Defense Race: Strong Test Records and Poor Operational Performance", Nuclear Threat Initiative, 16 September 2020, https://www.nti.org/analysis/articles/global-missile-defense-race-strong-test-records-and-poor-operational-performance/

[XIV] Icebreakers can also accommodate nuclear reactors. Thanks to global warming, the Arctic will increasingly become ice-free in the summer and it is likely that this area will become a geopolitical flashpoint by the mid-21st century. Yet, as it is the case with Russia's nuclear-powered icebreakers, these vessels would likely be owned by and operated by civilians, and, therefore, they will not be included in this analysis.

any GHGs while operating and could seriously decrease the navy's consumption of fossil fuels. This is particularly important as the bulk of the military's petroleum is used for operational purposes i.e. the actual use of planes, ships and land vehicles.[38] Last, but not least, nuclear propulsion could make the vessels more future proof. Nuclear reactors could allow surface ships to meet the energy demands of even the most power-hungry equipment, such as advanced radars, energy weapons and other high-tech systems, which otherwise could not be installed on smaller ships without some negative trade-offs.

While all this sounds great, there are also major drawbacks to deploying nuclear reactors on some of the smaller surface ships. By far the greatest problem is the price tag. Nuclear reactors are incredibly expensive to build, and, by most accounts, the life-cycle costs of a nuclear-powered ship are significantly higher than those of a petroleum-powered ship.[39] For example, a 2011 US Congress Budget Office study concluded that the acquisition-cost premium for a nuclear-powered destroyer type of warship, would be about €900 million per unit, and that for such ships to be cost-effective, oil prices should over time increase to well over €200 per barrel.[40] While in other countries the construction costs might somewhat differ, given the soaring costs of nuclear technologies, there are no doubts that the acquisition-cost premiums of nuclear-powered vessels are still very great.[41] Therefore, even if the development of small modular nuclear reactors (or similar technological advances) could trim the average reactor costs by a considerable margin, it is still unclear if it would make much sense to install nuclear reactors on warships other than very large and heavy ones.[XV]

Then there is also the issue of nuclear waste. If, hypothetically speaking, over the coming decades we would see a development surge of hundreds of new nuclear warships, then, at some point, there would be a lot of nuclear waste in the form of spent fuel and contaminated equipment[XVI] This would seriously aggravate the existing problem of the global nuclear spent fuel stockpile, which, according to the Stimson Centre, a US think-tank, currently totals some 400,000 tons (and is poised to grow some 11,000 tons annually).[42] Also, more vessels would eventually have to be retired and undergo a time-consuming and costly decommissioning process, thereby further reducing their economic appeal. The decommissioning of a nuclear-powered vessel can take up to a couple of decades, and, according to some estimates, it could cost more than €100 million to scrap a single nuclear submarine.[43]

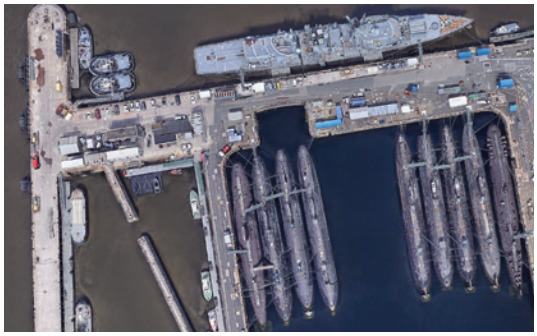


Figure 7. Retired nuclear submarines await decommissioning at Plymouth, United Kingdom (Credit: Google Earth)

Nuclear-powered torpedoes or unmanned underwater vehicles, however one puts it, like the Russian-built *Poseidon* is also a technology that is worth to be mentioned. However, it should be viewed as an example of what should not be done for several reasons.

Despite the seemingly impressive features of torpedoes like the *Poseidon* (near-unlimited range, stealth, etc.), the military utility of such water vehicles would actually be pretty low. To begin with, even at 70 knot speeds (the presumed top speed of *Poseidon*), it would likely take up to a day or more before a torpedo could reach the shores of a strategic rival, if launched from

[XV] By some estimates, petroleum-powered submarines and aircraft carriers are significantly more expensive to build and operate than their nuclear-powered counterparts. However, it is generally believed that nuclear-powered submarines and aircraft carriers have a clear strategic and operational advantage over non-nuclear ones, which justifies their costs.

[XVI] The average lifespan of a nuclear submarine is some 20-30 years.

Western coastal waters.[44] By contrast, it would take an ICBM like the *Minuteman III* under an hour to reach a major target of a strategic rival, if launched from the US mainland. In addition, because a nuclear-powered torpedo would likely be faster than a regular torpedo, it would create more noise and could likely be easier detected by sonars.[45] Though this does not mean that these torpedoes could be easier to intercept, it does mean that the country that is being targeted could make timely adjustments to their second strike capabilities. Ultimately, there is little sense in resorting to the use of underwater nuclear bombs to shower radioactive waste upon coastal towns or naval facilities. Such wanton destruction and killing of (mostly) civilians not only rests on dubious morality, but also is unlikely to achieve any strategic objectives, which could not otherwise be met without crossing the nuclear threshold.

AIR

The idea of nuclear-powered flight has long been a dream for aircraft enthusiasts and military planners alike. And rightly so. In theory, the atom holds the promise of unlimited flight, which would allow planes to circle the globe and operate without refuelling for days, weeks, if not more. Moreover, such planes would not emit any GHG emissions, which would help the military to slash its reliance on fossil fuels.

Yet, this is where the advantages end and the problems with nuclear-powered airplanes begin. Just as it was the case some sixty years ago, the issue of reactor shielding remains the main reason why these planes are not going to fly anytime soon, if ever. Nuclear fission reactors emit high amounts of radiation (alpha, beta, gamma and neutron), which can relatively easily go through less dense materials and might pose a threat to the airplane crew. Therefore, nuclear reactor designers have to use large amounts of dense (and usually very heavy) materials such as steel, lead, concrete, cadmium or tungsten (or a combination of them) to block the radioactive rays. By contrast, in order to be able to take off, airplanes have to be as light as possible. All of this means that planes with adequate reactor shielding would either become too heavy to fly, or, if the shielding would be somewhat thinner, the crew would be at risk of being exposed to dangerous levels of radiation, especially if there would be a reactor malfunction.

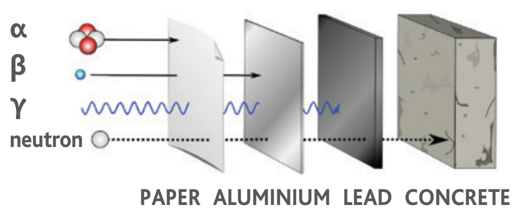


Figure 8. Penetration power of different types of radiation. (Credit: Wikipedia Commons)

Moreover, if, theoretically speaking, due to some breakthroughs in reactor shielding technology it would be possible to safely install a nuclear reactor on an airplane, it is still rather unlikely that such a plane would be ever approved to leave the testing grounds. Even if the odds of plane accidents are quite low, it is almost certain that no nuclear reactor shielding would survive a fall from a cruising altitude of some 10 kilometres and a head-on collision with the ground. This means that virtually every single nuclear airplane accident, however infrequent, would result in a mini-Chernobyl disaster, which would spew large amounts of radioactive materials across of the crash site. Considering that nearly every airplane crash would result in a nuclear catastrophe, it is also rather inconceivable that any government would allow such an airplane to get anywhere near a place where it could be at risk of being shot down.

Now, some may argue that in this day and age it is no longer necessary to have people on board of a nuclear-powered aircraft, and that such vehicles could easily be controlled from a distance. This, by extension, would mean that it would be possible to reduce if not completely eliminate the need for heavy reactor shielding. While technically this may be true, it still would be a pretty bad idea to develop either nuclear-powered unmanned aerial vehicles (UAVs) or cruise missiles. There are plenty of reasons for this, but one of the most obvious is that it is rather unlikely that any democratic government, nuclear regulator, international body or the public at large would be willing to accept the idea of nuclear reactors whizzing over or even anywhere near any populated areas. For instance, it is worth mentioning that, according to media reports, in 2012, a US research facility seemed interested in exploring the prospects of nuclear-powered UAVs. These UAVs would have reportedly been developed by Sandia National Laboratories and the defence contractor Northrop Grumman. However, the whole idea of nuclear-powered UAVs was extremely short-lived because it was nearly immediately shut down due to worries that public opinion would not accept the idea of such a potentially hazardous technology.[46]

Moreover, in the unlikely event that the military would somehow get a go-ahead from the government to proceed with the development of a nuclear-powered UAV or a cruise missile, it still would be incredibly dangerous and irresponsible — even in a test environment — to send a virtually unshielded nuclear reactor into the air. In fact, back in August 2019, five Russian nuclear scientists were killed due to likely radiation poisoning during a failed test of the *Burevestnik* missile at the Nenoksa testing facility.[47]

Finally, if a UAV or, more likely, a nuclear-powered cruise missile would rely on a ramjet engine for thrust, there is the very real risk that it would spew radioactive exhaust wherever it goes and endanger everyone and everything in its path. This is one of the main reasons why the US's *Project Pluto* was abandoned in the 1960s and the probably the primary explanation why no one in the West wanted to continue work on nuclear-powered cruise missiles ever since. Besides, this explains why the *Burevestnik* missile, which presumably uses a ramjet engine, has frequently been referred to as a "flying Chernobyl" by Western and Russian media alike.[48]

LAND

While at first glance, the prospects of near unlimited range and zero GHG emissions might pique some interest in the development of nuclear-powered land vehicles (either transport or combat), it would generally be unwise to pin any greater hopes on this technology. The reasons for that are legion, but for all intents and purposes, they could be boiled down to three basic categories: safety, security and economics.

First and foremost, the idea of installing nuclear reactors on land vehicles is a pretty risky one. Even if, in the extremely unlikely event, engineers would somehow manage to squeeze a nuclear reactor into a Unimog truck or a Humvee, it would still be rather dangerous to have these vehicles on the roads, hurling at speeds of around 100 kilometres per hour. More likely than not, a head-on collision with another vehicle or some static object would obliterate the (presumably thin) reactor shielding and spread nuclear waste. On top of that, as it would be the case with nuclear airplane crashes, there is the likelihood that such a vehicle accident could cause a criticality event (basically an uncontrolled nuclear fission chain reaction within the reactor), which could kill everyone that has not been directly involved in the

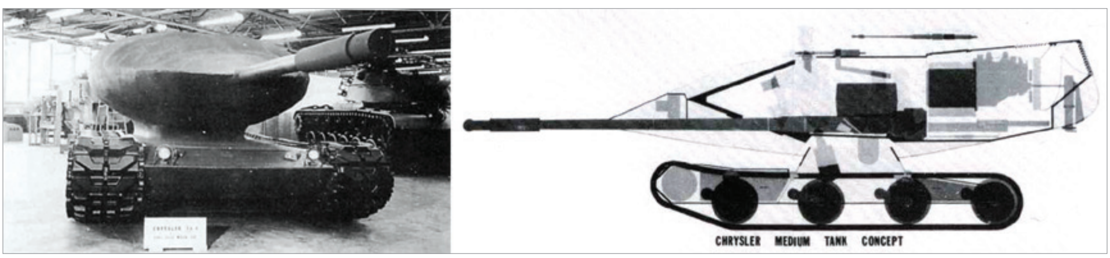


Figure 9. The Chrysler TV-8 was supposed to be world's first nuclear-powered tank. Predictably, it did not go beyond the drawing-board stage. (Credit: Wikipedia Commons)

collision, and shower the area in deadly radiation. Similarly, it goes without saying that it would be an even worse idea to install a nuclear reactor on a battle tank or some other vehicle, which could be exposed to enemy fire. In the event that such a vehicle would suffer critical damage, it is fairly likely that its reactor would quickly become unstable and engulf the whole area in a cloud of nuclear waste, killing friend and foe alike, and contaminating the land for decades if not centuries to come.

Furthermore, a nuclear-powered land vehicle could be a serious nuclear proliferation liability. From a security perspective, it is vastly more difficult to protect a small and moving vehicle than a large, well-protected nuclear power plant or a 100,000 ton nuclear aircraft carrier, closely guarded by an entire carrier battle group that may include fighter aircraft, frigates, destroyers, anti-submarine and anti-aircraft ships. Therefore, if a nuclear-powered land vehicle would somehow end up being captured by a terrorist organisation or a pariah state, then they could use the radioactive fuel from the reactor for the construction of a "dirty bomb". Alternatively, there is also the theoretical possibility that the adversaries could convert some of the captured nuclear reactors from the land vehicles into fast breeder reactors, which could then be used to produce weapons-grade fissile material.[49] Granted, the likelihood of such an event is very slim as not that many countries (not to mention non-state actors) have the technological know-how for such a conversion. Yet, there is still the risk that a stolen nuclear reactor could one way or the other inadvertently contribute to nuclear proliferation.

Ultimately, nuclear-powered land vehicles would make even less economic sense than small surface ships. While it is unclear if it would even be possible to install a miniaturized nuclear reactor on a truck or a battle tank, the costs of such a vehicle would be astronomical. Even in the most optimistic scenario, it is reasonable to assume that it would cost tens of millions of euros to fit a nuclear reactor into a truck or a tank (the economics of adding a nuclear reactor on a light transport vehicle like a Humvee do not even warrant consideration). By contrast, the most expensive main battle tank in the world, the South Korean *K2 Black Panther*, carries a price tag of around €7 million, and the one of the most expensive military trucks, the German-built *Man HX81*, costs some €1 million.[50] All of this means that with existing technology it is almost inconceivable to come up with a scenario where it would be cost-effective to install a nuclear reactor on a land vehicle.

On the whole, nuclear propulsion seems to offer rather interesting opportunities for the military across the sea, air and land domains. However, the keyword here is "interesting". While it impossible to deny that nuclear reactors might offer some theoretical advantages over conventional combustion engines, in most cases, the cons far outweigh the pros. Nuclear reactors are extremely expensive to build and maintain, they could become serious security liabilities if not handled carefully and they would also result in a lot of radioactive waste that would have to be dealt with.

CONCLUSION

The splitting of the atom and the dawn of nuclear propulsion were arguably some of the most important military technological developments of the 20th century. They gave rise to nuclear submarines that can navigate the oceans without refuelling for months and those mammoth-sized nuclear aircraft carriers that have become almost mystical symbols of naval strength. Owing to their immense success at revolutionizing naval warfare, it is unsurprising that there had also been attempts to develop nuclear-powered missiles and planes. These, it was believed, could also have a game-changing effect on the Cold War balance of power.

Much has changed since the first experiments with nuclear propulsion took place, and, thanks to a number of technological advances, hitherto science fiction-like ideas like nuclear-powered flight are not as impossible as they were before. After all, some fifty or sixty years ago it was almost inconceivable that it would be possible to control an aircraft from the safe confines of a military base thousands of kilometres away. However, this does not mean that it would be wise for

Western militaries to re-visit some of these Cold War-esque ideas or emulate countries like Russia by developing exotic weapon delivery systems like the *Burevestnik* or *Poseidon*.

In general terms, there are hardly any good reasons why nuclear reactors should be installed on mobile military equipment, other than submarines, large warships or aircraft carriers. There are some merits to the arguments that nuclear propulsion could significantly reduce the military's acute reliance on fossil fuels, cut its greenhouse gas emissions, and offer some operational advantages. However, the benefits are clearly outweighed by the drawbacks.

In terms of naval capabilities, nuclear-powered ships tend to have much greater lifecycle costs than those with combustion engines and, over time, they also produce significant amounts of nuclear waste. Meanwhile, nuclear-powered torpedoes are unlikely to bring any operational advantages that would justify their costs. When it comes to aircraft or missiles the situation is even more lopsided. Nuclear-powered airplanes are not only difficult (if not impossible) to build, and would be too dangerous to operate. Moreover, nuclear-powered cruise missiles are not only way too risky to be developed, but it is also unclear if they would provide any significant advantages over existing missile systems, ballistic or otherwise. Finally, nuclear-powered land vehicles would pretty much always be a terrible idea. Not only would they create more problems than solve, could contribute to nuclear proliferation, but they also would make zero economic sense.

There are perfectly good reasons why Western researchers have long abandoned plans for exotic nuclear-powered vehicles or weapon delivery systems and have never looked back. Briefly put: nuclear fission is a dangerous and unstable process, if not handled properly, and it is generally always a bad idea to install fragile nuclear reactors — which emit copious amounts of radiation — on equipment that may crash into a wall or would be flung into the air with minimal protection. Therefore, Western militaries should not be swayed by Russia's development of its "doomsday weapons", or any calls from external observers to mirror its moves, as these weapon delivery systems would likely prove to be greater liabilities than assets.

Instead, Moscow's current posturing should be understood for what it really is: a desperate attempt to cling to the past and its great power status, a bid to impress domestic audiences and a general inability to adjust to the realities of the post-Cold War era.

REFERENCES

[1] "'I'm Not Bluffing': Putin Touts New, Advanced Russian Arsenal", Radio Free Europe/Radio Liberty, 1 March 2018, https://www.rferl.org/a/putin-new-advanced-russian-arsenal-nuclear-capable-weapons/29071274.html

[2] Peter Brookes, "Responding to Troubling Trends in Russia's Nuclear Weapons Program", Heritage Foundation, 26 March 2021, https://www.heritage.org/defense/report/responding-troubling-trends-russias-nuclear-weapons-program

[3] Matthew Kroenig, et. al., "Russia's Exotic Nuclear Weapons and Implications for the United States and NATO", Atlantic Council, July 2020, https://www.atlanticcouncil.org/wp-content/uploads/2020/07/Russias-Exotic-Nuclear-Weapons.pdf ; Rose Gottemoeller, "Russia Is Updating Their Nuclear Weapons: What Does That Mean for the Rest of Us?", Carnegie Endowment for International Peace, 29 January 2020, https://carnegieendowment.org/2020/01/29/russia-is-updating-their-nuclear-weapons-what-does-that-mean-for-rest-of-us-pub-80895

[4] Jeffrey Lewis, "Russia's Nuclear Powered Cruise Missile", Arms Control Wonk blog, 24 March 2018, Russia's Nuclear Powered Cruise Missile (armscontrolwonk.com)

[5] "Review of Manned Aircraft Nuclear Propulsion Program," United States Department of Defense, February 1963, https://fas.org/nuke/space/anp-gao1963.pdf

[6] Karen Frankel, "Resuscitating the Atomic Airplane: Flying on a Wing and an Isotope", Scientific American, 5 December 2008, https://www.scientificamerican.com/article/nuclear-powered-aircraft/

[7] Larry Greenmeier, "Russia's New Nukes Are Similar to a Risky Project the U.S. Abandoned", Scientific American, 5 March 2018, https://www.scientificamerican.com/article/russias-new-nukes-are-similar-to-a-risky-project-the-u-s-abandoned/

[8] Patrick Tucker, "Nuclear-Powered Cruise Missiles Are a Terrible Idea. Russia's Test Explosion Shows Why", Defense One, 14 August 2019, https://www.defenseone.com/technology/2019/08/nuclear-powered-cruise-missiles-are-terrible-idea-russias-test-explosion-shows-why/159189/

[9] Ole Reistad and Povl Ølgaard, "Russian Nuclear Power Plants for Marine Applications", Nordic Nuclear Safety Research, 2006, https://www.osti.gov/etdeweb/servlets/purl/20752557

[10] Ibid.

[11] Viktor Kudryavcev, "Flying Atomic Laboratory: Reactor on board", PopMech, 21 November 2008, https://www.popmech.ru/science/8408-kosmicheskie-istrebiteli-ubiytsa-sputnikov/

[12] Raul Colon, "Soviet Experimentation with Nuclear Powered Bombers", Aviation History, March 2009, http://www.aviation-history.com/articles/nuke-bombers.html

[13] Vasily Sychev, "Raketa O Kotoroy Nikto Ne Znal", Meduza, 4 March 2018, https://meduza.io/feature/2018/03/04/raketa-o-kotoroy-nikto-ne-znal

[14] Ibid.

[15] John Pike, "Nuclear Propulsion", Federation of Atomic Scientists, 29 February 2000, https://fas.org/man/dod-101/sys/ship/eng/reactor.html

[16] Will Davis, "Seawolf Tries Sodium", Nuclear Newswire, 15 November 2017, https://www.ans.org/news/article-1999/seawolf-tries-sodium/

[17] John Pike, "Nuclear Propulsion", Federation of Atomic Scientists, 29 February 2000, https://fas.org/man/dod-101/sys/ship/eng/reactor.html

[18] John Krzyzaniak, "Project Pluto and the trouble with Russia's nuclear-powered cruise missile", Bulletin of the Atomic Scientists, 20 August 2019, https://thebulletin.org/2019/08/project-pluto-and-trouble-with-the-russian-nuclear-powered-cruise-missile/

[19] "Legacy Power Systems", NASA, https://rps.nasa.gov/power-and-thermal-systems/legacy-power-systems/

[20] Adin Oyedele, "19 Of The Most Expensive Substances In The World", Business Insider, 22 September 2014, https://www.businessinsider.com/most-valuable-substances-by-weight-2014-9

[21] Mark Wolverton, "Stirling in Deep Space", Scientific American, 1 March 2008, https://www.scientificamerican.com/article/stirling-in-deep-space/

[22] "Nuclear-Powered Ships", World Nuclear Association, June 2021, https://world-nuclear.org/information-library/non-power-nuclear-applications/transport/nuclear-powered-ships.aspx

[23] "Navy Ford (CVN-78) Class Aircraft Carrier Program: Background and Issues for Congress", Congressional Research Service, 25 June 2021, https://fas.org/sgp/crs/weapons/RS20643.pdf; "Navy Columbia (SSBN-826) Class Ballistic Missile Submarine Program: Background and Issues for Congress", Congressional Research Service, 24 June 2021, https://fas.org/sgp/crs/weapons/R41129.pdf; "France's next-generation aircraft carrier will be nuclear-powered, says Macron", Reuters, 8 December 2020, https://www.reuters.com/article/france-nuclear-macron-carrier-idUKP6N2I9000; Claire Mills "Replacing the UK's strategic nuclear deterrent: progress of the Dreadnought class", Commons Briefing papers, 2 March 2021, https://researchbriefings.files.parliament.uk/documents/CBP-8010/CBP-8010.pdf; Minnie Chan, "Chinese military: fourth aircraft carrier likely to be nuclear powered, sources say", South China Morning Post, 13 March 2021, https://www.scmp.com/news/china/diplomacy/article/3125224/chinese-military-fourth-aircraft-carrier-likely-be-nuclear; H I Sutton, "Chinese Navy Steps Closer To New Generation Of Nuclear Submarines", Forbes, 19 June 2020, https://www.forbes.com/sites/hisutton/2020/06/19/chinese-navy-gets-closer-to-new-generation-of-nuclear-submarines/; Shishir Gupta, "Eye on China, India's plan for 6 nuclear-powered attack submarines back on track", Hindustan Times, 10 March 2021, https://www.hindustantimes.com/india-news/eye-on-china-india-s-plan-for-6-nuclear-powered-attack-submarines-back-on-track-101615327826084.html.

[24] Xavier Vavasseur, "Russia's Upgraded Kirov-Class Cruiser Admiral Nakhimov Set For Late 2022 Delivery", Naval News, 17 December 2020, https://www.navalnews.com/naval-news/2020/12/russias-upgraded-kirov-class-cruiser-admiral-nakhimov-set-for-late-2022-delivery/

[25] Brad Bergan, "The Weapon That Eradicates Cities by Creating 'Radioactive Tsunamis'", Interesting Engineering, 6 July 2021, https://interestingengineering.com/poseidon-nuclear-weapon-radioactive-tsunamis-russia

[26] Sebastian Roblin, "Four Russian Submarine Will Have the Poseidon Nuclear Torpedo Drone", National Interest, 18 January 2021, https://nationalinterest.org/blog/reboot/four-russian-submarine-will-have-poseidon-nuclear-torpedo-drone-176483

[27] Ibid.

[28] H I Sutton, "New Details of Russian Belgorod 'Doomsday' Submarine Revealed", USNI News, 25 February 2021, https://news.usni.org/2021/02/25/new-details-of-russian-belgorod-doomsday-submarine-revealed

[29] "Russia's new underwater nuclear drone should raise alarm bells", Washington Post, 27 December 2015, https://www.washingtonpost.com/opinions/russias-ship-of-terror/2015/12/27/b2085ee0-a9bb-11e5-bff5-905b92f5f94b_story.html

[30] Brad Bergan, "The Weapon That Eradicates Cities by Creating 'Radioactive Tsunamis'", Interesting Engineering, 6 July 2021, https://interestingengineering.com/poseidon-nuclear-weapon-radioactive-tsunamis-russia

31 Aleksandr Sharkovskij, "Jadernyj "Burevestnik" stal realnostju", Nezavisimaja gazeta, 17 February 2019, https://www.ng.ru/week/2019-02-17/7_7510_army.html

32 Jill Hruby, "Russia's New Nuclear Weapon Delivery Systems: An Open-Source Technical Review", Nuclear Threat Initiative, 13 November 2019, https://www.nti.org/analysis/reports/russias-new-nuclear-weapon-delivery-systems-open-source-technical-review/; John Haines, "What Happened at the Severodvinsk Naval Testing Range? Thoughts on the Severodvinsk Radioactive Release and When It Happened Here", Foreign Policy Research Institute, 19 August 2019, https://www.fpri.org/article/2019/08/what-happened-at-the-severodvinsk-naval-testing-range-thoughts-on-the-severodvinsk-radioactive-release-and-when-it-happened-here/

33 Douglas Barrie, "Burevestnik: US intelligence and Russia's 'unique' cruise missile", International Institute for Strategic Studies, 5 February 2021, https://www.iiss.org/blogs/military-balance/2021/02/burevestnik-russia-cruise-missile

34 Anastassia Gliadkovskaya, "Russian Ministry of Defence unveils new high-tech weaponry", Euronews, 19 July 2018, https://www.euronews.com/2018/07/19/russian-ministry-of-defence-unveils-new-high-tech-weaponry

35 Robert Burns, "Mattis: Proposed nuke missile is a bargaining chip", Associated Press, 6 February 2018, https://apnews.com/article/4a178441c4ef4a1f90a1e40e331999f0

36 "Presidential Address to the Federal Assembly", Presidential Executive Office, 1 March 2018, http://en.kremlin.ru/events/president/news/56957

37 "Nuclear Submarines and Aircraft Carriers", United States Environmental Protection Agency, 28 April 2021, https://www.epa.gov/radtown/nuclear-submarines-and-aircraft-carriers; "Axios reviews "green" fuel options for commercial shipping", Nuclear Newswire, 10 March 2021, https://www.ans.org/news/article-2701/axios-reviews-green-options-for-commercial-shipping/

38 Neta Crawford, "Pentagon Fuel Use, Climate Change, and the Costs of War", Brown University, 12 June 2019, https://watson.brown.edu/costsofwar/files/cow/imce/papers/2019/Pentagon%20Fuel%20Use%2C%20Climate%20Change%20and%20the%20Costs%20of%20War%20Final.pdf

39 "The Cost-Effectiveness of Nuclear Power for Navy Surface Ships", Congressional Budget Office, May 2011, https://www.cbo.gov/publication/41454

40 Ibid.

41 Robert Burns, "Nonpartisan budget report says future nuke costs are rising", Associated Press News, 25 May 2021, https://apnews.com/article/business-government-and-politics-40a28453aa03e721bd9fd4177f5467a7

42 Trinh Le, "Spent Nuclear Fuel Storage and Disposal", Stimson Center, 17 June 2020 https://www.stimson.org/2020/spent-nuclear-fuel-storage-and-disposal

43 Lucy Fisher, "Delays to scrapping navy's submarines 'cost £900m'", The Times, 3 April 2019, https://www.thetimes.co.uk/article/delays-to-scrapping-navy-s-submarines-cost-900m-kj8qqcdp0

44 Steven Pifer, "Russia's perhaps-not-real super torpedo", Brookings Institution, 18 November 2015, https://www.brookings.edu/blog/order-from-chaos/2015/11/18/russias-perhaps-not-real-super-torpedo/

45 Ibid.

46 Steven Aftergood, "Secret Drone Technology Barred by "Political Conditions"", Federation of American Scientists, 22 March 2012, https://fas.org/blogs/secrecy/2012/03/sandia_drone/ ; Nick Fielding, "US draws up plans for nuclear drones", The Guardian, 2 April 2012, https://www.theguardian.com/world/2012/apr/02/us-plans-nuclear-drones

47 "Rocket mystery: What weapon was Russia testing in Arctic?", BBC, 12 August 2019, https://www.bbc.com/news/world-europe-49319160

48 "Trump Nominee to Russia: Abandon 'Flying Chernobyl' Nuclear Missile", The Moscow Times, 22 July 2020, https://www.themoscowtimes.com/2020/07/22/trump-nominee-to-russia-abandon-flying-chernobyl-nuclear-missile-a70951

49 "How do fast breeder reactors differ from regular nuclear power plants?", Scientific American, 17 July 2006, https://www.scientificamerican.com/article/how-do-fast-breeder-react/

50 Mark Episkopos, "South Korea's K2 Black Panther: The Most Expensive Tank on the Planet?", National Interest, 10 June 2021, https://nationalinterest.org/blog/buzz/south-korea%E2%80%99s-k2-black-panther-most-expensive-tank-planet-187367 ; "HX 81", Army Guide, 2015, http://www.army-guide.com/eng/product4738.html