NATO ENERGY SECURITY
CENTRE OF EXCELLENCE

ENERGY HIGHLIGHTS

Is small really beautiful?
The future role of small modular nuclear reactors (SMRs) in the military

by **Mr. Lukas Trakimavičius**

"Amateurs talk strategy, professionals talk logistics" is a well-worn adage, which over the years was attributed to numerous famed individuals, ranging from Napoleon Bonaparte to Omar Bradley, General of the United States Army during World War II. Regardless who the real author was, this adage contains an obvious kernel of truth. Modern armies cannot move, fight or perform any of its duties without massively complicated supply lines and the tireless work of logisticians. Perhaps even more importantly, none of the above would be possible without a constant supply of energy, whether in the form of countless canisters of petroleum or a steady stream of electricity. In other words, energy is the undisputed lifeblood of the military.

For most of the 20th century, energy security for the military meant having an unfettered and abundant access to fossil fuels. Oil and its products would power the engines of ships, planes and vehicles, and, in times of conflict, it would generate electricity for bases and military facilities alike. However, in recent decades there has been a slow, but steady shift from a fossil fuel-dominated perspective of energy security. Owing largely to the looming threat of climate change and the shifting tides of politics, most Western militaries became increasingly conscious about the environmental toll of burning fossil fuels and consequently got involved in efforts to reduce greenhouse gas (GHG) emissions. On a more practical level, wars in Afghanistan and in Iraq taught Western militaries bitter lessons about the costs, both financial and human, of long supply lines, which extend through hostile and unforgiving terrain.

Under these circumstances, it is unsurprising that Western militaries started to look for ways to strengthen their operational capabilities by embracing clean and innovative energy solutions.

by **Mr. Lukas Trakimavičius**

Mr. Lukas Trakimavičius works at the Research and Lessons Learned Division of the NATO Energy Security Centre of Excellence. Previously, he worked at the Economic Security Policy Division of the Lithuanian Ministry of Foreign Affairs. He also held several positions at NATO, where he focused on energy security, arms control, disarmament and non-proliferation.

This is where small modular nuclear reactors (SMRs) come into play.

Proponents have long argued that by adopting SMRs militaries could limit GHG emissions and reduce their dependence on fossil fuels, long supply lines, and civilian energy grids. The civilian sector would also benefit from it, because it could take advantage of an innovative technology without having to shoulder all of the developmental risks and expenses.[1] Others, however, disagreed and claimed that SMRs made very little sense for the military. By pointing out the dubious economic rationale of these projects, the unaddressed issue of spent fuel, the threat of nuclear proliferation and the risk of accidents, they argued that SMRs would likely do more harm than good.[2]

Yet, as it usually is the case, the truth lies somewhere in the middle. Like most technology, SMRs do not easily lend themselves to generalization and by some accounts their benefits indeed outweigh the cons. At times, the opposite is also true.

In turn, this research paper will explore the history and development of SMRs, discuss their technological features and examine the utility of SMRs through a number of different angles, all while trying to address the question of whether SMRs could be useful to Western militaries.[i]

HISTORY OF SMALL NUCLEAR REACTORS IN THE MILITARY

It is a common misconception that smaller-than-usual nuclear reactors — the predecessors of modern day SMRs — are based on fundamentally new technology. In fact, this is a technology that is nearly 70 years old and whose origins can be traced all the way back to the early days of the Cold War.

In the United States, the earliest research and development on multiple types of small nuclear reactors began in the immediate aftermath of World War II. From 1946 to 1961, the US Air Force spent around €1 billion trying to build a reactor to power long-range bombers, though to little avail.[3] The US Navy had better success with harnessing nuclear energy and, in 1954, it built the *USS Nautilus*, the world's first nuclear-powered submarine.[4] Six years later, the US Navy launched the word's first nuclear-powered aircraft carrier, the *USS Enterprise*.[5] Meanwhile, the US Army also ran a nuclear energy program from 1954 to 1979. Over two decades, it built and operated eight small power reactors, which mostly were deployed at remote military bases.[6] This program was moderately successful, but it was gradually abandoned due to the questionable cost-effectiveness of the technology and the post-Vietnam war spending cuts.[7]

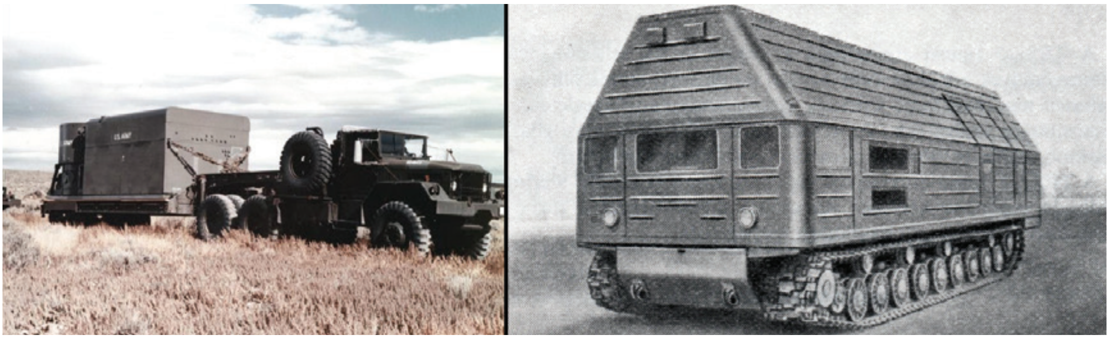


Figure 1. Early experimental portable small nuclear reactors. ML-1, United States; TES-3, Soviet Union (left to right). (Credit: Bellona.org)

---

[i] This article does not intend to provide a comprehensive assessment of the benefits and challenges associated with developing and deploying SMRs at a strategic, operational or a tactical level. There are existing studies and that have already accomplished this task with great success. Nor is the goal of this paper to provide a detailed technical analysis of the SMR market or a history of nuclear energy research. Rather, its goal is to provide a brief introduction of SMRs and a broad policy-level overview of the pros and cons of using SMRs in a military setting.

The Soviet Union, too, was busy maintaining an active small nuclear reactor program. In 1958, the Soviet Navy launched their own nuclear-powered submarine — the *K-3 Leninsky Komsomol*.[8] Three years later, the Soviets succeeded in building a mobile small nuclear reactor, named TES-3, which was carried around on a modified chassis of a T-10 tank.[9] At around the same time, the Soviet Air Force has also developed a nuclear-powered aircraft. The retrofitted Tupolev Tu-95LAL bomber managed to complete some 40 research flights, but following a high-number of cases of radiation-linked deaths, the program was scrapped in 1969.[10] Lastly, in 1988, the Soviet Navy started working on the *Ulyanovsk* — the country's first nuclear-powered aircraft carrier — but due to the collapse of the USSR, the project was scrapped in 1991.[11]

During the Cold War, only the US and the USSR seriously entertained the thought of using small land-based nuclear reactors for military purposes.[12] Due to a number of reasons, including cost and utility, other nuclear powers had fairly little interest in small nuclear reactors beyond the realms of naval engineering and scientific research.

PUTTING THE M IN THE SMR

While small nuclear reactors are hardly a novelty, the same cannot be said about SMRs. They are quite similar to small nuclear reactors in terms of size, power output and the basic technology, but differ in one very key respect: modularity. Within this context, the term "modular" means that, unlike conventional nuclear reactors, both small and large, SMRs were manufactured in a factory and could be transported by truck, rail or plane directly to the plant site. Even if most nuclear reactors, both new and old, rely extensively on factory-built components, a good deal of field work is still necessary to assemble these components into an operational nuclear power plant (NPP). In contrast to small and large nuclear reactors, SMRs have a much more streamlined design, enhanced safety features and their modules can be added incrementally to meet changing energy demand. In other words, SMRs are thought to be ready to "plug and play" upon arrival, reducing both capital costs and construction times.

In terms of power output, SMRs are defined by the International Atomic Energy Agency (IAEA) as reactors that are capable to generate up to 300 MWe per module. This contrasts with medium-sized nuclear reactors, which can produce between 300 MWe and 700 MWe, and large nuclear reactors whose maximum power output is 1000 MWe or greater. SMRs can also be subdivided into different categories. Some institutions and energy companies employ a wide variety of terms, including "micro modular reactors" (MMRs) and "very small modular nuclear reactors" (vSMRs) to describe SMRs that have the capacity to generate up to 10-25 MWe per module.

However, considering that the terms "MMRs", "vSMRs" and "SMRs" are frequently used almost interchangeably and that, conceptually speaking, they refer to relatively similar objects (though the size and the power output of the reactors vary), for the sake of convenience, mostly the broader term "SMRs" will be used throughout this research paper.

From a reactor design perspective, the majority of today's SMRs can be broadly divided into two categories: those whose mature designs use water for cooling purposes, and those whose advanced designs do not. The latter's designs may employ a diverse range of materials such as helium, sodium, lead, molten salt and others. As things stand now, light-water reactors and gas-cooled reactors have by far the greatest technological maturity (based on the number of reactor-years of experience) and, therefore, they are best suited for near-term deployment.[13] Other designs, such as liquid-metal cooled reactors, have great potential for longer term development and deployment, but they need additional work to achieve viability in the marketplace.

Currently, there are around 70 SMR designs and concepts globally. The bulk of the research is concentrated in countries such as Canada, China,

---

[11] The United Kingdom launched its first nuclear-powered submarine, the HMS Dreadnought, in 1960. Eleven years later, France commissioned its own nuclear-powered submarine, the Redoutable.

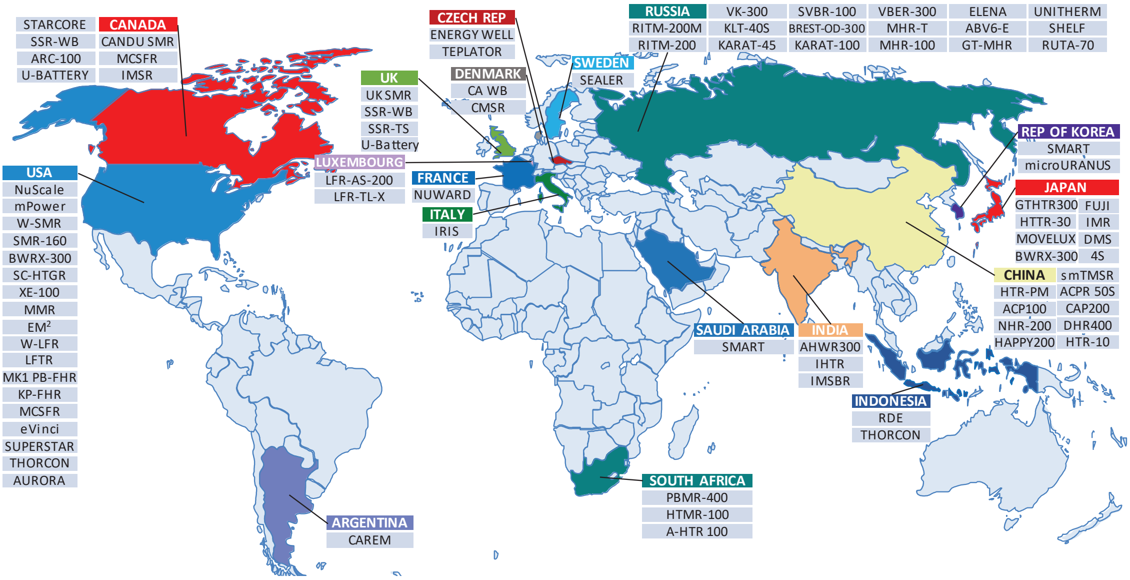


Figure 2. Global map of SMR technology development (Credit: IAEA)

Japan, Russia, the US and South Korea.[14] Most of these SMRs are in rather early stages of development, though some are claimed as being mature enough to be near-term deployable. For instance, the Korea Atomic Energy Research Institute is eying to launch its first commercial 100 MWe SMR in Saudi Arabia in 2028.[15] Meanwhile, NuScale Power, a US-based company, is hoping to get its first commercial 60 MWe SMR module up and running in Idaho by 2029.[16]

There are also other promising designs from companies such as GE Hitachi Nuclear Energy, Terrestrial Energy and OKBM Afrikantov (a subsidiary of ROSATOM), just to name a few, whose commercial land-based SMRs might be built in the coming decade. Though it still remains to be seen if any of these companies will succeed in actually building their SMRs, or if they will fail like some of their predecessors.[III]

MILITARY INTEREST IN SMRS

In light of the changing politics, technological advances and operational requirements, recent years have been marked by an unprecedented surge of interest in military applications of SMRs.

The Russian military was among the first to make it clear that it wants to have SMRs at its disposal. Back in 2015, Russia's Ministry of Defense said that it was planning to develop up to 30 SMRs in its Arctic region. These reactors would provide electricity to remote bases and military facilities, which are currently under development as part of Russia's broader Arctic militarization plan. The SMRs would be small enough, so that they could be shipped by truck, on a sledge or even carried by heavy cargo helicopter, such as the Mi-26.[17]

More recently, in 2019, Russia launched its first floating NPP, the *Akademik Lomonosov*.[18] Named after the 18th-century Russian scientist, the 144 meters long and 30 meters wide vessel houses two 35 MWe modular nuclear reactors. According to its designers, *Lomonosov* is a "working prototype" for a future fleet of floating NPPs and land-based installations based on SMRs technology.[19] To date, Russia has not made it explicit that Lomonosov will be actively used by the country's

---

[III] In recent years a number of high-profile energy companies have abandoned their plans to develop SMRs. Westinghouse — a US energy company — worked on a mature SMR design for about a decade before dropping it in 2014. More recently, a mature SMR design by Babcock & Wilcox — another US energy company — was scrapped in 2018, despite €95 million funding from the US government.

military and claimed that its SMRs would be mostly used to power remote cities or research facilities. Yet, given their versatility, there are few doubts that floating NPPs like *Lomonosov* could eventually be used at military bases along the north coast of Siberia and on remote archipelagoes such as Novaya Zemlya or Franz Josef Land.

China's military, too, has expressed its interest in SMRs. In 2016, reports have surfaced that the Chinese Academy of Sciences' Institute of Nuclear Energy Safety Technology was developing an experimental SMR — dubbed the *hedianbao* — and received partial funding from the People's Liberation Army for the project. According to the researchers, these SMRs would be very small, measuring about 6.1 meters in length and 2.6 meters in height. They could be moved inside a shipping container, generate up to 4 MWe and would be installed on islands of the South China Sea.[20]

In 2019, the state-owned China National Nuclear Corporation (CNNC) also stated that it was interested in developing floating SMRs. According to the CNNC, the first demonstration unit — *the Linglong One* — will have the capacity of 125 MWe and it will be built on the island province of Hainan.[21] The CNNC's public statements suggests that the floating SMRs will be predominantly used to power islets and offshore drilling platforms that may otherwise have little or no access to the onshore grid power supply. However, bearing in mind Beijing's rapid militarization of the South China Sea, and its fierce rivalry with neighboring countries, there is little doubt that the floating SMRs could also be used to strengthen China's military foothold in the region.

The US military has also signaled its interest in SMRs. In 2019, the US Department of Defense (DOD) announced its plans to develop a SMR as part of a program called "Project Pele". According to the DOD, the reactor would be able to generate between 1-5 MWe for over three years without refueling, weigh less than 40 tons and be small enough to be transported by truck and cargo aircraft, such as the C-17 Globemaster. The DOD hopes that it would not take more than 72 hours to assemble the SMR on-site and that it could be disassembled in less than a week. In early 2020, the DOD already issued contracts for three US nuclear energy companies (BWXT, Westinghouse, X-Energy) to start work on a SMR design. It is hoped that, following a two-year engineering competition, a mature SMR design prototype will be selected, and that its outdoor testing could begin in 2024.[22]

To date, there has been little evidence to suggest that with the exception of Russia, China and the US any other countries would be seriously considering to develop and deploy SMRs for their military needs. This is likely the case because only a limited number of countries have enough experience of working with nuclear energy at a sufficiently advanced level. And, even within this slightly narrower list of countries, which possess the industrial capacity and the know-how to develop SMRs, there are even fewer countries, which have the military need or the financial resources for such an endeavor. Therefore, if things stay as they are right now, it is very likely that in the coming years and decades, most of the military-related SMR innovation will take place within this group of three.

Yet, despite the recent surge in popularity, SMRs, and, especially the highly-portable MMRs, remain a fundamentally unproven technology. It might take decades before they could be adopted by the militaries in large numbers, if at all. Considering the time, effort and money that any large-scale military SMR program would require, it is only prudent to review and examine the different factors that could affect their development and deployment.

POLITICAL CONSIDERATIONS

For better or worse, civil nuclear energy is already a controversial topic in itself. Advocates claim that it's the only way to meet global climate goals, while opponents hold adamant views over safety, security, and radioactive waste matters. However, when one adds SMRs and the military into the mix, things become even more complicated and politically charged. This is because its supporters not only have to take into account the traditional concerns of nuclear energy, but also address worries that relate to the use of SMRs on the battlefield.[23] From a policy perspective, it might also be difficult to secure adequate and sustained funding for SMRs. Given that there are existing substitutes to SMRs, any major SMR program will likely be at the crosshairs of every public budgetary scrutiny and would be the last one to be added and first one to be cut from any spending bill.

Granted, just because there is an uphill battle for the SMR industry, it does not necessarily mean that it's not worth the climb. Given that most Western countries are very much in a nuclear-energy slump, there are sound political arguments to support the idea of the military being the "first mover" in supporting the development of SMRs. By absorbing the initial round of development costs and providing encouragement to risk-averse commercial operators to invest in SMR technology, the military could have a profound impact on the industry. This, by extension, could mean that new jobs might be created, know-how acquired and the foundations of the nuclear energy industry strengthened. After all, many of the West's large militaries have ample experience of working with nuclear energy, and the military in general has often played a key role in spearheading the development of advanced technology, which later was successfully commercialized for civilian use.

Though, it must be noted that the transition from military-grade to civilian SMRs would unlikely be as effortless as it might initially seem. The SMRs used by the military would likely have more robust safety and security features and very different operational requirements than their civilian counterparts. This would likely mean that military SMRs would be vastly more expensive than civilian ones and their electricity would be insufficiently competitive for the civilian energy market.

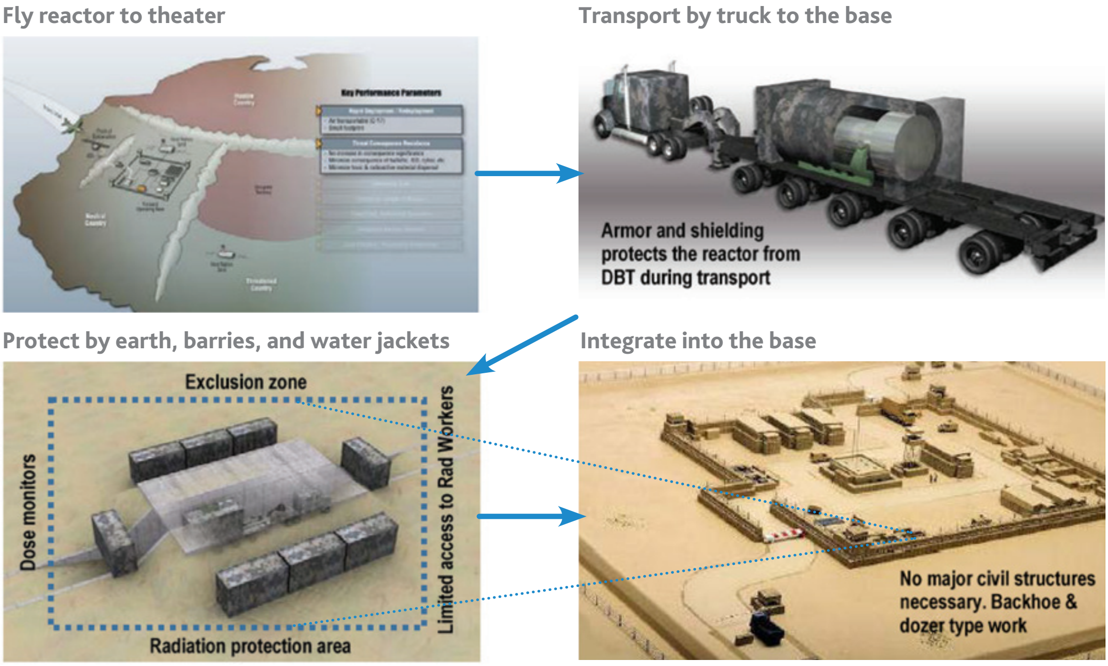
More broadly speaking, there is also the political risk that if Western nuclear energy companies would not step up their game in developing SMR technology, the industry could likely end up being dominated by Russian and Chinese companies. This could have serious implications for the global nuclear energy market and even beyond. First, given the close links of these governments with state-owned companies like ROSATOM and CNNC, there is good reason to believe that Russian and Chinese nuclear energy exports could be used to pursue broader foreign policy goals.[24] Second, bearing in mind Moscow's and Beijing's close links with a legion of pariah states, some of whom would likely be interested in acquiring SMR technology, there is the risk that SMR sales to these states could inadvertently lead to the weakening of current nuclear non-proliferation regimes.[25]

STRATEGIC MILITARY CONSIDERATIONS

At first glance, SMRs might make a lot of strategic sense for a number of Western militaries. SMRs could greatly reduce the logistical burden of out-of-area missions by "unleashing" the military "from the tether of fuel", as James Mattis, former US Defense Secretary once famously put it.[26]

In practical terms, SMR's might allow the military to cut its fuel bill and help save lives on the battlefield. Evidence suggests that the cost of air-dropped fuel rose up to €340 per gallon when it was delivered to US forward operating bases (FOB's) in Afghanistan.[27] While it is difficult to estimate the electricity cost of military-grade SMRs (as none have yet been built), there are few doubts that it would be markedly lower than the cost of air-dropped fuel. Even more importantly, SMRs would reduce the military's reliance on fuel resupply convoys and the number of troops exposed to roadside bombs and enemy attacks. It was estimated that between 2001 and 2010, over 18,000 US troops were killed in Iraq and Afghanistan during land transport missions.[28] In Afghanistan this may have equaled to nearly one casualty for every 24 fuel resupply missions.[29]

Yet, going forward, it is rather uncertain if there will be an urgent need for any new FOBs. Both opinion polls and the general political sentiment across much of the West clearly indicates that most countries are tired of the so-called "forever wars" in far-flung corners of the world, which over the decades have resulted in hundreds of thousands of casualties and costed trillions of euros.[30] As a matter of fact, it is not very far-fetched to suggest that, at least in recent history, there



Fly reactor to theater

Transport by truck to the base

Protect by earth, barries, and water jackets

Integrate into the base

Figure 3. Concept of SMR operations (Credit: US Department of Defense)

has hardly been a time when public support for new boots-on-the-ground and out-of-area military missions was as low as it is right now. Hence, if Western political leadership would be reluctant to get involved in new military conflicts — as it currently very much seems to be the case — or unwilling to extend their stay in places such as Afghanistan or Iraq by a considerable margin, the strategic argument for developing SMRs for the military becomes somewhat nebulous.

Not everyone is convinced that the current distaste for new and large out-of-area missions is a sufficient reason not to develop military SMRs. In 2018, the US Army released a study on the use of the SMRs in ground operations, which, among other things, argued that the SMRs would allow the US to be ready to conduct large-scale combat operations against near-peer competitors, such as Russia or China. More specifically, it claimed that SMRs could support strategic and operational deployment and could "meet the anticipated power demands in both highly developed mature theaters, such as Europe, and immature theaters and lesser developed areas globally."[31]

While there is nothing inherently wrong with the core assumptions of this study, its conclusions do not seem very convincing. For the sake of both national and international security, it is undoubtedly key that the US would be adequately prepared to face near-peer competitors such as Russia and China on the battlefield. But this alone hardly justifies the development of new, costly and unproven energy systems. First, it is widely agreed that, due to a number of reasons, including the risk of a nuclear holocaust, the odds of a large-scale military conflict among the nuclear powers is relatively low. Second, all of Washington's near-peer rivals already possess a wide arsenal of ballistic and cruise missile systems, and are currently developing a new generation of highly accurate and blazingly fast hypersonic weapons.[32] This means that even in the unlikely event of a military showdown, limited or all-out, battle-deployed SMRs would undoubtedly be among the first objects to be taken down by enemy forces.

OPERATIONAL MILITARY CONSIDERATIONS

Whereas at the strategic level the utility of SMRs is somewhat mixed, it is at the operational level that they truly excel. Arguably the greatest military advantage of SMRs relates to its capacity to provide a continuous source of high-density power. Unlike diesel generators, SMRs do not need to be constantly resupplied, and, unlike renewables, the help of additional power storage equipment. Therefore, the deployment of SMRs at FOBs could free up troops that would otherwise have to participate in fuel resupply convoys or have to manage and maintain renewable energy systems.

Considering that SMRs could meet the power needs of even the most power-hungry systems, they would also allow FOBs to expand their operational capabilities. SMRs might provide the necessary energy for additional military hardware, which could include unmanned aerial vehicles, high-power radars, air defense/missile batteries (such as the Terminal High Altitude Area Defense) or other weapons systems. On top of that, SMRs could help the military, and the land forces in particular, to become more future-proof because SMRs would be able to meet the potential energy demand of all-electric brigades, if they would ever come to existence.[33] In a word, SMRs have the potential to act as real force multipliers.

SMRs could also strengthen the energy resilience of bases and military facilities. A significant number of Western military bases are overly reliant on the commercial power grids for their energy supplies. This means that if the central power grids would go down due to cyber-attacks, extreme weather events, human errors or equipment failure, some military facilities would go down too. While virtually all military sites have rigorous emergency power generation plans, which usually involve back-up diesel generators, many military facilities have only enough fuel to last a couple of days. Hence, if there was a prolonged power outage, the operational capacity of the military site could be at risk.[34]

SMRs would address this problem head on. By providing an independent source of power, they could allow the military facilities to enter an emergency “island mode” and stay fully operational even if the central power grid was down. Granted, a similar effect could be accomplished by substituting SMRs with a combination of smart micro grids, batteries and renewable sources of energy, such as solar or wind power. In the event that the main power grid would go offline, the micro grid could disconnect itself from the main grid and, by relying on either local or on-site energy sources, it could continue to work relatively unharmed. But given the intermittency of renewable energy generation and the current challenges of energy storage technology, SMRs would likely prove to a better option for the military, at least for the foreseeable future.

The operational advantages of SMRs, and especially MMRs, might extend well beyond purely military endeavors. Given their size and mobility, SMRs could be well equipped to assist civilian authorities in humanitarian assistance and disaster relief operations. They might not only quickly provide electricity to disaster-hit areas, but also, in the event of a total blackout (as seen in Puerto Rico in 2018 or Venezuela in 2019) to do a “black start” – a complete reboot of the central power grid.

ECONOMIC CONSIDERATIONS

The economics of SMRs are not as straightforward as one might expect. There is strong evidence to suggest that nuclear energy never made much economic sense. In 2019, the German Institute for Economic Research, has released a survey of 674 nuclear plants that have ever been built to prove that purely commercial considerations have never been the dominant motivation building NPPs.[35] While at a per megawatt hour (MWh) level, NPPs are able to provide one of the cheapest sources of electricity, once the full capital (including the near-ubiquitous construction overruns) and operating costs are factored in, which include dismantling and long-term nuclear fuel storage costs, nuclear energy becomes one of the most expensive sources of energy. For this reason, it is unsurprising that the energy source that was once deemed to be “too cheap to meter” has frequently led its operators into heavy debt or even outright financial ruin.[36]

This mismatch between the electricity costs and the relative popularity of nuclear energy (some

408 reactors are currently generating nearly 10 percent of the world's total energy) can be explained by the presence of other, non-purely-commercial considerations.[37]

First, it makes sense for energy-poor countries, which do not have access to abundant low-cost energy, to develop NPPs. Investments in nuclear energy can provide plenty of electricity, ensure a high degree of energy independence (though most countries still rely on nuclear fuel imports), usually don't require costly and lengthy cross-border transport infrastructure (unlike oil or gas) and also create jobs at the host country (both at the NPPs and the supporting sectors).

Second, there has always been a close overlap between civilian and military nuclear programs. Even though militaries no longer rely on NPPs for their weapons-grade nuclear material, both of these programs depend on the virtually same know-how. Nuclear power and nuclear weapons require similar expertise in engineering, modelling, metallurgy, chemistry, along with scientific expertise in physics and mathematics, just to name a few.[38] Therefore, governments that possess nuclear weapons have a clear reason to maintain a pool of highly trained personnel in the civil nuclear energy sector, so that it would support and maintain their nuclear weapons programs.

Considering that conventional NPPs have not been able to generate electricity at a profit, it seems very unlikely that SMRs would be able to do it either. It is a well-established fact that one of the greatest issues with conventional NPPs are their incredibly long construction times (on average the construction time of a NPP is around 10 years) and capital expenditures – estimated to be between €7.5-10 billion per 1000 MW facility.[39] While civilian SMRs intend to remedy these shortcomings with considerably lower per-unit costs and construction times, the SMRs would lose out on economies of scale.[V] Larger reactors are cheaper on a per MWh basis than SMRs because their material and work requirements do not scale linearly with generation capacity.[40]

Moreover, it is estimated that manufacturers would need to mass produce SMRs by the hundreds, if not by the thousands, to sufficiently keep their production costs low and make the SMRs competitive in the energy market.[41] Seeing that, to date, there has been scant demand for SMRs, and, that there are scores of manufactures who will be competing for a limited number of customers, it is very unlikely that any one of them would be able to dominate the market and significantly cut their per-unit costs anytime soon.

The economic justification of using SMRs at FOBs is similarly built on shaky footing. On a per MWh basis, it is definitely cheaper to supply electricity to FOBs by SMRs than to ship prohibitively expensive canisters of petroleum via air, road or sea. However, if the research, development, construction and the full nuclear fuel cycle costs of SMRs are factored in, the costs of nuclear energy might exceed the costs of shipped petroleum. Unless, obviously, the petroleum is shipped for a very long time, in very large quantities and to very remote locations.

Ultimately, it almost goes without saying that it makes little economic sense to power military bases or other installations, which already have access to the central power grid by an SMR. The cost of electricity at the centralized power grid will nearly always be considerably lower than the cost of electricity from a SMR, especially if it is a MMR.

SAFETY AND SECURITY CONSIDERATIONS

As it is the case with conventional NPPs, the safety and security of SMRs is of paramount importance. If something goes wrong, one might have a nuclear disaster, which could result in widespread ecological devastation, the loss of life and the destruction of property on a truly massive scale. It is also worth noting that in the current political environment, which is marked by a very

---

[IV] According to the 2020 World Nuclear Industry Status Report, only electricity that is generated at gas peaking plants is more expensive than nuclear energy.

[V] NuScale Power estimates a first-of-a-kind cost for its SMR design of €3.14 billion/1000 MW and an nth-of-a-kind cost of €2.6 billion/1000 MW.

low tolerance for nuclear failures, any major incident at a SMR facility could prove to be a death knell to the nuclear energy industry as a whole.

Safety is one of the main challenges associated with SMRs. The reason is very simple: no civilian or military-grade genuinely land-based SMRs have yet been built or deployed. This contrasts greatly with conventional NPPs with hundreds if not thousands of accident-free reactor years under their belt. Virtually everything that is known about the safety features of SMRs comes from the design plans that have been provided by the companies who intend to build them. Hence, all assumptions about the safety of SMRs should be taken with a great pinch of salt.

According to the developers, SMRs are much safer than conventional NPPs. Many SMR companies have simplified the reactor designs by either reducing the number or completely eliminating pumps, valves and other moving parts, which can malfunction. The new SMR designs have also introduced additional safeguards such as passive cooling mechanisms. All of this, at least in theory, should make the SMRs nearly completely impervious to meltdown. Furthermore, SMRs will have the capacity to be built on land or underground (to make them less vulnerable to external threats, though exposing them to earthquakes) and will be able to operate 3-7 years without refueling (conventional NPPs need to be refueled every 1 or 2 years), with some reactors even designed to operate for up to 30 years without refueling.[42]

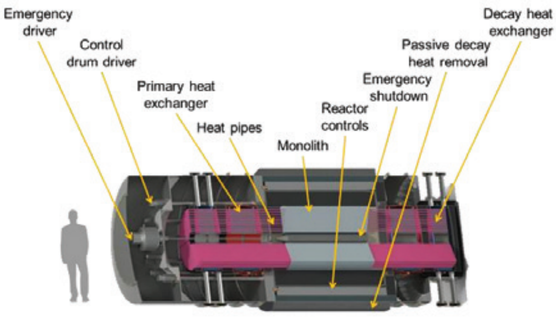


Figure 4. Conceptual Design of the eVinci SMR (Credit: Westinghouse)

To maximize safety and security, and reduce the number of personnel that would be necessary to man the plant, some SMR designs might also be completely sealed shut at the factory, only to be reopened once the SMR is brought back to the factory for refueling.[43]

Regardless how good it sounds on paper, there are some glaring safety concerns with these sealed SMRs designs, particularly those which would likely see heavy use on the battlefield. Taking into account that many SMRs will have to be shipped over long distances and rough terrain to reach a FOB, there exists the chance that the SMR might be damaged during the journey. Because no one would be able to open the SMR and inspect its interior before it gets connected to a power grid, there is a possibility that the reactor might malfunction. While these SMRs would doubtlessly be equipped with multiple high-tech reactor-monitoring sensors, this would still not be a completely fail-proof way to ensure the safety of its end-users. After all, the possibility exists that the sensors themselves could be damaged during the trip or would malfunction, making their data unreliable or outright unavailable.

Battle-deployed SMRs might also become the targets of hostile actors. If recent decades are a guide, many FOBs would be likely located in, or near, countries that are home to hostile insurgent groups. In turn, these installations would be frequently subject to weaponized drone and missile strikes or mortar attacks, making SMRs extremely high-value targets. Even if the odds are rather slim that the SMR could be outright destroyed, the risk still exists that it could be buried by debris or damaged to the extent that it could no longer cool itself.[44] If the SMR would be unable to prevent its temperature from rising and it would not be possible to open the reactor, inspect it and repair it, the forces stationed at the FOBs could be facing the prospects of an imminent nuclear meltdown, without even knowing it.

The SMRs at FOBs could also be at risk of being captured by the enemy. This would either contribute to the proliferation of nuclear weapons, or, alternatively, allow a terrorist organization to build a dirty bomb by using its spent fuel. The latter could be a particularly serious concern if the SMR uses high-assay low-enriched uranium (not to be confused with highly enriched uranium), as it is the case with a number of MMR designs under development.[VI]

Though, admittedly, the likelihood of nuclear theft from FOBs is probably much lower than it is generally believed. Spent fuel is essentially "self-protecting" due to very high levels of radioactivity and FOBs tend to have very stringent security standards, making them difficult to be overrun.[45]

ENVIRONMENTAL CONSIDERATIONS

At first glance, SMRs can provide very clear environmental benefits to the military. Most armed forces around the world are major consumers of fossil fuels and, therefore, are responsible for large amounts of greenhouse gas emissions. In fact, a recent Brown University study has revealed that the US military is the country's largest institutional consumer of petroleum and correspondingly, the single largest institutional emitter of GHG in the world. It was responsible for 59 million metric tons of GHG emissions in 2017.[46] These emissions were the result of not only military operations, but also of on-going non-war operations and maintenance of military installations. To put it in perspective, the US military's GHG emissions in 2017 were greater than the emissions of countries such as Sweden or Denmark.

This is by no means a unique US military problem. It just so happens that it is by far the largest military in the world with the most active missions around the globe. Most other Western militaries suffer from the same faults and, in relative terms, are equally significant consumers of petroleum. This means that they too are responsible for a significant share of GHG emissions.

While in recent years Western militaries have sought and to an extent succeeded in becoming more "green" and environmentally friendly by investing in alternative fuels and improving energy efficiency, it is generally agreed that they still have a very long way to go. The fact that there has been a longstanding international convention, which has caused many governments around the world not to report on the GHG emissions of their militaries, let alone include them within national targets, has not helped the cause either.[47]

Fortunately, SMRs could provide the military a helping hand in its fight against climate change. Unlike fossil-powered power plants, SMRs produce electricity via nuclear fission rather than combustion. SMRs do not cause air pollution or produce any GHGs while operating. Therefore, if Western militaries would adopt SMRs in large numbers, they could seriously decrease their petroleum consumption and cut their GHG footprint.

Granted, virtually no militaries could fully substitute petroleum with nuclear energy because the bulk of their petroleum is used for operational purposes i.e. the actual use of planes, ships and vehicles. And it does not seem very likely that the military could go all-electric anytime soon. But if nuclear energy could replace even a tiny fraction of the petroleum that is used for non-war operations or the maintenance of bases or installations, that would still be a commendable achievement for the military.

While all of this sounds great, there is one major drawback with SMRs that it shares with conventional NPPs: nuclear waste. According to the Stimson Center, a US think-tank, some 400,000 tons of highly radioactive spent fuel has been stored at hundreds of sites across dozens of countries since the 1950s. The amount of spent fuel in storage is expected to continue to grow and, it is estimated that, on average, the global spent nuclear fuel stockpile will increase by around 11,000 tons annually.[48]

Despite the fact that commercial NPPs have been in operation for more than sixty years, the issue of spent fuel has arguably been insufficiently ad-

---

[VI] Most existing nuclear reactors run on uranium fuel that is enriched up to 5% with uranium-235 — the main fissile isotope that produces energy during a chain reaction. In contrast, high-assay low-enriched uranium (HALEU) is enriched between 5% and 20%. This is done to allow reactors to get more power per unit of volume. It is also believed that HALEU will allow reactors to have longer core lives, increase their efficiency and ensure better fuel utilization.

dressed so far. Given its highly radioactive properties, spent fuel must be stored for thousands of years, but to date, no country in the world has yet built a deep geological repository where the fuel could be stored for the long haul. Finland is the only country that is currently constructing a permanent repository for this type of nuclear waste.[49] In the meanwhile, all of the other countries have largely pursued interim strategies by building temporary facilities for spent fuel storage purposes.

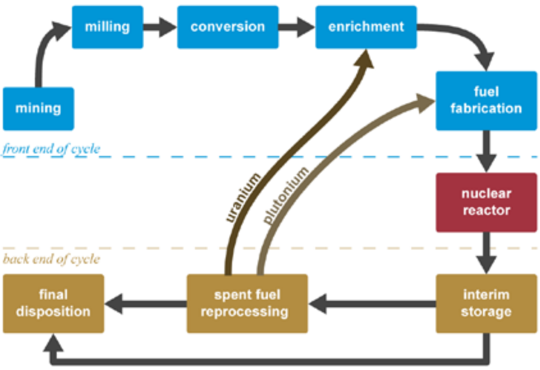


Figure 5. Nuclear fuel cycle (Credit: US Energy Information Agency)

Certainly, it is possible to reprocess some of the spent fuel by recycling usable portions of the fuel for secondary use. And countries like France and the UK have done this with considerable success. Yet, this is a very difficult and expensive process, which alone could unlikely address the world's growing nuclear spent fuel stockpile. In fact, a single reprocessing plant with a meaningful annual recycling capacity may take decades to build, can cost many tens of billions, and this sum may not even include the operational or the decommissioning costs of the plant itself.[50]

REGULATORY CONSIDERATIONS

Whereas there are fairly few purely technical obstacles for the development and deployment of SMRs, there are serious regulatory challenges that would still need to be addressed. Unlike civilian SMRs, which would likely be subject to the same or similar regulations as conventional NPPs, military SMRs would likely need to receive special treatment so that they could reach their intended potential. Yet, this is something that is easier said than done.

Considering their niche applications and unique operational requirements, it is uncertain who would be responsible for regulating the work of the SMRs. On the one hand, the majority of the world's existing civilian NPPs are regulated by mostly independent governmental bodies, which, among other things, oversee reactor safety and security, administer reactor licensing, the storage and the disposal of nuclear fuel. On the other hand, it might make sense that SMRs, which would be specifically designed for the battlefield or for large military installations, would be regulated by the military itself. After all, it is only reasonable to assume that they would know better than anyone the operational needs of their own facilities.

However, there are several problems associated with self-regulation that cannot be ignored.

First, militaries would unlikely have the personnel with sufficient expertise to act as regulators. Unlike nuclear reactors that are used by the navies, the regulation of land-based SMRs would likely be a much more complicated task, given that the military would have to take into consideration a much broader specter of safety and security issues, and deal with many more stakeholders. While, obviously, this is not an unsurmountable obstacle, in most countries it would likely take years and huge amounts of resources for the military to develop a level of expertise on par with the civilian regulators.

Second, even if the military would agree to self-regulate its SMRs, it would likely inherit all the unenviable tasks that are associated with managing nuclear energy. Taking into account that it would be responsible for issuing the licenses for the reactors, the military would likely receive a fair share of the blame and might be even liable for some of the damages in the event of a nuclear accident. Self-regulation might also mean that the military would have to shoulder the decommissioning and waste disposal costs, both financial and time-related. That would not only provide additional strain on its budget, but also create an institutional nightmare as no nuclear energy company, or even any government for that matter, has yet managed to conclusively address the question of spent fuel.

The alternative to self-regulation for the military is also not very appealing. If things remain as they are and SMRs would be regulated by governmental bodies in line with existing safety and security standards, these SMRs would likely be subject to the same or very similar licensing requirements as conventional NPPs. This means that the developers would have to take into consideration factors as varied as geology, seismology, population density, emergency planning, ecology and biota for each and every SMR proposal. As a result, even if the licensing process would be accelerated by a significant margin (if compared to conventional NPP licensing), it might still take years for a single license to be issued. This would, by definition, undermine the whole point of having readily deployable SMRs, and especially the highly-portable MMRs.

Regulatory matters could also greatly complicate SMR deployment efforts. According to existing international law, foreign-deployed SMRs would likely be subject to a plethora of rules that regulate the handling of nuclear material and seek to reduce the risk nuclear proliferation.[51] SMRs would have to respect the domestic laws of the host country, too.[52] Yet, since nuclear energy is a relatively sensitive topic, it is not that difficult to assume that some governments of would-be host countries could be, due to political or other reasons, unable or unwilling to issue a permit for the deployment of a SMR. Thus, the regulator, whoever it may be, would have to pursue a fine balancing act of meeting various international agreements and respecting the laws of host countries, all while ensuring the operational flexibility for the SMRs.

In light of these constraints, leading SMRs developers have publicly advocated to relax some of the regulatory requirements. They argued that existing nuclear regimes, their supporting treaties, and other international agreements have not kept pace with progress and that they are fashioned to support conventional NPPs and not SMRs.[53]

To an extent, the developers are right. Many of today's safety and security regulations are geared towards traditional NPPs, and even the IAEA seems to agree that some adjustments might have to be made to accommodate the needs of the SMRs industry.[54] Especially because there is the real risk that heavy-handed regulation could strangle the SMRs industry before it had the chance to really get going.

But there's also the other side of the coin. Despite the confidence of the developers, SMRs still remain a fundamentally unproven technology and it will take years of rigorous testing before they could be deemed to be at least as safe as conventional NPPs.

CONCLUSION

Small modular nuclear reactors are a promising technology that one day may very well power Western militaries. They not only could contribute to military operations by increasing energy assurance, reduce the military's reliance on fossil fuels, but also help cut greenhouse gas emissions. In fact, it would not be an overstatement to suggest that SMRs, and especially the highly-portable micro modular reactors, could prove to be a truly game-changing technology both for military applications and civil use. From a political point view, their development might also make a lot of sense because it could help strengthen the Western nuclear energy industry and prevent the weakening of global nuclear non-proliferation standards.

However, SMRs also pose some serious questions that have to be tackled by political and military leaders alike. Given that SMRs would unlikely make much economic sense anytime soon, it would only be reasonable to develop SMRs if militaries would actually intend to use them. In other words, the full benefit of SMRs could be seen if Western leaders would genuinely be determined to launch new missions to remote places with little-to-no access to electricity. Or, alternatively, if they would be willing to extend existing out-of-area missions for years and years to come.

In the event that Western leaders would become convinced that there was a clear strategic need to deploy SMRs, both the militaries and the SMR developers would have to carefully think about other, less high-brow matters. First, they would have to ensure that the SMRs would be sufficiently robust to survive a battlefield environment and not put its personnel at unnecessary risk. Second, they would have to carefully consider all the regulatory obstacles associated with SMRs, especially if there would be any plans to ship them to foreign countries. Few things would be more damaging to the reputation of the military than the inability to deploy SMRs in the way they were intended to be. Third, the issue of spent fuel would have to be addressed. If Western militaries really want to burnish their green credentials, they should help address the issue of spent nuclear fuel and prove that they would be part of the solution and not the problem.

Only if these matters are properly dealt with, it would make sense to invest in military SMRs. Otherwise, there is the very real risk that, despite its enormous potential, this technology could one day become as much a liability as an asset.

---

[1] Hakenson, Alex, "Rescuing the Nuclear Renaissance: Why the Military Should Adopt Small Modular Reactors", George Washington Journal of Energy and Environmental Law, 2016; Vol. 7: 242–253; Andres, Richard and Breetz, Hanna, "Small Nuclear Reactors for Military Installations: Capabilities, Costs, and Technological Implications", Strategic Forum, 2011, https://ndupress.ndu.edu/Portals/68/Documents/stratforum/SF-262.pdf

[2] Ramana, M.V and Mian, Zia, "One size doesn't fit all: Social priorities and technical conflicts for small modular reactors", Energy Research & Social Science, Vol. 2, June 2014, pp. 115-124; Lyman, Edward. "The Pentagon wants to boldly go where no nuclear reactor has gone before. It won't work.", Bulletin of the Atomic Scientists, 22 February 2019, https://thebulletin.org/2019/02/the-pentagon-wants-to-boldly-go-where-no-nuclear-reactor-has-gone-before-it-wont-work/

[3] Ramana, M.V, "The Forgotten History of Small Nuclear Reactors", IEEE Spectrum, 27 April 2015, https://spectrum.ieee.org/tech-history/heroic-failures/the-forgotten-history-of-small-nuclear-reactors

[4] King, Marcus, Huntzinger, LaVar and Nguyen, Thoi, "Feasibility of Nuclear Power on U.S. Military Installations", Center for Naval Analysis, March 2011, https://www.cna.org/CNA_files/PDF/D0023932.A5.pdf

[5] "CVN-65 Enterprise", Federation of American Scientists, 9 May 2000, https://fas.org/man/dod-101/sys/ship/cvn-65.htm

[6] South, Todd, "The Pentagon wants mobile nuclear reactors for FOBs, but some scientists say that's 'naive'", Army Times, 1 March 2019, https://www.armytimes.com/news/your-army/2019/03/01/the-army-wants-mobile-nuclear-reactors-for-fobs-but-some-scientists-say-thats-naive/

[7] Pfeffer, Robert and Macon, William, "Nuclear Power: An Option for the Army's Future", Army Logistician, Vol 33, Issue 5, Sept/Oct 2001, https://alu.army.mil/alog/issues/SepOct01/MS684.htm

[8] Larson, Caleb, "K-3 Leninsky Komsomol: The Nuclear Submarine Workhorse of the Soviet Navy", National Interest, 20 March 2020, https://nationalinterest.org/blog/buzz/k-3-leninsky-komsomol-nuclear-submarine-workhorse-soviet-navy-137277

[9] Ozharovsky, Andrey, "Belarus unveils latest folly, resuscitates eccentric mobile nuke plant project", Bellona, 24 March 2010, https://bellona.org/news/nuclear-issues/2010-03-belarus-unveils-latest-folly-resuscitates-eccentric-mobile-nuke-plant-project

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

[11] Pickrell, Ryan, "Russia is planning to build its first nuclear-powered aircraft carrier after breaking its only flattop", Business Insider, 8 May 2019, https://www.businessinsider.com/russia-wants-to-build-its-first-nuclear-powered-aircraft-carrier-2019-5

[12] Nilsen, Thomas, "Russia's mini nuclear reactors plan causes concern", The Barents Observer, 7 November 2015, https://thebarentsobserver.com/ru/node/95

[13] King, Marcus, Huntzinger, LaVar and Nguyen, Thoi, "Feasibility of Nuclear Power on U.S. Military Installations", Center for Naval Analysis, March 2011, https://www.cna.org/CNA_files/PDF/D0023932.A5.pdf

[14] "Advances in Small Modular Reactor Technology Developments", International Atomic Energy Agency, September 2020, https://aris.iaea.org/Publications/SMR_Book_2020.pdf

[15] "Nuclear Technology Review", International Atomic Energy Agency, September 2020, https://www.iaea.org/sites/default/files/gc/gc64-inf2.pdf

[16] "With DOE funds in hand, UAMPS preps for NuScale SMR licensing phase", American Nuclear Society, 20 October 2020, https://www.ans.org/news/article-2300/with-doe-funds-in-hand-uamps-preps-for-nuscale-smr-licensing-phase/

[17] Nilsen, Thomas, "В России планируется строить военные мини-АЭС для использования в Арктике", The Barents Observer, 4 November 2015, https://thebarentsobserver.com/ru/arctic/2015/11/russia-build-military-mini-nuclear-power-plants-arctic

[18] Parfitt, Tom, "Akademik Lomonosov: Russian nuclear plant on barge lights up the Arctic", The Times, 24 December 2019, https://www.thetimes.co.uk/article/akademik-lomonosov-russian-nuclear-plant-on-barge-lights-up-the-arctic-qn6gmgrcl

[19] "Russia connects floating plant to grid", World Nuclear News, 19 December 2020, https://world-nuclear-news.org/Articles/Russia-connects-floating-plant-to-grid; Trevithick, Joseph, "Here's What We Know About Russia's New Floating Nuclear Power Plant Heading To The Arctic", The Drive, 1 May 2018, https://www.thedrive.com/the-war-zone/20564/heres-what-we-know-about-russias-new-floating-nuclear-power-plant-heading-to-the-arctic

[20] Chen, Stephen, "Could China build the world's smallest nuclear power plant and send it to the South China Sea?" CNBC, 11 October 2016, https://www.cnbc.com/2016/10/11/could-china-build-the-worlds-smallest-nuclear-power-plant-and-send-it-to-the-south-china-sea.html

[21] "Ocean-going nuclear plants for South China Sea", Asia Times, 21

March 2019, https://asiatimes.com/2019/03/ocean-going-nuclear-plants-for-south-china-sea/

[22] Waksman, Jeff, "Project Pele Overview Mobile Nuclear Power For Future DoD Needs", Strategic Capabilities Office, March 2020, https://ric.nrc.gov/docs/abstracts/waksmanj-th34-hv.pdf

[23] Ford, Michael and Abdullah, Ahmed, et. al., "Nuclear Power Needs Leadership, but Not from the Military", Issues in Science and Technology, 2018, https://issues.org/nuclear-power-needs-leadership-but-not-from-the-military/

[24] "Research report: Nuclear energy is a potential tool for geopolitical influence", European Centre of Excellence for Countering Hybrid Threats, 9 October 2019, https://www.hybridcoe.fi/news/research-report-nuclear-energy-is-a-potential-tool-for-geopolitical-influence/

[25] "US Nuclear Energy Leadership: Innovation And The Strategic Global Challenge", Atlantic Council, 20 May 2019, https://www.atlanticcouncil.org/in-depth-research-reports/report/us-nuclear-energy-leadership-innovation-and-the-strategic-global-challenge-2/

[26] Douquet, Greg, "Unleash us from the tether of fuel", Atlantic Council, 11 January 2017 https://www.atlanticcouncil.org/content-series/defense-industrialist/unleash-us-from-the-tether-of-fuel/

[27] Hodge, Nathan, "U.S.'s Afghan Headache: $400-a-Gallon Gasoline", The Wall Street Journal, 6 December 2011, https://www.wsj.com/articles/SB10001424052970204903804577080613427403928

[28] Daehner, Endy and Matsumura, John et. al., "Integrating Operational Energy Implications into System-Level Combat Effects Modeling" RAND Corporation, 2015, https://www.rand.org/pubs/research_reports/RR879.html

[29] "Casualty Costs of Fuel and Water Resupply Convoys in Afghanistan and Iraq", Army Technology, 25 February 2010, https://www.army-technology.com/features/feature77200/

[30] Baron, Kevin, "Do Americans Really Want to End 'Forever Wars?' Survey says…", Defense One, 10 September 2019, https://www.defenseone.com/policy/2019/09/do-americans-really-want-end-forever-wars-survey-says/159760/

[31] Vitali, Juan and Lamothe, Joseph, et. al., "Mobile Nuclear Power Plants for Ground Operations", U.S. Army, 26 October 2018, https://apps.dtic.mil/dtic/tr/fulltext/u2/1064604.pdf

[32] Stone, Richard, "'National pride is at stake.' Russia, China, United States race to build hypersonic weapons", Science, 8 January 2020, https://www.sciencemag.org/news/2020/01/national-pride-stake-russia-china-united-states-race-build-hypersonic-weapons

[33] Judson, Jen, "US Army ventures down path to electrify the brigade", Defense News, 16 March 2020 https://www.defensenews.com/2020/03/16/us-army-ventures-down-path-to-electrify-the-brigade/

[34] Trakimavičius, Lukas, "Cyberattacks: the military considers micro grids as the answer", Energy Post, 1 March 2019, https://energypost.eu/cyberattacks-the-military-considers-micro-grids-as-the-answer/

[35] Wealer, Ben and Bauer, Simon et. al., "High-Priced and Dangerous: Nuclear Power Is Not an Option for the Climate-Friendly Energy Mix," DIW Weekly Report, German Institute for Economic Research, 2019 Vol. 9, pp. 235-243.

[36] Cardwell, Diane, Soble Jonathan, "Westinghouse Files for Bankruptcy, in Blow to Nuclear Power", The New York Times, 29 March 2017, https://www.nytimes.com/2017/03/29/business/westinghouse-toshiba-nuclear-bankruptcy.html ; Smil, Vaclav, ""Too Cheap to Meter" Nuclear Power Revisited" IEE Spectrum, 26 September 2016, https://spectrum.ieee.org/energy/nuclear/too-cheap-to-meter-nuclear-power-revisited

[37] "World Nuclear Industry Status Report 2020" , WNISR, September 2020, https://www.worldnuclearreport.org/-World-Nuclear-Industry-Status-Report-2020-.html

[38] Shachtman, Noah, ""Civilian," "Military" Nukes: What's the Difference?", Wired, 10 December 2007, https://www.wired.com/2007/12/a-week-after-it/

[39] "Small Modular Reactors: Adding to Resilience at Federal Facilities", U.S. Department of Energy, December 2017, https://www.energy.gov/sites/prod/files/2018/01/f47/Small%20Modular%20Reactors%20-%20Adding%20to%20Resilience%20at%20Federal%20Facilities%20.pdf; "World Nuclear Industry Status Report 2020", WNISR, September 2020, https://www.worldnuclearreport.org/-World-Nuclear-Industry-Status-Report-2020-.html

[40] Ramana, M.V, "Small modular reactors for nuclear power: hope or mirage?", Energy Post, 21 February 2018, https://energypost.eu/small-modular-reactors-for-nuclear-power-hope-or-mirage/

[41] Ramana, M.V, "Small modular reactors for nuclear power: hope or mirage?", Energy Post, 21 February 2018, https://energypost.eu/small-modular-reactors-for-nuclear-power-hope-or-mirage/

[42] Chatzis, Irena, "Small Modular Reactors: A Challenge for Spent Fuel Management?", International Atomic Energy Agency, 8 August 2019, https://www.iaea.org/newscenter/news/small-modular-reactors-a-challenge-for-spent-fuel-management

[43] "Small Modular Reactors: Regulatory Strategy, Approaches and Challenges", Canadian Nuclear Safety Commission, 4 May 2016, http://nuclearsafety.gc.ca/eng/acts-and-regulations/consultation/comment/d-16-04/index.cfm

[44] Mizokami, Kyle, "Critics Roast the Department of Defense's Battlefield Nuclear Reactor", Popular Mechanics. 25 February 2019, https://www.popularmechanics.com/military/research/a26521406/army-battlefield-nuclear-reactor/

[45] Neuheuser, Alan, "How Real Is the Dirty Bomb Threat?", USNews, 24 March 2016, https://www.usnews.com/news/articles/2016-03-24/how-real-is-the-dirty-bomb-threat

[46] Crawford, Neta, "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

[47] Parkison, Stuart, "The Environmental Impacts of the UK Military Sector", Scientists for Global Responsibility, May 2020, https://www.sgr.org.uk/sites/default/files/2020-05/SGR-DUK_UK_Military_Env_Impacts.pdf

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

[49] Curry, Andrew, "What Lies Beneath", The Atlantic, October 2017, https://www.theatlantic.com/magazine/archive/2017/10/what-lies-beneath/537894/

[50] "Japan's troubled nuclear reprocessing plant passes safety checks", Nikkei Asia, 20 July 2020, https://asia.nikkei.com/Politics/Japan-s-troubled-nuclear-reprocessing-plant-passes-safety-checks

[51] Virgili, Nicole, "The Impact of SMRs on Non-Proliferation and IAEA Safeguards", Vienna Center for Disarmament and Non-Proliferation, 2 September 2020, https://vcdnp.org/the-impact-of-smrs-on-non-proliferation-and-iaea-safeguards/

[52] Sainati, Tristano, Locatelli, Giorgio and Brookes, Naomi "Small modular reactors: licensing constraints and the way forward", Energy, Vol. 82, 15 March 2015, pp. 1092–1095.

[53] Tucker, Patrick, "US Military Eyes Tiny Nuclear Reactors for Deployed Troops", Defense One, 24 January 2019, https://www.defenseone.com/technology/2019/01/us-military-eyes-tiny-nuclear-reactors-deployed-troops/154406/

[54] "Deployment Indicators for Small Modular Reactors: Methodology, Analysis of Key Factors and Case Studies", International Atomic Energy Agency, 2018, https://www.iaea.org/publications/13404/deployment-indicators-for-small-modular-reactors