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Small Nuclear Reactors for Military Installations: Capabilities, Costs, and Technological Implications

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Key Points

- Without Department of Defense (DOD) intervention, the United States runs the risk of a small reactor market dominated by foreign countries, further eroding U.S. commercial nuclear power capabilities and damaging U.S. control over nuclear energy proliferation.
- DOD has recently expressed interest in the possibility of integrating small nuclear reactors on military bases as part of its strategy to "island" bases from the fragile civilian power grid.
- Small nuclear reactor technology offers a host of benefits over traditional large reactors—namely, a smaller footprint, scalable design, factory-based construction, portability, and passive safety features.
- DOD has a chance to become a "first mover" in the emerging small reactor market; by providing assistance and guidance to the private sector, DOD can ensure that successful designs meet its operational needs.

In recent years, the U.S. Department of Defense (DOD) has become increasingly interested in the potential of small (less than 300 megawatts electric [MWe]) nuclear reactors for military use.[1] DOD's attention to small reactors stems mainly from two critical vulnerabilities it has identified in its infrastructure and operations: the dependence of U.S. military bases on the fragile civilian electrical grid, and the challenge of safely and reliably supplying energy to troops in forward operating locations. DOD has responded to these challenges with an array of initiatives on energy efficiency and renewable and alternative fuels. Unfortunately, even with massive investment and ingenuity, these initiatives will be insufficient to solve DOD's reliance on the civilian grid or its need for convoys in forward areas. The purpose of this paper is to explore the prospects for addressing these critical vulnerabilities through small-scale nuclear plants.

Several Congressional and DOD actors have already indicated an interest in military applications of small reactors. In early 2008, the Air Force, at the behest of former Senators Pete Domenici and Larry Craig, considered a pilot program to deploy small reactors on at least one of its bases.[2] In late 2009, the National Defense Authorization Act authorized a study on the feasibility of developing nuclear power plants on military installations. Additionally, a handful of defense analysts have publicly advocated using nuclear power plants for military electricity and mobility, and a joint DOD–Department of Energy (DOE) working group, in cooperation with the Nuclear Regulatory Commission (NRC), is now studying options for small nuclear reactors on DOD installations.

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All current proposals and discussions center on microreactors (small, modular, and potentially transportable) rather than on the megareactors that have been the focus of commercial nuclear energy development.[3] These kinds of innovative small reactors have been rapidly generating interest outside the military as well. The NRC held stakeholder workshops in October 2009 and February 2010 to begin discussing novel licensing issues, and it released a paper on potential policy, licensing, and technical issues in March 2010.[4] DOE conducted a June 2010 workshop on small reactors, including technical panels on assessment, instrumentation, materials, modeling, and policy.[5] Three bills related to small reactors have been making their way through the Senate: the Nuclear Energy Research Initiative Improvement Act and the Nuclear Power 2021 Act were placed on the Senate legislative calendar in September 2010, while the Clean Energy Act of 2009 remains in the Energy and National Resources Committee. Moreover, President Barack Obama's 2011 budget request included $39 million for the development of small modular reactors.

DOD's "first mover" pursuit of small reactors could have a profound influence on the development of the industry

It should be emphasized that none of the small reactor designs currently under consideration for commercial development have been licensed by the NRC, let alone constructed, demonstrated, or tested. Given the early stage of the technology, DOD's "first mover" pursuit of small reactors could therefore have a profound influence on the development of the industry. DOD does have substantial experience with nuclear energy—historically, both the U.S. Army and Navy have incorporated nuclear reactors into their operations[6]—that could make it particularly well suited to taking a leading role in testing small reactors.

The initial analysis offered in this paper suggests that small reactors could be instrumental in addressing DOD's challenges of grid insecurity at domestic installations and fuel supply at forward operating bases. The next step is to conduct more fine-grained analysis to answer questions about costs, personnel needs, technological options, and security and transportability issues. The Secretary of Defense's feasibility study and the research undertaken by the DOD/DOE/NRC working group are crucial steps forward. We recommend that DOD continue to invest in research and analysis on small reactor options, with a goal of building a demonstration plant as soon as the technical, financial, and regulatory hurdles have been adequately resolved.

Small Reactors and Energy Security

The DOD interest in small reactors derives largely from problems with base and logistics vulnerability. Over the last few years, the Services have begun to reexamine virtually every aspect of how they generate and use energy with an eye toward cutting costs, decreasing carbon emissions, and reducing energy-related vulnerabilities. These actions have resulted in programs that have significantly reduced DOD energy consumption and greenhouse gas emissions at domestic bases. Despite strong efforts, however, two critical security issues have thus far proven resistant to existing solutions: bases' vulnerability to civilian power outages, and the need to transport large quantities of fuel via convoys through hostile territory to forward locations. Each of these is explored below.

Grid Vulnerability. DOD is unable to provide its bases with electricity when the civilian electrical grid is offline for an extended period of time. Currently, domestic military installations receive 99 percent of their electricity from the civilian power grid. As explained in a recent study from the Defense Science Board:

> *DOD's key problem with electricity is that critical missions, such as national strategic awareness and national command authorities, are almost entirely dependent on the national transmission grid . . .* [which] *is fragile, vulnerable, near its capacity limit, and outside of DOD control. In most cases, neither the grid nor on-base backup power provides*

> *sufficient reliability to ensure continuity of critical national priority functions and oversight of strategic missions in the face of a long term (several months) outage.*[7]

The grid's fragility was demonstrated during the 2003 Northeast blackout in which 50 million people in the United States and Canada lost power, some for up to a week, when one Ohio utility failed to properly trim trees. The blackout created cascading disruptions in sewage systems, gas station pumping, cellular communications, border check systems, and so forth, and demonstrated the interdependence of modern infrastructural systems.[8]

More recently, awareness has been growing that the grid is also vulnerable to purposive attacks. A report sponsored by the Department of Homeland Security suggests that a coordinated cyberattack on the grid could result in a third of the country losing power for a period of weeks or months.[9] Cyberattacks on critical infrastructure are not well understood. It is not clear, for instance, whether existing terrorist groups might be able to develop the capability to conduct this type of attack. It is likely, however, that some nation-states either have or are working on developing the ability to take down the U.S. grid. In the event of a war with one of these states, it is possible, if not likely, that parts of the civilian grid would cease to function, taking with them military bases located in affected regions.

Government and private organizations are currently working to secure the grid against attacks; however, it is not clear that they will be successful. Most military bases currently have backup power that allows them to function for a period of hours or, at most, a few days on their own. If power were not restored after this amount of time, the results could be disastrous. First, military assets taken offline by the crisis would not be available to help with disaster relief. Second, during an extended blackout, global military operations could be seriously compromised; this disruption would be particularly serious if the blackout was induced during major combat operations. During the Cold War, this type of event was far less likely because the United States and Soviet Union shared the common understanding that blinding an opponent with a grid blackout could escalate to nuclear war. America's current opponents, however, may not share this fear or be deterred by this possibility.

In 2008, the Defense Science Board stressed that DOD should mitigate the electrical grid's vulnerabilities by turning military installations into "islands" of energy self-sufficiency.[10] The department has made efforts to do so by promoting efficiency programs that lower power consumption on bases and by constructing renewable power generation facilities on selected bases. Unfortunately, these programs will not come close to reaching the goal of islanding the vast majority of bases. Even with massive investment in efficiency and renewables, most bases would not be able to function for more than a few days after the civilian grid went offline.

making bases more resilient to civilian power outages would reduce the incentive for an opponent to attack the grid

Unlike other alternative sources of energy, small reactors have the potential to solve DOD's vulnerability to grid outages. Most bases have relatively light power demands when compared to civilian towns or cities. Small reactors could easily support bases' power demands separate from the civilian grid during crises. In some cases, the reactors could be designed to produce enough power not only to supply the base, but also to provide critical services in surrounding towns during long-term outages.

Strategically, islanding bases with small reactors has another benefit. One of the main reasons an enemy might be willing to risk reprisals by taking down the U.S. grid during a period of military hostilities would be to affect ongoing military operations. Without the lifeline of intelligence, communication, and logistics provided by U.S. domestic bases, American military operations would be compromised in almost any conceivable contingency. Making bases more resilient to civilian power outages would reduce the incentive for an opponent to attack the grid. An opponent might still attempt to take down the grid for the sake of disrupting civilian systems, but the powerful incentive to do so in order to win an ongoing battle or war would be greatly reduced.

Operational Vulnerability. Operational energy use represents a second serious vulnerability for the U.S. military. In recent years, the military has become significantly more effective by making greater use of technology in the field. The price of this improvement has been a vast increase in energy use. Over the last 10 years, for instance, the Marine Corps has more than tripled its operational use of energy. Energy and water now make up 70 percent of the logistics burden for troops operating in forward locations in the wars in Afghanistan and Iraq. This burden represents a severe vulnerability and is costing lives. In 2006, troop losses from logistics convoys became so serious that Marine Corps Major General Richard Zilmer sent the Pentagon a “Priority 1” request for renewable energy backup.[11] This unprecedented request put fuel convoy issues on the national security agenda, triggering several high-level studies and leading to the establishment of the Power Surety Task Force, which fast-tracked energy innovations such as mobile power stations and super-insulating spray foam. Currently, the Marine Corps is considering a goal of producing all non-vehicle energy used at forward bases organically and substantially increasing the fuel efficiency of vehicles used in forward areas.

Nevertheless, attempts to solve the current energy use problem with efficiency measures and renewable sources are unlikely to fully address this vulnerability. Wind, solar, and hydro generation along with tailored cuts of energy use in the field can reduce the number of convoys needed to supply troops, but these measures will quickly reach limits and have their own challenges, such as visibility, open exposure, and intermittency. Deploying vehicles with greater fuel efficiency will further reduce convoy vulnerability but will not solve the problem.

A strong consensus has been building within planning circles that small reactors have the potential to significantly reduce liquid fuel use and, consequently, the need for convoys to supply power at forward locations. Just over 30 percent of operational fuel used in Afghanistan today goes to generating electricity. Small reactors could easily generate all electricity needed to run large forward operating bases. This innovation would, for instance, allow the Marine Corps to meet its goal of self-sufficient bases. Mobile reactors also have the potential to make the Corps significantly lighter and more mobile by reducing its logistics tail.

if the wars in Iraq and Afghanistan are indicative of future operations, using small reactors at forward locations has the potential to save U.S. lives

Another way that small reactors could potentially be used in the field is to power hydrogen electrolysis units to generate hydrogen for vehicles.[12] At forward locations, ground vehicles currently use around 22 percent imported fuel. Many ground transport vehicles can be converted to run on hydrogen, considerably reducing the need for fuel convoys. If the wars in Iraq and Afghanistan are indicative of future operations, and fuel convoys remain a target for enemy action, using small reactors at forward locations has the potential to save hundreds or thousands of U.S. lives.

Technical Background: Small-scale Nuclear Reactors

Small-scale nuclear reactor technology is not entirely new, but it is evolving rapidly. Small reactors played a major role in the early development of the nuclear power industry. The earliest commercial reactors in the United States were essentially scaled-up versions of the Navy's Pressurized Light Water Reactors, and most of the U.S. reactors commissioned through 1973 were small or medium reactors.[13] Economies of scale in siting, licensing, and construction eventually drove the commercial nuclear power industry toward increasingly large reactors up to 1,300 MWe.

In recent years, global interest in small reactors has returned. A major factor in this resurgence has come from developing countries, where expressed and projected demands for electricity are rapidly growing and limited infrastructural and investment capacity generates interest in reactors that can be deployed rapidly and incrementally.[14] Most of the innovative small reactor designs, however, are meant for a broad variety of applications—including baseload electricity generation, process heat applications, seawater desalination, and hydrogen production—that can be useful to industrial, municipal, and institutional actors in developed countries.[15] The wide range of emerging designs is confronting potential civilian and military users with both significant opportunities and risks.

Range of Designs. In anticipation of projected demand, small reactor developers are taking action (see table). The International Atomic Energy Agency has reported on nearly 60 small and medium reactor concepts under development in 13 countries, about half of which are small reactors without on-site refueling (the kind that is commonly discussed in U.S. policy debates).[16] Many of the concepts are simply scaled-down versions of conventional large light water reactor (LWR) designs. However, an important subset are deliberately designed as small or "mini" reactors, some as small as a residential hot tub, which take advantage of their compactness to achieve specific fabrication and performance goals (for example, integrated cooling systems, factory-based construction, portability, and passive or inherent safety features).

Two general points about these reactors should be emphasized. First, even within the category of small reactors without on-site refueling, there are significant variations in electrical output (10–335 MWe), coolants (water, sodium, lead, molten salt), refueling times (2–30 years) and procedures (returning the entire module to the factory, changing out the cassette, recharging the in-situ pebble bed), construction types (factory-built versus location-built), site footprints, portability, modularity, staffing requirements, and technological readiness. Small reactor concepts range from designs like Westinghouse's International Reactor Innovative and Secure (IRIS) model, which mostly uses mature LWR technology in a stationary, site-constructed 335 MWe plant, to Hyperion's Power Module, which has been designed as a factory-sealed, truck-transportable, 25 MWe "nuclear battery" with minimal in-core moving mechanical components.[17]

most small reactor designs are meant for a variety of applications that can be useful to industrial, municipal, and institutional actors

Second, these reactors today exist only on paper; as Ingersoll explains, "None of the designs are ready for construction today or have even initiated the design certification review process."[18] This means that there are unresolved economic, technical, and regulatory issues associated with these designs. For some of the more novel concepts, it may be a decade or more before they get design approval from the NRC.[19]

Capabilities, Costs, and Uncertainties. Although generalizing about the next generation of small reactors is difficult, this category of reactors promises a number of unique benefits and capabilities. Small reactors tend to have a strong reliance on passive and inherent[20] safety design features due to faster removal of decay heat and a lower or even eliminated risk of coolant pipe breaks.[21] Many of the designs promise to be proliferation-resistant due to their use of low-enriched or even spent fuel and/or sealed reactor cores, which can be returned intact to the factory after use.[22] The

Small Nuclear Reactors: Three Design Examples

Name	Manufacturer	Generating Capacity	Fueling Cycle	Transportable
Hyperion Power Module	Hyperion Power Generation	25 megawatt (MW), scalable	8–10 years, returned to factory for refueling and waste removal	Ship, rail, or truck
NuScale	NuScale Power	45 MW, scalable	2 years, on-site refueling and spent fuel cooling	Ship, rail, or truck
mPower	The Babcock and Wilcox Company	125MW, scalable	4.5 years, on-site refueling and waste storage	Ship or rail

Sources: <www.hyperionpowergeneration.com/product.html>; <www.nuscalepower.com/ot-Facts-NuScale-System-Technology.php>; <www.babcock.com/products/modular_nuclear/>.

Small Reactor Design Safety Features: The reactors highlighted above carry features that make them significantly safer than prior generations. Generation IV technology is less prone to accidents by design as many flaws and problematic features of generation II and III reactors have been eliminated. Small reactor designs are simpler than their larger predecessors, allowing for fewer moving parts, fewer systems to monitor, and fewer points of potential failure. Small reactor models are also generally buried in independent underground containment facilities, creating an additional layer of physical protection. To further guard against proliferation risks, many of these reactors are factory sealed with a supply of fuel inside, run longer between refueling cycles, and feature on-site waste storage—all of which serve to insulate and secure the units. Finally, due to their small size, the reactors do not require the vast water resources of large reactors and in the event of an emergency are easier to isolate, shut off, and cool down.

ability to add reactors on a faster schedule and with a modular approach provides greater flexibility and lowers investment risk. Many have simplified operational requirements and, therefore, lower risks of human maintenance error. Some designs do not use heated water and are not under high pressure. Their smaller footprint and lower cost mean that the reactors can be built in closer proximity to end-users, reducing transmission losses and providing greater opportunities for cogeneration and heat process applications.[23] These features have the potential to remove many of the risk factors associated with larger reactors.

The small size and newness of these reactor concepts have projected downsides as well. From a financial perspective, small reactors represent substantial losses in economies of scale. They are likely to be less economical domestic energy sources per kilowatt-hour than larger reactors—although at forward locations where liquid fuel used to power generators is more expensive, they may be more economical than traditional methods.[24] Making reliable projections about these reactors' economic and technical performance while they are still on paper is a significant challenge.

Furthermore, the regulatory timeline and costs for licensing are also sources of financial uncertainty. NRC licensing processes have historically evolved around LWRs, and although NRC officials have begun dialogue on licensing for small reactors, they have estimated in the past that it could take a decade to develop new regulatory guides and licensing reviews.[25] The NRC fee structure is also a barrier for small reactors. Under current regulations, the annual fee to operate each licensed nuclear reactor is $4.5 million—a prohibitive cost for many small reactor developers and users. The NRC is considering a variable fee structure based on reactor output, but it has deferred any actions or decisions until a licensing application is submitted.[26]

Small reactors used on domestic military bases are likely to face a number of additional siting hurdles. As a distributed energy source, they are likely to face substantial "not-in-my-backyard" battles. Moreover, dispersing a large number of reactors leads to questions about long-term nuclear waste disposal.[27] Arguably, reactors should be relatively safe on domestic military installations, certainly more secure than, for instance, the reactors situated in developing countries or intended for processing tar sands. Nevertheless, no issue involving nuclear energy is simple. Institutional and technical uncertainties—such as the security of sealed modules, the potential and unintended social and environmental consequences, or the design of reliable safeguards—make dispersing reactors across the country challenging. Some key issues that require consideration include securing sealed modules, determining how terrorists might use captured nuclear materials, carefully considering the social and environmental consequences of dispersing reactors, and determining whether Permissive Action Links technology could be used to safeguard them.

Using the emerging technology at expeditionary locations carries far greater risks. Besides the concerns outlined above, forward located reactors could be subject to attack. Today, forward operating bases in Iraq and Afghanistan are regularly subjected to mortar attacks, suggesting that reactors at such locations could make these bases prime targets for attack. Since forward bases are also subject to capture, any design proposal that envisions deployment at forward operating bases must incorporate contingency plans in the event that reactors fall into enemy hands.

Despite these potential events, a cost-benefit analysis should shape any decisions regarding the use of small reactors domestically or at forward locations. The real risks of deploying this technology should be put in perspective. The Navy has deployed more than 500 nuclear reactors since 1948 and never experienced a reactor accident. Further, in the current global context, every year the United States allows to go by without deploying small reactors represents a strategic gamble: domestic bases risk losing power should a competent opponent attack the U.S. domestic electric grid, while forward operating bases endanger American convoy support personnel who must deliver fuel.

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DOD as First Mover

Thus far, this paper has reviewed two of DOD's most pressing energy vulnerabilities—grid insecurity and fuel convoys—and explored how they could be addressed by small reactors. We acknowledge that there are many uncertainties and risks associated with these reactors. On the other hand, failing to pursue these technologies raises its own set of risks for DOD, which we review in this section: first, small reactors may fail to be commercialized in the United States; second, the designs that get locked in by the private market may not be optimal for DOD's needs; and third, expertise on small reactors may become concentrated in foreign countries. By taking an early "first mover" role in the small reactor market, DOD could mitigate these risks and secure the long-term availability and appropriateness of these technologies for U.S. military applications.

The “Valley of Death.” Given the promise that small reactors hold for military installations and mobility, DOD has a compelling interest in ensuring that they make the leap from paper to production. However, if DOD does not provide an initial demonstration and market, there is a chance that the U.S. small reactor industry may never get off the ground. The leap from the laboratory to the marketplace is so difficult to bridge that it is widely referred to as the “Valley of Death.” Many promising technologies are never commercialized due to a variety of market failures—including technical and financial uncertainties, information asymmetries, capital market imperfections, transaction costs, and environmental and security externalities—that impede financing and early adoption and can lock innovative technologies out of the marketplace.[28] In such cases, the Government can help a worthy technology to bridge the Valley of Death by accepting the first mover costs and demonstrating the technology’s scientific and economic viability.[29]

> **many promising technologies are never commercialized due to a variety of market failures**

Historically, nuclear power has been “the most clear-cut example . . . of an important general-purpose technology that in the absence of military and defense-related procurement would not have been developed at all.”[30] Government involvement is likely to be crucial for innovative, next-generation nuclear technology as well. Despite the widespread revival of interest in nuclear energy, Daniel Ingersoll has argued that radically innovative designs face an uphill battle, as “the high capital cost of nuclear plants and the painful lessons learned during the first nuclear era have created a prevailing fear of first-of-a-kind designs.”[31] In addition, Massachusetts Institute of Technology reports on the Future of Nuclear Power called for the Government to provide modest “first mover” assistance to the private sector due to several barriers that have hindered the nuclear renaissance, such as securing high up-front costs of site-banking, gaining NRC certification for new technologies, and demonstrating technical viability.[32]

It is possible, of course, that small reactors will achieve commercialization without DOD assistance. As discussed above, they have garnered increasing attention in the energy community. Several analysts have even argued that small reactors could play a key role in the second nuclear era, given that they may be the only reactors within the means of many U.S. utilities and developing countries.[33] However, given the tremendous regulatory hurdles and technical and financial uncertainties, it appears far from certain that the U.S. small reactor industry will take off. If DOD wants to ensure that small reactors are available in the future, then it should pursue a leadership role now.

Technological Lock-in. A second risk is that if small reactors do reach the market without DOD assistance, the designs that succeed may not be optimal for DOD’s applications. Due to a variety of positive feedback and increasing returns to adoption (including demonstration effects, technological interdependence, network and learning effects, and economies of scale), the designs that are initially developed can become “locked in.”[34] Competing designs—even if they are superior in some respects or better for certain market segments—can face barriers to entry that lock them out of the market. If DOD wants to ensure that its preferred designs are not locked out, then it should take a first mover role on small reactors.

It is far too early to gauge whether the private market and DOD have aligned interests in reactor designs. On one hand, Matthew Bunn and Martin Malin argue that what the world needs is cheaper, safer, more secure, and more proliferation-resistant nuclear reactors; presumably, many of the same broad qualities would be favored by DOD.[35] There are many varied market niches that could be filled by small reactors, because there are many different applications and settings in which they can be used, and it is quite possible that some of those niches will be compatible with DOD's interests.[36]

On the other hand, DOD may have specific needs (transportability, for instance) that would not be a high priority for any other market segment. Moreover, while DOD has unique technical and organizational capabilities that could enable it to pursue more radically innovative reactor lines, DOE has indicated that it will focus its initial small reactor deployment efforts on LWR designs.[37]

If DOD wants to ensure that its preferred reactors are developed and available in the future, it should take a leadership role now. Taking a first mover role does not necessarily mean that DOD would be "picking a winner" among small reactors, as the market will probably pursue multiple types of small reactors. Nevertheless, DOD leadership would likely have a profound effect on the industry's timeline and trajectory.

Domestic Nuclear Expertise. From the perspective of larger national security issues, if DOD does not catalyze the small reactor industry, there is a risk that expertise in small reactors could become dominated by foreign companies. A 2008 Defense Intelligence Agency report warned that the United States will become totally dependent on foreign governments for future commercial nuclear power unless the military acts as the prime mover to reinvigorate this critical energy technology with small, distributed power reactors.[38] Several of the most prominent small reactor concepts rely on technologies perfected at Federally funded laboratories and research programs, including the Hyperion Power Module (Los Alamos National Laboratory), NuScale (DOE-sponsored research at Oregon State University), IRIS (initiated as a DOE-sponsored project), Small and Transportable Reactor (Lawrence Livermore National Laboratory), and Small, Sealed, Transportable, Autonomous Reactor (developed by a team including the Argonne, Lawrence Livermore, and Los Alamos National Laboratories). However, there are scores of competing designs under development from over a dozen countries. If DOD does not act early to support the U.S. small reactor industry, there is a chance that the industry could be dominated by foreign companies.

if DOD does not support the U.S. small reactor industry, the industry could be dominated by foreign companies

Along with other negative consequences, the decline of the U.S. nuclear industry decreases the NRC's influence on the technology that supplies the world's rapidly expanding demand for nuclear energy. Unless U.S. companies begin to retake global market share, in coming decades France, China, South Korea, and Russia will dictate standards on nuclear reactor reliability, performance, and proliferation resistance.

Conclusion

The preceding analysis suggests that DOD should seriously consider taking a leadership role on small reactors. This new technology has the potential to solve two of the most serious energy-related problems faced by the department today. Small reactors could island domestic military bases and nearby communities, thereby protecting them from grid outages. They could also drastically reduce the need for the highly vulnerable fuel convoys used to supply forward operating bases abroad.

The technology being proposed for small reactors (much of which was originally developed in U.S. Government labs) is promising. A number of the planned designs are self-contained and highly mobile, and could meet the needs of either domestic or forward bases. Some promise to be virtually impervious to accidents, with design characteristics that might allow them to be used even in active operational environments. These reactors are potentially safer than conventional light water reactors. The argument that this technology could be useful at domestic bases is virtually unassailable. The argument for using this technology in operational units abroad is less conclusive; however, because of its potential to save lives, it warrants serious investigation.

Unfortunately, the technology for these reactors is, for the most part, caught between the drawing board and production. Claims regarding the field utility and safety of various reactors are plausible, but authoritative evaluation will require substantial investment and technology demonstration. In the U.S. market, DOD could play an important role in this area. In the event that the U.S. small reactor industry succeeds without DOD support, the types of designs that emerge might not be useful for the department since some of the larger, more efficient designs that have greater appeal to private industry would not fit the department's needs. Thus, there is significant incentive for DOD to intervene to provide a market, both to help the industry survive and to shape its direction.

Since the 1970s, in the United States, only the military has overcome the considerable barriers to building nuclear reactors. This will probably be the case with small reactors as well. If DOD leads as a first mover in this market—initially by providing analysis of costs, staffing, reactor lines, and security, and, when possible, by moving forward with a pilot installation—the new technology will likely survive and be applicable to DOD needs. If DOD does not, it is possible the technology will be unavailable in the future for either U.S. military or commercial use.

Notes

[1] The International Atomic Energy Agency (IAEA) classifies nuclear reactors as small if their equivalent electrical output is under 300 megawatts electric (MWe) and medium if their output is 300–700 MWe. These designations are often grouped into one category of small and medium reactors (SMRs). Unfortunately, the acronym *SMR* has also started to be used for *small modular reactors*. It is not clear where this semantic shift originated, but the effect is confusing. In this paper, we primarily use the term "small reactors," which, in any case, is more specific since most of the reactors under discussion are below or near 300 MWe and are not all modular. Where the SMR acronym is used, it is with the IAEA's usage.

[2] The Air Force was preparing a Letter of Intent for a privately designed, constructed, and operated reactor on an Air Force base, but the initiative was dropped during a change of administrative leadership in summer 2008.

[3] Robert A. Pfeffer and William A. Macon, Jr., "Nuclear Power: An Option for the Army's Future," *Army Logistician* 33, no. 5 (September–October 2001), 4–8; William A. Macon, Jr., "Nuclear Power Plants on Military Installations," Manuscript, Nuclear Regulatory Commission, 2009; Marvin Baker Schaffer and Ike Chang, "Mobile Nuclear Power for Future Land Combat," *Joint Force Quarterly* 51 (1st Quarter, 2009), 49–55.

[4] U.S. Nuclear Regulatory Commission (NRC), "Potential Policy, Licensing, and Key Technical Issues for Small Modular Nuclear Reactor Designs," SECY–10–0034 (Washington, DC: NRC, March 2010).

[5] Conference agenda and proceedings are available at <www.ne.doe.gov/smrworkshop/agenda.html>.

[6] The Army's Nuclear Power Program (1954–1977) developed, constructed, and operated eight compact reactors at remote installations from Alaska to Antarctica, including a 10 MWe reactor on a barge moored in the Panama Canal Zone. The Navy launched its first nuclear submarine in 1954 and continues to operate more than 100 reactors aboard nearly 80 submarines and aircraft carriers.

[7] Defense Science Board, *Report of the Defense Science Board Task Force on DOD Energy Strategy: More Fight—Less Fuel* (Washington, DC: Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, 2008), 18.

[8] Ibid.

[9] MITRE Corporation, "Power Grid Security," JSR–07–125 (McLean, VA: MITRE, January 2008).

[10] Defense Science Board.

[11] Mark Clayton, "In the Iraqi War Zone, U.S. Army Calls for 'Green' Power," *The Christian Science Monitor*, December 7, 2006, available at <www.csmonitor.com/2006/0907/p01s04-usmi.html>.

[12] Pfeffer and Macon; Schaffer and Chang.

[13] Daniel T. Ingersoll, "Deliberately Small Reactors and the Second Nuclear Era," *Progress in Nuclear Energy* 51 (2009), 589–603.

[14] IAEA, *Status of Small Reactor Designs without On-site Refuelling* (Vienna: IAEA, 2007).

[15] Vladimir Kuznetsov, "Design and Technology Development Status and Design Considerations for Innovative Small and Medium Sized Reactors," *Journal of Engineering for Gas Turbines and Power* 131 (2009), 064001-1–064001-2.

[16] IAEA, *Innovative Small and Medium Sized Reactors: Design Features, Safety Approaches and R&D Trends* (Vienna: IAEA, 2005); IAEA, *Status of Small Reactor Designs with On-site Refuelling* (Vienna: IAEA, 2006); and IAEA, *Status of Small Reactor Designs without On-site Refuelling*.

[17] The IAEA reports (2005, 2006, 2007) provide a comprehensive overview of all active designs. For more accessible summaries of the most prominent designs discussed in the United States, see Ingersoll and Kuznetsov.

[18] Ingersoll, 602.

[19] Ibid.

[20] On the semantics of "inherently safe" reactors, see Arjun Makhijani and Scott Saleska, *The Nuclear Power Deception: U.S. Nuclear Mythology from Electricity "Too Cheap to Meter" to "Inherently Safe" Reactors* (New York: Apex Press, 1999), who argue forcefully that

there is nothing inherently safe about nuclear reactors, regardless of design, because of the underlying radioactive material.

[21] Ingersoll.

[22] Matthew Bunn and Martin B. Malin, "Enabling a Nuclear Revival—and Managing Its Risks," *Innovations* 4, no. 4 (2009), 173–191.

[23] IAEA, 2007.

[24] Kuznetsov.

[25] Macon.

[26] Nuclear Regulatory Commission.

[27] A full treatment of this challenge is beyond the scope of this paper. A number of recent sources, such as the highly influential "Future of Nuclear Energy" reports from The Massachusetts Institute of Technology (MIT), can provide an informative overview of the waste issue. See MIT Nuclear Energy Study, *The Future of Nuclear Power* (Cambridge: MIT, 2003) and MIT Nuclear Energy Study, *Update of the MIT 2003 Future of Nuclear Power* (Cambridge: MIT, 2009); and Bunn and Malin.

[28] Robin Cowan and David Kline, *The Implications of Potential "Lock-In" in Markets for Renewable Energy*, NREL/TP–460–22112 (Golden, CO: National Renewable Energy Laboratory, 1996).

[29] There are numerous actions that the Federal Government could take, such as conducting or funding research and development, stimulating private investment, demonstrating technology, mandating adoption, and guaranteeing markets. Military procurement is thus only one option, but it has often played a decisive role in technology development and is likely to be the catalyst for the U.S. small reactor industry. See Vernon W. Ruttan, *Is War Necessary for Economic Growth?* (New York: Oxford University Press, 2006); Kira R. Fabrizio and David C. Mowery, "The Federal Role in Financing Major Inventions: Information Technology during the Postwar Period," in *Financing Innovation in the United States, 1870 to the Present*, ed. Naomi R. Lamoreaux and Kenneth L. Sokoloff (Cambridge, MA: The MIT Press, 2007), 283–316.

[30] Ruttan; Robin Cowan, "Nuclear Power Reactors: A Study in Technological Lock-In," *Journal of Economic History* 50, no. 3 (1990), 541–567; Robert Pool, *Beyond Engineering: How Society Shapes Technology* (New York: Oxford University Press, 1997).

[31] Ingersoll, 601.

[32] MIT, 2003, 2009.

[33] Ingersoll; Robert Bryce, "Nukes Get Small," *Energy Tribune*, July 16, 2008, available at <www.energytribune.com/articles.cfm?aid=948>.

[34] Cowan; Cowan and Kline.

[35] Bunn and Malin, 2009.

[36] Kuznetsov.

[37] U.S. Department of Energy, "Small Modular Reactors," fact sheet produced by the Office of Nuclear Energy (Washington, DC: Department of Energy, February 2010). This turns the conventional story about nuclear lock-in on its head. The dominance of light water reactor designs, which was a spillover from the Navy nuclear submarine program, has been used as a paradigmatic example of technological lock-in (Cowan; Ruttan). Here we raise the possibility that the military could be constrained by commercial lock-in rather than the other way around.

[38] Defense Intelligence Agency, "Foreign Government Ownership of Future U.S. Nuclear Power Plant Production?" September 16, 2008.

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