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Proposed U.S. Army Mobile Nuclear Reactors: Costs and Risks Outweigh Benefits

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Overview

In March 2020, the U.S. Army awarded contracts totaling $40 million to three nuclear reactor companies for initial research and development (R&D) of competing prototypes of a mobile nuclear power plant (MNPP) to provide energy at Forward Operating Bases (FOBs) in war zones.[1] This was an important milestone in a years-long effort by supporters in Congress to fund a program that has never been requested by the Pentagon. In FY 2020, the appropriation was $63 million,[2] and in FY 2021 another $70 million.[3] The total cost of achieving a first prototype reactor, projected for completion by 2023, could climb to several hundred million dollars, according to the Defense Science Board.[4] The lifetime cost of deploying even a handful of reactors would be in the billions.

Significant doubt remains about the need, advisability, and plausibility of this initiative. The original rationale – to reduce U.S. casualties from attacks on shipments of diesel fuel for electricity generation on foreign military bases – is a vestige because such casualties have dwindled virtually to zero. A second military rationale – to provide large amounts of power to future, high-energy weapons – is dubious because such weapons use energy intermittently and thus would not require the large steady-state power output of a nuclear reactor but instead could be powered much less expensively by diesel generators coupled with energy storage. A third rationale is to subsidize civilian microreactor development, but the Army reactor's rugged specifications make it too costly to compete with commercial versions that the U.S. government already is helping to develop.

The Army proposal also raises other concerns that could derail it. Reactor accidents that could radioactively contaminate thousands of nearby U.S. troops are a serious risk because an adversary attack – and efforts to defend against such attack by burying and covering the reactor – could disrupt air flow and thereby spur overheating of the fuel.[5] The vulnerability of FOBs to attack was illustrated in January 2020, when 11 Iranian ballistic missiles struck an Iraqi base housing U.S. forces, causing extensive damage and casualties.[6] Cost also could prove prohibitive, because the expense of mobile nuclear electricity would be many times higher than providing the same amount of power using traditional diesel generators, based on estimates from the nuclear industry itself. In addition, domestic licensing of the reactor could face severe political opposition, because the testing regime envisions flying a reactor containing highly radioactive spent fuel between and over American states. International legal requirements for air transport to foreign bases also could pose an obstacle, because the host country and all overflight countries would need to grant permission at the time of deployment, which could not be guaranteed in advance.

Despite these reasons for caution, and the absence of a Pentagon request, the U.S. Congress has expedited initial development of a prototype MNPP. In practice, it would take many years if not decades to resolve the above questions, whereas a prototype could be developed and constructed in less than three years according to the Pentagon. Thus, it is unclear why Congress would rush to spend hundreds of millions of dollars on a project that could well prove unnecessary. A more prudent course would be to suspend the development program until it becomes clearer in future years whether deployment of such a reactor is both feasible and desirable.

Historical Background

The U.S. Army initially developed mobile nuclear reactors in the 1950s, but they were deployed only to a few peaceful areas and proved too expensive, so the program died in 1977.[7] In the early 2000s, the concept was reexamined for FOBs in reaction to casualties incurred by resupply convoys in Afghanistan and Iraq, including for diesel fuel used partially for electricity generation. In 2010, the Defense Advanced Research Projects Agency (DARPA) explored a new R&D program for mobile reactors, but the idea was abandoned for budgetary reasons. In 2013, Congress mandated a Pentagon study on the feasibility of a "small modular reactor of less than 10 megawatts,"[8] and in 2016, the Defense Science Board (DSB) responded with a Task Force report that characterized "the need and benefit outweighing the difficulty," although conceding many unknowns.[9] In 2017, the U.S. Senate, in its report on the annual defense bill, mandated that the Pentagon "should produce a manufacturability feasibility report within 24 months, and should focus efforts to enable the deployment of a functioning prototype reactor within 7 years," specifying a power output of 10 megawatts electric (MWe) for potential needs including at "forward operating bases."[10] In 2018, the Army's Deputy Chief of Staff for Logistics (G-4) issued a study claiming that, "nuclear power can reduce supply vulnerabilities and operating costs" at FOBs.[11]

To date, however, the Pentagon has not established a program of record or requested funding for the program in its annual budget submissions to Congress. In May 2019, in response to the Congressional direction, the Defense Secretary did issue a Request for Solutions (RFS) for the "Pele Program," inviting vendors to submit proposals for a MNPP.[12] Congress then provided the initial $63 million for FY 2020 to the Pentagon's DoD Strategic Capabilities Office, enabling the Army in March 2020 to award Pele contracts totaling $40 million to three vendors – BWXT, Westinghouse, and X-energy – for initial R&D on reactor prototypes. In March 2021, the Pentagon extended the contracts for two of those companies, BWXT and X-Energy, to complete their reactor designs.[13] The Pentagon's Joint Requirements Oversight Council (JROC) has approved the R&D program as satisfying inter-service operability requirements, and an Army Mobile Reactor Advisory Council was established in April 2020.[14]

The proposed MNPP entails a nuclear micro-reactor, alternately called a micro nuclear reactor or very small modular reactor (vSMR), and the balance of plant for electricity production – and the Pele RFS establishes strict requirements. The fuel must comprise high-assay, low-enriched uranium (HALEU), fabricated into TRi-structural ISOtropic (TRISO) particles. This enrichment level, below 20 percent and thus unsuitable for nuclear weapons, is consistent with longstanding U.S. nonproliferation policy to minimize the global use (except in nuclear weapons) of highly enriched uranium (HEU), which is enriched to at least 20 percent and thus weapons-usable. By contrast, first-generation Army mobile reactors, predating this U.S. nonproliferation policy established in the 1970s, had used HEU fuel except in one case.[15]

Under Pele, the entire MNPP must weigh less than 40 tons and fit into a C-17 transport aircraft for deployment to a war theater by air. The power output must be from 1 to 10 MWe, which is less than one percent of a large commercial nuclear powerplant. (Subsequent to the RFS, the maximum power was halved to 5 MWe, according to a March 2020 presentation by Pele's manager, but no official record of such a decision has been identified.)[16] The fuel must last for at least three years. In the event of an attack or accident, the reactor must shut down safely without intervention – relying on passive cooling – and avoid any significant release of radioactivity or health consequences to nearby personnel or the public. During Pele's Phase 1 that runs through 2022, the awardees are finalizing designs of prototype reactors. If the Biden Administration decides to proceed after that, the Army will select one or more of the designs for prototype construction and demonstration during Phase 2 running through 2024. Full-power testing is projected in 2023, and a mobile demonstration in 2024.[17] After prototype testing and demonstration, the Army would decide whether to adopt the technology and establish requirements for deployable systems.

Separately, Congress and the Executive Branch have expressed interest in <u>non</u>-mobile micro-reactors to provide electricity at permanent U.S. government sites, including facilities of the Department of Defense (DOD) – especially in remote areas such as Alaska – and the Department of Energy (DOE). That concept, however, has yet to be funded by Congress or implemented by the Pentagon. In 2009, Congress did direct the Pentagon to "conduct a study to assess the feasibility of developing nuclear power plants on military installations" in the United States, including assessing the applicable "Federal, State, and local regulatory processes."[18] In 2018, Congress required the Pentagon to produce a report on a potential, "pilot program to provide resilience for critical national security infrastructure at DOD facilities with high energy intensity and currently expensive utility rates and DOE facilities," including assessing the possibility of contracting for construction and operation by 2027 of a licensed micro-reactor with power output as high as 50 MWe, which is five to ten times larger than the maximum for the mobile Army reactor.[19] In April 2020, the Energy Department confirmed that the Pentagon was "assessing how commercial micro-nuclear reactors could power military installations at home," which the department said, "could be ideal for providing resilient and reliable off-grid power directly to military installations and other national security infrastructure."[20] In January 2021, President Donald Trump issued an executive order stating that, "the Secretary of Defense shall, within 180 days of the date of this order, establish and implement a plan to demonstrate the energy flexibility capability and cost effectiveness of a Nuclear Regulatory Commission-licensed micro reactor at a domestic military installation."[21] However, that domestic concept is distinct from the Pele Program for mobile reactors at FOBs – regarding rationale, risks, economics, and licensing procedures – and so will not be analyzed in this study.

Safety and Security

Typically in the nuclear field, "safety" refers to accidents that release radioactivity, while "security" refers to adversaries attacking a reactor or stealing material for weapons. The two concepts are related, especially when contemplating a reactor on a FOB. The Pele Program requires MNPPs to be "inherently safe," meaning they would avoid radiation release in the event of an accident or an adversary attack, but this may not be physically possible for reasons explained below.

Reactor designers for decades have pursued inherent safety via two main strategies. The first is ensuring passive cooling of the fuel in the event of an accident – to prevent melting, fire, or explosion that could release radiation. The second is creating encapsulated fuel with a high melting point to contain radioactive material inside the fuel even if passive cooling were to fail.

However, potential attacks on MNPPs, and counter-measures intended to provide security, could undermine inherent safety. The most obvious threat is from precision-guided munitions. This danger was highlighted in the January 2020 attack by Iran on U.S. forces at Iraq's al-Asad base using ballistic missiles of two varieties including the larger Qiam-2, which is 40-feet long and has an estimated 750 kilogram (kg) warhead containing fragmentation high explosive and/or cluster munitions. Eleven missiles hit the base and damaged or destroyed at least five structures, leaving craters as large as 30 feet in diameter (Figure 1), and igniting a large fire (Figure 2). American forces received warning several hours in advance, and so were able to take cover and disperse to avoid any deaths, but more than a hundred troops still suffered traumatic brain injuries, and 29 received Purple Hearts.[22]

Figure 1. Crater caused by Iranian missile strike, January 8, 2020

Source: "60 Minutes," CBS News, February 28, 2021.

The missiles were fired from approximately 500 km and were extremely accurate, estimated to have a 50 percent chance of landing within tens of meters of their intended target, known as the Circular Error Probable-50 (CEP50).[23] By contrast, in its 2018 report on mobile reactors, the Army had assumed Iranian missiles were much less accurate, having a CEP50 ten times bigger.[24] Several of the strikes may have been direct hits, including one in the middle of several structures (Figure 3). Experts assess that the missiles did not require satellite geolocation but were terminally guided and maneuverable. The base did not have anti-missile protection until after the attack, when three air-defense systems were installed belatedly.[25] However, even such systems might not have prevented the damage because, as a respected French think-tank notes, "Iran's growing mastery of maneuverability technologies poses the fundamental problem of adapting the terminal anti-missile defenses deployed in the Gulf, whose technologies are essentially optimized for the interception of un-maneuverable craft."[26]

Figure 2. Fire caused by Iranian missile strike, January 8, 2020

Source: "60 Minutes," CBS News, February 28, 2021.

If a MNPP were deployed to such a FOB, an adversary's terminally guided munitions could target the distinct signature of its footprint, heat output, connection to a microgrid, and related characteristics. This vulnerability will grow as adversary munitions become increasingly accurate. On January 1, 2021, Congress reflected such concerns in the enacted annual defense bill by requiring the Pentagon to provide, "an assessment of physical security requirements for use of such reactors on … non-domestic installations or locations, including fully permissive, semi-permissive, and remote environments, including a preliminary design basis threat analysis."[27]

The U.S. Army, in its 2018 report, conceded that, "the MNPP is not expected to survive a direct kinetic attack," but it argued that defensive measures could prevent a direct impact, thereby averting significant radiation release. However, as Dr. Edwin Lyman, a physicist at the Union of Concerned Scientists, has explained, measures to avert kinetic damage might undermine the reactor's inherent safety, which relies crucially on convective air flow to reduce overheating of fuel that could disperse radioactivity.[28] The Army suggests it would defend the reactor from attack by both burying it underground and enclosing it under a shelter – "dug in with overhead cover"[29] – but each of those tactics would inhibit passive cooling. Thus, protecting the reactor from kinetic-induced radiation dispersal could increase the risk of heat-induced radiation dispersal. If so, there might be no way to ensure against radioactive release, which the Pele Program says is a requirement.

Overheating of fuel could be triggered by at least two attack scenarios: a kinetic blast burying the reactor in debris, or infiltrators sabotaging the reactor by covering it with an insulating blanket. TRISO fuel, mandated by the Pele Program, is designed to retain its radioactive material even at very high temperatures, but tests at Oak Ridge National Laboratory (ORNL) have revealed fuel failures and release of highly radioactive cesium-137 at temperatures above 1500° C.[30] Micro-reactors using TRISO fuel are designed not to exceed 1400° C, even in a loss of coolant accident, but that assumes "direct heat transfer to the surrounding environment,"[31] which might not be possible if passive cooling were blocked by an adversary attack or the Army's defensive measures. Lyman also warns of "incendiary weapons that burn hotter, such as thermite," and potential graphite oxidation.[32]

Figure 3. Iranian missile hits the center of several structures on Iraqi base, January 8, 2020

Source: Reuters

Because a MNPP would generate less than one percent of the power of a commercial nuclear reactor, any release of radiation from an attack or accident would be proportionally smaller. However, the Army's 2018 report makes a bolder claim – that the new design of MNPPs would virtually eliminate risks. Traditionally, the U.S. Nuclear Regulatory Commission (NRC) has required nuclear powerplants to establish radiation Emergency Planning Zones

(EPZs) of approximately 10 miles for inhalation and 50 miles for ingestion.[33] By contrast, the Army claims that, "The MNPP system reduces the EPZ to hundreds of feet, a substantive leap forward in safety."[34] However, the top counter-terrorism official at the U.S. National Nuclear Security Administration criticized proposed EPZ reductions for new reactor designs in July 2020, warning the NRC that, "Historically, reactor accidents have been the result of or complicated by unforeseen risks or hazards and/or the inability to respond accordingly."[35]

Thousands of U.S. troops would be in close proximity to a MNPP on a large FOB and thus potentially susceptible to radioactive exposure from an attack or accident. Personnel tasked with rapid evacuation of an irradiated and possibly damaged reactor core could receive especially high exposure.[36] If U.S. forces abandoned the FOB but could not evacuate the MNPP, the adversary would come into possession of several hundred kilograms of highly radioactive spent fuel in millions of tiny balls that could be used for radiological terror attacks. If the adversary could disperse these balls, which emit dangerous radiation, it could contaminate large areas and induce panic even if the balls were not ruptured to further spread their contents. The Pele Program manager implicitly acknowledged such concerns in an August 2020 presentation, conceding that, "I don't think anytime soon we're going to have these things actually at the front, there are a lot of safety concerns with that."[37]

Rationale #1: Casualty Reduction

The main rationale cited to justify Army mobile reactors for FOBs is to reduce casualties from convoys that deliver diesel fuel for generators to produce electricity, a risk typically illustrated by a stock photograph (Figure 4). The statistical evidence for this rationale is quite old, dating to 2010, as cited in a 2015 RAND report: "From October 2001 to December 2010, of the approximately 36,000 total U.S. casualties in OIF [Iraq] and OEF [Afghanistan], about 18,700 (52 percent) occurred from hostile attacks during land transport missions."[38] This outdated statistic is still cited in recent government documents including the 2018 Army report, a 2018 Energy Department report, and a 2021 Army presentation.[39] However, the historical claim cannot be verified, because it is based on a Pentagon study that is "not available to the general public."[40]

Figure 4. Diesel fuel convoy to forward operating base

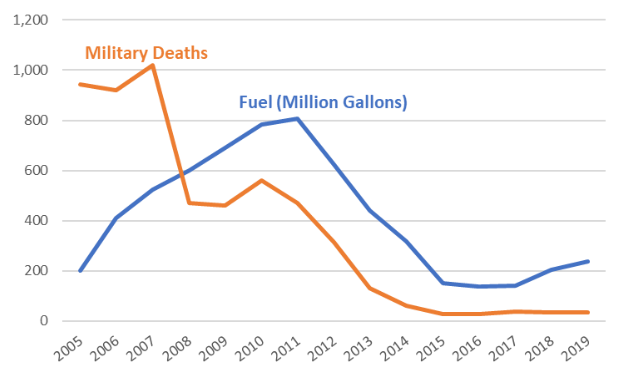
Source: Michael E. Canes, "Managing Military Energy for Greater Cost Effectiveness," November 6, 2012.

Contradictory evidence is provided in a publicly available 2009 Army study that cites a much lower casualty rate from convoys, as follows: "Resupply casualties have been significant in Iraq and Afghanistan. According to the Center for Army Lessons Learned, they have historically accounted for about 10-12% of total Army casualties – the majority related to fuel and water transport."[41]

Even if the 2010 statistic were accurate, it would not justify MNPPs for several reasons. First, according to the Army, only about half of the cited land convoys were for fuel, while the rest were for water and other supplies.[42] Second, according to a 2009 GAO study of five FOBs in June 2008, an average of 65 percent of the diesel fuel delivered was <u>not</u> for electricity generation but rather for land vehicles and aircraft.[43] This evidence suggests that only about 18 percent (.5 x .35) of the convoys comprised diesel for electricity generation. Thus, even if the 2010 statistic were correct that 52 percent of casualties had been from convoys, and assuming no bias in the distribution of convoy attacks or resulting casualties, <u>only nine percent (.18 x .52) of casualties during this period ending a decade ago were attributable to convoys of diesel for electricity generation</u>. Moreover, the share of delivered diesel fuel that is used for electricity generation is even smaller than 35 percent at big bases, which are the main candidates for MNPPs. Thus, mobile reactors at best could eliminate only a small fraction of the casualties associated with a war base.

The 2010 statistic is further misleading because during the past decade the incidence of casualties per convoy has plummeted dramatically. Figures 5 and 6 show that annual military deaths in Afghanistan and Iraq dropped sharply from 2007 to 2019, even as fuel deliveries increased, so the ratio of military deaths to delivered fuel decreased by 25-fold. In 2005, there were 4.7 military deaths per million gallons of fuel used, but nine years later this ratio had declined dramatically to 0.19, despite similar amounts of fuel being used. This evidence indicates that, by 2014, the Pentagon had largely solved the problem of U.S. casualties arising from fuel convoys, apparently through several innovations: better roads, an improved relationship with Pakistan, outsourcing transport to non-U.S. personnel, and use of airlift where land routes were especially vulnerable.[44] This finding is not an artifact of troop withdrawal because the largest decrease in the casualty rate, from 2007 to 2009, occurred during an increase in the number of deployed forces (Figure 7).

Figure 5. Annual U.S. fuel use and military deaths in Afghanistan and Iraq



Sources: See Appendix 1.

It is not known why the Army, in its 2018 report, cited an outdated casualty ratio that was 25 times higher than the reality at the time, but this misleading statistic cannot be used to justify mobile nuclear reactors. Even if convoys still were a large cause of U.S. troop deaths, it is unlikely that the most efficient way to reduce such casualties would be to develop, manufacture, and deploy expensive nuclear reactors that could eliminate only a fraction of the 18 percent of convoys that carry diesel for electricity generation. As a 2016 scholarly article concluded, "Since water and waste trucks are exposed to similar risks and subject to similar costs as fuel trucks … it is possible that much greater benefits with much less investment can be achieved by targeting water and waste logistics volumes instead of fuel."[45]

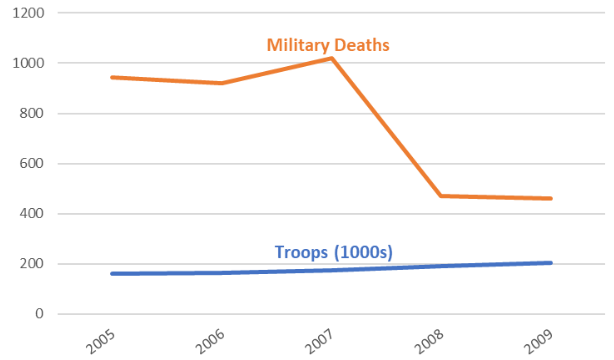
Figure 6. Ratio of U.S. military deaths in Afghanistan and Iraq per million gallons of fuel delivered

Sources: See Appendix 1.

Rationale #2: High-Energy Weapons

A second stated rationale for MNPPs is to provide sufficient power at FOBs for "future energy-intensive capabilities."[46] In the near term, this refers mainly to two types of "high energy" armaments: directed energy (DE) weapons that use lasers for air defense, and electro-magnetic (EM) guns that propel munitions without conventional explosives. Of the two, DE weapons appear to have greater likelihood of near-term deployment to FOBs. The U.S. Navy deployed a small DE weapon in 2014,[47] and although that armament has never been fired in combat, multiple branches of the military plan to deploy larger DE weapons this decade, especially for air defense. FOBs have pressing needs for improved air defense as noted above, and the power ratings of planned DE weapons might suggest an electricity requirement on the order of a MNPP. However, the DE weapons that might plausibly be deployed at FOBs actually have modest demands for electrical energy that could be provided much less expensively by diesel generators coupled with energy storage such as batteries. Additional energy demands on FOBs might someday arise from additive manufacturing, fuel production, data processing, autonomous systems, and water production and treatment – but these are even more speculative as to need, feasibility, timeline, and power requirements,[48] and thus should not drive current investments in deployable energy production.

Figure 7. U.S. Casualties Declined Sharply from 2007 to 2009 Despite Troop Increases



Sources: See Appendix 1.

Directed Energy Weapons

High-energy lasers (HELs) offer several potential attributes for air defense. They could in theory incapacitate a full range of adversary weapons – mortars, artillery shells, rockets, drones, cruise missiles, and ballistic missiles – including those that maneuver to elude conventional air defenses. They would do so by damaging at least one of several components of the incoming munition, such as the fuel tank, engine, guidance system, fuselage, wings, or warhead.[49] Since HELs eliminate the need to resupply expensive ammunition, the total cost per shot might be reduced by an order of magnitude compared to conventional anti-air missiles. However, HELs also face technical challenges – including massive heat output, and a reduction in lethality due to atmospheric dispersion and absorption – which have delayed deployment for decades.

The required power input for the laser is determined by three main factors: (1) size of target; (2) distance of target; and (3) electro-optical efficiency, which is the percentage of incoming power that is converted into the laser beam rather than waste heat. The power rating of a HEL signifies the outgoing laser beam, not the required input power. 50 kW HELs are believed sufficient for short-range destruction of aircraft, cruise missiles, drones, and ballistic missiles, but at least 300kW HELs may be required to engage such targets at longer range.[50]

Last decade, the Pentagon actively developed HELs of 50 to 100 kW.[51] The appropriation for FY 2018 included more than $150 million for such programs.[52] In 2019, the Army awarded $203 million for development of two competing prototypes of the 50 kW version, intended to be deployed in 2022 on a Stryker – which is a lightly armored, wheeled vehicle measuring approximately 23 feet x 9 feet x 9 feet.[53] Meanwhile, the Pentagon abandoned the 100 kW HEL in favor of pursuing a higher-power 300 kW version for "multi-Service/Agency needs," and in 2020 it awarded $178 million to three companies to each produce a prototype of the 300 kW HEL using different technologies, aiming for deployment in 2024.[54] Reportedly, this larger "laser will be mounted on a truck and likely accompanied by a generator vehicle with plenty of diesel fuel."[55]

Figure 8. Army 100 kW Laser Truck Concept

Source: Lockheed

Electricity supply requirements for a HEL depend on four main factors: (1) laser power; (2) ratio of time firing versus recharging and dissipating heat; (3) energy storage capacity; and (4) electro-optical efficiency. HELs do not operate continuously but rather are pulsed weapons. When the HEL is fired, it depletes the energy storage and creates enormous amounts of waste heat that must be dissipated. In between firings, the energy storage is recharged by the electricity supply, while the excess heat is dissipated gradually with assistance of a thermal management system that shrinks the required heat sink.[56]

A notional 100 kW HEL fires for one of every seven minutes.[57] The maximum electro-optical efficiency achieved in modern HELs is reported to be 40 percent,[58] so a 100 kW HEL would require an input of 250 kWe for one minute during each seven minutes. With sufficient energy storage capacity, this would require a continuous electricity supply of 250/7 or about 35 kWe, but to account for losses during charging and discharging the battery, it is conservative to assume 50 kWe, which could be produced by the Army's medium-sized 60 kWe diesel-fueled Tactical Quiet Generator (TQG). By contrast, a MNPP (1 to 10 MW) would produce 20 to 200 times the power needed, even if a HEL operated continuously, but in reality the HEL would operate only rarely.

The Army assumes a single Stryker vehicle would provide enough energy from its diesel fuel to both transport and power a 100 kW HEL. As of 2018, the Stryker's engine was rated at 260 kW but produced only 16 kW of onboard power including for any HEL, so there were plans eventually to increase the onboard power to 120 kW for various purposes.[59] The variable cost of each firing of a 100 kW HEL is estimated at merely $1 to $10 of diesel fuel,[60] compared to a MNPP's estimated lifetime cost of at least $200 million. In other words, <u>a 100 kW HEL would have to be fired more than 20 million times to incur diesel fuel costs equal to the price of a MNPP</u>. In practice, however, a HEL might be fired as few as hundreds of times during its life, including both training and combat. Such a weapon, which would rarely be used and thus only intermittently require electricity, is perhaps the worst imaginable rationale for a MNPP that produces extremely expensive, steady-state electricity. A MNPP might not even increase the firing rate of a HEL, if the time between shots were determined by the rate of heat dissipation rather than energy supply, as appears likely.

It is not known whether a FOB might require a higher-power 300 kW HEL for long-range targets. Lower-power HELs could destroy the full spectrum of plausible short-range targets, and the long-range targets might better be targeted by airborne platforms. However, if a 300 kW rather than 100 kW HEL were deployed to a FOB, the electricity requirement would increase only three-fold to about 150 kWe, which could be provided by the Army's large-sized 200 kWe diesel-fueled TQG.

The required duration of lasing to destroy a target depends on the laser power and target vulnerability. Several studies estimate an average lasing time per target of about five seconds by a 100 kW HEL, including for air defense.[61] Accordingly, such a HEL could destroy up to a dozen incoming targets in one minute, but afterwards would need to recharge for six minutes. If the Army sought a continuous fire capability, it could deploy seven such HELs, enabling destruction per hour of up to 60 x 12 = 720 targets. This capacity would far exceed current needs, considering that when Iran attacked U.S. troops in Iraq in January 2020, it launched only 16 ballistic missiles over the course of an hour.

The Army, as noted, has discontinued development of the 100 kW HEL but is proceeding with the 50 kW version. If the Army deployed seven 50 kW HELs at a FOB, with 40-percent optical efficiency, and sufficient energy storage capacity, the power supply requirement would be 7 HELs x 50 kWt x (1/7 minutes firing) / 0.4 optical efficiency = 125 kWe, which could be provided by one 200 kW TQG, accounting for losses in charging and discharging the battery. Such an electricity supply would be sufficient even if all seven HELs fired around the clock, whereas in practice they would operate only during the rare adversary attack, so the diesel generator would mainly comprise surplus power capacity. In this context, a MNPP would be gratuitous as it would produce 5 to 50 times as much electricity as the traditional diesel generator that itself would be more than sufficient for the mission of powering seven HELs to achieve continuous fire capability in the unlikely event such need ever arose.

Electro-Magnetic Railgun

The Pentagon also has been developing electro-magnetic railguns for many decades, mainly for the Navy, but unlike the HEL no such system ever has been deployed. The weapon works by sending a massive pulse of electricity along two rails, creating a magnetic field that propels a sliding armature carrying the projectile. In 2018, General Atomics won a three-year contract to develop and test an Army prototype 10 megajoule (MJ) railgun, intended to be able to fire 10 precision-guided projectiles in one minute to destroy targets via impact without an explosive warhead.[62] If such railguns worked, they could have several operational advantages over conventional artillery and rocket launchers: doubled range (to 100 miles), tripled speed (to 5,000 miles per hour), and safer ammunition storage (due to absence of explosive).[63] Ammunition expenses also could be slashed, because each EM projectile is expected to cost $25,000, lower by an order of magnitude than conventional anti-air missiles – not accounting for the comparative prices of the launch systems.[64] However, the weapon still faces major technological uncertainties, including whether electronics in the projectiles could survive the massive acceleration and electro-magnetic fields at launch, and whether the gun rails or barrels would wear out quickly.

Figure 9. Army Electro-Magnetic Railgun Concept

Source: General Atomics

Energy requirements at a FOB for EM weapons would be similar to HEL weapons in several ways. EM railguns also use pulsed power – necessitating both an electricity supply and energy storage – and produce massive amounts of waste heat that must be dissipated gradually between bursts of fires. The electricity supply requirement would be determined by several factors: (1) Power of the gun, which is the projectile's kinetic energy at exit; (2) electro-mechanical efficiency, which is the percentage of incoming electricity that is converted into projectile energy rather than waste heat; (3) the ratio of time firing versus time recharging the energy storage and dissipating waste heat; and (4) energy storage capacity. Estimates for these factors are still speculative, because no deployable railgun has yet been produced. For illustrative purposes, if the Army acquired a 10 MJ railgun that could fire five rounds per minute, and if 20 minutes were required for cooling and recharging between such bursts, and if the electro-mechanical efficiency were 20 percent, and assuming adequate energy storage, and ignoring losses in charging and depleting the battery, then the required electricity supply would be: 10 MJ x 5 shots x 16.67 kw-minutes/MJ x (1/21 minutes) x (1/0.2 electro-mech efficiency) = 198 kW.

Diesel generators could easily provide such electricity supply. Indeed, the Army envisions that a truck equipped with a hybrid diesel-electric drive could power both the vehicle and a 10 MJ railgun.[65] For air defense, which is the main objective of the Army's current railgun development efforts, the weapon would be used only during rare enemy attacks, and even then only intermittently. As with a HEL, this makes EM weapons suitable for spot power generation using diesel fuel coupled with energy storage, rather than expensive steady-state power generation by a MNPP.

Few Suitable FOBs

Even proponents of MNPPs concede that manufacturing the first one would be expensive, but they argue that per-unit costs would decline sharply as large numbers were ordered. In reality, however, there will be few if any FOBs that use enough electricity to potentially justify a MNPP, so it is unlikely that economies of scale from mass production could be realized. The Pele Program RFS specified the power output of MNPPs as ranging from 1 to 10 MWe, but as noted the maximum apparently was subsequently capped at 5 MWe. The cost per unit of power would likely decline with increasing size, so low-power MNPPs with output of 1 MWe would be least economical. If casualties from convoys of diesel ever again became a problem, the lower power MNPPs also would do less to address it, since they could eliminate fewer convoys. Therefore, the strongest possible case for MNPPs can be made for larger ones with maximum output of either 5 or 10 MWe. This raises a key question: How many FOBs use so much electricity?

Electricity demand and supply at a FOB typically correlate positively with number of personnel, but not necessarily linearly. Small FOBs have few amenities and thus low electricity demand per capita. They also tend to be inefficient in producing electricity, because they simultaneously run multiple generators well below capacity in the absence of a microgrid. Larger FOBs have a broader range of activities and amenities, and thus higher electricity demand per capita. They also can produce electricity more efficiently by operating prime generators at or near capacity for distribution via a microgrid, although in practice they also operate many smaller generators less efficiently. Usage of electricity also varies within and between days, so that in the absence of energy storage the production capacity must exceed not only the average usage but the peak demand.

Table 1. Energy Usage at Afghanistan FOBs: 2010 Per Capita Estimates

FOB Size	*Electricity Supply Capacity (kW)*	*Electricity Demand Average (kW)*	*Fuel Demand Overall Average (gpd)*	*Fuel Demand for Electricity Average (gpd)*
Large support camps	4	1 – 1.2	7 – 9	3
Battalion size bases	1 – 3	.5 – 1.2	2.5 – 4.5	1.5 – 2.5
Company size or smaller	< 2	< 1	.25 – 2.5	?

Source: Michael Bowes and Barry Pifer, "Reducing Energy Footprint on the Battlefield," CNA, CRM D0022638.A2/Final, June 2010, 17-19.
Note: gpd = gallons of diesel fuel per day (per capita).

Previous research suggests that at large FOBs, the per capita electricity demand is about 1 kW average and 2 kW peak, and the supply capacity is larger. A 2010 study of Marine Corps FOBs in Afghanistan by CNA (Table 1) found that such camps, which typically house at least 5,000 personnel, had average demand of 1.0 to 1.2 kW, which was supplied by a capacity of 4 kW per person. Exemplifying this, in August 2009, Camp Leatherneck in Afghanistan housed about 5,000 Marines and had an average electricity demand of 5 MW, supplied by 196 generators with total capacity of 19 MW,[66] indicating that the electricity capacity was about four times the average demand. Army test base studies suggest that peak usage is typically about twice average usage,[67] so Leatherneck's peak usage may have been around 10 MW, or 2 kW per person.[68]

Electricity supply capacity on FOBs often dwarfs both average and peak demand due to inefficiencies, as at Camp Leatherneck in 2009, but the Pentagon is working to fix that in two main ways. First, microgrids allow electricity from any generator to be channeled to any end user, so that supply capacity can be reduced to slightly above peak demand. Second, energy storage allows electricity produced at times of low usage to be utilized at times of high usage, so that supply capacity can be reduced further to slightly above average demand. This suggests a FOB with 5,000 personnel could be adequately supplied by 5 to 10 MWe of electricity generation, depending on the extent of the microgrid and energy storage.

Assuming that Pele MNPPs would be most cost efficient if they produced at the maximum power level (5 to 10 MWe), and that such output would suffice for 5,000 personnel, it is necessary to explore how many U.S. FOBs have at least that population. According to a RAND analysis, from 2012 to 2014, when the U.S. averaged 60,000 troops in Afghanistan, six of its bases each exceeded 3,000 personnel on average, including contractors.[69] By extrapolation, a very rough estimate is that at the peak of US deployment to Afghanistan and Iraq, in 2009, when slightly over 200,000 troops were deployed, about a dozen bases contained 5,000 or more personnel and thus potentially could have been suitable for the most economic utilization of one or more MNPPs.[70] Today, by contrast, the number of such FOBs is zero, which would inhibit the economic utilization of MNPPs. Prospectively, as well, in light of diminished U.S. public support for large deployments of forces, few if any cost-effective opportunities for MNPPs on FOBs may arise in the foreseeable future.

The Pentagon also is cutting electricity capacity needs on FOBs through efficiency reforms such as insulating barracks and equipping them with thermostats, and adding microgrids and energy storage.[71] The Army has found such changes can cut by more than half the diesel fuel required for electricity at a large base in Afghanistan by diminishing the demand for electricity and increasing the efficiency of its production.[72] Renewable energy, including solar and wind, can help decrease the remaining demand for non-renewable sources.[73] A U.S. national laboratory also has explored connecting FOBs to the power grids of their host countries,[74] as is typical for other types of overseas U.S. bases.[75] Such reforms will reduce further the likelihood that a future FOB would require 5 to 10 MWe of power from a MNPP, as necessary to optimize the reactor's economics. In light of this reality, the Army in 2018 modified its rhetoric, claiming instead that MNPPs could be deployed to large rear bases – rather than forward bases in war zones. However, this switch undermined the Army's ostensible main rationale for expensive MNPPs: to reduce casualties from delivering diesel fuel to FOBs. The rear bases that the Army identifies as candidates for MNPPs are located in secure locations such as Alaska and Puerto Rico,[76] which face little risk of casualties from fuel deliveries. Such bases already have secure and affordable electricity supply, typically either from the local power grid or generators utilizing diesel fuel that can be delivered by surface vessels without armed escort, thereby sharply reducing the fully burdened cost of fuel and energy.[77]

Absent substantial demand for MNPPs on FOBs, even advocates concede that the per-unit cost would rise sharply, as detailed below, suppressing demand further. This by itself should not rule out research and development, but it does suggest little need to rush towards building and testing one or more prototypes in anticipation of imminent widespread deployment. Civilian demand for micro-reactors may arise, for example at remote mining sites, but such systems would have less rugged requirements than the military versions for FOBs. If the main goal of the Pele Program is actually to subsidize next-generation civilian reactors, as some have speculated,[78] then its strategy of spending hundreds of millions to develop rugged military reactors that would be too expensive for civilian use appears misguided.

Costs of MNPPs on FOBs

The Army's 2018 report asserts that MNPPs would produce electricity less expensively than traditional diesel generators on FOBs, but it relied on unrealistic reactor cost estimates several times lower than even the industry claims. The prospective cost of MNPP electricity depends on various assumptions: reactor design and licensing costs, construction cost, discount rate, power rating, lifetime, and capacity factor (the percentage of lifetime actually operating). Another complication is that electricity cost is typically substantially higher for First of a Kind (FOAK) than Nth of a Kind (NOAK) plants, which benefit from economies of scale and amortization of one-time expenses such as design and licensing.

The Army's 2018 report projects that, "the cost is just 8 cents per kWh," for MNPP electricity on a FOB, using a NOAK plant. That is less than half of the report's estimated electricity cost using diesel, 18.2 cents per kWh, which is based on contemporaneous fuel prices and a 75-percent capacity factor for generators. The Army claims its estimated MNPP electricity cost is actually conservative because it assumes only a 75-percent reactor capacity factor, whereas the cost could be reduced to 7 cents per kWh by increasing that capacity factor to 97 percent.[79]

However, other studies – including by nuclear energy advocates – project the electricity cost from civilian micro-reactors to be much higher, even without expensive military requirements for rapid mobility and wartime security. For example, the Nuclear Energy Institute (NEI), the U.S. lobbying arm of the industry, analyzed the cost of "Micro-Reactors for Remote Markets," in April 2019. Its report projected that the overnight capital cost alone for a 5 MWe civilian reactor would be $75 million, and that the electricity cost could reach 41 cents per kWh for a FOAK reactor, or 33 cents even for a NOAK – despite optimistically assuming a 40-year lifetime and 95-percent capacity factor.[80]

Such rosy assumptions are implausible for war bases, so Army reactors would have even higher electricity costs. FOBs typically have lifetimes much shorter than 40 years, and their harsh conditions and fluctuating operational tempo would constrain the reactor's capacity factor. A more realistic lifetime of 10 years would increase the electricity cost of even a civilian reactor to as much as 65 cents per kWh, according to NEI.[81] Reducing the capacity factor to a more realistic 48 percent would double the cost again, according to NEI,[82] potentially up to $1.30 per kWh – which is 16 times the Army's estimated cost of MNPP electricity and seven times the Army's estimate for diesel-generated electricity. The Pele

Program manager also revealed in August 2020 that MNPPs likely would have lower power and shorter lives than previously indicated, saying that, "We're talking about 1 MW, 2 MW for 3 or 4 years." Any reduction in power would further increase the cost of producing each unit of electricity. Similarly, if "3 or 4 years" pertains to the life of the reactor not merely its fuel, that too would increase the cost per kWh.

NEI's price tag for civilian micro-reactor electricity excludes the upgrades required for Army versions, which Idaho National Laboratory (INL) stated in a 2015 report would be substantial. INL is the premier U.S. laboratory for advanced reactor development, and its report on prospective Army reactors warned that, "Adding design requirements for portability, air portability, extreme passive safety, liquid fuel production, and rapid removal create the need for additional development, technology, and cost." Accordingly, the national laboratory concluded that the current goal of placing a MNPP on a FOB, as proved true for the Army's previous reactor program, "may be impracticably expensive."[83]

Regulatory Hurdles

The Pele Program's goal of deploying MNPPs to FOBs also faces substantial regulatory hurdles – at home and abroad – that could delay or derail it. Domestically, the Pentagon envisions at least three key regulatory milestones: (1) DOE safety approval and testing of one or more prototype reactors at INL or ORNL by 2023;[84] (2) a deployment demonstration starting in 2024, lasting perhaps until 2027, encompassing airlifting at least one MNPP with fresh fuel to a remote domestic government facility, possibly in Alaska, operating the reactor, and then return airlifting the reactor including its irradiated fuel;[85] (3) an NRC licensing process of about three years, to enable commercial entities to operate such plants and potentially provide electricity to the Army via power-purchase agreements. The first milestone is ambitious enough – entailing the design, safety review, and construction of at least one entirely new reactor within four years of the initial contract award – but it could be the most plausible of the three steps, because its challenges are mainly technical not political. DOE's regulatory procedures involve less public input than do the NRC's, thereby expediting the process – although at greater risk of subsequent technical and political challenges.

The second milestone, airlifting a reactor to and from a domestic installation, may be unprecedented and could face political obstacles. This demonstration is deemed necessary to avoid making guinea pigs of Army troops, the host country, and any overflight countries when the first actual deployment occurs. In the demonstration, the outbound flight of the reactor would be controversial due to concerns that a crash into a body of water could initiate a chain reaction in the fresh fuel composed of HALEU, which is enriched to a considerably higher level than traditional nuclear powerplant fuel. Even greater controversy would arise from the return flight, containing hundreds of kilograms of highly radioactive spent fuel, including plutonium and cesium-137. In the past, domestic ground shipment of spent nuclear fuel has occurred, but air transport would pose different and potentially much greater dangers.

Previous attempts to airlift over the United States a single component of spent nuclear fuel, plutonium, have provoked intense public opposition. In 1975, the Scheuer Amendment (P.L. 94-79) was enacted, banning such shipments until development of a transport cask that could survive a simulated air crash. The NRC certified a small cask in 1978 for a maximum of only 2 kg of plutonium, and in 1981 an even smaller cask for amounts up to 40 grams.[86] Since that time it does not appear that civilian plutonium has been flown over the United States in substantial quantities. In 1987, planned plutonium air shipments from Europe to Japan sparked controversy due to anticipated refueling in Washington state or Alaska. In December of that year, the U.S. government responded by enacting the Murkowski Amendment (P.L. 100-203), banning such flights until rigorous certification procedures including an actual crash test of a cargo aircraft,[87] which never took place, so the plutonium ultimately was transported by sea instead. Interestingly, Sen. Frank Murkowski of Alaska led the successful campaign in 1987 to block plutonium air transport into and out of his state, due to fears of radioactive contamination from an accident, but now Alaska is considered a prime candidate for test deployment of the MNPP including air shipment of plutonium.

For NRC licensing, the Army's 2018 report optimistically estimated the "cost and time for performing a design, siting, and environmental review at approximate[ly] $10 million and 35 months."[88] U.S. government experts, however, suggest the process could take many times longer. For example, INL concluded in 2015 that, "Experience with NRC reactor licensing indicates that 20-25 years are required for development and approval of new reactor designs. Although military applications may not utilize the full NRC approval process, a near equivalent process will be used, requiring similar development and approval times."[89] A subsequent INL study of microreactors in 2018 underscored that NRC approval could prove the longest step, warning that, "due to strict licensing practices, regulatory approval can take 10 to 15 years."[90] The NRC is currently exploring relaxing licensing procedures for future non-mobile microreactors,[91] which might expedite their domestic use, but no analogous initiative has been announced for mobile reactors.

Foreign regulation also could stymie deployment of a MNPP to a FOB for several reasons, as acknowledged by the Defense Science Board.[92] First, a target country might have its own regulatory process for assessing the safety, evacuation plan, and air transport of a MNPP – and might not even start that process until the United States completed its own regulatory procedures and requested deployment of the reactor. Second, liability concerns could compel the target country and reactor vendor to demand that the U.S. government assume all responsibility in the event of an accident, which could trigger protracted diplomatic negotiations and domestic legislative processes. Third, if air transport necessitated overflying third countries, they too would have to approve the deployment, which could pose major hurdles. In rare prior incidents of international air transport of spent fuel, aircraft were diverted to circuitous routes to avoid such overflight obstacles. For example, even though a shipment from Romania to Russia in 2010 contained less than 24 kg of spent fuel, the "route avoided all transit countries and all major population areas" (Figure 10).[93] An Army MNPP would contain about 20 times that amount of fuel, potentially exacerbating the logistical and political challenges in deploying to and from countries that are nearly landlocked, such as Iraq, or totally landlocked such as Afghanistan.

Figure 10. Air Shipment of Spent Fuel in 2010 Avoids Overflights

Source: Igor Bolshinsky, et al., "Air Shipment of Spent Nuclear Fuel from Romania to Russia," INL/CON-10-17669, PATRAM 2010, October 2010.

Finally, air transport would need to satisfy international rules, including the IAEA's "Regulations for the Safe Transport of Radioactive Materials," which now require a Type C package capable of withstanding severe aircraft accidents. Russia qualified the first such Type C package in 2012, the TUK-145/C, with maximum capacity of 450 kg of spent fuel,[94] which could be sufficient for a MNPP's fuel. However, the Pentagon previously has implied that the MNPP including its fuel would be transported as a single unit,[95] weighing many tons, which might make it difficult if not impossible to satisfy the IAEA regulations.

Conclusion

There is currently no good argument for deploying mobile nuclear reactors to U.S. military bases in war zones. In light of adversary precision weapons, and U.S. defensive measures that might inhibit ambient cooling, a reactor accident could radioactively contaminate thousands of nearby U.S. troops. The cost of electricity from the reactor, due to its likely short life and low capacity factor in a hostile environment, would be many times higher than from diesel generators. The original rationale for the reactors, to reduce casualties from diesel fuel shipments, evaporated nearly a decade ago when the U.S. military figured out how to deliver such fuel with few if any U.S. casualties. An ostensible secondary rationale, to power future high-energy weapons, makes little sense because such weapons use only intermittent electricity, which could be provided at a fraction of the cost by diesel generators coupled with energy storage. Moreover, due to U.S. withdrawals from Iraq and Afghanistan, the Pentagon no longer has any forward bases with sufficient troops to require the amount of electricity produced by even a small reactor of 5 to 10 MWe. Finally, testing and deploying such a reactor, including flying highly radioactive spent fuel over the United States and foreign countries, would provoke substantial domestic and foreign opposition that could derail the project. Admittedly, some of these obstacles might diminish in coming decades, so it could make sense to continue low-level research of mobile Army reactors. For now, however, there is no justification for rushing to spend hundreds of millions of dollars by 2023 to develop and test the prototype of a reactor that could not be deployed safely, securely, and efficiently in the foreseeable future, if ever.

Appendix 1
Afghanistan and Iraq Statistics on U.S. Fuel, Troops, and Deaths

Fiscal Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Gallons of fuel (millions)	200	410	525	600	692	784	807	625	440	318	151	138	141	204	239
U.S. military deaths	943	919	1019	470	460	562	470	314	132	60	29	28	39	34	35
Deaths per million gallons	4.72	2.24	1.94	0.78	0.66	0.72	0.58	0.50	0.30	0.19	0.19	0.20	0.28	0.17	0.15
Troops deployed (1,000s)	162	163	173	190	204	178	133	72	61	30	10	11	19	19	14
Deaths per 1,000 troops	5.84	5.63	5.89	2.48	2.26	3.15	3.54	4.36	2.17	1.99	2.84	2.59	2.02	1.77	2.55

Sources:

- *Deaths: U.S. Department of Defense.*
- *Troops: "Afghanistan Index," Brookings Institution, August 2020; "Iraq Index," Brookings Institution, August 2020.*
- *Fuel use 2005-2008: Army Environmental Policy Institute.*
- *Fuel use 2010-2019: U.S. Defense Logistics Agency.*
- *Note: 2009 fuel use is not publicly reported, so the table interpolates from the immediately prior and subsequent years.*

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